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Radiocarbon

An International Journal of Cosmogenic Isotope Research

INTCAL 98: CALIBRATION ISSUE

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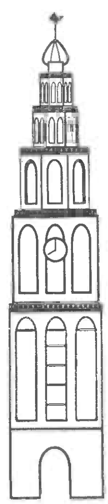
Cover design by M. Stuiver, P. J. Reimer and T. L. Saling of the University of Washington's Quaternary Isotope Laboratory

N.B. The annual List of Laboratories traditionally published in the third issue of *RADIOCARBON* is omitted from this issue because *RADIOCARBON* 39(3), containing a current list, appeared in mid-1998. Volume 41, Number 3 (1999), will contain our next published list. In the meantime, please refer to the up-to-date list on our WWW server at http://www.radiocarbon.org/Info/lablist.html.



RADIOCARBON wishes to acknowledge the generosity of the Centre for Isotope Research at the University of Groningen, The Netherlands, in making a donation to help subsidize the printing of this issue.

Photo courtesy of Stephen C. Porter

A TRIBUTE TO MINZE STUIVER UPON HIS RETIREMENT

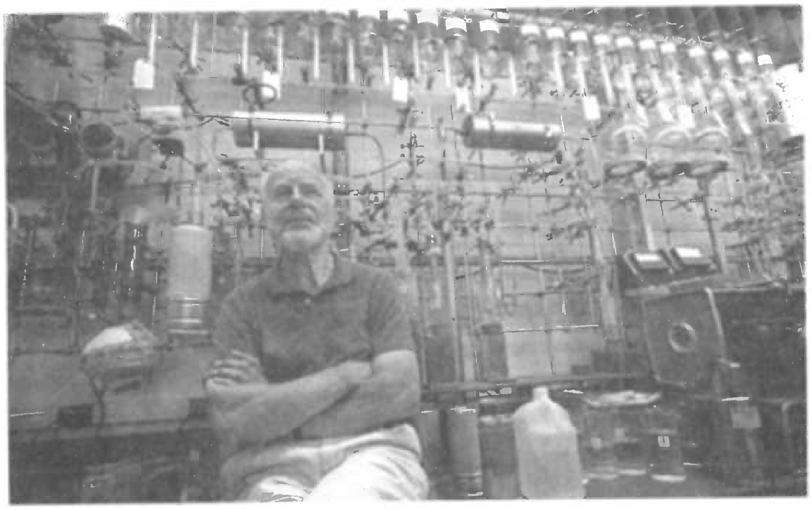
Former *Radiocarbon* Editor and *INTCAL98* Guest Editor Minze Stuiver retired in October 1998 as head of the Quaternary Isotope Laboratory at the University of Washington, Seattle. The renowned lab, which Minze founded 29 years ago, will close when he leaves. Throughout his long and productive career, Minze's integrity and dedication to science have earned him the respect and admiration of his peers. We are pleased to present the following tributes from just a few of his many friends and colleagues.

* * *

Austin Long

Whether you are a relative newcomer or a veteran to either the production side or as a user of radiocarbon measurements, the comments below from Minze's colleagues will give you personal recollections of a scholar and also an awareness of some less overt aspects of radiocarbon dating. If you are a new reader of *Radiocarbon*, you may notice what the veteran readers are aware of: the sense of international community that exists among those of us in the field. The remembrances below well illustrate this. The interesting aspect of this community is that its common thread is a technology rather than a discipline. Its triennial gatherings allow archaeologists to mingle with oceanographers, chemists and physicists. Happily, these scientific interfaces often are productive, and Minze's life illustrates this.

Minze began as a biophysicist, and applying his knowledge of physics and chemistry, he helped oceanographers understand oceanic upwelling and mixing, showed archaeologists how better to understand chronological uncertainties and apply corrections to their ^{14}C dates, and was involved in revealing the geophysical processes modulating the production rates and levels of radiocarbon in the atmosphere. Minze is a scholar who selects important problems, works meticulously toward their completion, and presents results in calm, dispassionate and thorough fashion. He edited this journal for 10 years until the heart surgeon demanded he cut back on his long work days. His editing has not stopped, as you saw from the 1993 calibration, and as you will see in this issue. Minze is not really retired, just redirecting his energy and talents.

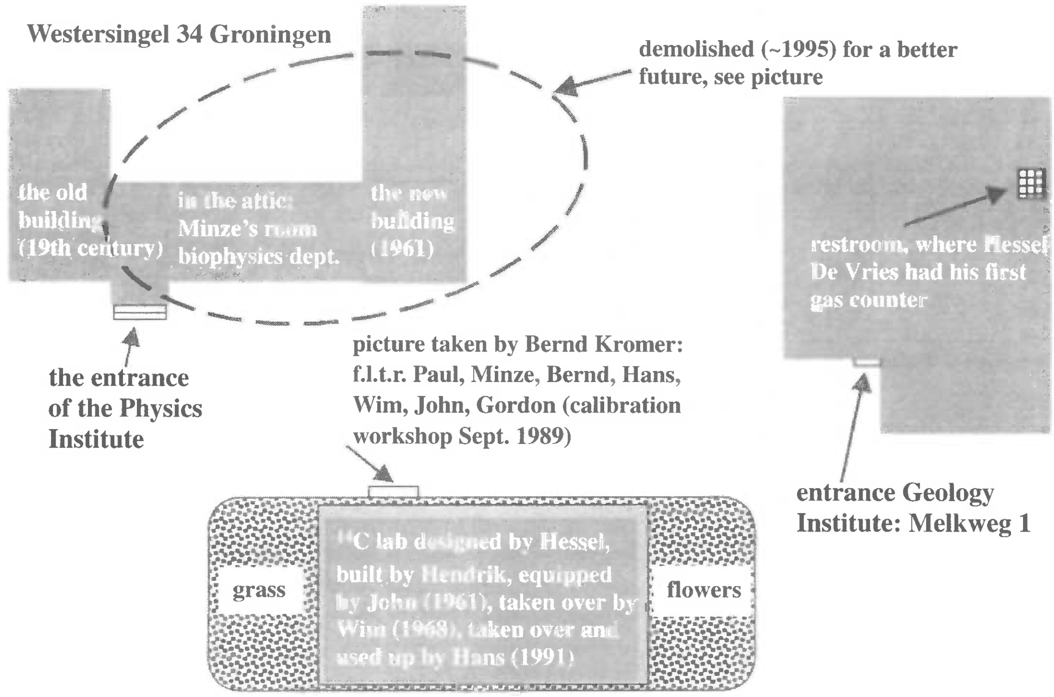


Minze Stuiver in his Seattle ^{14}C lab. Photo by Jimi Lott/The Seattle Times.

Minze and Anneke Stuiver. Photo by Stephen C. Porter, University of Washington.

Minze in 1970 (left) and 1976 (right, in Seattle). Photos courtesy of Stephen C. Porter, University of Washington.

WIM MOOK AND HANS VAN DER PLICHT



As a student of Hessel de Vries, Minze wrote a thesis on "The Physics of the Sense of Smell". In his career, he proved to have developed a "good nose" for selecting his interests. One can wonder whether this "nose" led him not to continue working in Groningen on ^{14}C, considering the position of the first gas counter. He would have been involved in the demolition of 3 laboratories after all.

E. H. WILLIS

Hessel de Vries and the Groningen Laboratory: Recollections of Pioneers in Radiocarbon Dating

The radiocarbon community owes a very considerable debt to the early work at the University of Groningen, Holland. Throughout the fifties, it was arguably the leading radiocarbon laboratory in Europe. It also happens to be Minze Stuiver's Alma Mater so one has rummaged among the cobwebs in the attic of one's mind for some recollections of that most productive era. It is a story of imagination, improvisation, hard work, and dedication; the sort of qualities for which the Dutch are justifiably renowned. It was an environment of which Minze can be justly proud to have been part, as I am proud to have been but a witness. These recollections portray a world of difference between life in a laboratory in Minze's early days, and conditions in laboratories prevailing upon his retirement.

I first visited Groningen in 1953. It was as isolated a place as one can imagine; it was literally at the end of the line from Amsterdam, and although the German border was only about thirty kilometers away there was little or no cross border traffic. Later, Groningen was to become a center for the oil and gas industry, but for the moment it remained what it was, a parochial little town on the flat damp lands of northern Holland. World War II had been traumatic and the immediate postwar years had been protracted and difficult; bitter memories had been slow to fade. The main square of the town still bore the sad evidence of the savage fighting between Canadian contingents and the retreating SS, and pock-marks could be seen on some of the buildings that remained. Universities everywhere in Europe were, at best, still trying to claw their way back to the standards existing before 1939. Money was scarce beyond today's imagination, and old and dilapidated buildings had to serve for the moment. The science faculty of the University of Groningen was no exception. I well remember getting off the bus from the railway station on that cold and foggy December afternoon, and gazing somewhat despondently upon its somber and forbidding red brick exterior. Its uninviting interior proved faithful to its exterior promise, for it made no concessions whatever to either aesthetic taste or creature comfort. Fortunately, the downside stopped right there. Whatever its physical constraints, it had more than its share of bright people. For all the cruel legacies of the recent war, a positive one then on display in Groningen was a fervored drive to be a part of the new world being opened up by science. In this environment thrived Hessel de Vries, a single minded and energetic young professor of Biophysics. His interests ranged from the role of visual purple in sight, the phenomenon of smell and, of course, the exciting new technique of radiocarbon dating.

For all his biophysical interests, it was radiocarbon which was to consume most of his energies. Libby's screen wall Geiger counter had been adopted by each new radiocarbon laboratory in turn simply because it worked—no other redeeming feature comes to mind for it was extremely inefficient. The most obvious alternative, gas proportional counting, could not be made to work reliably. Acetylene proved to work quite well as a counting gas, but had the dismaying propensity for demolishing everything in sight at the slightest provocation, a fact that I was to prove conclusively at Cambridge. Carbon dioxide, the obvious gas to use, was thoroughly un-cooperating when it came to good counting characteristics—until De Vries that is. A letter in a relatively obscure journal, *Physica* (XVIII, p. 652), towards the end of 1952 by De Vries and his student Barendsen recorded on one half of the very last page the simple fact that when carbon dioxide was purified to a very high degree it provided excellent counting characteristics. They later published a more comprehensive report in *Physica* (XIX, p. 987) in 1953, after the first Groningen date was achieved on January 15th of that year. Shortly after, Fergusson, in New Zealand, published a similar finding in *Nucleonics* (13, p. 18, 1955). Groningen had taken a major leap forward in the accuracy in radiocarbon dating, and gas proportional counting was the technique embraced for the next decade or so.

Never was there a man so free as De Vries in his help for others in the field, and many of us owe him a special debt of gratitude. As a young graduate student assigned the task of creating the Radiocarbon Laboratory at Cambridge University I was eager to learn more, and was cordially invited to visit. In those days, such visits were arranged mostly by post card because the postage was cheaper—the terse "Please come" on a post card was all that was needed—that was cordiality! De Vries' intensity for the subject became legendary. Later, in 1956, when I boarded the SS *Nieuw Amsterdam* at Southampton bound for America, en route to the Andover, Massachusetts Radiocarbon Conference, I was unexpectedly hailed from the upper deck by a familiar voice—De Vries talked incessantly of radiocarbon from one side of the Atlantic to the other, and it was the only time I nearly gave up.

The shortage of space, and the ability to get the most from strained resources to pursue meaningful research, were very obvious in that old building at Groningen. The purification system for the carbon dioxide was arranged around the walls of a landing on a stairway between two floors of the building. The landing had normally housed a toilet, which was still there in its cubicle but surrounded now with glass tubing, John Vogel, a later Director of the Groningen Laboratory, tells me that De Vries got his high voltage apparatus as surplus from a Canadian military dump. One could only marvel at the ingenuity of these people in making the most out of so very little. This was a classic example of "if only you want the result badly enough you will find a way to achieve it, however inelegant the apparatus and constrained the resources". One might add that academic salaries at that time were invariably commensurate with the frugality of one's surroundings, and this was amply reflected in our life styles. As it turned out, our contemporary graduate students in the USA were living equally frugally, which was not what we had been led to expect since our views of Americans were conditioned by the apparent opulence of visiting professorial rank scientists, who naturally enough traveled by plane and not by ship.

Groningen was a welcoming community and made you feel part of the family. It was in the course of one of many visits that I was introduced to a young graduate student working with De Vries in a rather antiquated (if he will pardon that description) laboratory, trying to measure the threshold of smell—he was Minze Stuiver. It is a joy to me that Minze and I have remained friends ever since that first meeting. He was trying to determine with mounting frustration how many molecules of mercaptan remained in a flask after many many dilutions. It was no mean task, since the wretched things wanted to latch on to every surface they could find, and not obey neat dilution factors. I admired him then, as I do now, for his ingenuity, discipline, and tenacity. These qualities were to be the hallmark of his career.

In the late fifties, Groningen, De Vries and the Radiocarbon Laboratory were prospering. De Vries had established a national reputation in Holland, and had secured funding from the Dutch Government for research stimulated by the disastrous floods of 1952 which took hundreds of lives. Groningen had also a fine tradition of archaeology, first under the aging Van Giffen who had held the fort during the war, and later under the youthful and energetic Waterbolk. It had been Van Giffen who had given De Vries the first impetus to make his "machine". The Groningen Laboratory was thus in the right setting and with the right track record to receive what meager support was available at the time. This support enabled the laboratory to be moved in February of 1954 into new single story facilities which in those days seemed indescribably modern. De Vries was pursuing some new ideas with newer low-background counters, and later was to induce Minze Stuiver to join him in the expanded endeavor on conclusion of his thesis work—a perfect choice.

In 1958 there occurred a discovery which promised to rock the foundations of radiocarbon dating. Henrik Tauber of Copenhagen, myself, and De Vries were in Hamburg at a conference on pre- and protohistoric science. Karl Otto Munnich of Heidelberg had had some suspicions that some dates from tree rings of known age from an oak from the Spessart Forest were not in line with their dendrochronology. He sent the specimens to De Vries, who repeated the measurements, and with his greater counting precision extended them to other well-dated material. His first results seemed to suggest the unthinkable—radiocarbon years and sidereal years were not a one-to-one match over the last few hundred years. This was a seeming blow to the integrity of a method which had been touted as an absolute chronological tool. The Hamburg conference was to have been his opportunity to present his case publicly for the first time, and was thus of some importance. De Vries was easily bored by conferences, and a day not spent in the laboratory was a day wasted—he wanted to go back home before it ended, and quite unexpectedly asked me if I would give his paper for him. Since I had recently spent a fair bit of time editing it for him, I agreed, but not without some trepidation. Henrik and I did a lot of head-scratching over the next few days on how best to make the presentation. Based on this paper, Henrik and I, joined by Karl Otto Munnich, performed a three-way experiment with De Vries' enthusiastic blessing, using tree rings at fifty year intervals from a giant sequoia going back 1300 years. Each sample was measured independently by two out of the three laboratories. They confirmed De Vries' findings, and the results were presented at the Radiocarbon Conference in Groningen in 1959, and published in one of the early numbers of what was to become *Radiocarbon* (*American Journal of Science Radiocarbon Supplement*, Vol. 2, p. 1, 1960). Thus began a more intense effort, so ably refined by others with greater precision than we could muster, using the bristlecone pine to produce a reliable calibration of radiocarbon years with sidereal years. It is an irony of progress that these corrections are now taken for granted as part of the technique.

The Groningen Laboratory continued to prosper over the years ahead under Vogel and then Mook, but I draw these recollections to a close with De Vries' tragic and untimely death in December of 1959. This was a blow to us all working in the field at the time, but especially to those in Groningen not least of whom was Minze. His patient work under De Vries' tutelage should be recognized for the singular contribution that it was, only serving to reinforce the luster of his later achievements. In his indefatigable way Minze moved on to those other challenges which I shall leave to others to describe. But I shall always remember Minze admiringly for those early years when we shared so much and when a "brave new world" was no cliche—it was real.

PAUL DAMON

Reminiscence of Minze in the Early Days of ^{14}C and Solar Cycles

We first met when you came to Yale as a Postdoctoral Research Fellow to set up the Yale radiocarbon laboratory in 1959. I was there to visit Karl Turekian. Then you and Anneke visited us during your spring(?) vacation in 1960. Anneke was pregnant with Ingrid. You were soon to publish your paper, using De Vries' electrical analog computer model of the carbon cycle, demonstrating for the first time the correlation of ^{14}C variations and the sunspot cycle (*JGR* 1961; *Science* 1965). We had just built a proportional counter laboratory and we were in the process of independently confirming the *ca.* 1.5% increase in atmospheric Δ^{14}C, which we renamed the De Vries effect (*Radiocarbon* 1962).

During your visit, we visited Andrew Ellicott Douglas, who was then 93 and fast declining, but with occasional flashes of energy and interest. Although dendrochronology and dendroclimatology had been so successful and took so much of his time, he had never lost interest in solar cycles. Our visit, telling him about our new approach to tree rings and solar cycles, seemed to evoke one of those flashes of interest and energy. His wife said that he had been depressed but obviously perked up and showed keen interest in the conversation. She thanked us for our visit and remarked that he had got a little tired of only female company.

The GEOSECS program that helped build your laboratory absorbed your attention for a while. This was followed by high-precision calibration of the radiocarbon time scale in which you took the lead beginning about 1962, but you got back to solar cycles during the last two decades with outstanding contributions. I have enjoyed your work and your friendship. Best wishes for a happy, healthy and productive retirement with much more leisure time than you have allowed yourself during many years of hard and productive work.

REIDAR NYDAL

At an early stage in my childhood I regarded retirement as a kind of illness. In the small village where I lived there where only a couple of persons who had an official employment with a regular income. When some of them retired, they were normally observed slowly walking on the road or resting in a chair. Such sudden difference was generally not observed for other people on the small farms, who regularly were growing potatoes and fishing as usual all the time.

In your case, Minze, you have already done more than growing potatoes and fishing, and will certainly make further scientific contributions. Your activity has been successful in a large number of main topics in the field of radiocarbon, including counting technique, natural ^{14}C variation, calibration, and the study of ocean circulation by participation in the WOCE and GEOSECS programs for the Atlantic, Pacific and Indian Oceans. Your most important contribution is probably the high-precision calibration curve for radiocarbon dating, also in collaboration with Gordon Pearson, Belfast, and Henry Polach, Canberra. The whole radiocarbon community relies on this curve and also follows your advice in reporting data.

I believe that scientists in the future will mainly appreciate you for your scientific contribution, as you have not announced much of your other qualities. You have certainly been aware early that scientific activity and success are not enough. With increasing age we are gradually more focused on your friendship and kindness which have blessed us for more than 30 years. It has always been nice to meet you, but we should have had more time. Finally, I wish you and your family all the best for your future and hope to see you again in radiocarbon or private connection.

WALLY BROECKER

Minze Stuiver will always be remembered as "Dr. Radiocarbon." He not only set a standard for excellence of measurements, but he also delved into all the important aspects of radiocarbon science, calibration, ocean circulation, very old samples, sunspots...

In 1984 at Zurich when asked what would happen to the beta counting labs in light of the emerging accelerator method, I made the seat-of-the-pants prediction that they would likely be retired along with their mentors. Now, this prediction is becoming a reality. An era which lasted almost 50 years is coming to an end. Sad, yes in a way, but for those who developed the radiocarbon method over these five decades perhaps, it is a fitting honor. The great research done with these old war-horse counting cylinders will stand as a permanent symbol of those who slugged it out making sure the gas was pure and the radon was gone. Minze will surely stand out as the best of them all.

I remember well the first meeting of ^{14}C scientists of my generation. It was in Groningen in 1959. It was there that I became acquainted with K. O. Munnich, Eric Willis, Heinrich Tauber, and, of course, Minze. There was also a Russian whose name I have long ago forgotten. We called him Shutka because of his broad smile and wonderful laugh. It's been many moons since those early days. Minze has remained a close friend and colleague. I wish him well in his retirement.

PAULA REIMER

Minze Stuiver has been a guiding light in science for those who know him and his work. His intuition is phenomenal, often predicting the results of much more complicated approaches. He never fails to go to the root of a problem. He has stubbornly remained ethical in all aspects of life. Those of us who were lucky enough to work with Minze have, hopefully, learned some of the more important lessons in life.

PIETER GROOTES

I first met Minze in Groningen, The Netherlands in 1975, during my Ph.D. study. He visited to compare notes on thermal diffusion enrichment of ^{14}C as a way to extend the ^{14}C dating range to 70,000 years and beyond. When, after finishing my Ph.D., I asked Minze whether he might have a postdoc opportunity, he answered with characteristic brevity that a one-year stay would not be a problem, but that I should not count on anything more. Yet one-year visits to the States may last a long time, as Minze demonstrated by going for such a visit to Yale in 1959! The Seattle thermal diffusion effort was successful and produced some of the oldest ^{14}C dates in the world (>70,000 BP).

Over the years Minze has had a lively interest in trees, which was decidedly unhealthy for the trees. Along the West Coast he collected sections of old-growth trees to create a tree-ring calibration for the last few thousand years independent of the bristlecone pines. After a field trip the lab would look like a wood workshop. Later, those trips extended farther afield from Kodiak Island to Patagonia and focussed on poor lonely trees from windy places. In the lab these told their story about their youth and their response to location and weather and to a slow change of CO_2 in the atmosphere. Minze's interaction with trees can also be seen around his home(s) in Bellevue and later Lopez Island. Minze and Anneke love the quiet of the forest, yet in his free time, Minze set to work to cut trees for a clearing to make a nice Dutch vegetable garden.

Visits to Minze's lab were common, and many visitors stayed at Minze's home in Bellevue. Yet quite a few he managed to confuse about the exact location of both home and lab by using, whenever possible, a different route between them every time.

Minze's long and prominent involvement in radiocarbon dating led at the Seattle Radiocarbon Conference to the pronouncement by a colleague that to be really "in" in radiocarbon dating one would have to learn Dutch.

Over these 17 years of collaboration, Minze has always been an innovative critical scientist, a great devil's advocate to test any plan or theory on, but also a generous and great colleague to work with.

[RADIOCARBON, VOL. 40, NO. 3, 1998, P. xi]

A NOTE FOR NOVICES

RADIOCARBON's previous special Calibration Issues in 1986 and 1993 (Stuiver and Kra 1986; Stuiver, Long and Kra 1993) have been among our most popular and widely distributed issues. This is not surprising, as reliable calibration of radiocarbon dates is crucial to researchers in disciplines where chronological interpretation of data is fundamental—archaeology, paleoenvironmental studies, and Near Eastern history, to name a few that are often represented in the pages of this journal. With INTCAL98, the precision of the calibration curves has been increased and their backwards range extended.

The theory of ^{14}C calibration is relatively straighforward: naturally occurring materials that exhibit annual growth phenomena (*e.g.*, tree rings, lake and marine varves) are ^{14}C-dated as precisely as possible over age ranges that can (ideally) be dated absolutely. The resulting calibration curve shows the relation between conventional ^{14}C dates and calendar ages, its trends and "wiggles" reflecting the variation over time of ^{14}C in the geosphere. Once generated, the calibration curves (or more accurately, their underlying data sets) enable the conversion of a date in radiocarbon years (BP) to a calendar age range or ranges (cal BC/AD). For many users of ^{14}C dates, this is a simple matter of plugging a conventional age into one of the computer calibration programs, or even of accepting and reporting the calibrated dates calculated by the laboratory when it returns results on a sample.

However, it is crucial to remember that a calibrated ^{14}C age is *probabilistic,* and must not be confused with an absolute calendar date. The papers in this issue report in great detail on the data sets used to construct the INTCAL98 curves; the methods used in choosing, treating and measuring samples; and the statistical assumptions made to arrive at calibrated dates and their associated margins of uncertainty. Understanding this background is important when using calibrated ^{14}C dates as evidence for a chronological argument, particularly when conventional ^{14}C dates intersect multiple ranges on the calibration curve or when claiming very narrow calendar ranges as probable dates of origin.

Introductory discussions of ^{14}C calibration can be found in Aitken (1990: Chapter 4), Bowman (1990: Chapter 4), Bronk Ramsey (1998b) and Taylor (1987: 133–142). The manuals for the OxCal (Bronk Ramsey 1998a), CAL25 (van der Plicht 1998) and CALIB (Stuiver and Reimer 1998) calibration software also discuss the principles of calibration as used in those programs.

David R. Sewell

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[RADIOCARBON, VOL. 40, NO. 3, 1998, P. xii–xiv]

EDITORIAL COMMENT

Welcome to INTCAL98, the last calibration issue of the present millennium. This 1998 calibration volume is the third of a series published in *RADIOCARBON*, amending and extending the previous issues (28(2B), 1986 and 35(1), 1993). The advisability of publishing a third calibration issue was agreed upon at the 16th International Radiocarbon Conference in Groningen, June 1997, following a thorough review of the existing tree-ring data sets by a working group meeting in Heidelberg in late 1996 (Kromer *et al.* 1996).

Calibration is the conversion of radiocarbon ages (BP) into calibrated ages (cal BC, cal AD, or cal BP). For INTCAL98, we used paired data sets of 1) tree rings dated by ^{14}C and by dendrochronological counting, and 2) corals dated by ^{14}C and uranium-series, as we did in the previous 1993 calibration issue. In both cases, considerably more measurements have become available in the past few years. We present here an INTCAL98 calibration curve based upon tree rings for its more recent segment, and upon corals for its older section. In addition, as an exception to the rule, it was decided to include Late Glacial marine varves because this newly developed data set strengthens the coral/tree-ring link considerably.

Other paired datings (between ^{14}C and other dating methods using, *e.g.*, thermoluminescence, speleothems and various laminated sediments) are not included in INTCAL98. Instead, *RADIOCARBON* has planned a "comparison issue" in the near future that will contain these records. Their future incorporation into the INTCAL data set is foreseen when discrepancies among the records are resolved.

The major revisions here to the dendrochronological calibration involve the German oak chronology from Hohenheim, corrected by intercomparison with the Göttingen dendrochronology. The important record from the floating German Preboreal pine chronology has been extended and shifted with respect to previous publications.

Since the publication of the 1993 calibration issue, there has been some disagreement about which tree-ring data set to use—the 1986 version, which carried the status "recommended" (Mook 1986), or the more recent, but never formally recommended, 1993 version. Some of the corrections applied to the 1986 data and included in 1993 were questioned as reflecting possible local effects. This question has not really been resolved, but we stress here that these effects are very small (15 ^{14}C years or less) and for most practical purposes negligible. (For further details, see the discussion and references in Stuiver *et al.* "INTCAL98 Radiocarbon Age Calibration", in this issue.)

The INTCAL98 data set is decadal, *i.e.* has a time resolution of 10 calendar years, in its tree-ring portion. For certain time spans, higher-resolution data sets are available, such as a 3-yr curve for the 3rd and 4th millennia BC from Pretoria/Groningen and an annual curve for the last three centuries from Seattle. For use of these particular records, we refer to the original publications.

The tree-ring part of the INTCAL 98 data set is based on the ^{14}C determinations of several radiocarbon laboratories. The dendrodated samples for which ^{14}C ages are available do not always overlap between laboratories (Fig. 1).

The new INTCAL98 calibration curve has more detail than the 1993 curve (Fig. 2). This is mainly due to the incorporation of a larger coral and varve data set (corrected for a 500 ^{14}C yr reservoir defi-

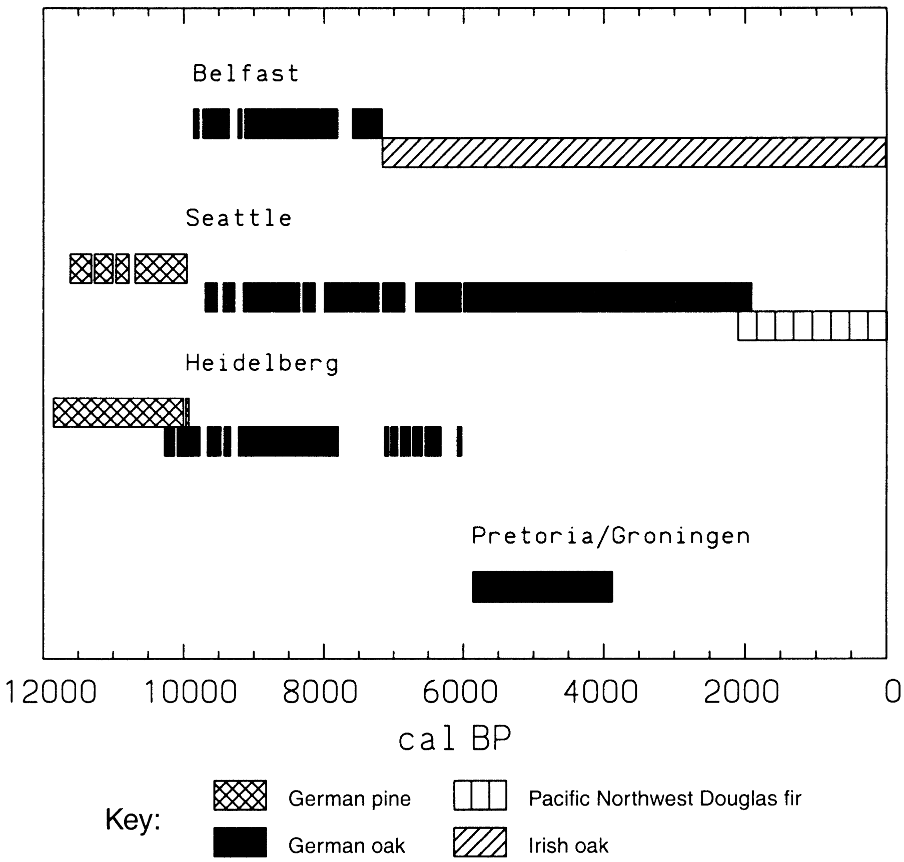

Fig. 1. Age ranges of tree-ring samples used for the construction of the INTCAL98 calibration curve

ciency) for the pre-11,800 cal BP portion. Century-scale shifts of the 11,800–7200 cal BP interval were introduced by the dendrochronological reassessment of the German oak series. The calibration curve differences are limited to a decade, or less, for the 7200–0 cal BP interval.

With all mentioned constraints in mind, the INTCAL98 calibration curve is recommended for general use from now until further notice. Both the data used to generate it and the CALIB computer program can be downloaded *via* the Internet from the Quaternary Isotope Laboratory (QIL) in Seattle, Washington (http://depts.washington.edu/qil/). Calibration programs must be upgraded with the new data set.

We appreciate the efforts of the many researchers who have contributed to the present work, and hope that you will find their results useful.

Minze Stuiver (Seattle) and
Hans van der Plicht (Groningen),
Guest editors

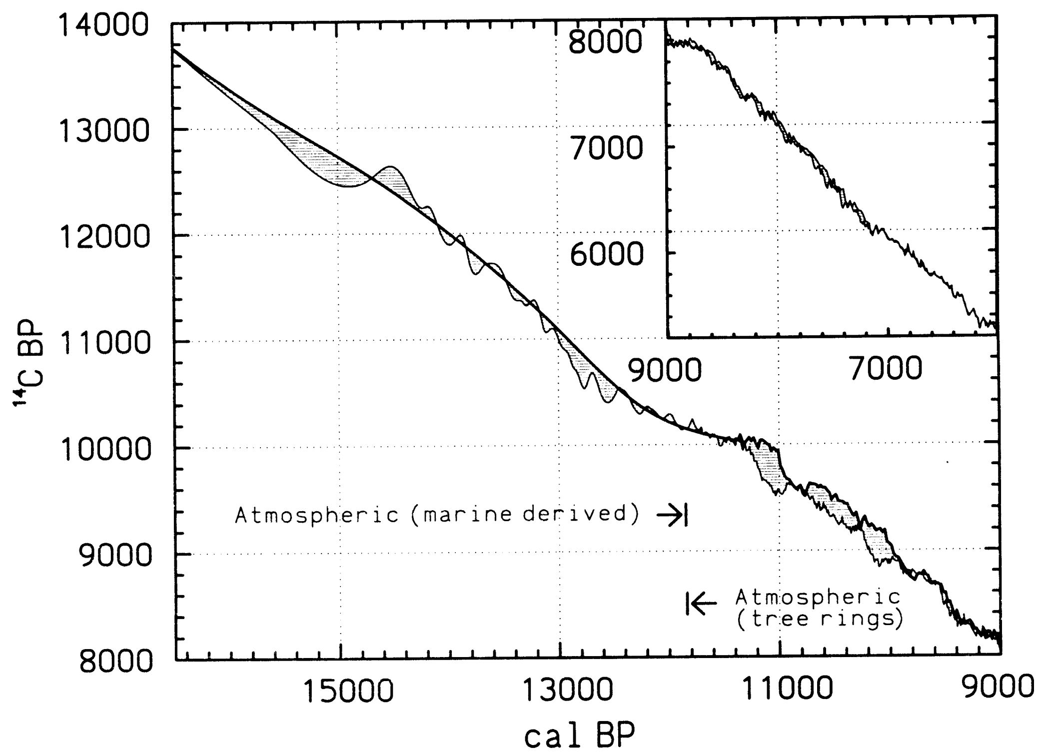

Fig. 2. The new atmospheric INTCAL98 calibration curve, and the "old" curve used since 1993. Prior to 11,800 cal BP the 1993 curve is the smoothest of the two. Given an identical ^{14}C age, the INTCAL98 cal ages are shifted towards the left (older cal BP ages) for the 11,800–7200 cal BP part. Curve differences are minimal (one decade at most) for the 7200–0 cal BP interval.

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INTCAL98 RADIOCARBON AGE CALIBRATION, 24,000–0 cal BP

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ABSTRACT. The focus of this paper is the conversion of radiocarbon ages to calibrated (cal) ages for the interval 24,000–0 cal BP (Before Present, 0 cal BP = AD 1950), based upon a sample set of dendrochronologically dated tree rings, uranium-thorium dated corals, and varve-counted marine sediment. The ^{14}C age–cal age information, produced by many laboratories, is converted to Δ^{14}C profiles and calibration curves, for the atmosphere as well as the oceans. We discuss offsets in measured ^{14}C ages and the errors therein, regional ^{14}C age differences, tree–coral ^{14}C age comparisons and the time dependence of marine reservoir ages, and evaluate decadal *vs.* single-year ^{14}C results. Changes in oceanic deepwater circulation, especially for the 16,000–11,000 cal BP interval, are reflected in the Δ^{14}C values of INTCAL98.

INTRODUCTION

The radiocarbon age time frame has been used extensively during the past 50 years in many disciplines. Because uncorrected ^{14}C ages and calibrated (cal) ages differ in a time-dependent fashion, the conversion of ^{14}C ages to cal ages is especially important for improving the validity of time estimates. Participants at the 16th International Radiocarbon Conference at Groningen (16–20 June 1997) discussed and recommended an update of previous calibration publications (Stuiver and Kra 1986; Stuiver, Long and Kra 1993). Following the advice of the international radiocarbon community, we present here an extended ^{14}C calibration data set, INTCAL98, that caps the 20th century ^{14}C age calibration efforts.

Dendrochronology provided the cal ages of the wood used for ^{14}C dating; their accuracy is established through standard dendrochronological checks and counterchecks for double or missing tree rings. The Irish oak (Pilcher *et al.* 1984) and the German oak and pine chronologies (Spurk *et al.* 1998) play a crucial role. The German oak chronology provides absolute counts of dendroyears back to *ca.* 10,300 cal BP. ^{14}C matching of the latest part of a floating German pine chronology to the earliest absolutely dated German oak extends this chronology to 11,857 cal BP. Errors in the matching may amount to 20 cal years (Kromer and Spurk 1998).

Uranium-thorium (U-Th) dating of corals extends the cal age range (Bard *et al.* 1998; Burr *et al.* 1998; Edwards *et al.* 1993). Whereas tree-ring ^{14}C, *via* the photosynthetic cycle, equilibrates with atmospheric carbon dioxide, corals equilibrate with mixed-layer ocean bicarbonate. The slightly lower ^{14}C activity (per gram of carbon) of the mixed layer, relative to the atmosphere, results in an offset (the ^{14}C reservoir age correction) between "atmospheric" and "oceanic" ^{14}C ages of samples with identical cal age. The reservoir correction (509 ± 25 ^{14}C yr over the 12,000–10,000 cal BP interval) was fixed by comparing Early Holocene tree-ring and coral ^{14}C activities of contemporaneous samples. Adding coral results extends the calibration curve to 24,000 cal BP. Although only two

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coral measurements exist for the 40,000–24,000 cal BP interval (Bard *et al.* 1998), they seem to point towards increasing differences between ^{14}C and cal ages.

Terrestrial varve chronologies, to be discussed in a future issue of *RADIOCARBON*, have not been used for construction of INTCAL98. A floating marine varve chronology, however, was used to strengthen the coral information from the 14,500–11,700 cal BP interval. To fix absolute time, the younger varve ^{14}C ages were matched with tree-ring ^{14}C ages (normalized on marine ^{14}C level).

Decadal wood samples were emphasized in *RADIOCARBON*'s 1986 and 1993 calibration issues. The ^{14}C content of a 10-yr wood sample, however, is not necessarily a perfect reflection of the atmospheric ^{14}C level of that decade. Tree-ring ^{14}C does not represent the seasons equally because a major portion of the wood is formed in spring and early summer. Tree-ring thickness also differs from year to year, causing variable annual ^{14}C contributions to the decadal average.

Decadal results were used in 1986 and 1993 for the construction of a (mostly) decadal Seattle calibration curve (Stuiver and Becker 1986, 1993). Combining these results with those obtained by Belfast for bidecadal samples led to a 20-yr calibration curve which has until now been used for most age calibrations (Pearson and Stuiver 1993; Pearson, Becker and Qua 1993; Stuiver and Reimer 1993).

Many ^{14}C ages have been determined on dendrodated wood covering only a couple of years. Instead of disregarding these high-precision measurements, we used a different approach for the INTCAL98 calibration curve. INTCAL98 "decadal" ^{14}C is obtained by averaging full-decadal and part-decadal (single- or multiple-year) results. ^{14}C ages of samples covering 20 yr also are included by allocating to each decade the bidecadal age with a standard deviation (σ) multiplied by 1.4. Adding these data to the pool of "actual" decadal information ultimately produces ^{14}C ages with a smaller σ.

DECADAL *VERSUS* SINGLE-YEAR AGE CALIBRATION

The smaller INTCAL98 σ comes at a price, of course, because ^{14}C dates of single years and decadal averages need not be identical. The impact on the decadal averages can be assessed by comparing single-year ^{14}C ages (Stuiver, Reimer and Braziunas 1998: Table 2) to decadal ones.

Part of single-year $\Delta^{14}C$ (expressed as the per mil (‰) deviation of tree-ring ^{14}C activity from NBS oxalic acid activity, corrected for isotope fractionation, Stuiver and Polach 1977) is tied to 11-yr-cycle solar modulation of atmospheric ^{14}C production. Pacific Northwest single-year data (when averaged with those of a Kodiak Island tree) yield a three-year moving average for the AD 1897–1945 interval with 11-yr-cycle $\Delta^{14}C$ modulation averaging 2.5‰ (peak to peak) over four cycles (Stuiver and Braziunas 1998). Twenty ^{14}C years appears to be an upper limit for single-yr ^{14}C age change induced by the 11-yr cycle. The standard deviation introduced by 11-yr modulation around the long-term (*e.g.*, decadal average) trend is a much smaller 8 ^{14}C yr (as derived from a 2.5‰ peak-to-peak sinusoidal $\Delta^{14}C$ cycle).

A frequency distribution of single-year (AD 1510–1950) ^{14}C age differences around a smoothing spline (the spline closely resembles a 10-yr moving average) agrees with a Gaussian scatter σ_2 of 14.4 ^{14}C yr (Fig. 1). The laboratory errors reported with the data predict an average measurement standard deviation σ_1 of 13.4 ^{14}C yr for these ^{14}C age differences. If the additional variability σ_n is attributed to natural causes (*e.g.*, the 11-yr cycle) then, since $\sigma_2{}^2 = \sigma_1{}^2 + \sigma_n{}^2$, the increase in sigma from 13.4 to 14.4 ^{14}C yr would be accounted for by $\sigma_n = 5$ ^{14}C yr. The same technique, when applied to a three-year (instead of single-year) moving average, again produces natural ^{14}C variance with $\sigma_n = 5$ ^{14}C yr ($\sigma_1 = 8.4$ ^{14}C yr and $\sigma_2 = 10$ ^{14}C yr).

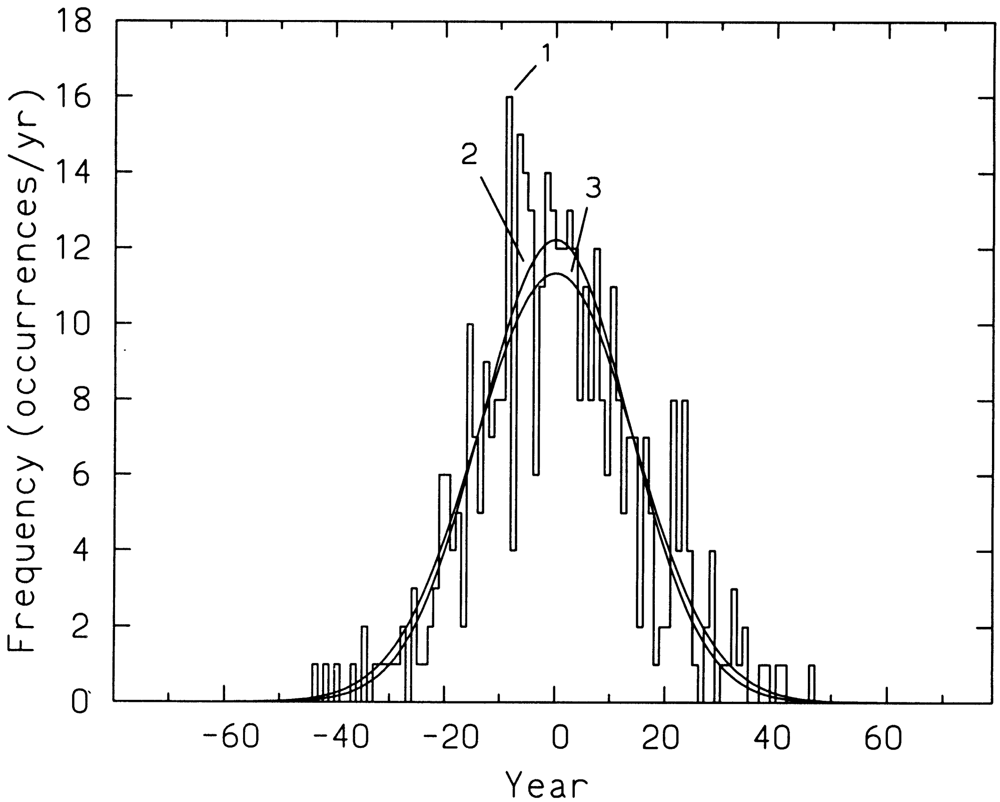

Fig. 1. Plots of the actual frequency distribution of single-year ^{14}C age differences from smoothed spline fitted to a 10-year moving average (AD 1510–1950, diagram indicated by 1), the Gaussian distribution with scatter $\sigma = 14.4$ yr (curve 3), and the Gaussian distribution constructed from the average measurement standard deviation with $\sigma = 13.4$ ^{14}C yr (curve 2)

The above calculations suggest single-year and three-year natural variability (around long-term decadal trends) with σ's in the 5 to 8 ^{14}C yr range (the frequency distribution and solar considerations are for different time intervals). Natural variability plays a role in constructing INTCAL98 "decades" from a mixture of decadal and single (or multiple) year results. Given the above considerations, most INTCAL98 decades should deviate, on average, by only a couple of ^{14}C years from "pure" decadal ones. This statement, of course, only applies to INTCAL98 decades constructed from multiple measurements. When constructing a (hypothetical) INTCAL 98 decade from only one nondecadal ^{14}C age, the INTCAL 98 decadal value would contain, relative to actual decadal values, an additional σ_n in the 5 to 8 ^{14}C yr range.

Information contained in single-year (and three-year) results will be lost to the tune of 5 to 8 ^{14}C yr (σ's) when constructing decadal data. Conversely, when calibrating single-year results against the decadal INTCAL98 curve, the single-year ^{14}C ages will differ from decadal ^{14}C ages (σ in the 5 to 8 ^{14}C yr range). Here we recommend, prior to calibration, an increase of sample standard deviation σ_x to $\sqrt{(\sigma_x^2 + 8^2)}$. The correction is very minor for most samples and only plays a role in high-precision determinations (a σ_x of, *e.g.*, 10 ^{14}C yr transforms into 13 ^{14}C yr).

TREE-RING ^{14}C AGE OFFSETS, "ERROR MULTIPLIERS" AND MINOR ADJUSTMENTS

The major laboratories involved in the determination of tree-ring ^{14}C for INTCAL98 purposes are Seattle (S), Belfast (B), Heidelberg (H), and Pretoria/Groningen (P/G). For the tree-ring cal age portion of the INTCAL98 calibration curve we used the data sets reported in this calibration issue (Stuiver, Reimer and Braziunas 1998; Kromer and Spurk 1998; and McCormac *et al.* 1998a), and previously reported ^{14}C sequences (Vogel and van der Plicht 1993; Pearson, Becker and Qua 1993; Kromer *et al.* 1986; McCormac *et al.* 1998b). When applicable, the older German oak and pine chronologies were adjusted in conformity with the Spurk *et al.* (1998) corrections.

The ^{14}C age differences of samples of identical cal age yield an average offset and (scatter) standard deviation σ_2. The σ_2 can be compared to the standard deviation (σ_1) predicted for the ^{14}C age differences from the laboratory reported errors. The increase in variance (excess variance) σ_E is derived from $\sigma_E{}^2 = \sigma_2{}^2 - \sigma_1{}^2$, whereas the ratio σ_2/σ_1 yields the "error multiplier" k (Stuiver 1982).

The above statistical considerations are valid for ^{14}C determinations of identical samples. However, the samples to be compared here are rarely fully identical, because the time over which the sample was formed may differ (*e.g.*, 10 yr *vs.* 3 yr). Furthermore, cal ages (time-midpoints) of the wood used by different laboratories samples differ. Different selection criteria (*e.g.*, should two samples be compared if one is a 10-yr and the other a 3-yr sample, and the difference in midpoints is ten years) yield variations in σ_E (and k) estimates. Given these uncertainties, the σ_E and k calculations are only approximate.

The interlaboratory comparisons provide information on the sum total of uncertainty tied to the processes of wood allocation, dendroage determination, sample pretreatment, laboratory ^{14}C determination, regional ^{14}C differences and individual tree ^{14}C differences.

^{14}C results determined in different laboratories for samples of the "same" dendroage usually yield offsets in the 0–20 ^{14}C yr range. Values twice as large are occasionally encountered. The larger offsets are, for reasons unknown, over shorter (century-scale) intervals.

Offset information can be derived from ^{14}C age comparisons when results are available from three or more laboratories over an identical time interval. Because average S ^{14}C ages between 6600 and 5800 cal BC differed more than 2σ from those reported by H and B, we increased the S ^{14}C ages over this interval by 27 ^{14}C yr for INTCAL98 purposes. The offset correction is relatively mild: we allow a 2σ difference between the corrected S average and the average of the other laboratories. The same technique reduces Heidelberg ^{14}C ages by 31, 27, and 26 yr for, respectively, 4400–4200, 5200–5000, and 7200–7000 cal BC. The ^{14}C age offsets (number of comparisons = n) between the individual laboratory data sets used for INTCAL98 construction (the minor corrections discussed above are included), as well as σ_1, σ_E, and k, are listed in Table 1.

The trees forming the dendrodated portion of the INTCAL98 curve are predominantly from South Germany, Ireland, California and Washington. For the data sets used for INTCAL98 construction we list in Table 2 tree species, regions, offsets, σ_1, σ_E and k (relative to Seattle). The offsets need not be specifically species-related, and ^{14}C results for trees from different regions may reflect laboratory, as well as regional, influences.

Time-dependent millennium offsets, relative to the INTCAL98 curve, are listed in Table 3. The largest millennium offset of 26 ^{14}C yr, based on a small number of points, is not very significant given the ±10 ^{14}C yr standard deviation. The complete data sets of individual laboratories differ only marginally (up to 11 ^{14}C yr) from INTCAL98.

TABLE 1. A comparison of Seattle, Belfast, Pretoria/Groningen (P/G) and Heidelberg ^{14}C ages of dendrodated wood. The offset equals the weighted mean ^{14}C age difference of samples for which the midpoint cal ages fall within the same decade. n is the number of comparisons, σ_1 is the predicted average standard deviation in single ^{14}C age comparisons (based on quoted laboratory errors), σ_E represents the difference between the observed standard deviation in the age difference (σ_2) and σ_1 (see text). The σ_2/σ_1 ratio = k. Offset, σ_1 and σ_E are in ^{14}C yr.

Laboratories	Offset	σ_1	s_E	k	n	Cal yr interval
Belfast – Seattle	12 ± 1	27	22	1.29	866	7745 BC–AD 1935
Heidelberg – Seattle	19 ± 2	40	22	1.14	230	9665–4085 BC
P/G – Seattle	17 ± 1	22	17	1.26	194	3905–1935 BC
Heidelberg – Belfast	30 ± 3	43	30	1.22	142	7715–4075 BC
P/G – Belfast	−2 ± 2	26	23	1.33	194	3905–1935 BC

TABLE 2. A comparison of tree-ring ^{14}C results of laboratories involved in the INTCAL98 project. (See Table 1 for nomenclature.) Offset, σ_1 and σ_E are in ^{14}C yr.

Laboratories	Offset	σ_1	s_E	k	N	Cal yr interval
Belfast – Seattle Irish oak – U.S. conifers	14 ± 2	24	11	1.1	202	150 BC–AD 1940
Belfast – Seattle Irish oak – German oak	11 ± 1	26	22	1.3	501	5210 BC–AD 30
P/G – Seattle both German oak	17 ± 2	22	17	1.3	194	3910–1930 BC
Belfast – Seattle both German oak	10 ± 2	32	35	1.5	181	7750–5260 BC
Heidelberg – Seattle both German oak	21 ± 3	41	28	1.2	128	7720–4080 BC
Heidelberg – Seattle both German pine	16 ± 4	38	12	1.0	102	9670–8000 BC

A portion of the variance increase (expressed by σ_E or k) is tied to factors unrelated to the laboratory operation (*e.g.*, variable regional ^{14}C differences). Previously (in 1993) k = 1.6 was used to calculate the errors in the decadal Seattle ^{14}C age calibration curve. The Table 1 data suggest k values of 1.14 to 1.33. A conservative k = 1.3 was chosen for the calculation of the errors in decadal INTCAL98 tree-ring ^{14}C ages.

HEMISPHERIC AND REGIONAL OFFSETS

Latitude-dependent differences in ocean surface area, and ocean circulation, cause corresponding latitude-dependent ^{14}C transfer to and from the oceans. Rapid tropospheric mixing of air masses counteracts the oceanic influence but does not fully nullify the atmospheric response. As suggested by an atmospheric transport model (GISS GCM), regional atmospheric $\Delta^{14}C$ gradients may amount to several per mil, especially between Northern and Southern Hemispheric localities (Braziunas, Fung and Stuiver 1995).

The INTCAL98 tree-ring data set is based on a mix of mid-latitude Northern Hemisphere trees (Germany, Ireland, Washington, Oregon and California). The atmospheric transport model predicts $\Delta^{14}C$

TABLE 3. Offsets (millennial time separation) between individual laboratory and INTCAL98 (I) results. P/G is Pretoria/Groningen. All parameters following the cal age interval are in ^{14}C yr. (See Table 1 for nomenclature.)

	I – Seattle		I – Heidelberg		I – Belfast		I – P/G	
Cal age interval	Offset	σ_1	Offset	σ_1	Offset	σ_1	Offset	σ_1
10 – 9 ka BC	3 ± 4	29	−4 ± 5	36				
9 – 8 ka BC	7 ± 3	28	−7 ± 4	33				
8 – 7 ka BC	0 ± 3	28	−12 ± 5	39	11 ± 4	31		
7 – 6 ka BC	2 ± 2	23	−11 ± 5	41	−1 ± 3	29		
6 – 5 ka BC	9 ± 2	23	−26 ± 10	40	−16 ± 3	26		
5 – 4 ka BC	7 ± 2	21	−19 ± 4	34	0 ± 3	27		
4 – 3 ka BC	10 ± 2	17			−8 ± 2	24	−5 ± 2	16
3 – 2 ka BC	9 ± 2	18			−6 ± 2	21	−7 ± 2	19
2 – 1 ka BC	0 ± 2	20			0 ± 2	24	3 ± 6	18
1 – 0 ka BC	2 ± 2	18			−4 ± 2	23		
AD 0 – 1 ka	3 ± 2	18			−9 ± 3	26		
AD 1 – 2 ka	1 ± 1	11			−13 ± 2	19		
10 ka BC – AD 2 ka	**3 ± 1**	**21**	**−11 ± 2**	**37**	**−6 ± 1**	**25**	**−6 ± 1**	**18**

differences of ~1‰ for these areas. Such differences are at the limit of ^{14}C dating and difficult to measure. The fine structure in ocean circulation (*e.g.*, in coastal waters) and differences in regional carbon cycle sources and sinks (*e.g.*, permafrost areas, Damon *et al.* 1996) increase Northern Hemispheric $\Delta^{14}C$ variability. The location-dependent $\Delta^{14}C$ offsets also need not be constant over time. Measurements (not necessarily covering identical time intervals but mostly of the 19th century) of Northern Hemispheric localities yield differences (relative to Washington) of *ca.* −21, *ca.* +22, 16 ± 9, −26 ± 6 (AD 1545–1615), 2 ± 6 (AD 1615–1715), and 14 ± 3 ^{14}C yr for, respectively, the Santa Catalina Mountains in Arizona (Damon 1995), Mackenzie River Valley, Canada (Damon 1995), Dean of Forest oak, England (Stuiver and Quay 1981), Russia (high latitude, two comparisons) and Kodiak Island, Alaska (Stuiver and Braziunas 1998). Furthermore, Irish oak yielded 41 ± 9 ^{14}C yr younger dates than bristlecone pine of Nevada (McCormac *et al.* 1995) and German oak was 23 ± 6 ^{14}C yr younger than California sequoia (Stuiver 1982).

Southern Hemisphere offset measurements (Stuiver and Braziunas 1998) yield 25 ± 7 ^{14}C yr for Tasmania–Washington (19th century), and 38 ± 5 ^{14}C yr and 21 ± 5 ^{14}C yr for South Chile–Washington (respectively, AD 1670–1722 and 19th century). Other offsets are 40 ± 5 ^{14}C yr for South Africa–the Netherlands (AD 1835–1900, Vogel *et al.* 1993) and 27 ± 5 ^{14}C yr for New Zealand–British Isles (AD 1720–1885, McCormac *et al.* 1998a).

For the 1993 calibration program (Stuiver and Reimer 1993), a 40 ^{14}C yr correction was recommended for the entire Southern Hemisphere. The recent measurements of 19th century wood (Tasmania, New Zealand, South Chile) are in line with a smaller Southern Hemispheric offset of 24 ± 3 ^{14}C yr.

The above Southern Hemisphere–Washington offset is for "natural" conditions. During the first half of the 20th century, fossil fuel CO_2 release depressed atmospheric ^{14}C levels to a greater extent in the Northern Hemisphere. Whereas 19th century Chile/Tasmania ^{14}C ages are about 23 yr older than those of Washington, the offset is reduced during the first half of the 20th century. There is even a switch to younger Southern Hemispheric ages *ca.* AD 1940 (Stuiver and Braziunas 1998; McCormac *et al.* 1998b).

Tree-ring and Coral ^{14}C Age Differences

The ^{14}C ages of dendrodated tree-rings, together with $^{230}Th/^{234}U$-dated corals, ultimately yield the ^{14}C age axis of the INTCAL98 curve. Tree-cellulose ^{14}C activity reflects the atmospheric $^{14}C/^{12}C$ ratio of CO_2, after correction for isotope fractionation. Similarly, coral-carbonate ^{14}C activity mirrors the mixed ocean layer $^{14}C/^{12}C$ ratio. The ^{14}C-specific activity in the mixed layer (depth ~75 m) is lower than that in the atmosphere because mixed-layer ^{14}C depends on atmospheric as well as deep ocean ^{14}C supply (the main cause for the lower ^{14}C activity of the deep ocean is radioactive decay during its ~1000 yr isolation from the atmosphere). Because ^{14}C ages are based on comparison to a (postulated) stable atmospheric ^{14}C level (*via* the oxalic acid standard), the coral ^{14}C dates have to be corrected for mixed layer ^{14}C reservoir (R) ages.

Late Holocene (preanthropogenic) ^{14}C reservoir ages in the Atlantic, Pacific and Indian Oceans depend on geographic latitude. As luck has it, the tropical areas where coral reefs are formed are part of the oceanic 40°S–40°N region with a fairly constant (non-latitude dependent) pre-bomb R of 300 to 500 ^{14}C yr (Bard *et al.* 1994; Bard 1988; Edwards *et al.* 1993; Burr *et al.* 1998 with 35 pre-bomb samples yielding 494 ± 10 yr for Vanuatu).

R is the ^{14}C age difference between samples grown in equilibrium with the atmosphere, and the mixed layer of the ocean. To make tree-ring and coral results from the 19th century compatible, coral ^{14}C dates should be reduced by 300 to 500 ^{14}C yr. A similar correction does not automatically apply to older samples because ocean and climate variables (rates of deepwater formation and upwelling, average wind speed, ice cover, *etc.*) influence R values (Bard *et al.* 1994).

Tropical paleo-R values of the Early Holocene can be estimated from tree-ring (INTCAL98 values) and coral ^{14}C age differences. Estimated errors used for the following ^{14}C age difference calculations are 2σ for coral ages, and 1σ for INTCAL98 tree-ring ages.

For the 11,800–8300 cal BP interval, the Bard *et al.* (1998), Burr *et al.* (1998), and Edwards *et al.* (1993) coral data yield tree-ring–coral offsets of, respectively, 298 ± 33 ^{14}C yr (11,590–8450 cal BP, number of comparisons n = 19), 537 ± 38 ^{14}C yr (11,770–11730 cal BP, n = 5) and 587 ± 29 (11,045–8363 cal BP, n = 10). Omitting one outlier from the Edwards *et al.* data reduces the 587 ± 29 ^{14}C yr to 502 ± 33 ^{14}C yr. Without the outlier, the weighted average offset for all samples is 440 ± 21 ^{14}C yr.

Differences between oceans are relatively small: R is 406 ± 65 ^{14}C yr (11,590–8450 cal BP, n = 6) for the Atlantic Ocean and 440 ± 20 ^{14}C yr (11,770–8363 cal BP, n = 27) for the Pacific (one outlier omitted). However, there is the suggestion of substantial Pacific intraocean R difference with R = ~300 ^{14}C yr for Tahiti *vs.* R = ~500 ^{14}C yr for New Guinea and Vanuatu.

Between 10,000–8,000 and 12,000–10,000 cal BP the coral data generate a weighted mean R value of, respectively, 414 ± 31 ^{14}C yr (n = 12) and 509 ± 25 ^{14}C yr (n = 21). Omitting the outlier reduces the latter to R = 451 ± 26 ^{14}C yr. The older sample ages appear to have slightly larger R's, as depicted by the 1000 yr averages in Figure 2. Good agreement between mixed-layer corrected coral dates and tree-ring ^{14}C dates (Fig. 3) is obtained when using R = 500 and 400 ^{14}C yr for, respectively, the 12,000–10,000 cal BP and 10,000–8000 cal BP intervals.

Future adjustments of the pine–oak chronology, if any, will influence the derived R values. The 100 ^{14}C yr R "increase" is perhaps tied to missing rings in the earliest part of the pine tree-ring chronology. Given our current state of knowledge, however, we do accept an R value of 500 ^{14}C yr for the 12,000–10,000 cal BP interval, and postulate the same tropical R for the Late Glacial ocean.

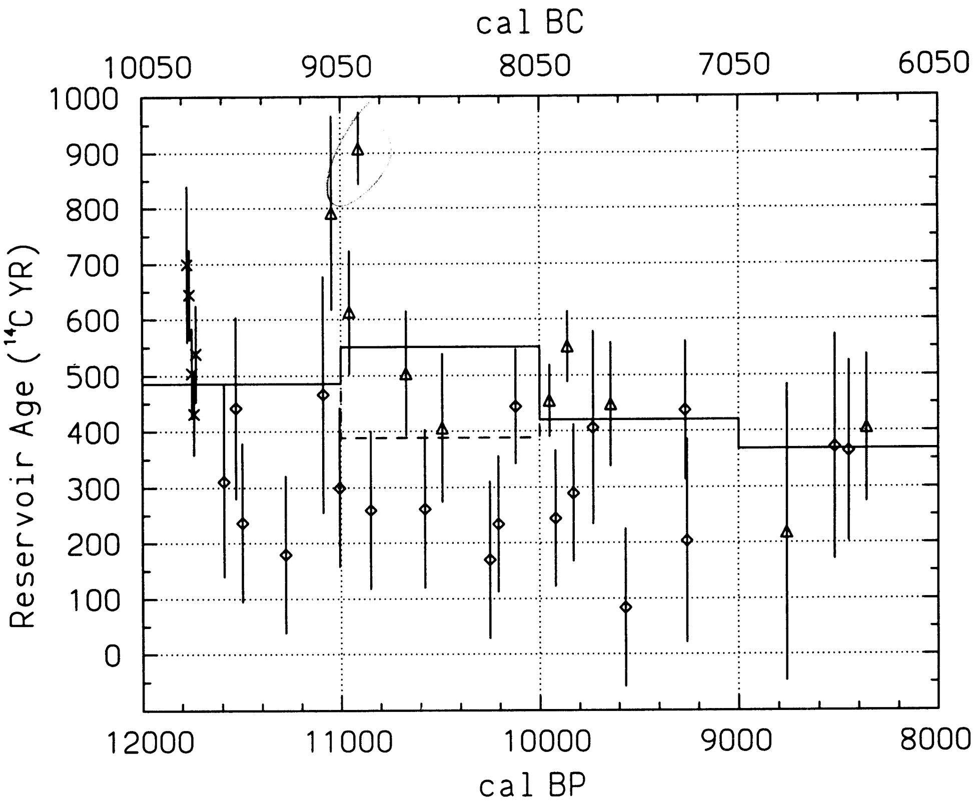

Fig. 2. Reservoir ages (^{14}C age difference between coral and tree-ring samples of similar cal age) between 12,000 and 8000 cal BP. Coral measurements given here and in the following figures are from Bard *et al.* 1998 (◇), Burr *et al.* 1998 (×), Edwards *et al.* 1993 (△). R values averaged over millennia are represented by the solid line. The dashed line is the R value for the 11,000–10,000 cal BP millennium when omitting the 900 ^{14}C yr data point. Vertical bars represent the calculated error in the ^{14}C age difference calculation, based on a 2σ error in the coral ^{14}C age determination, and a 1.3σ error in the tree-ring ^{14}C age determination.

Coral ^{14}C Age Variability

The corals are assumed to be ideal closed systems with regard to ^{14}C, ^{234}U and ^{234}Th exchange. The overall agreement (Fig. 3) between reservoir-corrected coral (with the reservoir correction averaged over millennia), and tree-ring ^{14}C dates suggests that this condition is fairly well adhered to for carefully collected samples. Nevertheless, the scatter σ_2 of INTCAL98 tree-ring minus reservoir-corrected coral ^{14}C ages (12,000–8000 cal BP, n = 33) is 260 ^{14}C yr, whereas the quoted measuring precision alone produces a σ_1 = 69 ^{14}C yr, resulting in σ_E = 255 ^{14}C yr and error multiplier k = 3.7. Similar comparisons between tree-ring data sets yield an average k value of only ~1.3.

The above calculation uses a fixed R of 500 and 400 yr for, respectively, 12,000–10,000 cal BP and 10,000–8000 cal BP. Normalizing each individual data set on its own R value (which aligns the average of each individual coral data set with that of the INTCAL98 tree-ring record) yields an improved k = 2.3 when the INTCAL98 reservoir-corrected ^{14}C ages are subtracted from the tree-ring ages.

To generate a pre-12,000 cal BP atmospheric record, one has the choice of 1) assuming R to be constant for each individual site, or 2) assuming average tropical R to be constant (the 500 ^{14}C yr dis-

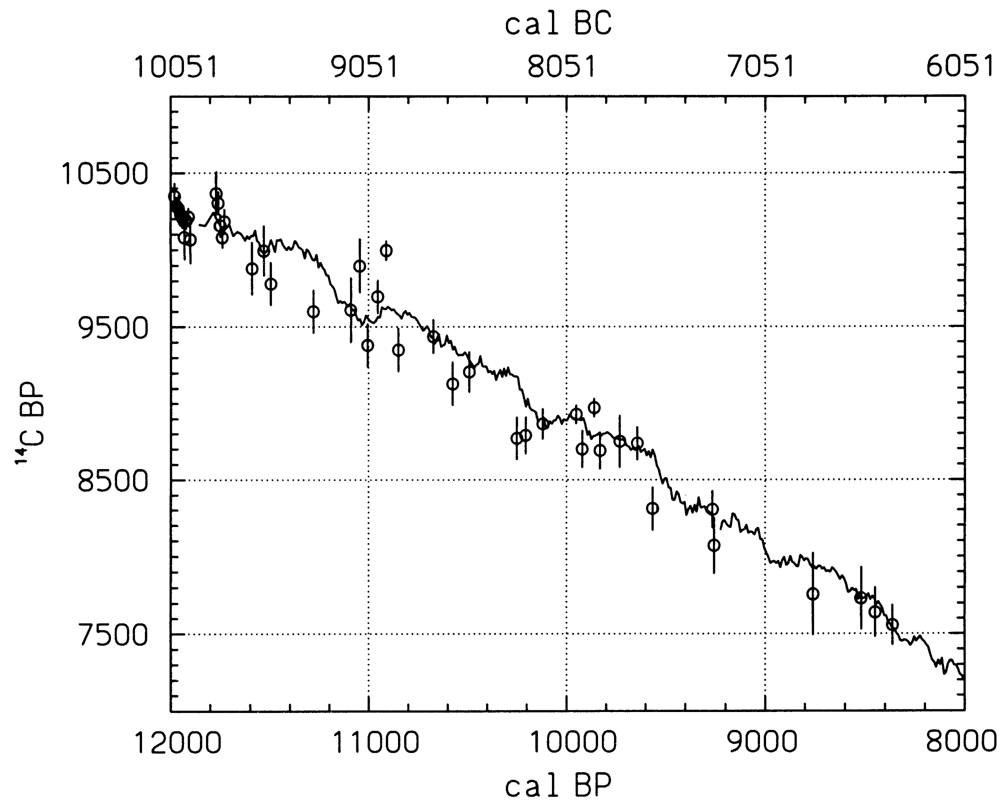

Fig. 3. Position of coral ^{14}C ages (O), relative to INTCAL 98 tree-ring ^{14}C ages (solid line), after a reservoir deficiency correction of the coral ^{14}C ages by 400 and 500 ^{14}C yr for, respectively, 10,000–8000 cal BP and 12,000–10,000 cal BP. Vertical bars equal 2σ in the coral ^{14}C age measurement.

cussed previously). It is likely (but not proven) that prior to 12,000 cal BP single-site R variability was larger than average R variability. We decided to generate the pre-12,000 cal BP atmospheric record by deducting an average tropical R = 500 ^{14}C yr from all coral data.

The atmospheric and mixed-layer ^{14}C records are filtered differently by natural processes. Mixed-layer response to postulated decadal atmospheric forcing resembles a ~100–200 yr moving average (*e.g.*, Stuiver, Reimer and Braziunas 1998). Using a similar 200-yr moving average for tree rings, however, does not reduce the coral ^{14}C–tree-ring σ_E. Mechanisms resulting in increased variance could be 1) varying tropical reservoir deficiency R, 2) post-depositional ^{14}C activity modification and 3) U/Th age uncertainty.

Post-depositional ^{14}C modification can be accounted for by using twice the standard deviation of the measurement. Many investigators routinely double the measuring precision of coral ^{14}C determinations (Edwards *et al.* 1993; Bard *et al.* 1990). For INTCAL98 purposes the assigned standard deviation of coral ^{14}C ages is based on a 2σ error in the coral ^{14}C age determination, and a k = 1.3 error multiplier similar to the one used for tree-ring derived ^{14}C ages. The combined multiplier of 2.6 accounts for most of the variance actually observed.

Marine Reservoir Age Considerations

Causes for century-scale atmospheric ^{14}C variability include solar modulation of the cosmic-ray flux and ocean circulation change. Model calculated R values depend on the forcing mechanism. Switching from a solar to an oceanic mode produced century-scale global R change of ~150 ^{14}C yr in a global carbon reservoir model (Stuiver, Reimer and Braziunas 1998).

Splining of the reservoir-corrected coral ^{14}C ages (R = 500 ^{14}C yr) generates the pre-11,850 cal BP portion of the "atmospheric" INTCAL98 calibration curve. Before 11,850 cal BP, tropical ocean R is assumed to be identical for the Atlantic, Pacific and Indian Ocean, as well as nonvariable over time. It is difficult to estimate the limits of tropical R change. Figure 2 suggests tropical R change of only ~100 ^{14}C yr for millennia-scale oceanic changes between the end of the Ice Age and 8000 cal BP. A comparison of Cariaco Basin (Hughen *et al.* 1998) varve and INTCAL98 tree-ring chronologies (discussed in the following section) suggests that decadal- to century-scale tropical R variability is restricted to ~100 ^{14}C yr (11,700–9000 cal BP interval). Larger millennia-scale tropical R changes further back in time cannot be excluded, but are not very likely given the limited tropical R variability between the end of the Pleistocene and the present.

The globally integrated atmospheric ^{14}C levels, and global R, depend on a globally integrated ocean circulation and ocean-atmospheric exchange rate. To derive global INTCAL98 atmospheric values, we used a constant late-glacial tropical R value of 500 ^{14}C yr. Implied in the switch from tropical to global conditions is the notion that tropical R and global R parallel each other over the 24,000–11,850 cal BP interval.

The corals discussed so far were formed in the mixed surface layer of the tropical ocean. Deep-sea corals, on the other hand, live mostly between 500 and 2000 m depth and are not confined to tropical latitudes. These corals exhibit substantial century-scale deepwater R change in the Atlantic (16,000–12,000 cal BP interval: Adkins *et al.* 1998; Mangini *et al.* 1998). Atlantic deepwater ^{14}C levels are tied to specific deepwater masses (*e.g.,* Stuiver and Östlund 1980) and the deepwater R changes are most likely caused by shifts in their depths. These relatively fast regional ocean circulation changes have the potential to modify (to an unknown extent) the values of both late-glacial atmospheric ^{14}C and mixed-layer R.

Marine Varve Chronology

Marine sediments of the Cariaco Basin in the Atlantic Ocean (at the northern continental margin of Venezuela) yield a ^{14}C–varve count sequence (Hughen *et al.* 1998) useful for INTCAL98 construction. The floating chronology is tied to the absolute time scale by matching marine ^{14}C ages to the INTCAL98 tree-ring data (the tree-ring data are increased by 500 and 400 ^{14}C yr for, respectively, 12–10 and 10–8 ka cal BP). The best fit between the ^{14}C ages of the adjusted tree-ring record and the Cariaco Basin is shown in Figure 4. The absolute time scale produced in this manner for the floating varves reduces the Hughen *et al.* (1998) varve count time scale by 40 yr. The latest tree-ring and R adjustments cause this minor difference. The matching is secure within a statistical error (one σ) of 15 yr.

Applying R = 400 (10–8 ka cal BP) and 500 (14.5–10 ka cal BP) ^{14}C yr to the corals and calibrated varve series yields the Figure 5 "atmospheric" values. Relative to the INTCAL 98 tree-ring record, the varve-derived ^{14}C ages scatter less (k = 1.3) than the coral ^{14}C ages. The observed varve scatter σ of ~95 ^{14}C yr (11,700–9000 cal BP interval) suggests a ~100 ^{14}C yr limit on tropical R change on decadal/century time-scales.

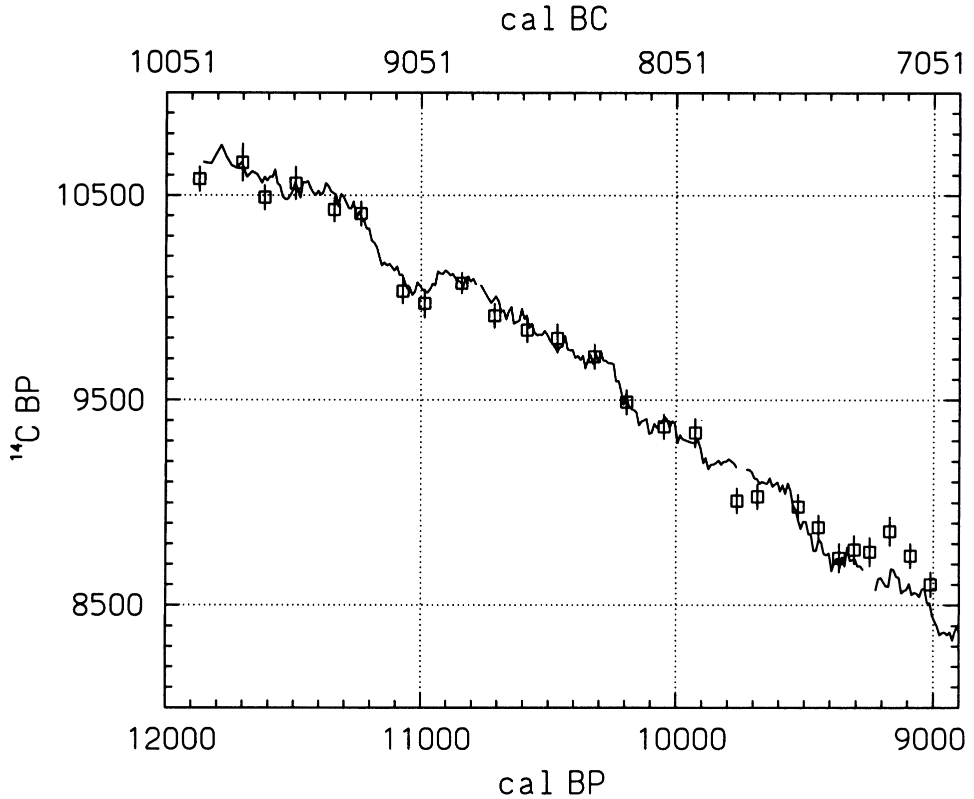

Fig. 4. Cal BP calibration of a floating marine varve record. The varve data given here, and in the following figures, are from Hughen *et al.* (1998). Shown is the best fit between the marine equivalent of the INTCAL98 tree-ring record (solid line, R values as noted with Fig. 3 were applied) and the measured varve results (□, with 1σ bars).

Atmospheric and Marine INTCAL98 Construction

The atmospheric INTCAL 98 curve consists of two segments, each derived from diverse materials and techniques. The materials used are wood (tree rings), coral and marine sediment. The ^{14}C activity measurement is common to all but the cal BP time scale determination differs. The wood samples (back to 11,850 cal BP) are dated through dendrochronological means, the corals through U-Th determinations, and the marine sediment through ^{14}C matching of (floating) varve and tree-ring chronologies. Marine coral and varve data, normalized on atmospheric levels, yield a 24,000–11,850 cal BP extension of the directly measured atmospheric values. Only two coral measurements are available for the 40,000–24,000 cal yr interval, resulting in rather speculative age "calibration" over this interval.

The 11,850–0 cal BP segment was constructed from ^{14}C age measurements reported by the Belfast, Heidelberg, Pretoria/Groningen and Seattle laboratories (Stuiver, Reimer and Braziunas 1998; Kromer and Spurk 1998; McCormac *et al.* 1998a and b; Pearson, Becker and Qua 1993; Vogel and van der Plicht 1993; Kromer *et al.* 1986). Decadal ^{14}C ages back to 11,614 cal BP were constructed by taking the average ^{14}C age of all samples with cal midpoints within the cal decade. The rationale for this approach can be found in the introduction. The 11,624–11,854 cal BP interval is covered by the measurements of a single laboratory (Heidelberg; Kromer and Spurk 1998) of 20- to 30-yr tree-ring samples. The segments of Figure A8–A19 (Appendix) depict for 1000 cal yr intervals the "dec-

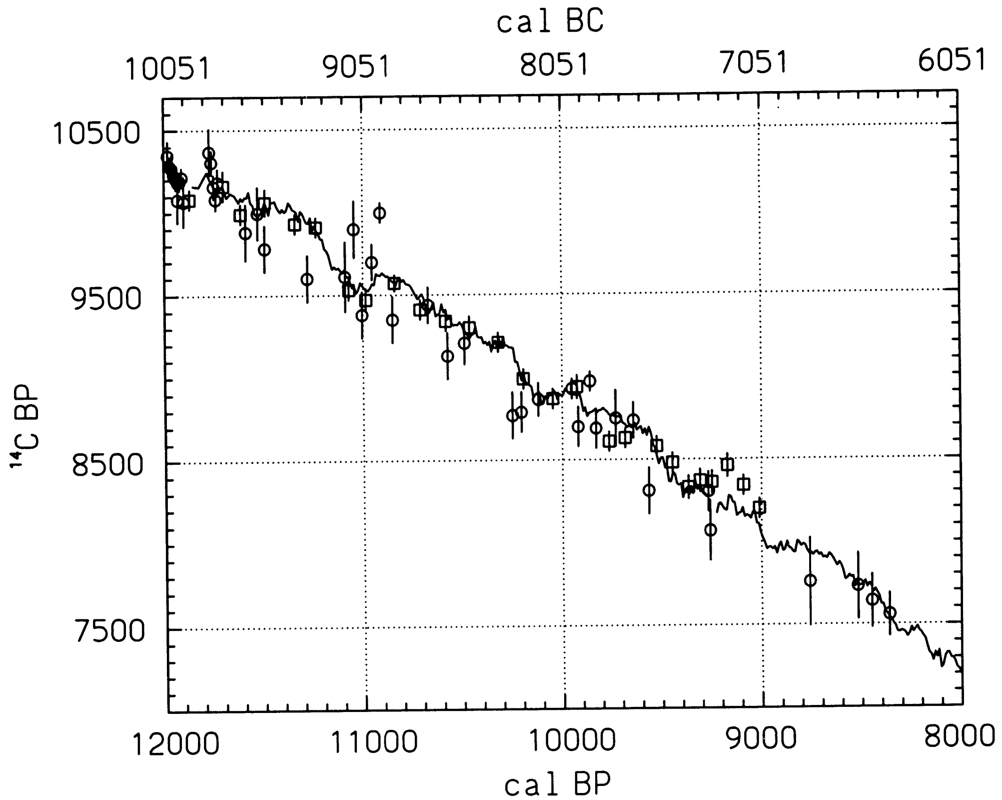

Fig. 5. INTCAL 98 tree-ring ^{14}C ages (solid line) and the atmospheric equivalent (obtained by using the R values noted with Fig. 3) of 1) coral ^{14}C ages (O, bar = 2σ) and 2) marine varve ages (□, bar = 1σ). The cal BP ages of the corals were determined by U/Th dating and the cal BP ages of the varves by a floating varve count that was shifted to the position given in Fig. 4.

adal" tree-ring derived portion of the atmospheric INTCAL 98 calibration curve (11,854–0 cal BP). The curve was constructed by linearly connecting the ^{14}C ages obtained for the decadal (plus a few bidecadal) cal age intervals. The INTCAL98 standard deviation (width of the calibration curve, not given in Fig. A) resulted from the linear connection of the ±1.3σ age errors.

The primary data of the 24,000–11,850 cal BP segment are coral and varve measurements (Bard *et al.* 1998; Burr *et al.* 1998; Edwards *et al.* 1993; Hughen *et al.* 1998). The ^{14}C ages of the 12,500–11,850, 15,000–12,500, 19,500–15,000, and 24,000–19,500 cal BP intervals, adjusted to atmospheric levels by deducting a reservoir deficiency of 500 ^{14}C yr (the rather minor 25 ^{14}C yr standard deviation was neglected) from the marine ages, are depicted in Figures 6–9 with vertical bars representing 1σ in the varve ^{14}C determinations, and 2σ for the coral ^{14}C determinations. The "atmospheric" ^{14}C ages of the 40,000–15,000 cal BP interval are given in Figure 10. Coral and varve data coverage is excellent for 16,000–11,850 cal BP, less so for 24,000–16,000 cal BP, and marginal for 40,000–24,000 cal BP.

The minimum smoothing spline (Reinsch 1967) of Figures 6–9, anchored at the last tree-ring point at 11,854 cal BP, was used to generate the atmospheric INTCAL98 ^{14}C ages of the 11,850–16,000 cal BP period. Due to the scarcity of coral samples, INTCAL 98 lacks detail between 24,000 and 16,000 cal BP. Here the spline is essentially linear, with cal BP = 1.15 ^{14}C BP + 680.

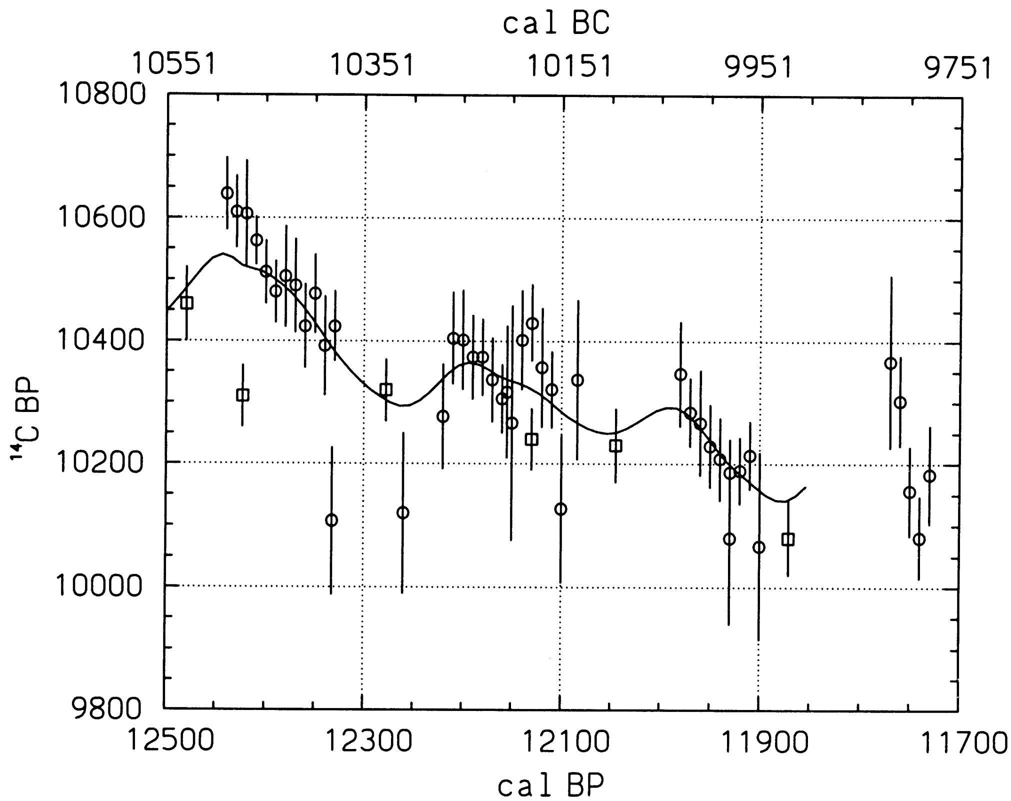

Fig. 6. "Atmospheric" coral (O, bar = 2σ) and varve (□, bar = 1σ) ^{14}C ages. The minimum smoothing spline (solid line), anchored at the last tree-ring point (11,854 cal BP), was used to derive the INTCAL 98 ^{14}C ages of the 12,500–11,854 cal BP time interval.

The 24,000–11,850 cal BP coral- and varve-derived segment of atmospheric INTCAL 98 is part of the Figure A calibration curve. For the marine-derived atmospheric ages we used, as discussed, a spline with minimum smoothing. The INTCAL98 standard deviation (width of the calibration curve) was derived by using a standard deviation of 2σ for the coral ^{14}C ages, 1σ for the varve ^{14}C ages, and a k=1.3 error multiplier for both (σ = standard deviation in the measurement).

There are only two data points between 40,000 and 24,000 cal BP, and a linear relationship is automatic (Fig. 10). This interval, due to the lack of corroborating data points, generates an error-prone calibration curve. The 40,000–24,000 cal BP interval, as a consequence, was not considered for INTCAL98 inclusion.

The conversion of marine ^{14}C age to atmospheric ^{14}C age (by deducting 500 ^{14}C yr from the marine age) is an approximation only. The marine record also contains less detail than the atmospheric one, especially for cosmic-ray induced ^{14}C production rate change (*e.g.*, Stuiver, Reimer and Braziunas 1998). Only the 15,000–12,000 cal BP interval, with a large number of marine data points, produces a century-scale fine structure.

The marine INTCAL98 curve (Fig. B) of the 8800–0 cal BP interval contains marine ^{14}C ages derived from the tree-ring record *via* carbon reservoir modeling (Stuiver, Reimer and Braziunas 1998). Coral and marine varve ^{14}C ages were used for the 24,000–8800 cal BP marine INTCAL98

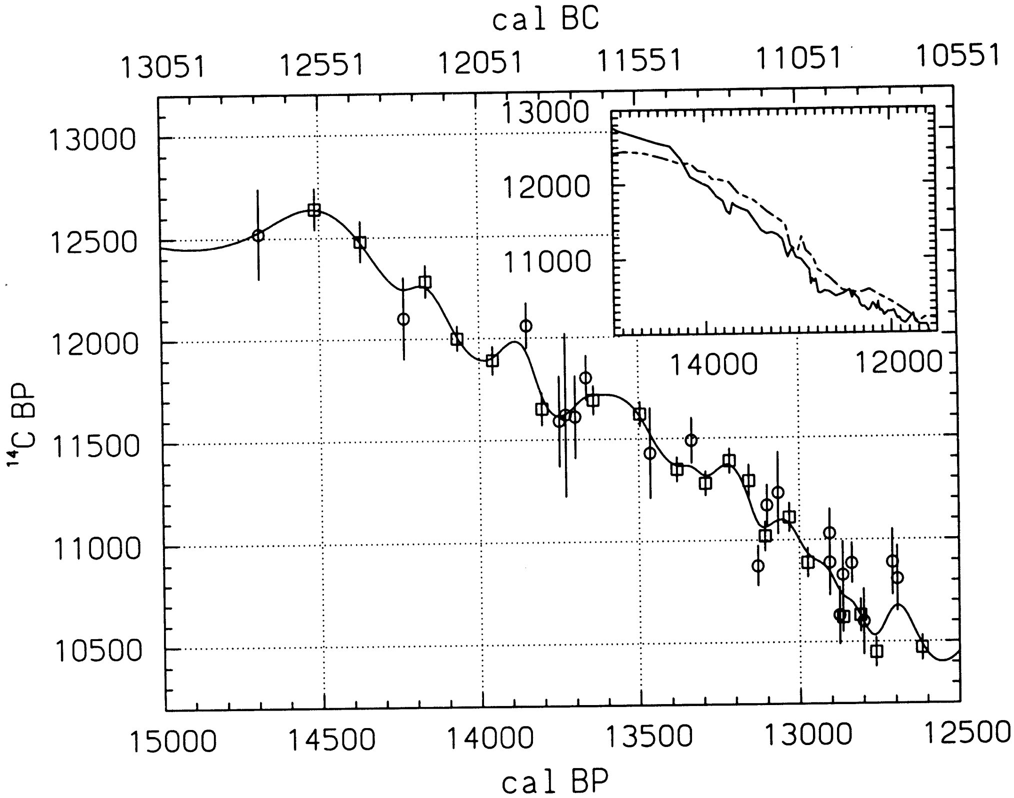

Fig. 7. Splined "atmospheric" coral and varve data 15,000–12,500 cal BP (solid line; see Fig. 6 caption for symbols). The inset compares three-point moving averages of "atmospheric" (marine derived) INTCAL 98 ^{14}C ages (solid line) to a similar moving average of terrestrial ^{14}C ages (dashed line) dated by varves (Kitagawa and van der Plicht 1998).

segment. Here we splined the available marine ^{14}C dates of the 15,585–8800 cal BP interval (Figs. 5–7), and used a linear approximation for the 24,000–15,585 cal BP interval (Figs. 8 and 9). The calculated INTCAL98 standard deviation (width of the calibration curve, not given in Fig. A) was derived from the measured 2σ deviation for the coral ^{14}C ages, 1σ for the varve ^{14}C ages, and a $k=1.3$ error multiplier for both (σ = standard deviation in the measurement). The connection between the splined and carbon reservoir calculated marine ^{14}C ages is depicted in Figure 11.

The INTCAL98 marine calibration curves (Fig. B) reflect global open ocean conditions. Regional departures from the global values can be expressed in a ΔR parameter, as discussed in Stuiver, Reimer and Braziunas 1998.

INTCAL98 $\Delta^{14}C$

Converting the atmospheric ^{14}C ages into $\Delta^{14}C$ values yields Figure 12. The long-term trend in $\Delta^{14}C$ is usually attributed to geomagnetically induced ^{14}C production rate change.

An interesting $\Delta^{14}C$ comparison can be made with the recently published 45,000 cal BP atmospheric varve chronology (Kitagawa and van der Plicht 1998). Although for the 15,000–12,000 cal BP interval the long-term trends of the Kitagawa and van der Plicht atmospheric record and the INTCAL98 atmospheric record derived from marine data are similar, century-scale detail is less fine in the varve

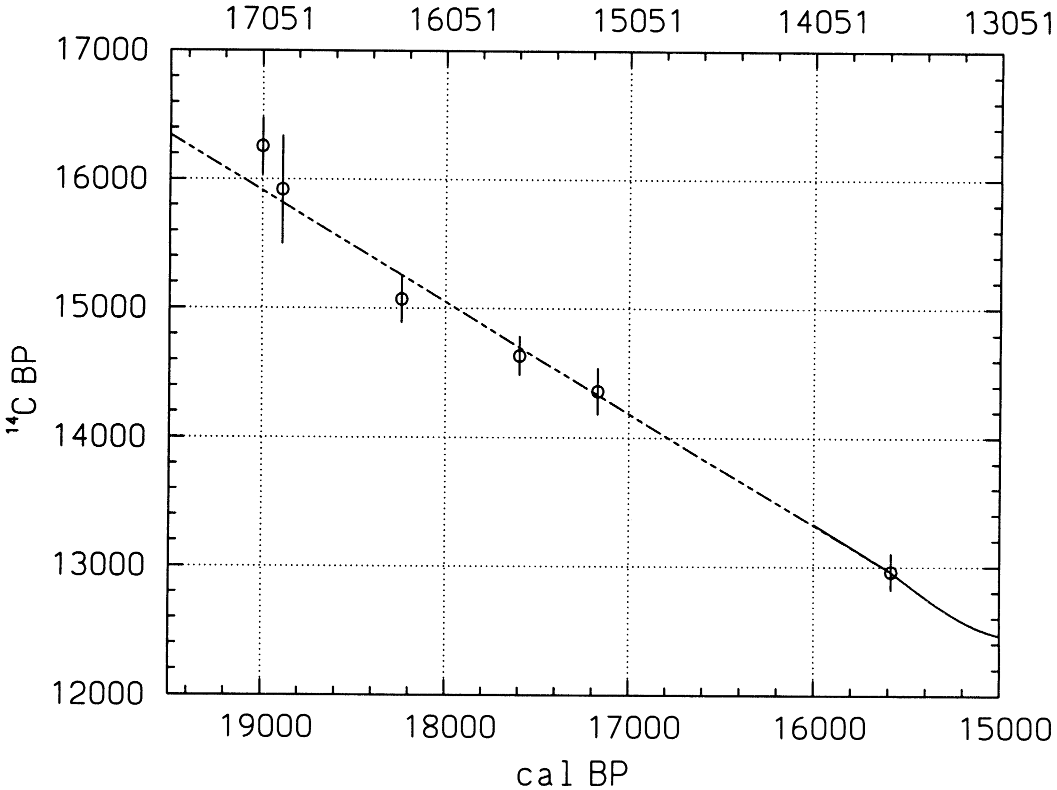

Fig. 8. Splined "atmospheric" coral data (19,500–15,000 cal BP; see Fig. 6 for symbols). The number of data points is too small to generate detail in the dashed curve.

record (the inset in Fig. 7 compares three-point moving averages of both data sets). The varve curve, on the other hand, is more detailed for pre-15,000 cal BP ages where the coral curve (due to the limited number of data points) appears linear.

Given a perfect varve chronology, the 175-yr offset (Fig. 7 inset) would indicate a marine reservoir correction of 325 ^{14}C yr instead of 500 ^{14}C yr. Because a zero-error varve chronology is unlikely, however, this cannot be definitely concluded.

The century- and millennium-scale $\Delta^{14}C$ variations (residual $\Delta^{14}C$, in per mil) of Figure 13 were obtained by deducting a 2000 yr moving average.

Reduced North Atlantic deepwater formation is tied to reduced surface-water transport toward the North (the "warm" Gulf stream), causing Northern regions (*e.g.*, Western Europe and Greenland) to become colder. Reduced deepwater formation is also tied to atmospheric ^{14}C increase. Because lower $\delta^{18}O$ values[9] accompany reduced atmospheric precipitation temperatures, one expects an inverse relationship between $\delta^{18}O$ and $\Delta^{14}C$ for oceanic-induced climate perturbations. The relationship (correlation coefficient $r = -0.54$, $\Delta^{14}C/\delta^{18}O = -20.4$) is depicted in Figure 14, where residual INTCAL98 $\Delta^{14}C$ (U/Th time scale) is compared to inverted $\delta^{18}O$ (ice layer count time scale) of the GISP2 Greenland ice core (Stuiver, Grootes and Braziunas 1995) for the 15,500–10,500 cal BP interval.

[9] $\delta^{18}O$ is the per mil deviation of the sample $^{18}O/^{16}O$ ratio from that of the SMOW standard .

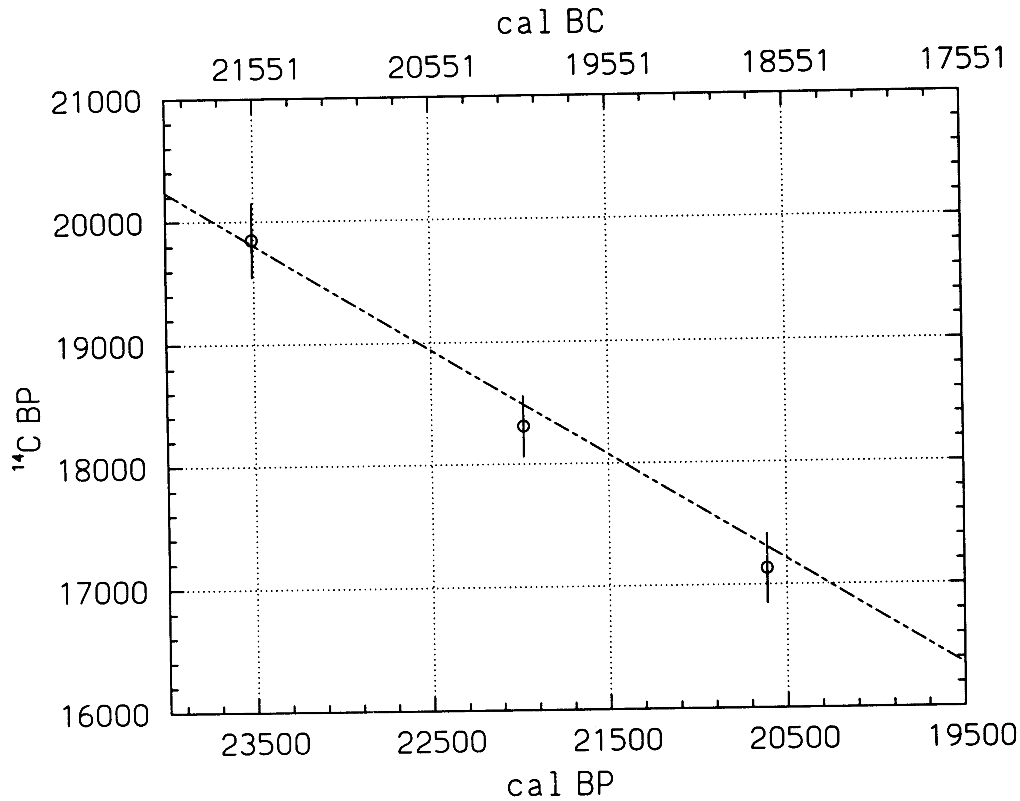

Fig. 9. Splined "atmospheric" coral data (24,000–19,500 cal BP; see Fig. 6 for symbols). The number of data points is too small to generate detail in the dashed curve.

The reduction of residual $\Delta^{14}C$ during the 15,000–14,500 cal BP interval suggests that the temperature increase of the Bølling (which starts *ca.* 14,670 cal BP) is tied to increased deepwater formation. The increase is followed by a two-step reduction and reverses again to increased deepwater formation (Broecker 1997, 1998; Hughen *et al.* 1998; Stuiver and Braziunas 1993) at the beginning of the Younger Dryas (~12,890 cal BP). This increase in deepwater formation ultimately leads to the relatively stable temperatures of the Holocene. To complicate matters, a Younger Dryas bipolar seesaw also may be operating (Broecker 1998). The Holocene itself has several century-scale oceanic and solar-induced (the solar connection yields $\Delta^{14}C = 60\ \delta^{18}O$) $\Delta^{14}C$ perturbations (Stuiver and Braziunas 1993; Stuiver *et al.* 1997).

Oceanic-induced atmospheric $\Delta^{14}C$ changes ($\Delta^{14}C$/yr) are caused by ^{14}C exchange rate variations between the mixed layer and deep ocean. For a complete cessation of ^{14}C transfer between mixed layer and deep ocean, the cosmic-ray-produced ^{14}C (global production rate Q in atoms/yr) will be distributed over a much smaller atmosphere, biosphere and mixed layer (ABM) reservoir. Present-day carbon reservoirs contain ^{14}C totaling 8260 yr of production (8260Q). The ABM reservoir contains only 7% of the total amount of exchangeable carbon (*e.g.*, Lal 1985), or 580 yr of ^{14}C production (580Q). When completely separated from the deep ocean, the atmospheric ^{14}C level of the ABM reservoir will double in *ca.* 650 yr (without radioactive decay the doubling time would be 580 yr). Thus the fastest rate of ^{14}C change in the atmosphere will be ~1% per 7 yr for a hypothetical deep ocean suddenly disconnected from the ABM reservoir. Rates of change of similar magnitude

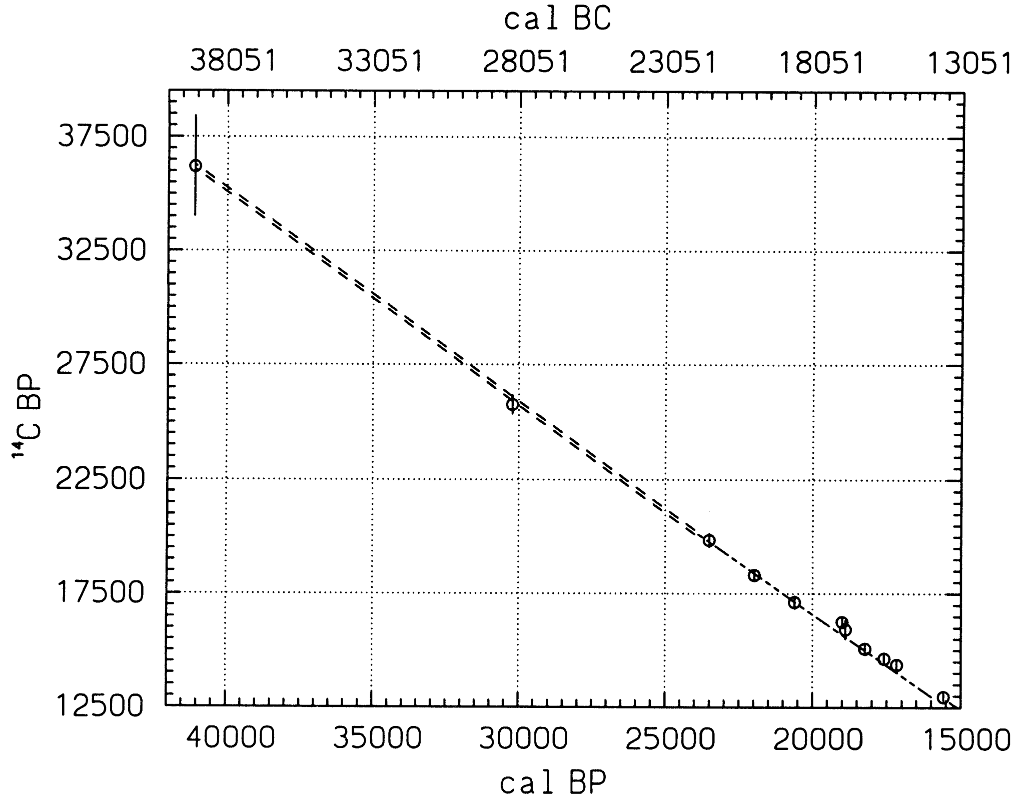

Fig. 10. The extension of the Figs. 6–9 spline to 40,000 cal BP. The double-dashed portion (only two coral measurements) is *not* acceptable as an INTCAL98 calibration curve.

will occur when fully reconnecting the mixed layer and deep ocean (the downward flux (0.93Q) is nearly identical to the production rate Q).

There are two modes of ^{14}C transport from the mixed layer to the deep ocean. Diffusion (including isopycnal advection) and deepwater formation play a key role. For the Holocene, deepwater formation transports about two-thirds of the global ^{14}C to the deep ocean (Toggweiler, Dixon and Bryan 1989). This yields a maximum $\Delta^{14}C$ change of 1% per 10.5 yr for full cessation of deepwater formation alone. The fastest observed century-scale $\Delta^{14}C$ change of 1% per 17 yr (near 13810, 13140 and 12720 cal BP, Fig. 14) delivers a 60% change in the rate of global deepwater formation. The well-defined maxima and minima in Figure 14 also suggest decadal switching times. And fast switching between the two modes of deepwater formation agrees with the symmetrical shape of several century-scale ^{14}C maxima and minima in Figure 14.

The $\Delta^{14}C$ decline near the start of the Bølling produces a fairly long plateau (15,000–14,400 cal BP) in the ^{14}C age–cal age relationship (Fig. 7 and 8). There are several Bølling-type oscillations in the GISP2 oxygen isotope record between 40,000 and 15,000 cal BP. Assuming similarity in atmospheric ^{14}C response, one expects *ca.* 600-yr-long ^{14}C age plateaus near 38,400, 35,300, 33,600, 32,300 and 29,100 cal BP (GISP2 time scale).

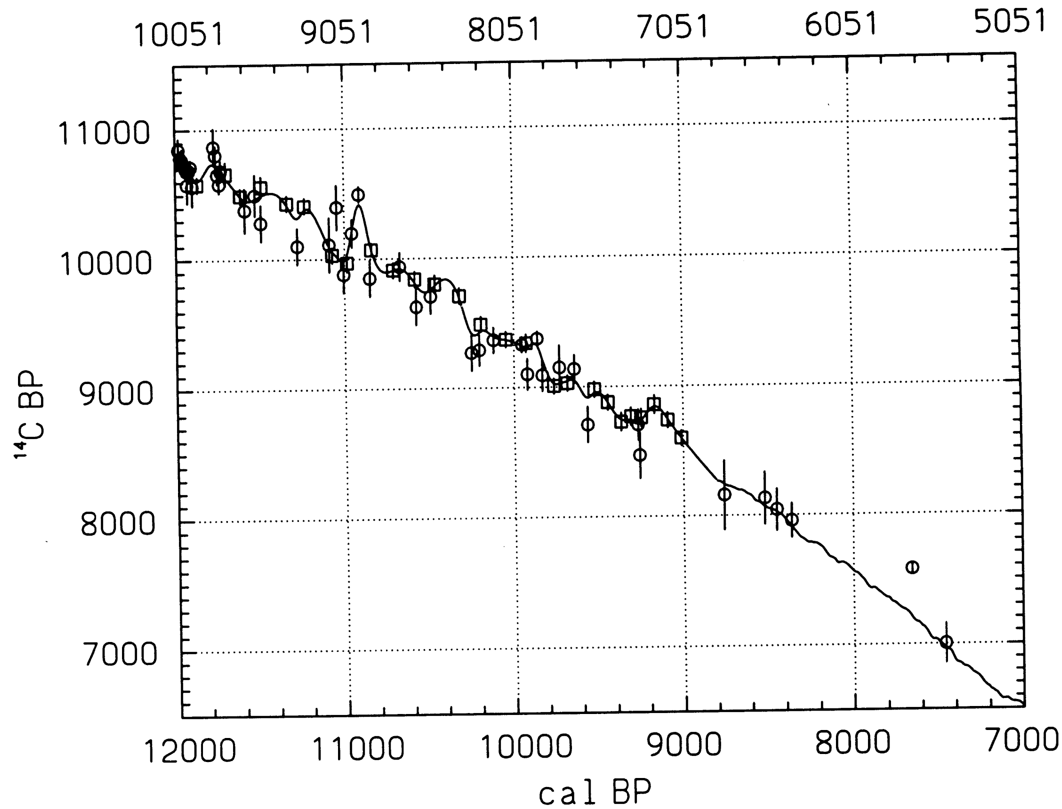

Fig. 11. Coral (O, bar = 2σ) and varve (□, bar = 1σ) ^{14}C ages splined (solid line) over the 12,000–8800 cal BP interval. The spline is connected to the carbon reservoir calculated decadal marine ^{14}C ages (solid line) of the 8800–7000 cal BP interval. The solid lines form the INTCAL98 calibration curve for marine samples.

CALIBRATION

It is not possible to suggest guidelines for specific regional (non-hemispheric) offsets due to the lack of precise information on time-dependent regional ^{14}C differences. Offsets (see "Hemispheric and Regional Offsets") introduce uncertainties of one or two decades in the age calibration process of atmospheric samples. Because the ^{14}C level of the Southern Hemisphere is, on average, below that of the Northern Hemisphere, we recommend for Southern Hemispheric samples a ^{14}C age reduction of 24 ± 3 ^{14}C yr prior to calibration (pre- AD 1900 atmospheric samples only).

As noted previously, the atmospheric calibration curve is based on 1) a linear connection of the tree-ring generated decadal data points (11,850–0 cal BP) and 2) a spline with minimum smoothing of reservoir-corrected coral and varve data (24,000–11,850 cal BP).

The marine calibration curve consists of 1) a linear connection of carbon reservoir calculated decadal marine ages (8800–0 cal BP) and a 2) a spline of measured coral and varve ages (24,000–8800 cal BP) with a degree of smoothing similar to the atmospheric calibration curve.

The standard deviation in the curves is not drawn in Figures A (atmospheric) and B (marine). For the tree-ring based portion of the atmospheric curve, the width of the curve (the one standard deviation includes a 1.3 error multiplier) starts with an average 9 yr for the youngest millennium and increases

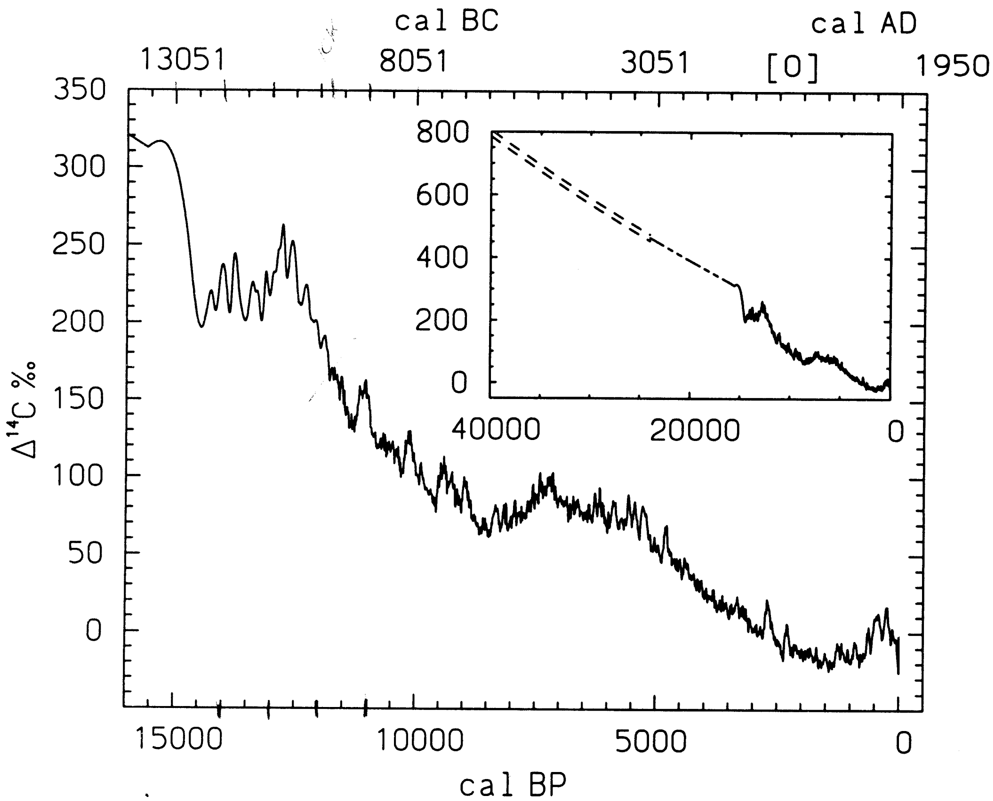

Fig. 12. Atmospheric $\Delta^{14}C$ profile for 1) 15,500–0 cal BP and 2) 40,000–0 cal BP (inset, with $\Delta^{14}C$ per mil scale). Tree-ring data were used for the 11,854–0 cal BP construction and marine (coral and varve) information for the remaining part. The solid line represents $\Delta^{14}C$ values derived from the INTCAL98 ^{14}C age–cal age relationship; the dashed portion is based on the splining of a limited number of data points (see Figs. 7 and 8). The double dashed curve is based on only two measurements.

to 23 yr for the older part (11,000–10,000 cal BP). The width of the spline, derived from the coral and varve ^{14}C age errors, is one standard deviation (as discussed, we use for the calculation of the actual standard deviation 2σ for the coral ^{14}C ages, 1σ for the varve ^{14}C ages, and a $k=1.3$ error multiplier for both) and ranges from an average 100 ^{14}C yr for the 13,000–12,000 cal BP interval to 300 ^{14}C yr for the 24,000–20,000 cal BP interval.

In its simplest form, the calibration process is a straightforward reading of the calibration curves (Stuiver and Pearson 1993). Because Figures A and B lack uncertainty estimates, we recommend the use of computer programs that include the error margin for age calibration. Computer programs (*e.g.*, CALIB, Stuiver and Reimer 1993; cal15, van der Plicht 1993; and OxCal v2.18, Bronk Ramsey 1994) also generate additional information, such as probability distributions *vs.* cal age. To avoid confusion, we recommend that all computer programs, as of 1999, incorporate the INTCAL98 database for marine and terrestrial age calibration. The INTCAL98 calibration data (atmospheric as well as marine, with one standard deviation uncertainty), the atmospheric $\Delta^{14}C$ and residual $\Delta^{14}C$ values, the CALIB 4.0 computer program based on INTCAL98 data, and $\delta^{18}O$ of the GISP2 ice core can be downloaded from the Quaternary Isotope Laboratory web site at <http://depts.washington.edu/qil/>.

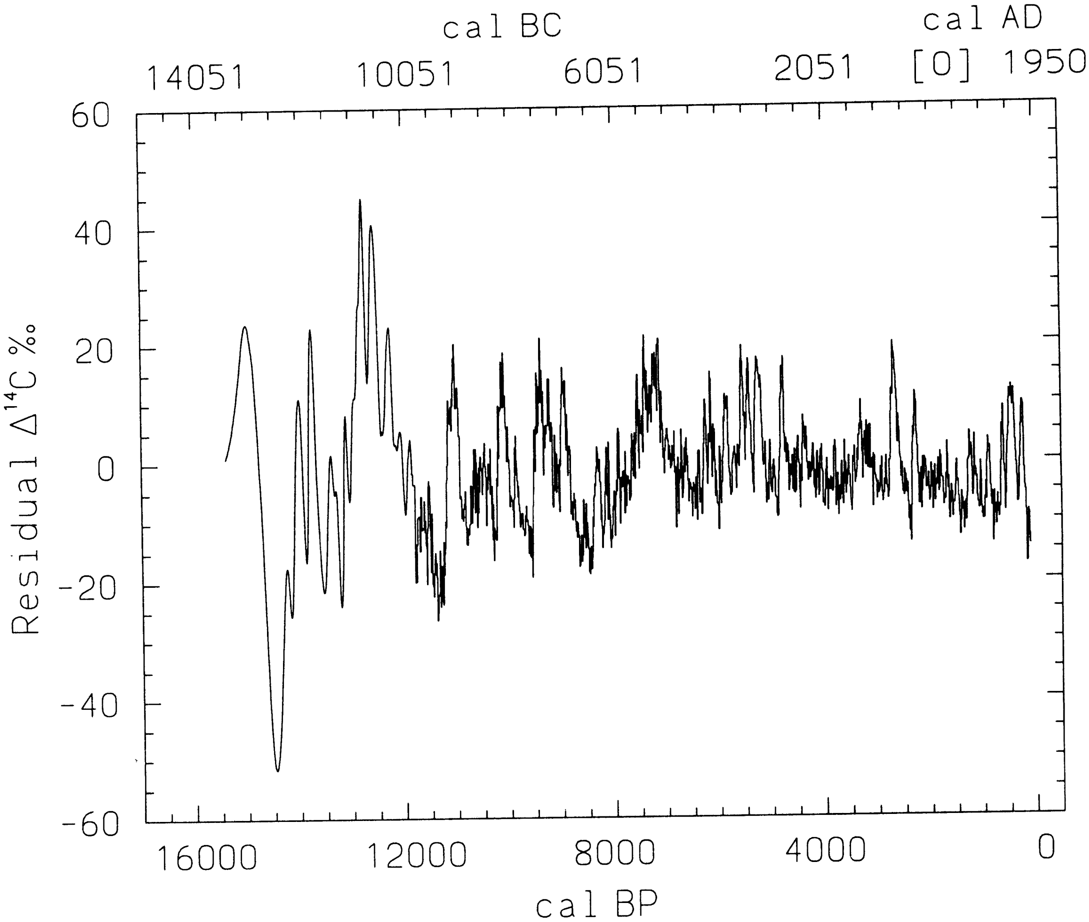

Fig. 13. $\Delta^{14}C$ residual variations, after removing a 2000-yr moving average from the Fig. 12 profile

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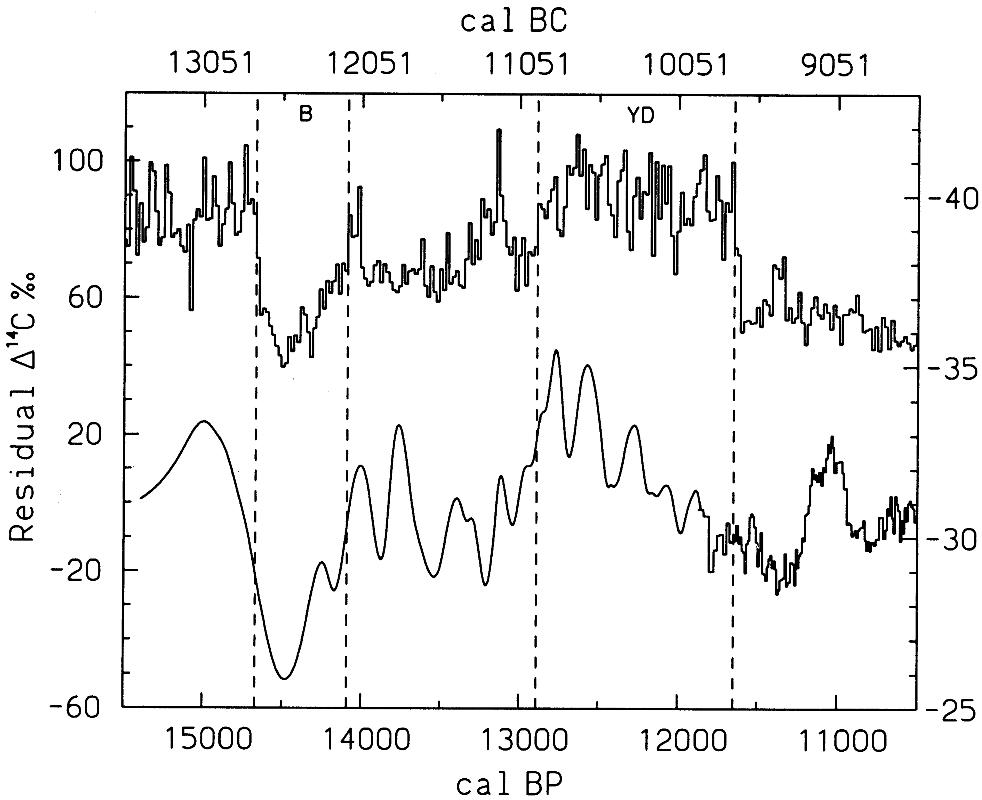

Fig. 14. The upper curve depicts the inverted GISP2 oxygen isotope ratio ($\delta^{18}O$) record with bidecadal time separation (Stuiver, Grootes and Braziunas 1995). The lower curve is based on INTCAL98 residual $\Delta^{14}C$. The cal BP scale of the oxygen isotope record is based on ice layer counts (Alley *et al.* 1997). B = Bølling, YD = Younger Dryas.

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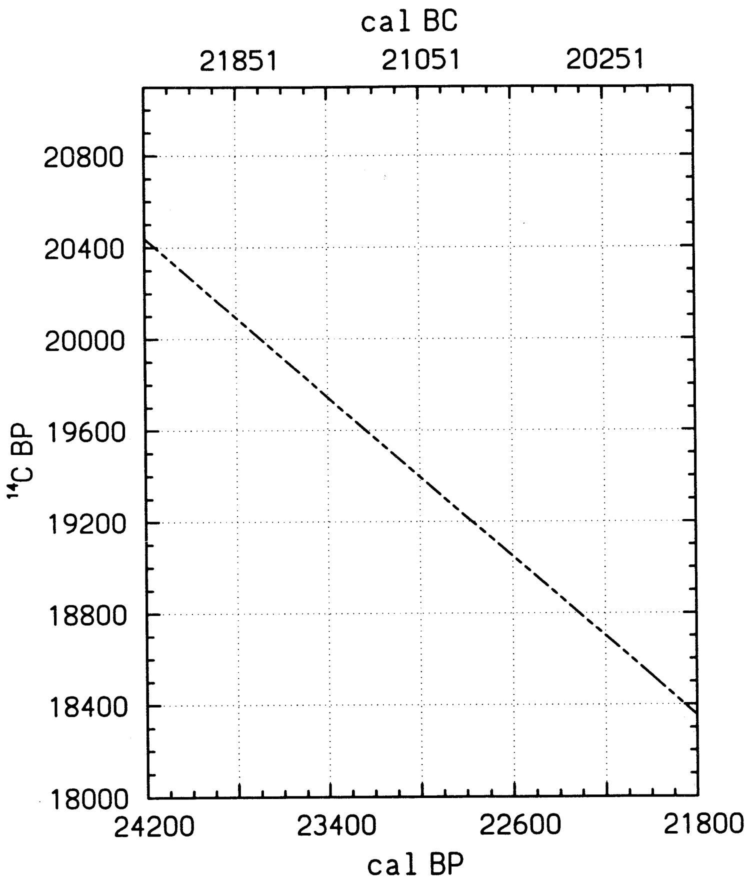

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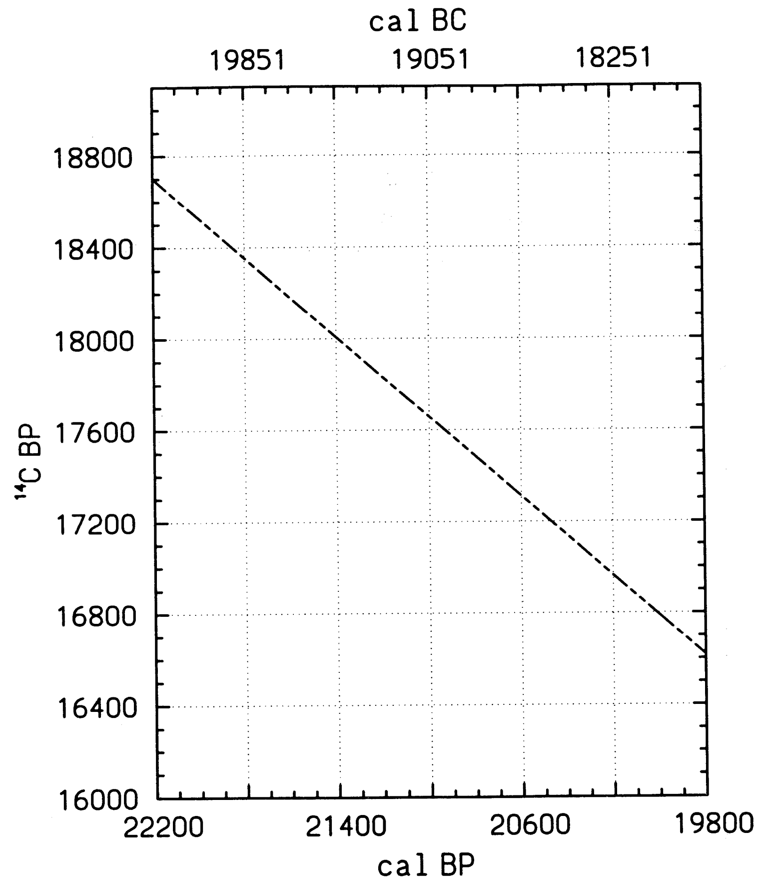
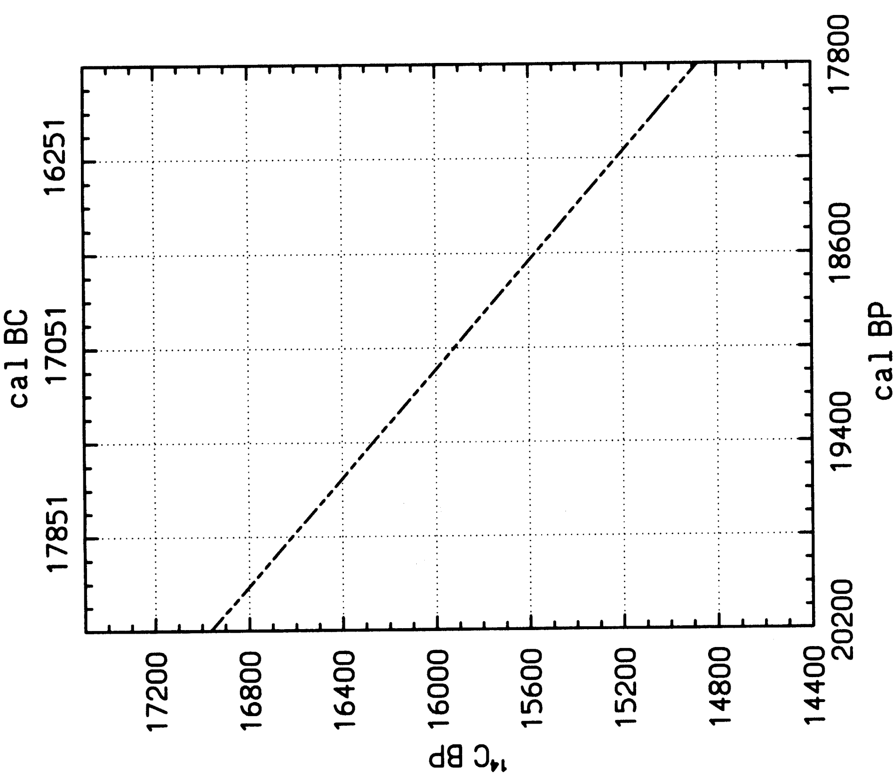


Fig. A2

Fig. A1–19. INTCAL98 atmospheric calibration curve with decadal resolution back to 11,850 cal BP. The remaining part of INTCAL98 was constructed from coral data with a time resolution of about one century near 12,000 cal BP, and about one millennium near 24,000 cal BP. The dashed portions are based on the splining of a limited number of data points (see Figs. 7 and 8).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14C BP
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16800
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15600
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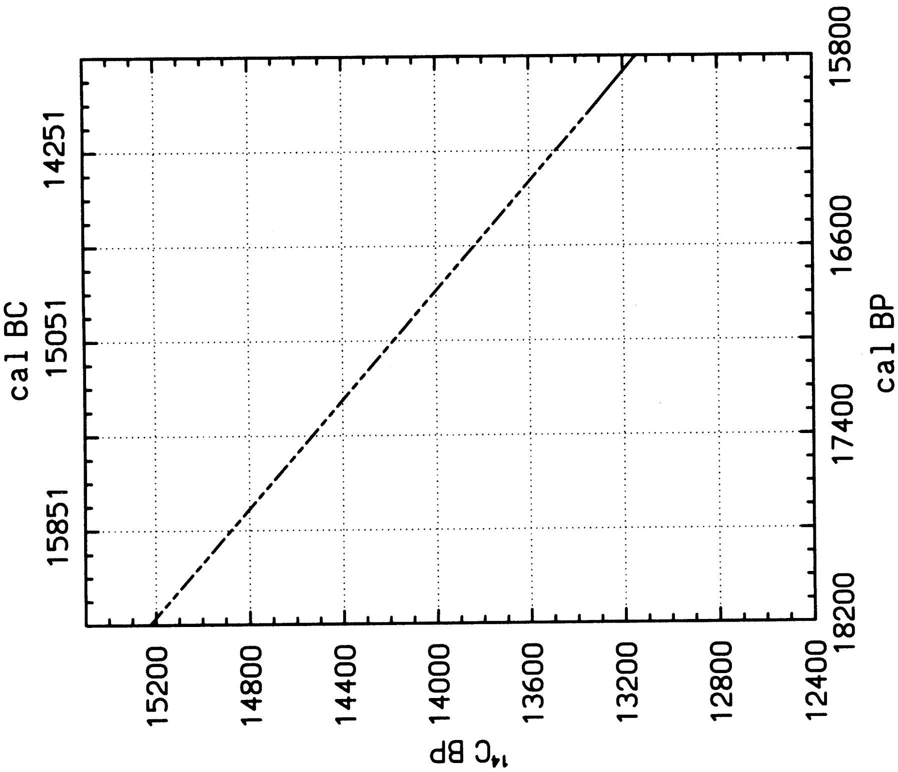
14800
14400

Fig. A3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12800
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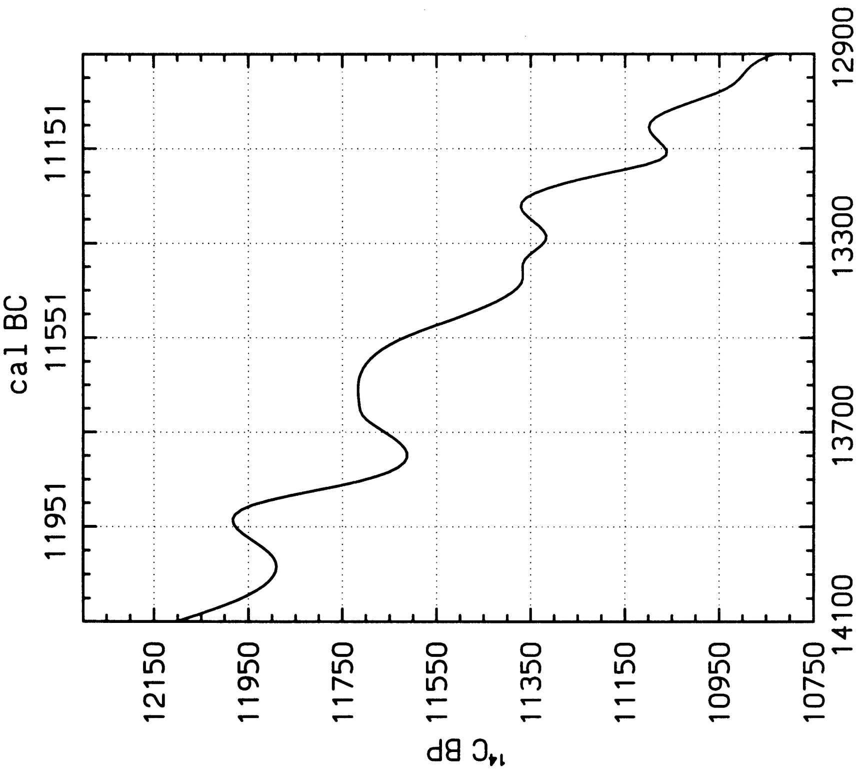
Fig. A4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10750

Fig. A6

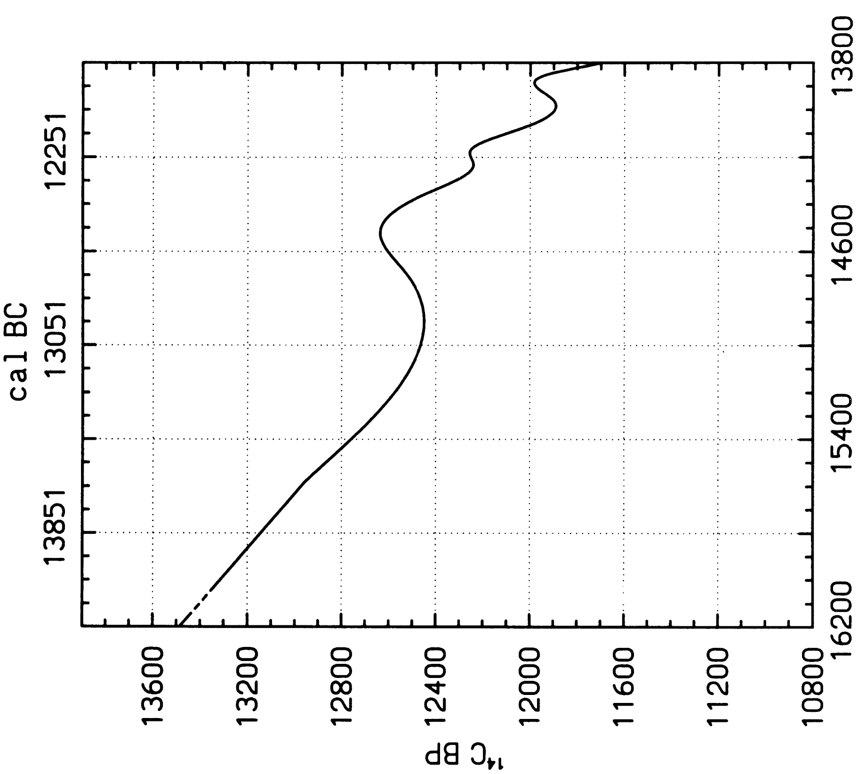
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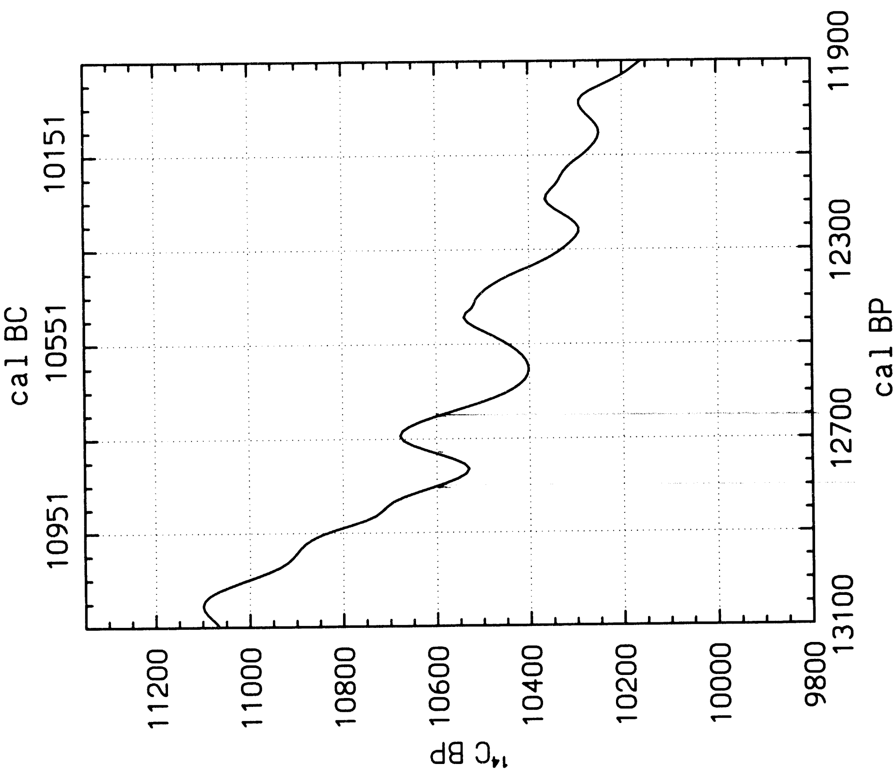
Fig. A5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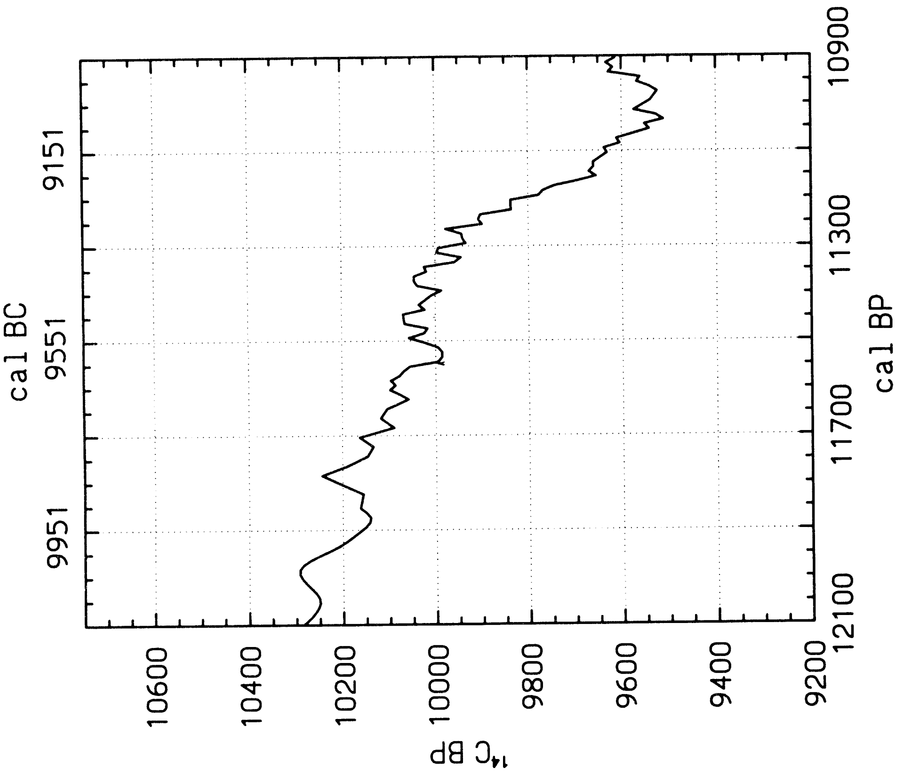
cal BP

Fig. A7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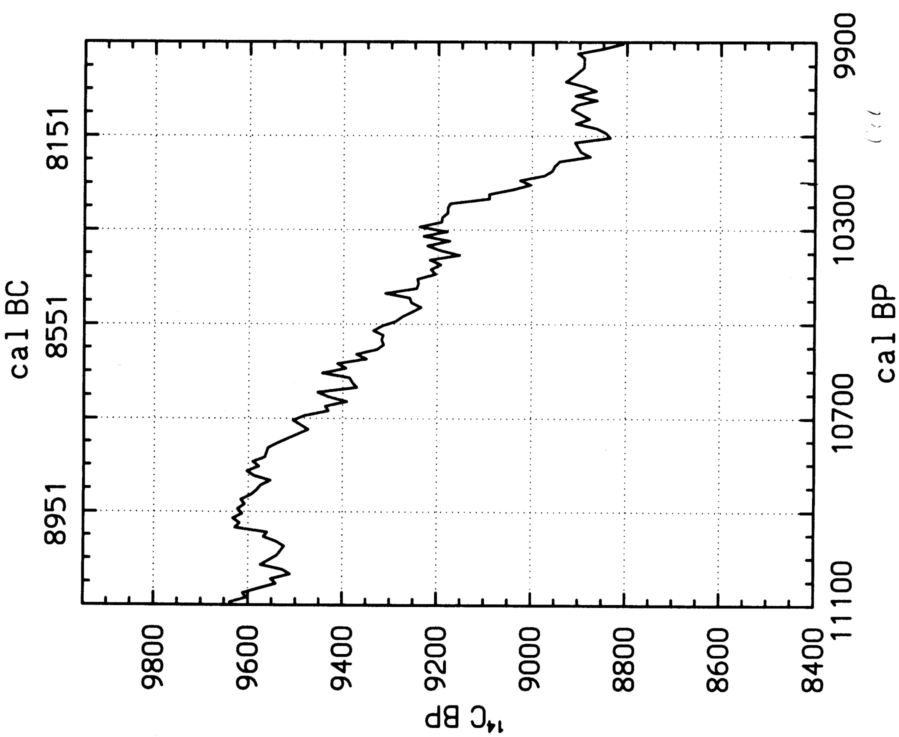
cal BP

Fig. A8



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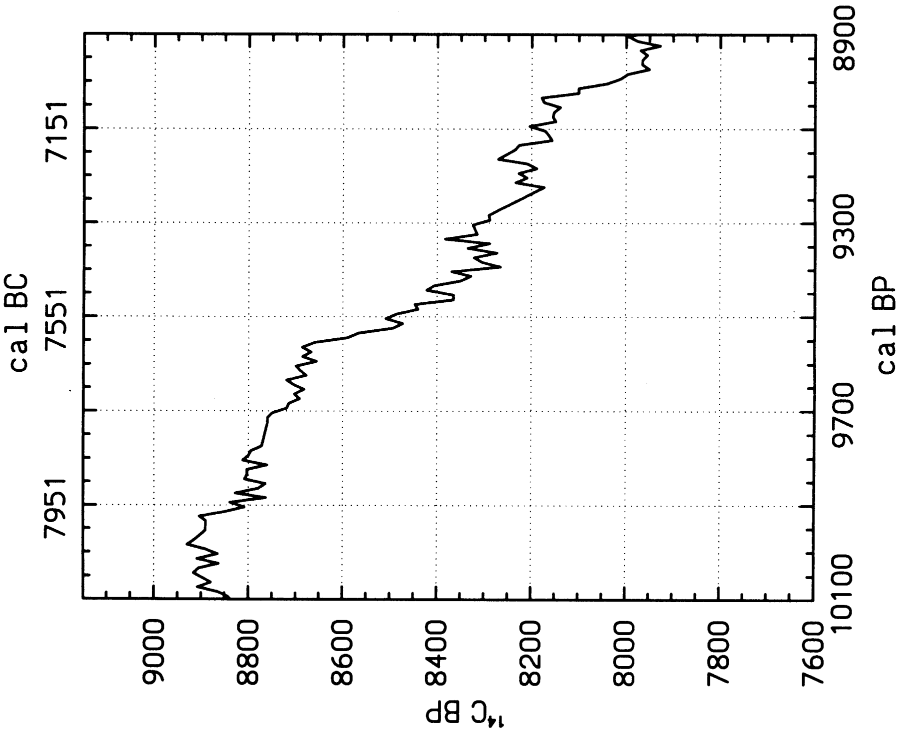

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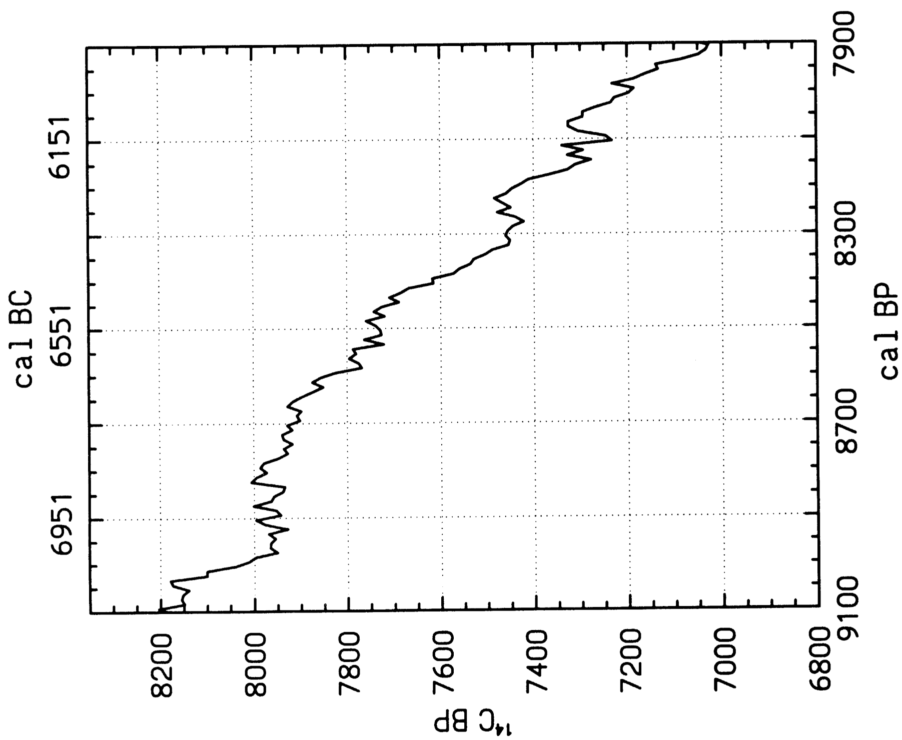

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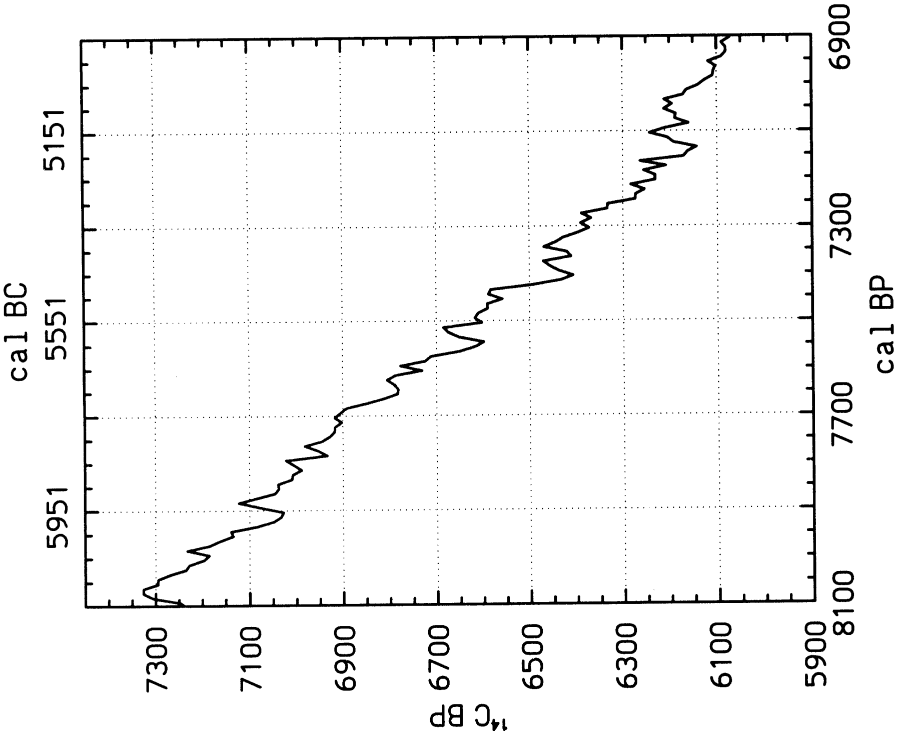

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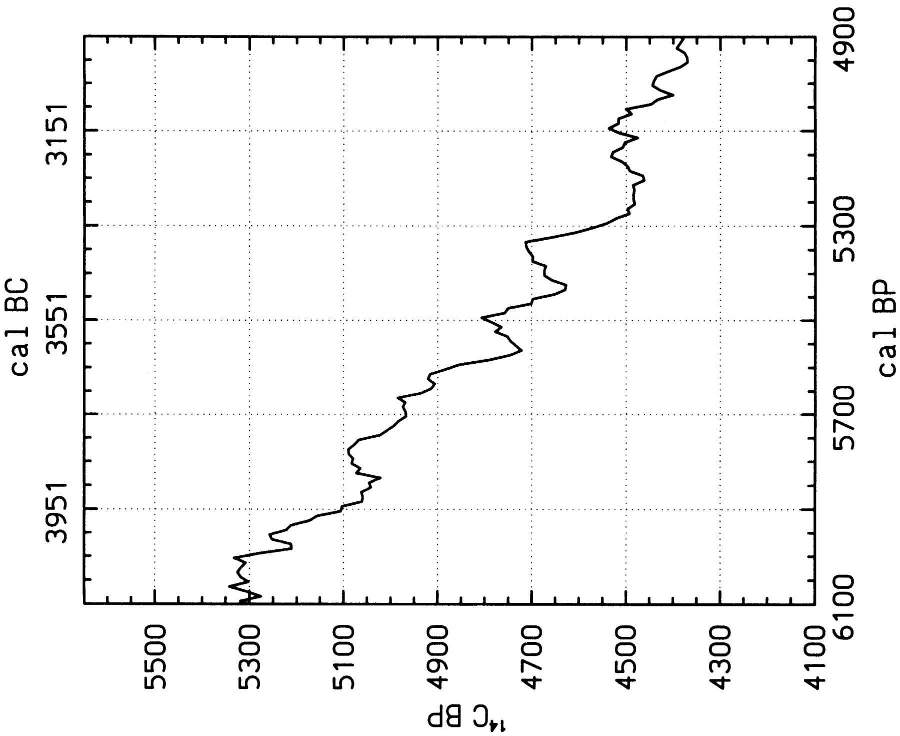

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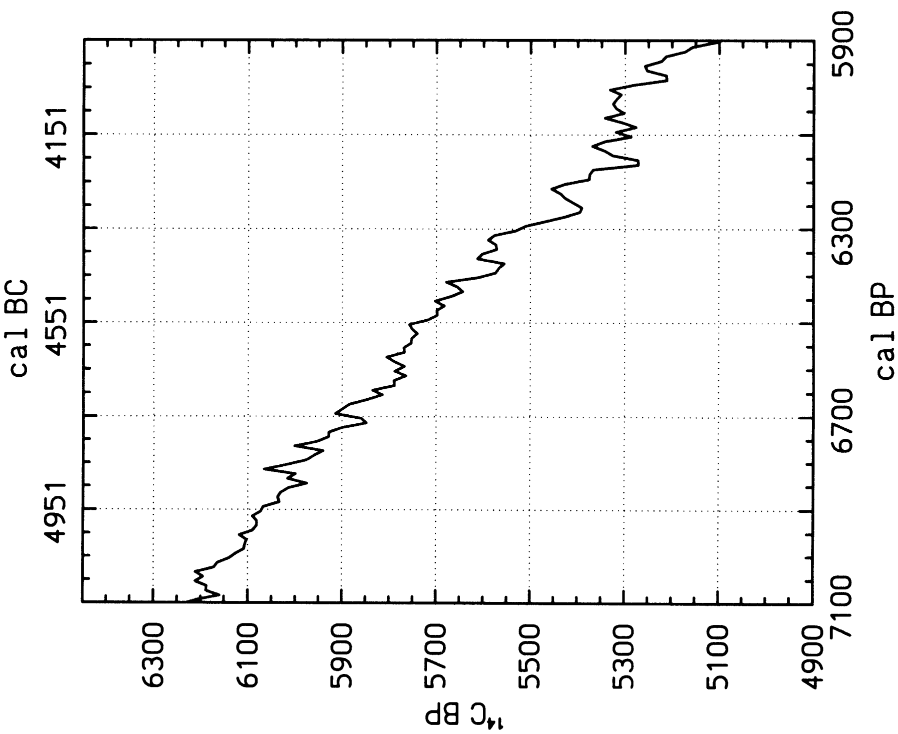

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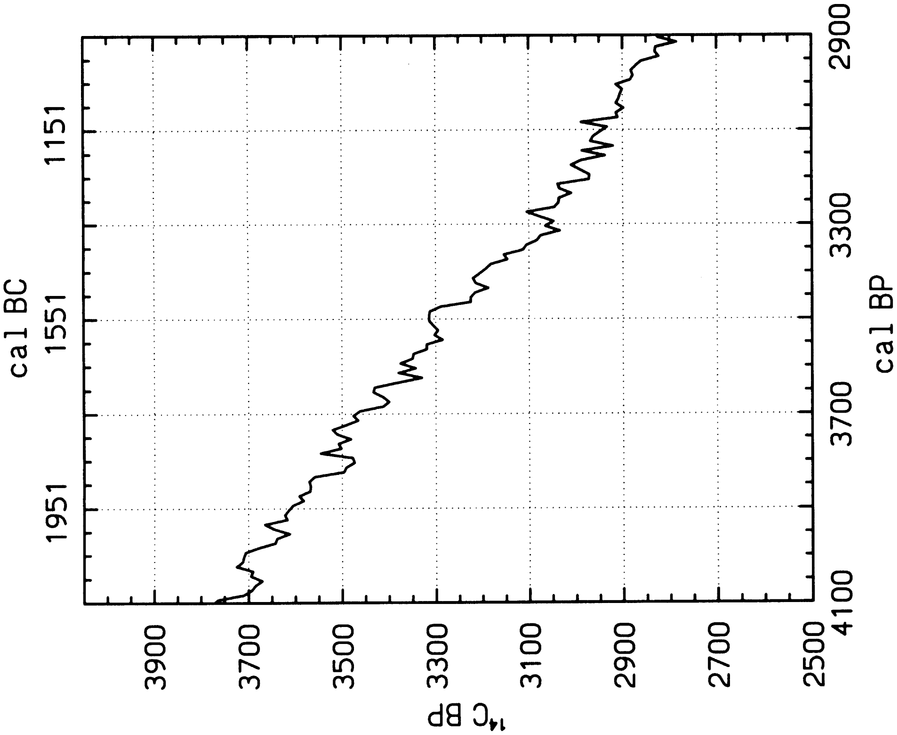

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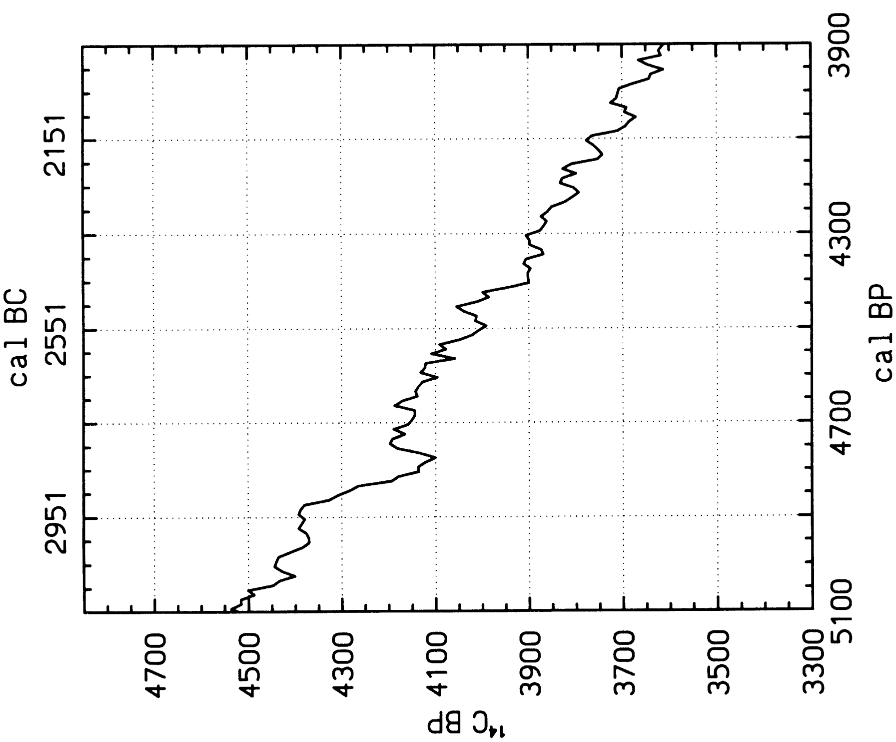

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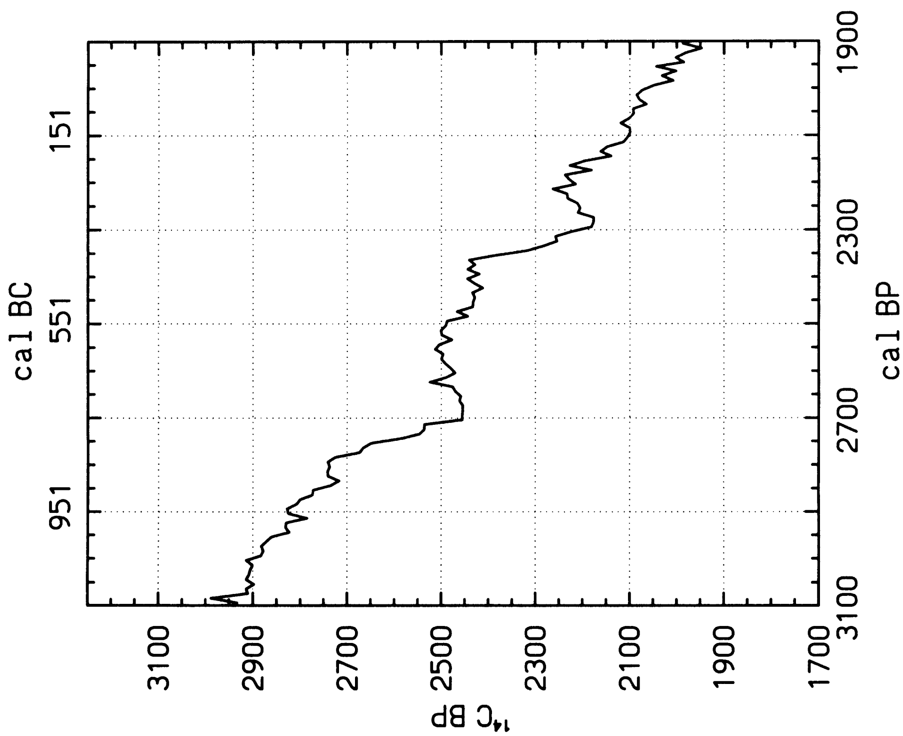

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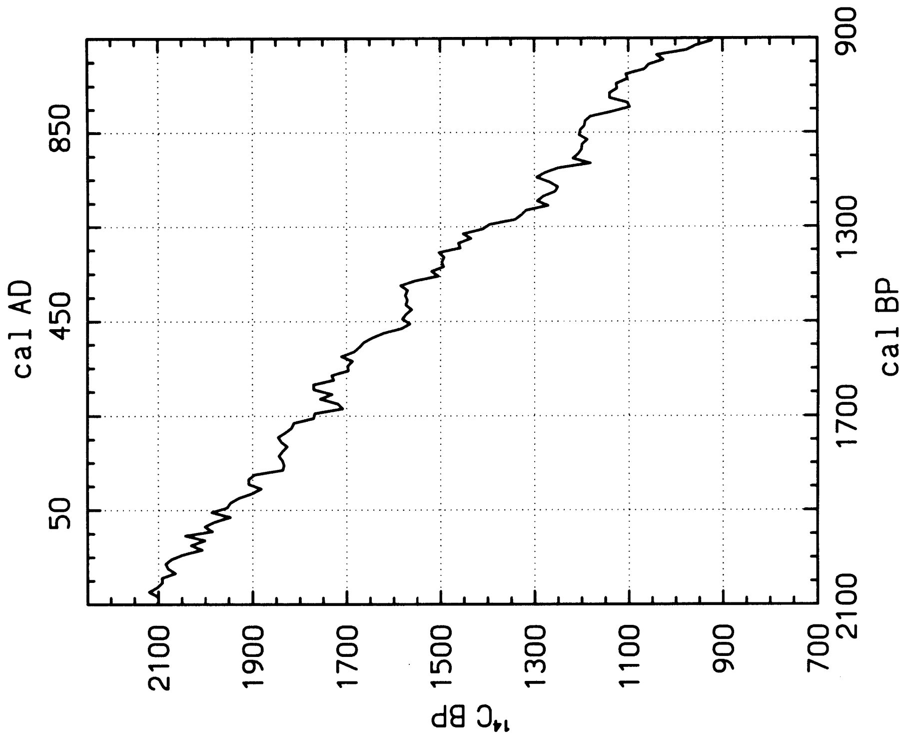

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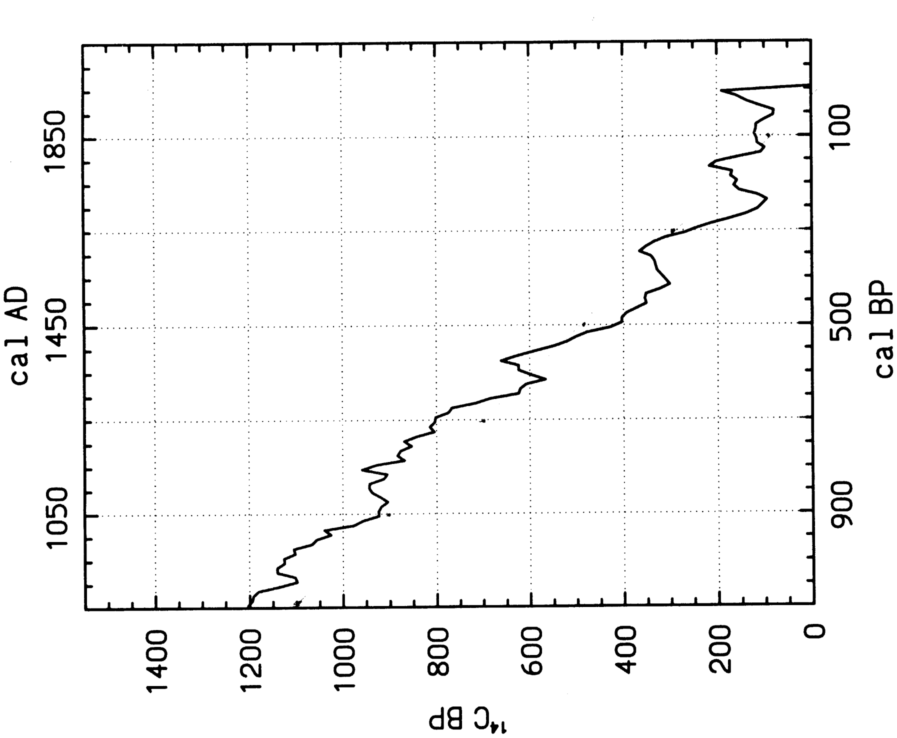
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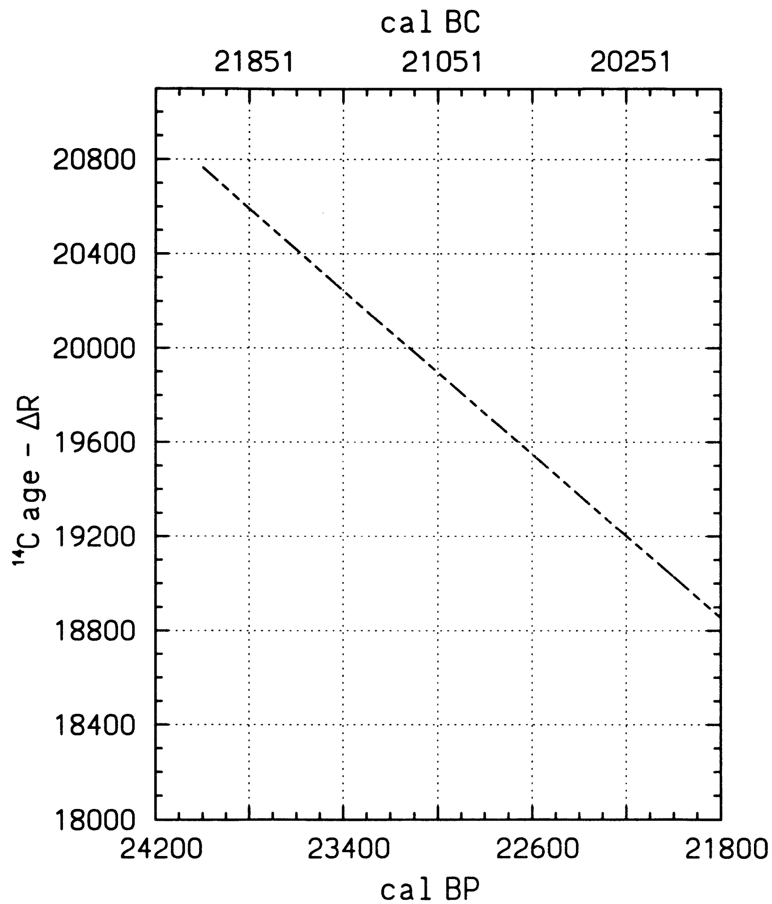
Fig. A19



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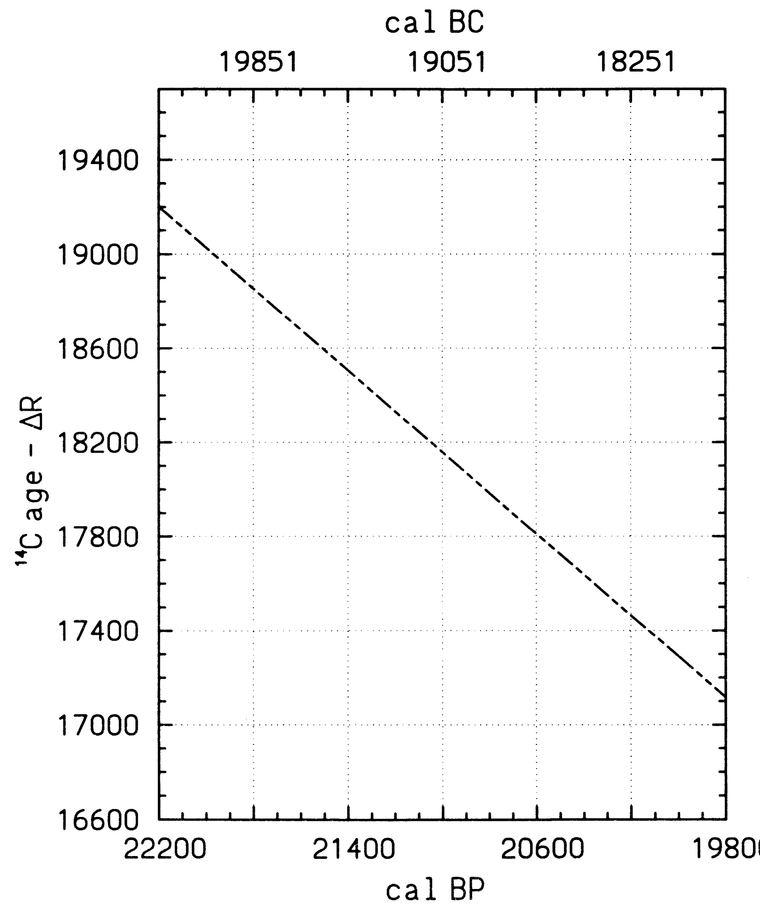

Fig. B2

Fig. B1–19. INTCAL98 marine calibration curve based on 1) carbon reservoir derived ^{14}C ages for the 8800–0 cal BP interval and 2) coral/varve ^{14}C age determinations for the 8800–24,000 cal BP interval. The dashed portions are based on the splining of a limited number of data points (see Figs. 7 and 8). The very substantial 10,900 cal BP perturbation is dashed because its maximum, generated by a single data point, lacks corroboration.

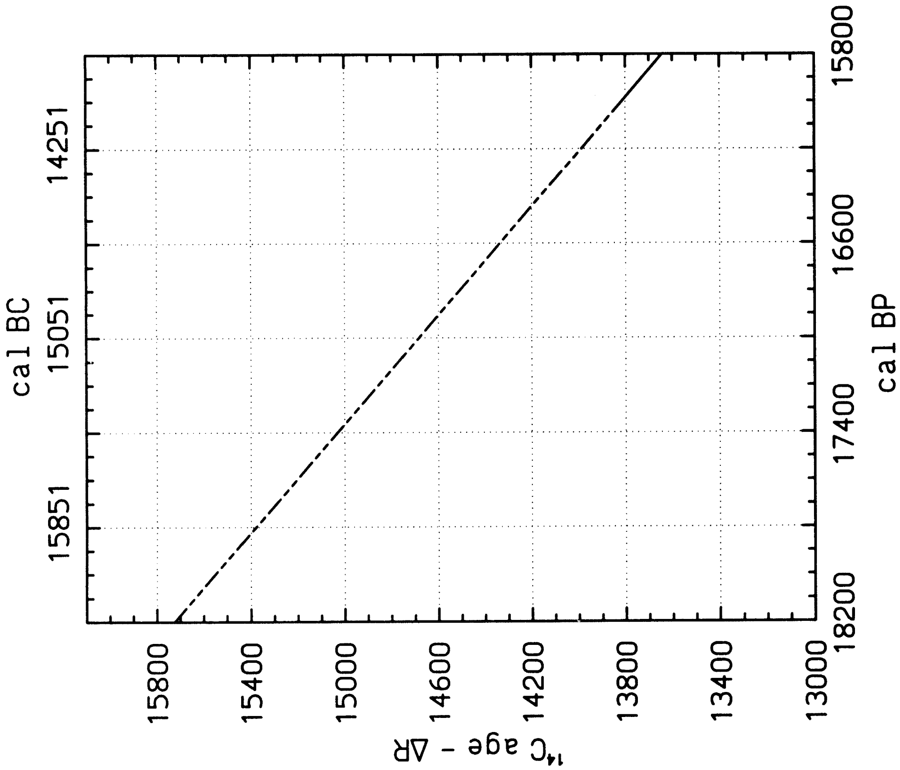
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Fig. B4

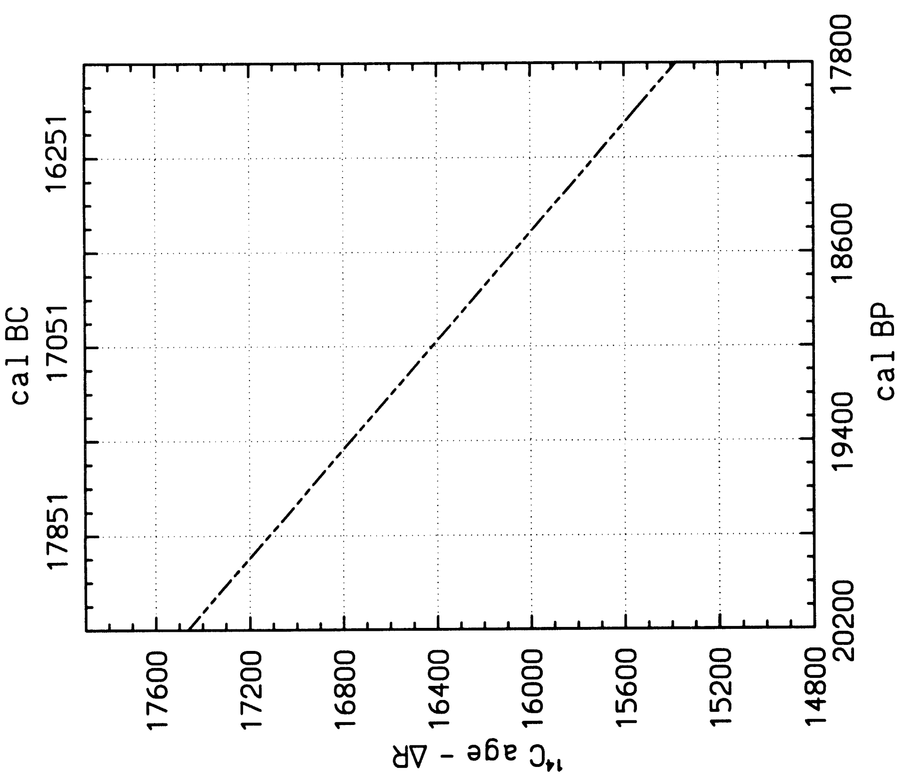
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Fig. B3

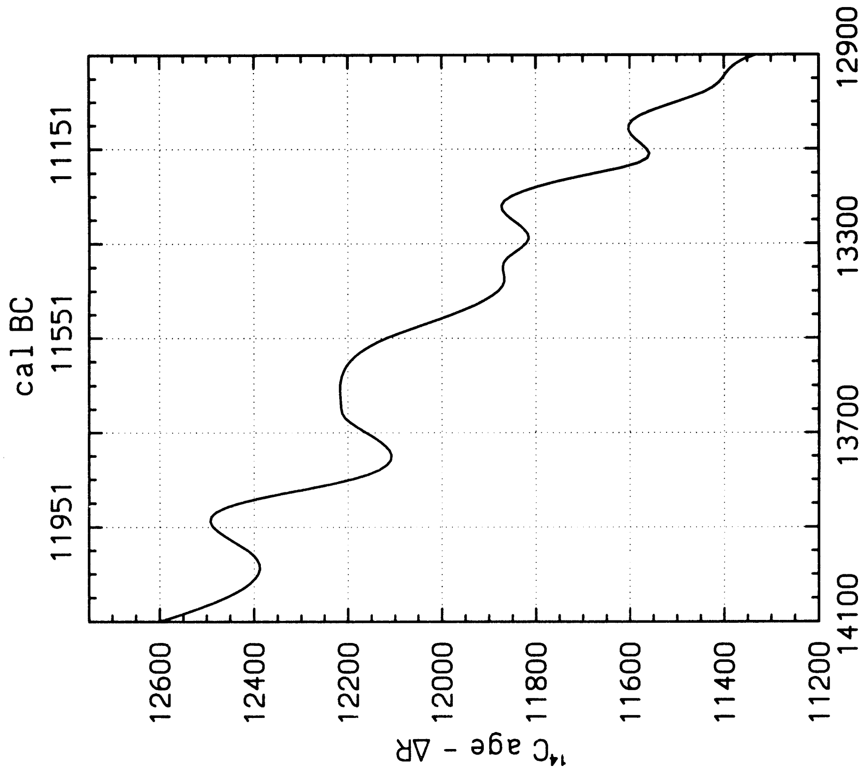
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Fig. B6

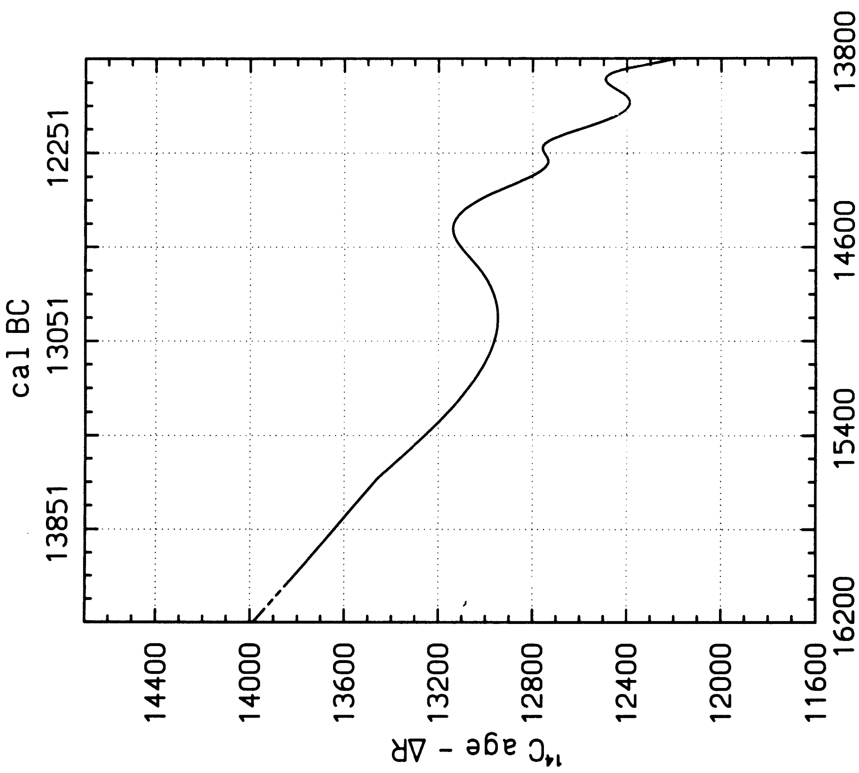
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Fig. B5

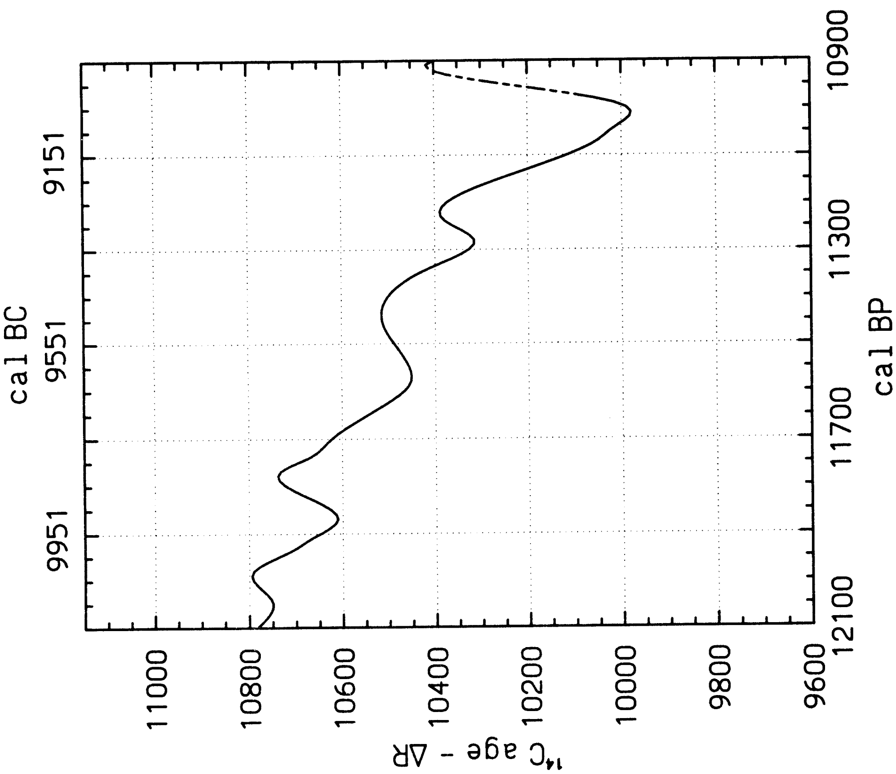
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Fig. B8

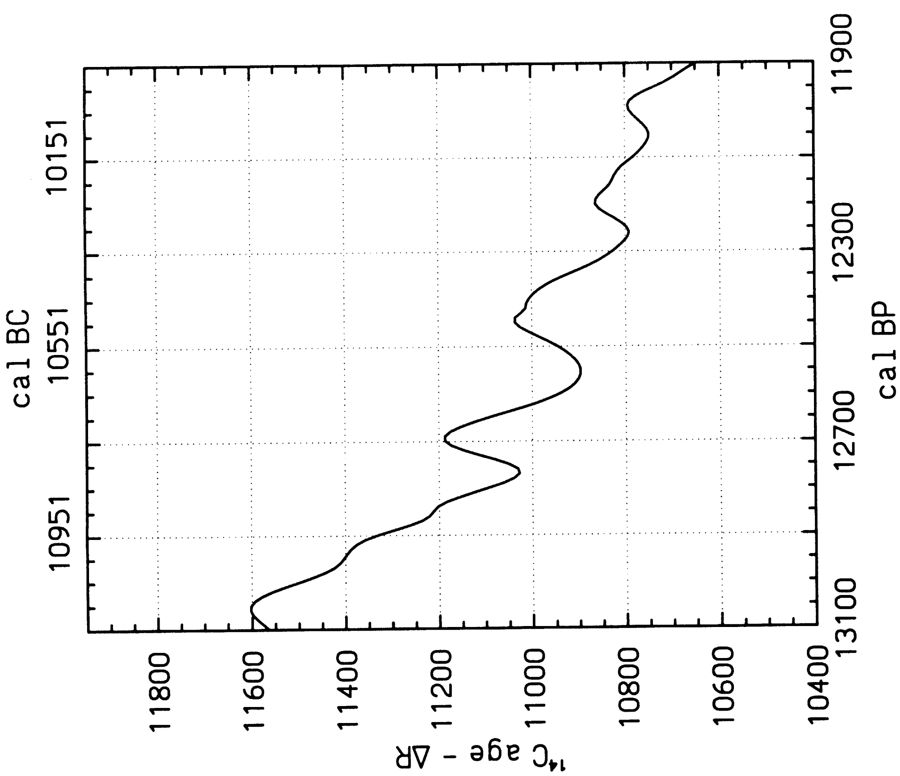
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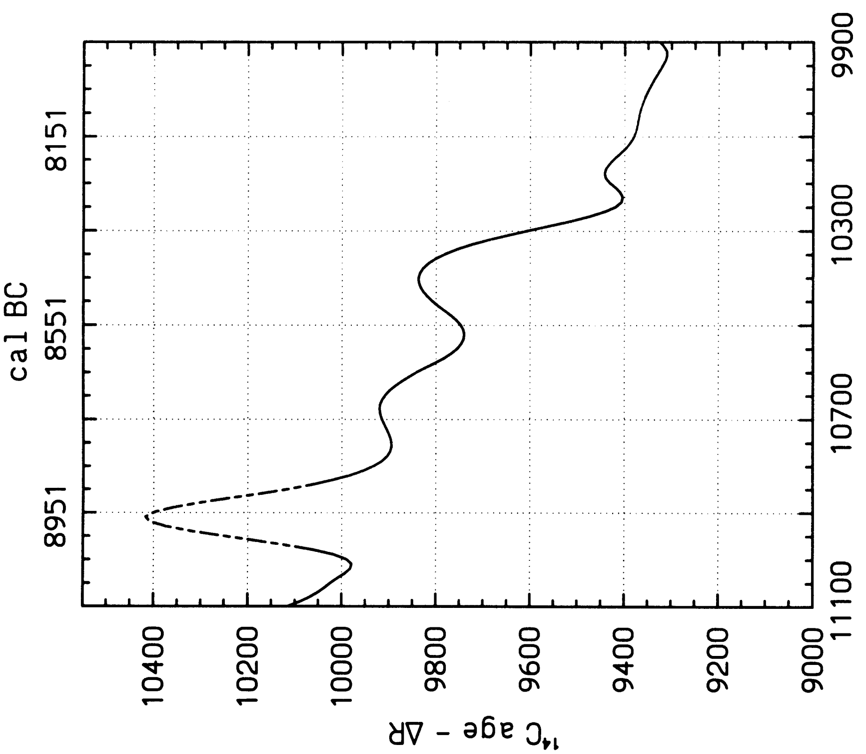
Fig. B7



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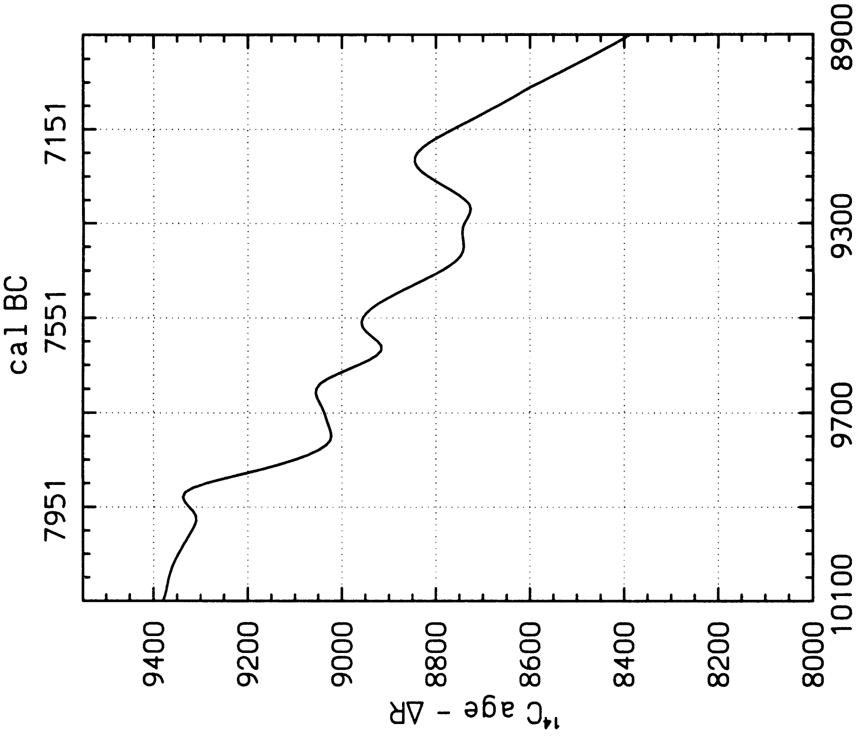

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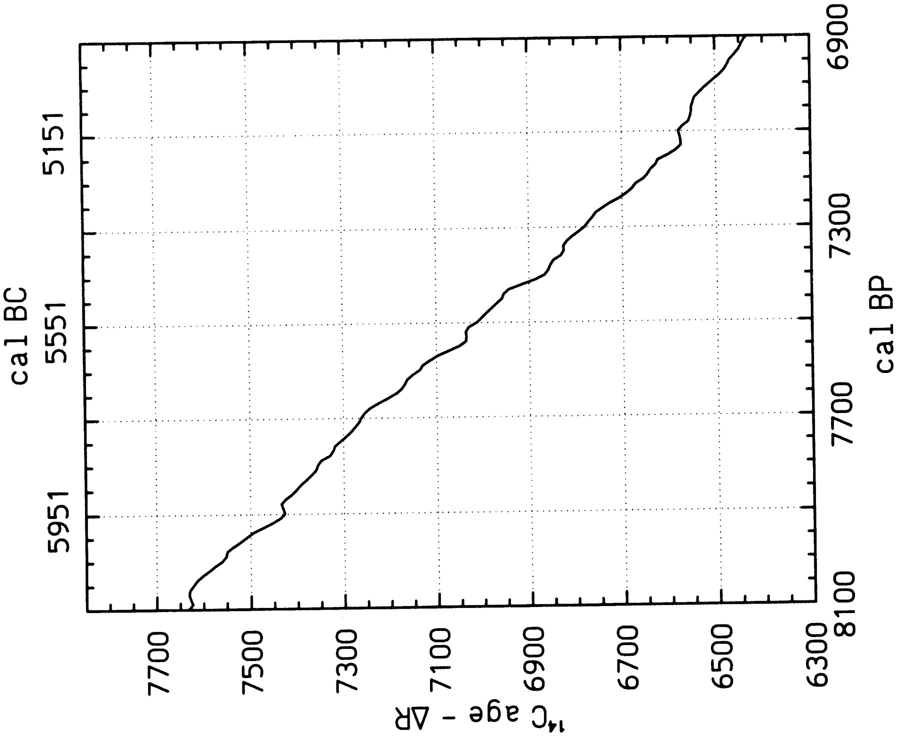

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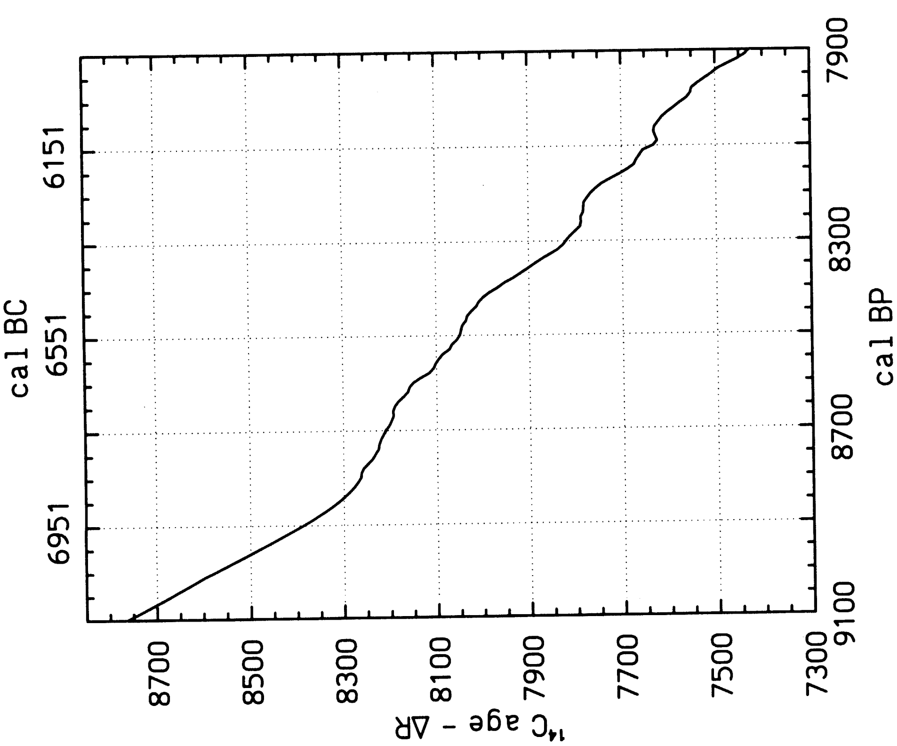

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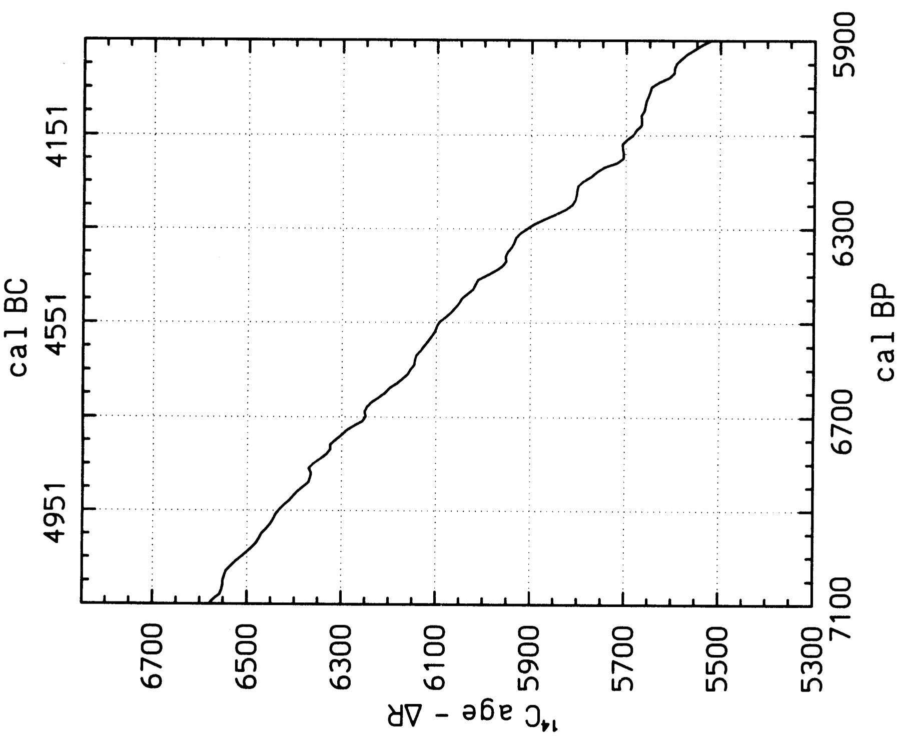

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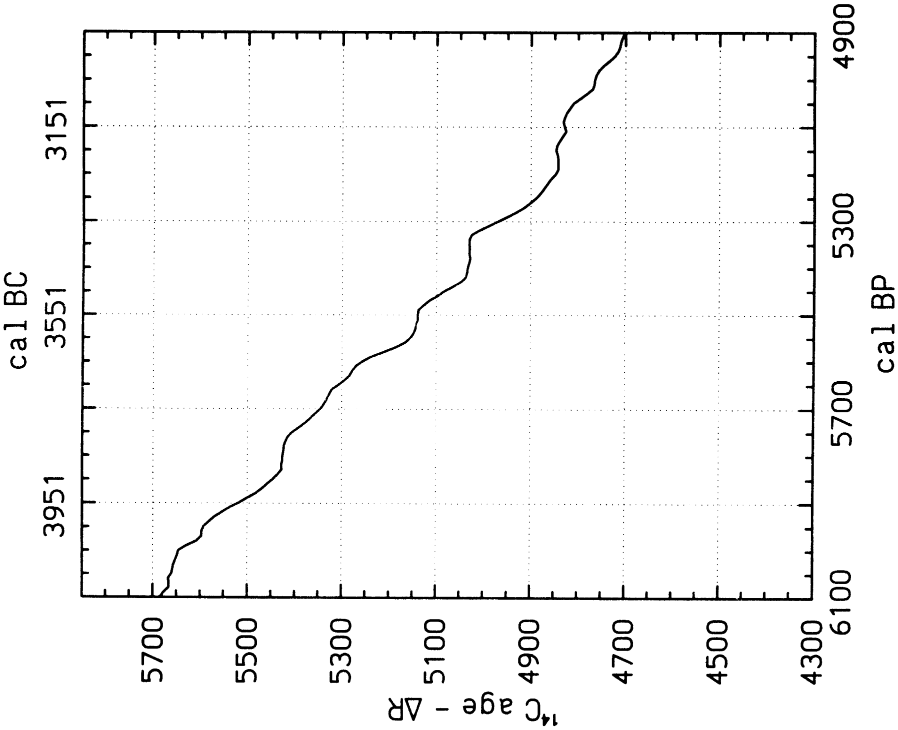

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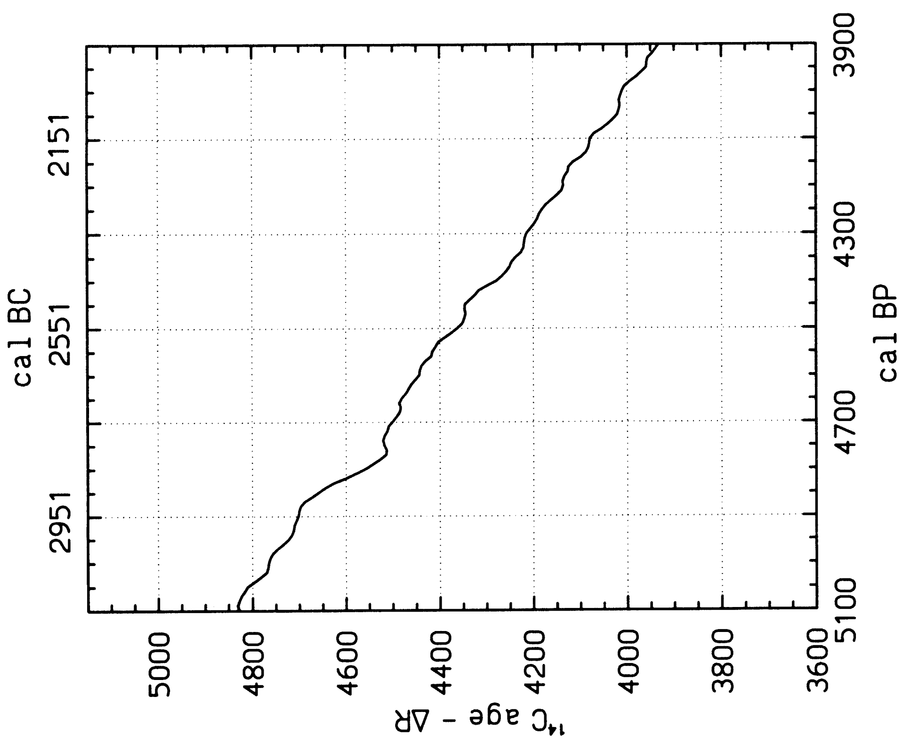

Fig. B15

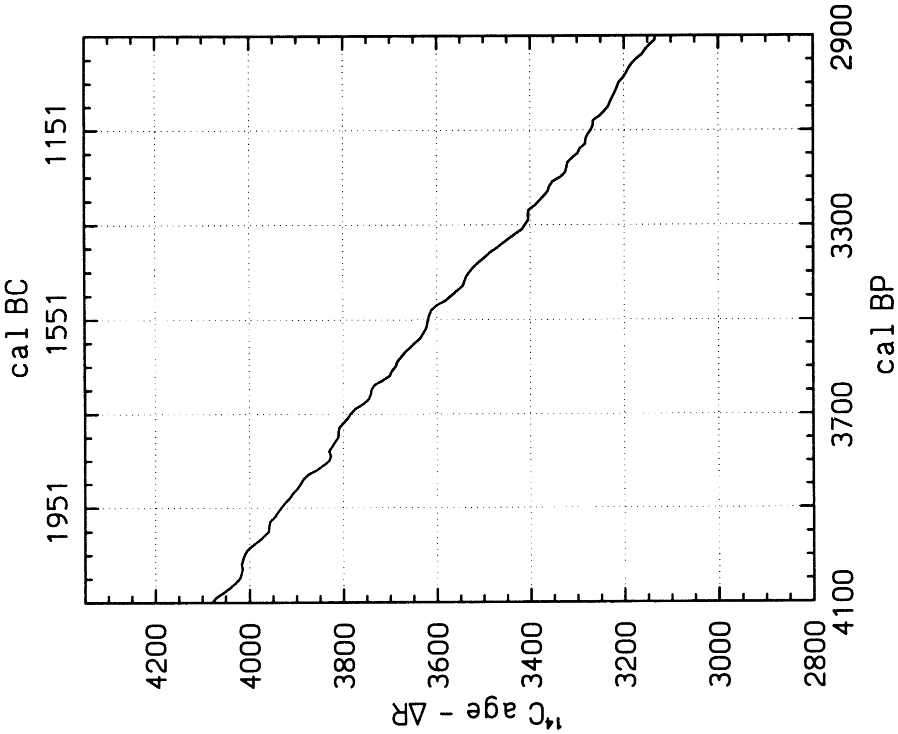

Fig. B16

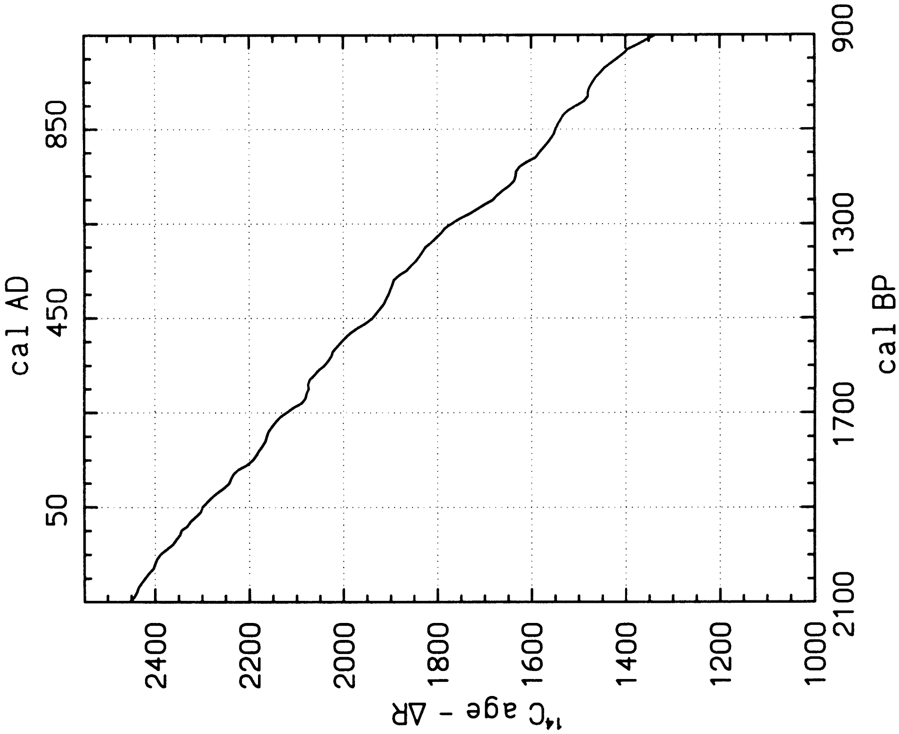

Fig. B18

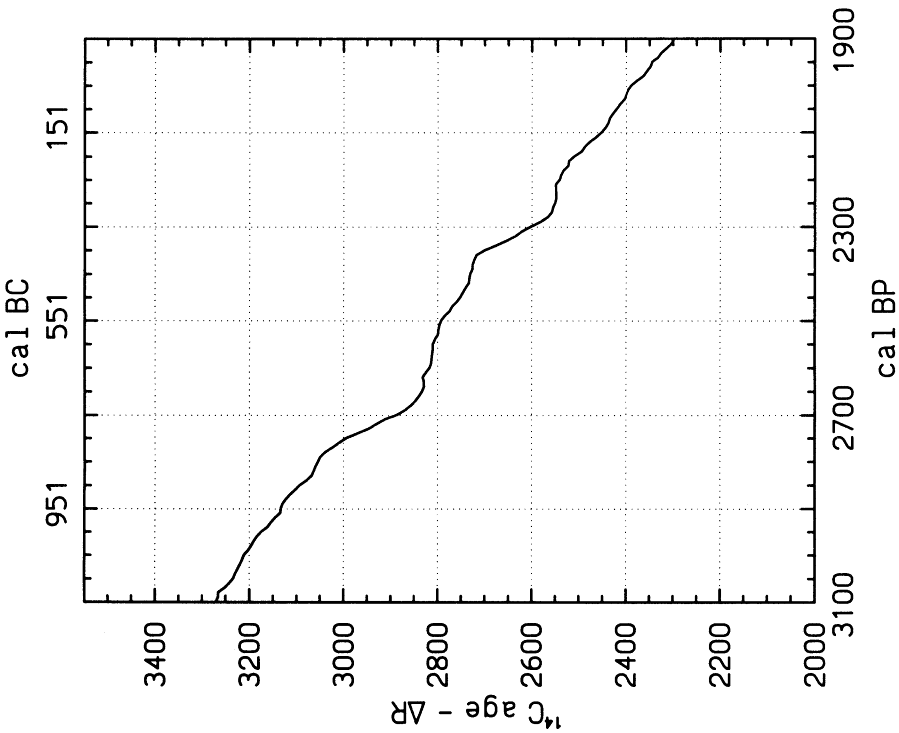

Fig. B17

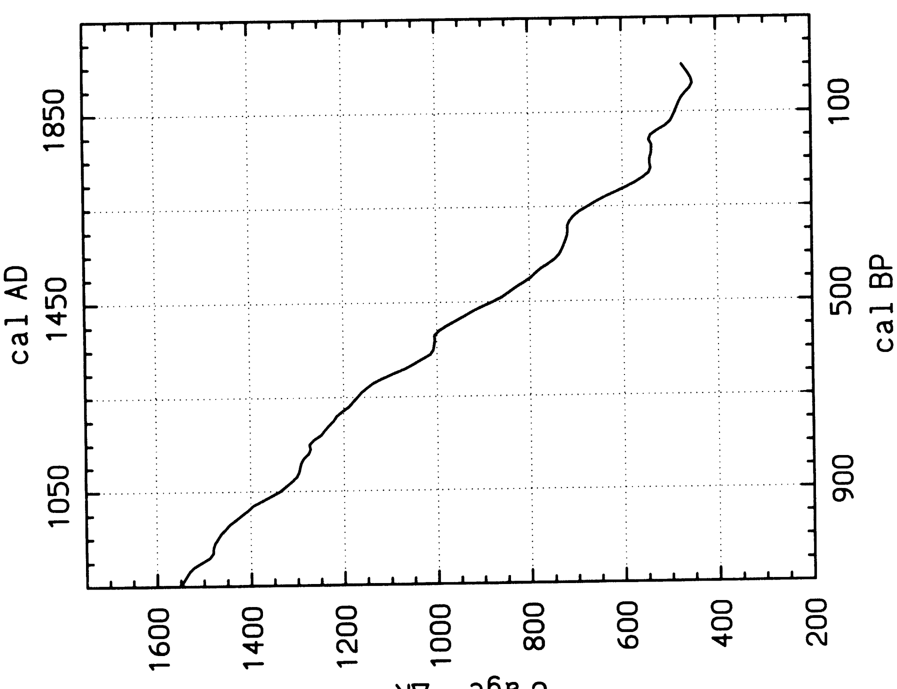
cal AD
1050
1450
1850
cal BP
900
500
100
14C age - ΔR
1600
1400
1200
1000
800
600
400
200

Fig. B19

[RADIOCARBON, VOL. 40, NO. 3, 1998, P. 1085–1092]

RADIOCARBON CALIBRATION BY MEANS OF MASS SPECTROMETRIC ^{230}TH/^{234}U AND ^{14}C AGES OF CORALS: AN UPDATED DATABASE INCLUDING SAMPLES FROM BARBADOS, MURUROA AND TAHITI

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ABSTRACT. As first shown by Bard *et al.* (1990a), high-precision ^{230}Th-^{234}U ages can be used successfully to calibrate the radiocarbon time scale beyond the high-precision tree-ring calibration that now reaches 11,900 cal BP (Kromer and Spurk 1998). Using mass spectrometric techniques, we measured ^{14}C and ^{230}Th ages on new samples collected from boreholes drilled off the islands of Tahiti and Mururoa (French Polynesia) in order to complement the database previously obtained on Barbados corals (Bard *et al.* 1990a, 1993).

METHODS

New ^{230}Th/^{234}U ages for Tahiti and Mururoa samples (Table 1) were measured with a VG-54-30 thermal ionization mass spectrometer (TIMS) fitted with an ion-counting Daly detector, at CEREGE (Aix-en-Provence). The chemical separations were similar to those previously described (Bard *et al.* 1990b). The 2σ precision of the ^{230}Th ages ranges from 30 to 60 yr, for ages between 8000 and 14,000 ^{230}Th yr BP.[4] This represents an improvement by a factor of 2 to 3 over the performance obtained on Barbados corals by single collection and analog Daly detector on an MM30 mass spectrometer (Table 1; Bard *et al.* 1990a,b). The precision of the ages was checked by measuring numerous replicates (Bard *et al.* 1996). In particular, we performed five analyses of different pieces of the same coral specimen (sample P7-7: 10,995 ± 40, 11,005 ± 30, 11,025 ± 30, 10,995 ±30 and 10,995 ± 30 ^{230}Th yr BP; ages are rounded to the nearest 5 yr). The five ^{230}Th/^{234}U ages agree with each other within the 2σ uncertainties, with an overall 2σ uncertainty on the mean of 12 yr and a maximum difference between replicates of *ca.* 30 yr.

Following Ludwig *et al.* (1992) and Stirling *et al.* (1995), the ^{229}Th/^{233}U ratio of our mixed spike was calibrated against the uraninite standard HU1 assumed to be at exact secular equilibrium. This calibration was shown to be accurate within 5‰ by means of gravimetric U and Th standards. This agreement is satisfactory if one takes into account the overall uncertainty on the half-lives of ^{234}U and ^{230}Th (2‰ and 8‰, respectively; see Ludwig *et al.* 1992).

Th samples are loaded with colloidal graphite on single-zone refined Re filaments and U samples on Re-Ta triple filaments. ^{234}U/^{238}U ratios are measured in dynamic multicollection mode: ^{233}U, ^{234}U and ^{235}U ion beams are measured with the Daly ion counting detector, whereas ^{235}U and ^{238}U ion currents are measured with Faraday cups. Correction for isotopic fractionation is performed by normalizing the measured ^{238}U/^{235}U atomic ratio to the natural value (137.88). Faraday/Daly gain is monitored with ^{235}U signals during each measurement block in order to correct for possible shifts of the gain.

The external precision on individual values of $\delta^{234}U_i$ (=[initial^{234}U/^{238}U – 1] × 1000) is on the order of 2‰ (at 2σ), as shown by repeated measurements of standards. The accuracy has been checked by

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[4]All radiometric ages expressed here as "BP" are relative to a fixed present of 1950.

TABLE 1. Comparison of Ages Obtained on Corals by AMS ^{14}C and TIMS ^{230}Th

Sample code	U/Th age (yr BP)	±2σ Th	^{14}C age (yr BP)	±2σ ^{14}C	$\Delta^{14}C$	±2σ Δ
Barbados						
RGF B-56*†	773	10	960	90	−26	11
RGF 7-4-2	7460	80	6605	150	83	23
RGF 7-5-5	8450	50	7640	160	74	22
RGF 7-12-2*†	9265	60	8305	120	91	18
RGF 7-16-2	9730	50	8750	170	92	24
RGF 7-27-4	11090	70	9710	210	142	31
RGF 12-5-2†	11590	60	9980	170	173	26
RGF 12-6-7†	11530	70	10095	160	148	25
RGF 12-9-5†	12260	90	10220	130	235	24
RGF 12-16-5*†	13100	80	11270	100	199	19
RGF 12-21-6	13700	170	11710	200	221	39
RGF 12-21-10*	13730	100	11720	400	224	63
RGF 9-8-2	14235	100	12200	200	225	34
RGF 9-13-3*†	14690	85	12620	220	229	36
RGF 9-21-11	18240	140	15170	180	374	39
RGF 9-24-4	18890	250	16020	420	337	81
RGF 9-27-5*†	19000	70	16360	220	299	37
RGF 9-32-4	20610	120	17230	280	416	53
RGF 9-34-8*†	21980	130	18410	250	443	50
RGF 12-30-2*†	30230	160	25870	410	547	84
Tahiti						
Ta-P6-10*	9565	20	8410	140	116	20
Ta-P6-11*	9830	30	8790	120	99	17
Ta-P6-12	9920	40	8800	120	110	17
Ta-P6-13*	10205	30	8990	120	122	17
Ta-P6-14†	10120	50	9065	100	100	15
Ta-P7-1*	8520	25	7830	200	57	27
Ta-P7-2*	9255	30	8170	180	108	25
Ta-P7-4	10250	40	8970	140	131	20
Ta-P7-5	10575	50	9330	140	125	21
Ta-P7-6	10850	50	9550	140	132	21
Ta-P7-7*	11005	12	9580	140	149	20
Ta-P7-8	11280	30	9800	140	155	21
Ta-P7-9	11495	30	9980	140	160	21
Ta-P7-10	11930	50	10280	140	177	22
Ta-P7-11	12875	40	10830	140	233	22
Ta-P7-12	12800	30	10800	160	226	25
Ta-P7-13	12695	60	11010	160	179	25
Ta-P7-14	12710	50	11090	160	170	24
Ta-P7-15	12865	50	11030	160	201	25
Ta-P7-16	12905	50	11090	160	198	25
Ta-P7-17	13065	30	11430	200	171	29
Ta-P7-18*	13465	40	11630	220	198	33
Ta-P7-19*	13750	30	11790	220	216	34
Ta-P8-1‡	12905	30	11230	120	177	18
Ta-P8-2‡	13335	30	11690	110	171	17
Ta-P8-3‡	13665	35	12010	110	171	17

BC = 11,715 INTCAL98 = 11707

12210
500
11710

TABLE 1. Comparison of Ages Obtained on Corals by AMS ^{14}C and TIMS ^{230}Th *(Continued)*

Sample code	U/Th age (yr BP)	±2σ Th	^{14}C age (yr BP)	±2σ ^{14}C	$\Delta^{14}C$	±2σ Δ
Ta-P8-4‡	13850	35	12260	110	161	17
Mururoa						
Mu 315*†	15585	50	13160	140	280	24
Mu 313*†	17595	70	14835	150	325	27
Mu 8-30-315‡	17170	40	14560	180	303	30
Mu 8-30-310.5‡	23510	70	20050	300	416	54
New Guinea						
KWA-I-1‡			*35770*	*1820*		
KWA-I-1‡			*35120*	*1660*		
KWA-I-1‡			*39600*	*2800*		
KWA-I-1‡			*34580*	*1620*		
KWA-I-1†‡	41100	500	35600	920	720	220

Note: All ages are expressed in yr before 1950 (BP) and statistical uncertainties are given at the 2σ level. ^{14}C ages are conventional ages with a reservoir correction of 400 yr for Barbados and New Guinea and 300 yr for Tahiti and Mururoa (see text). When several replicates were measured on different pieces of the same coral, the reported age and uncertainty are the weighted mean and error (except for sample KWA-I-1, for which individual ^{14}C ages are listed in italics). The U-Th ages of KWA-I-1 are from Dia *et al.* (1992). Sample Mu8-30-310.5 is composed of bothryoidal aragonite precipitated at shallow depth. All other samples are corals; species lists can be found in previous publications (Bard *et al.* 1990a, 1996). All samples were checked by XRD prior to dating to verify the absence of secondary low and/or high magnesium calcite (<1%).

*Reported ^{230}Th age is the weighted mean of 2 or more replicates (cf. Bard *et al.* 1993, 1996 for all individual ages).
†Reported ^{14}C age is the weighted mean of 2 or more replicates (cf. Bard *et al.* 1993, 1996 for all individual ages).
‡Age was not reported previously.

repeated measurements of NBS-010 (mean of −7.0 ± 0.7‰ $2\sigma_m$, 29 measurements) and NBS-SRM960-NIST4321B (mean = −35.6 ± 1.5‰ $2\sigma_m$, 6 meas.). The $\delta^{234}U_i$ values obtained on the Tahiti and Mururoa samples range between 140 and 150, with a mean value of 147 ± 2‰ (one standard deviation (SD) on 42 measurements). This average is very close to the values measured on present-day seawater (144 ± 4‰ SD on 9 meas., Chen, Edwards and Wasserburg (1986)) and on modern and recent corals (145 ± 5‰, SD on 25 meas., Bard *et al.* (1990a); 150 ± 1‰, SD on 20 meas., Edwards *et al.* (1993); 148 ± 2‰, SD on 3 meas., Szabo *et al.* (1994); 149 ± 1‰, SD on 3 meas., Stirling *et al.* (1995)). This further confirms that the samples used for this study are devoid of diagenetic alteration and remained closed systems for U-Th in the past. In addition, the absence of secondary calcite (<1%) was also checked in triplicate by x-ray diffraction (XRD) in the samples selected for dating.

^{14}C ages were measured by accelerator mass spectrometry (AMS) on the Tandetron facility installed at Gif-sur-Yvette (Arnold *et al.* 1987). 200–300 mg carbonate samples were first ground into millimeter-sized pieces preparatory to a strong acid leaching procedure (>40% weight loss) to remove surface contaminants (Bard *et al.* 1990b). Large carbonate subsamples (15–18 mg) were then converted to CO_2 and reduced to graphite in order to produce at least two accelerator targets for most samples and hence to increase the ^{14}C precision. Each carbonate subsample was composed of several grains selected randomly, which should help to minimize the influence of intra-annual changes of the ^{14}C reservoir ages, as shown by Brown *et al.* (1993). The ^{14}C ages for Mururoa and Tahiti samples were corrected for 300 yr, which is a mean ^{14}C reservoir age based on preanthropogenic data from the tropical South Pacific (Bard 1988). A reservoir age of 400 yr is used for corals from Barbados and New Guinea.

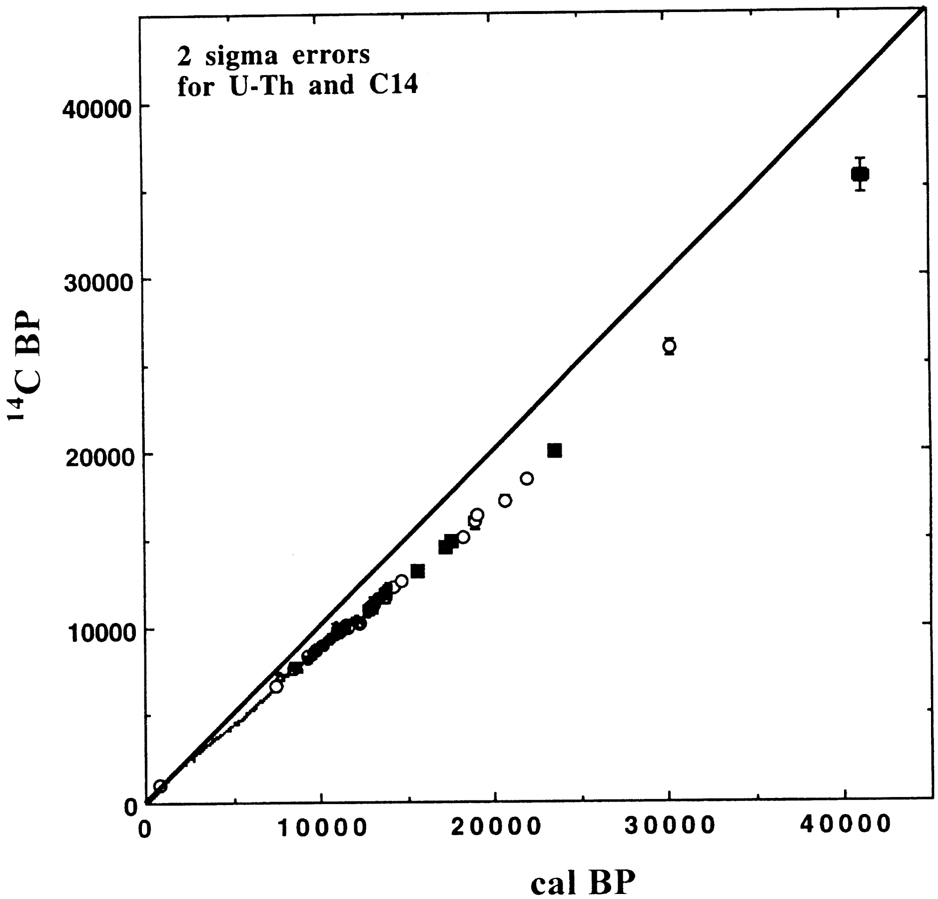

Fig. 1. AMS ^{14}C ages plotted *vs.* TIMS ^{230}Th ages obtained on corals. ^{14}C ages are conventional ages in yr BP with statistical errors given at the 2σ level. △ = the data from New-Guinea (Edwards *et al.* 1993), ○ = data from Barbados, ● = data from Tahiti and ■ = the data from Mururoa. The thin wiggly curve is the smoothed tree-ring calibration and the thick solid line is the 1:1 line. For ages beyond the Younger Dryas/Preboreal boundary (10,000 BP) the coral data can be approximated by a simple linear equation: [cal BP] = 1.168 × [^{14}C age BP], or even better by a second-order polynomial: [cal BP] = -3.0126×10^{-6} × [^{14}C age BP]^2 + 1.2896 × [^{14}C age BP] − 1005.

In addition to the samples collected by coring, we analyzed a very old *Porites lutea* sample collected in the lower uplifted terrace of Huon Peninsula, Papua New Guinea. This coral, sample KWA-I-1, was previously dated by TIMS U-Th at 41,100 ± 500 BP (Dia *et al.* 1992). Sample contamination and chemistry blank reproducibility are critical problems in dating such an old sample by ^{14}C (see Bard *et al.* 1993 for blank measurements obtained on calcite and aragonite). Four different pieces of KWA-I-1 were dated (*i.e.*, 8 C-Fe targets) and the individual ^{14}C ages are listed in Table 1 together with the weighted mean age based on these four values. The agreement among the four replicates is not optimal, which could be due to a small and residual contamination of this sample. The ^{14}C age of KWA-I-1 remains tentative and more samples should be dated in the same time range to confirm its surprisingly high Δ^{14}C (*ca.* 700 ‰).

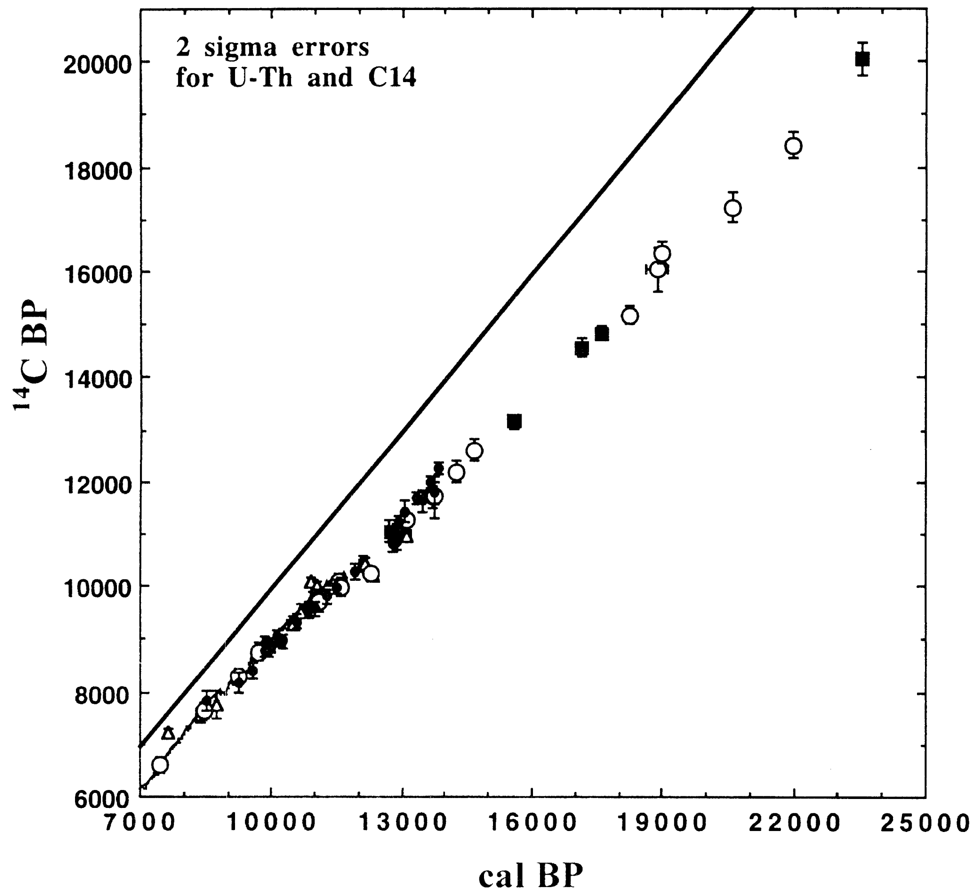

Fig. 2. Blowup of the Figure 1 diagram between 7000 and 25,000 cal BP. Symbols as in Fig. 1.

RESULTS AND COMPARISON WITH PREVIOUS CALIBRATIONS

As previously shown, there is a large difference between the ^{14}C and ^{230}Th ages (Bard *et al.* 1990a). The magnitude of the ^{14}C-^{230}Th age difference observed on the Tahiti and Mururoa samples (Figs. 1 and 2) agrees well with previous studies of corals (Bard *et al.* 1990a, 1993; Edwards *et al.* 1993). The accuracy of ^{230}Th ages is further demonstrated by the excellent agreement with the recently revised dendrocalibration by Kromer and Spurk (1998), in particular in the critical range of the German pine calibration (10,000–11,900 cal BP; see Fig. 3).

Altogether, these two different calibration methods lead to the reconstruction of significant variations of the atmospheric $^{14}C/^{12}C$ ratio through time (Fig. 4). In particular, the new data from Mururoa confirm clearly that the atmospheric $\Delta^{14}C$ was *ca.* 400–500‰ higher at *ca.* 20,000–30,000 cal BP and that it has essentially decreased during the period between 18,000 and 7000 cal BP. This long-term $\Delta^{14}C$ decrease has been attributed to a concomitant long-term increase of the intensity of the geomagnetic field (Bard *et al.* 1990a; Bard 1997; Stuiver *et al.* 1991).

In the critical range between 9500 and 12,000 cal BP, the coral results are in agreement with the data obtained from varved sediments from Lake Gościąż (Goslar *et al.* 1995), further confirming the new synchronization between the oak and the pine chronologies (Kromer and Spurk 1998). A new cali-

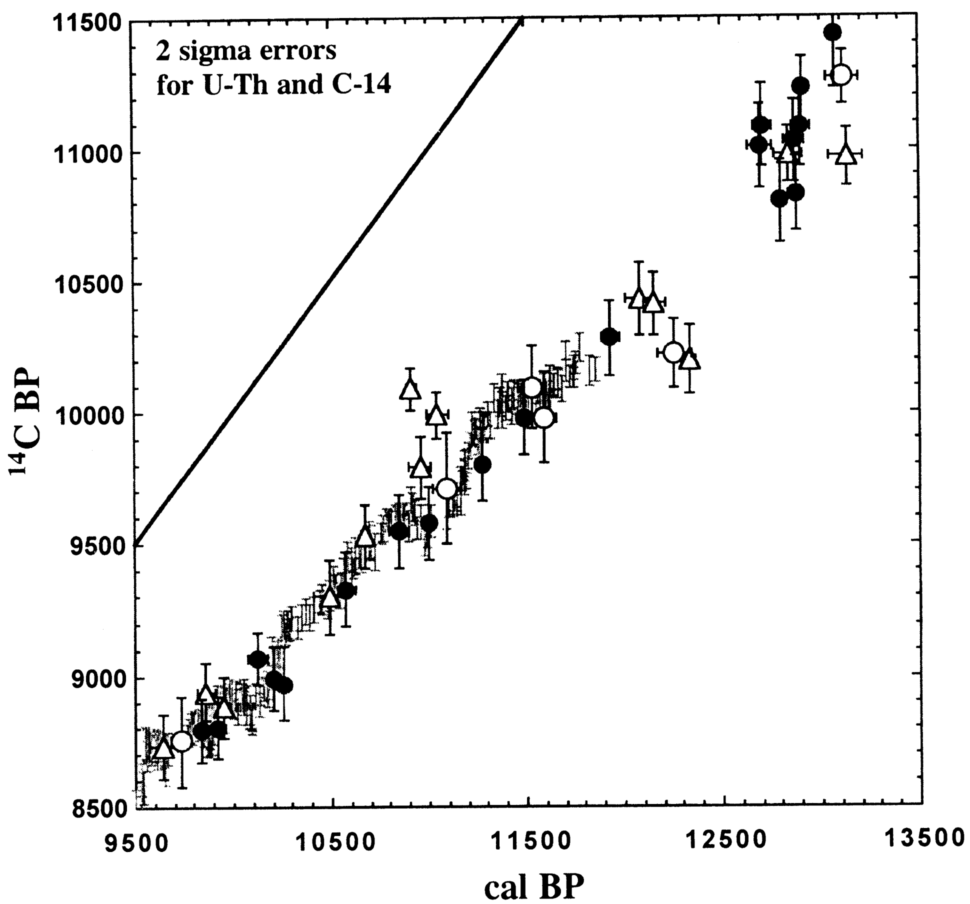

Fig. 3. Blowup of the Figure 2 diagram between 9500 and 13,500 cal BP. Symbols as in Fig. 1, except tree-ring calibration represented with gray error bars (from Kromer and Spurk 1998).

bration data set based on marine varves from the Cariaco Basin was recently proposed by Hughen *et al.* (1998). The Cariaco calibration curve goes back to 12,500 cal BP and is also in excellent agreement with our coral data (Hughen *et al.* 1998, especially Fig. 3b).

The coral ^{230}Th ages together with the Gościąż and Cariaco varve data finally confirm that the other calibrations based on varved sediments from Sweden (Wohlfarth 1996), Holzmaar in Germany (Hajdas *et al.* 1995), and Soppensee in Switzerland (Hajdas *et al.* 1993) are still in error even after the recent additions of so-called "missing varves" (~900 "missing varves" were added to the chronology from Holzmaar (Hajdas *et al.* 1995); ~550 "missing varves" were added to the chronology from Soppensee (Hajdas *et al.* 1993); ~500 "missing varves" were added to the Swedish chronology (Wohlfarth 1996)).

An independent check on the coral ^{14}C-^{230}Th calibration can be obtained by analyzing volcanic ash layers that can be recognized and dated by counting annual couplets in Greenland ice cores ("cryovarves"). Grönvold *et al.* (1995) have identified and characterized chemically the Saksunar and Vedde ash layers, which occurred respectively at 10,180 ± 120 and 11,980 ± 160 cal BP, according to the GRIP core chronology (2σ errors). These two ash layers have recently been redated by AMS

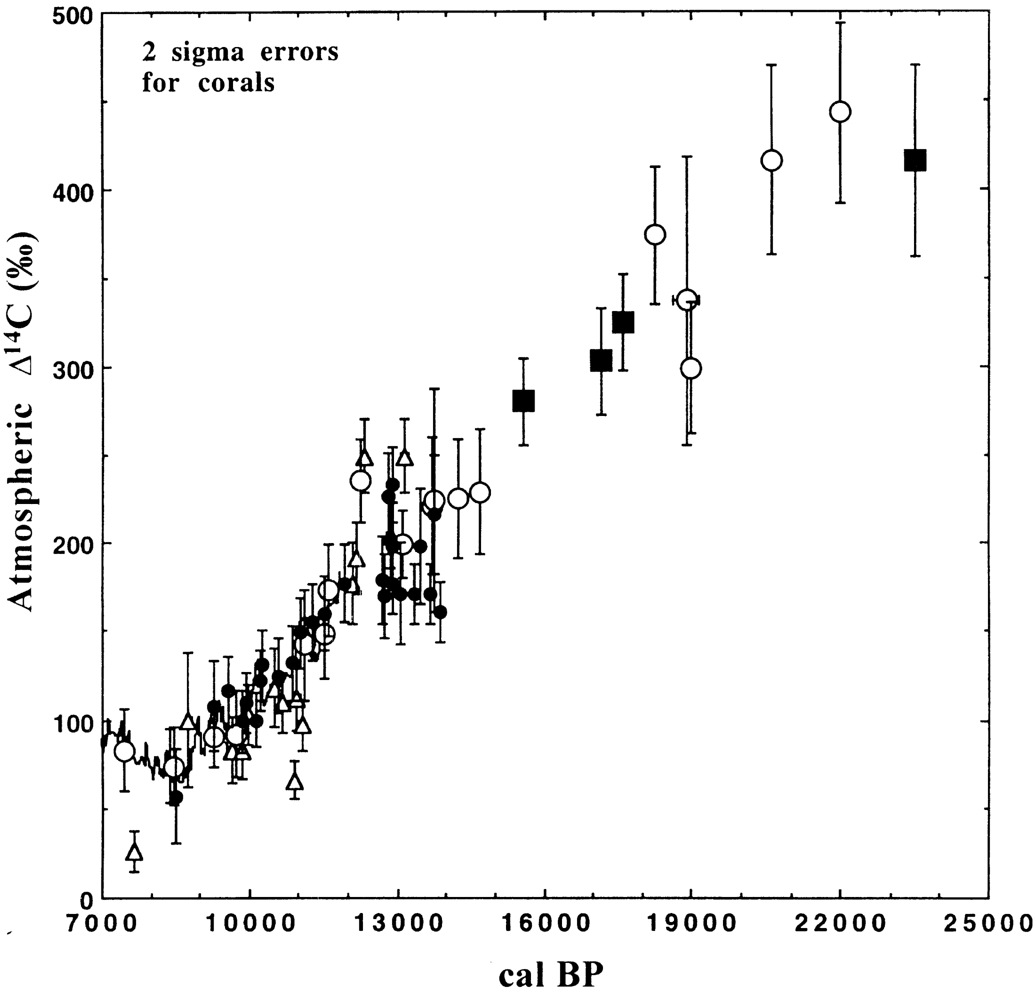

Fig. 4. $\Delta^{14}C$ *vs.* time as calculated by using the AMS ^{14}C ages *vs.* TIMS ^{230}Th comparison. Statistical errors for coral data are provided at the 2σ level. Symbols as in Fig. 1.

on terrestrial plant macrofossils at, respectively, 8960 ± 140 ^{14}C yr BP (2σ error based on 3 AMS ^{14}C ages from Birks *et al.* 1996) and 10,330 ± 60 ^{14}C yr BP (2σ error based on 11 AMS ^{14}C ages from Bard *et al.* 1994 and Birks *et al.* 1996). The data for these two volcanic events clearly demonstrate the compatibility of the German pine tree-ring chronology, ^{230}Th ages of corals, Gościąż varves and GRIP annual counts in the time range around the Younger Dryas/Preboreal boundary dated at *ca.* 11,500 cal BP.

Acknowledgments

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[RADIOCARBON, VOL. 40, NO. 3, 1998, P. 1093–1105]

A HIGH-RESOLUTION RADIOCARBON CALIBRATION BETWEEN 11,700 AND 12,400 CALENDAR YEARS BP DERIVED FROM ^{230}TH AGES OF CORALS FROM ESPIRITU SANTO ISLAND, VANUATU

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ABSTRACT. This paper presents radiocarbon results from a single *Diploastrea heliopora* coral from Vanuatu that lived during the Younger Dryas climatic episode, between *ca.* 11,700 and 12,400 calendar yr BP. The specimen has been independently dated with multiple ^{230}Th measurements to permit calibration of the ^{14}C time scale. Growth bands in the coral were used to identify individual years of growth. ^{14}C measurements were made on each year. These values were averaged to achieve decadal resolution for the ^{14}C calibration. The relative uncertainty of the decadal ^{14}C data was below 1% (2σ). The data are in good agreement with the existing dendrochronology and allow for high-resolution calibration for most years. Variations in the fine structure of the ^{14}C time series preserved in this specimen demonstrate sporadic rapid increases in the Δ^{14}C content of the surface ocean and atmosphere. Certain sharp rises in Δ^{14}C are coincident with gaps in coral growth evidenced by several hiatuses. These may be related to rapid climatic changes that occurred during the Younger Dryas. This is the first coral calibration with decadal resolution and the only such data set to extend beyond the dendrochronology-based ^{14}C calibration.

INTRODUCTION

The ^{14}C calibration curve commonly used today (Stuiver, Long and Kra 1993) evolved over the past 30 years and represents the efforts of a number of laboratories. The 1993 calibration covers the last 11.4 ka and is based on thousands of ^{14}C measurements of tree rings. The dendrocalibration has recently been extended to *ca.* 11.9 ka (Kromer and Spurk 1998), but beyond this point the tree-ring record is uncalibrated. The existence of relatively old floating Tasmanian tree-ring series should eventually provide a means for extending the existing dendrocalibration in the future (Barbetti *et al.* 1992; Tuniz *et al.* 1997).

Researchers in the field have sought to extend the dendrochronological limit using several alternative methods, including calibration based on counting varved sediments (Wohlfarth 1996; Hughen *et al.* 1998) and calibration using carbonates dated with ^{230}Th, such as corals (Bard *et al.* 1990, 1993; Edwards *et al.* 1993) and speleothems (Vogel and Kronfeld 1997; Goslar *et al.* 1997; Richards *et al.* 1997). Although these studies have produced useful information about past variations in the ^{14}C content of the atmosphere, none of them has approached the resolution and precision of dendrochronology. The purpose of this paper is to extract a high-resolution (decadal) ^{14}C calibration record from coral with precision comparable to the dendrocalibration. This is possible because certain corals are annually banded (see, *e.g.*, Knutson, Buddemeier and Smith 1972) and can be dated very accurately using the ^{230}Th age dating technique (Edwards, Chen and Wasserburg 1987). This is the first study to adopt such a strategy for the purpose of calibration.

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Methods

Site Selection and AMS ^{14}C Sample Preparation

The samples analyzed in this study were collected from a core drilled on the shore of a tectonically active coast on Espiritu Santo Island, Vanuatu (Fig. 1). The Late Quaternary tectonics and environmental history of this site were described by Taylor *et al.* (1987) and Cabioch *et al.* (1997). The Santo Island site has uplifted at a rapid and variable rate (up to *ca.* 5mm yr^{-1}) over the past 20 ka, which allowed for repeated coral colonization of the emerging reef. A portion of one of our cores intersected a single *Diploastrea heliopora* coral that lived between *ca.* 11.7 and 12.4 ka BP according to our ^{230}Th measurements (see below).

Four features of this specimen of *Diploastrea heliopora* are significant to this study: 1) this species produces annual growth bands that are visible in X-radiographs; 2) our core penetrated the coral nearly perpendicular to the plane of growth, permitting annual subsampling along its entire length; 3) the coral lived for *ca.* 400 yr over a 720-yr interval; and 4) the specimen lived during the Younger Dryas climatic episode, which is known to have been a time of rapid change in atmospheric $\Delta^{14}C$ (Edwards *et al.* 1993). The record is continuous over four intervals punctuated by three hiatuses. Individual years were identified from pairs of light and dark growth bands as seen in the X-radiographs of the sample. In order to reduce the variability introduced by subannual ^{14}C variations in the coral skeleton (Brown *et al.* 1993), combined light and dark couplets representing full years were sampled and analyzed together. To avoid contamination with modern carbon, the core was analyzed with the X-ray powder diffraction technique to check for calcite recrystallization. All of the samples analyzed in this study were pretreated using the selective dissolution technique described by Burr *et al.* (1992).

Definition of Terms and Analytical Procedures

^{14}C Dating

To calculate ^{14}C ages, $^{14}C/^{13}C$ ratios in the samples and standards were compared to determine the fraction of modern carbon (*F*) values, defined as

$$F \equiv (^{14}C/^{13}C)_S / (^{14}C/^{13}C)_{STD} \tag{1}$$

where $(^{14}C/^{13}C)_S$ is the measured ratio in the sample, normalized to $\delta^{13}C = -25‰$, and $(^{14}C/^{13}C)_{STD}$ is the calculated modern standard ratio (1950 AD), determined from measurements of NBS oxalic acid standards, also normalized to −25‰ (Donahue, Jull and Toolin 1990). The age of the sample is computed with the equation

$$^{14}C\ age = -\tau \ln F \tag{2}$$

where τ is the Libby mean life (5568/ln 2 = 8033 yr).

In order to compare ^{14}C dates with atmospheric ^{14}C values, the ^{14}C ages were reservoir-corrected using the relationship

$$^{14}C\ age_{RC} = {}^{14}C\ age - RC \tag{3}$$

where $^{14}C\ age_{RC}$ is the reservoir-corrected age and RC is the reservoir correction in years. To estimate the reservoir correction at the site, we measured 35 prebomb samples of known age and calculated the average. The reservoir age calculated in this manner is 494 ± 10 yr. We assume in our calculations that the reservoir correction is constant. This is consistent with the dendrocalibration for the past 11.9 ka, but it should be emphasized that the reservoir age is affected by the source of surface ocean water and could vary with changing paleo-ocean circulation patterns.

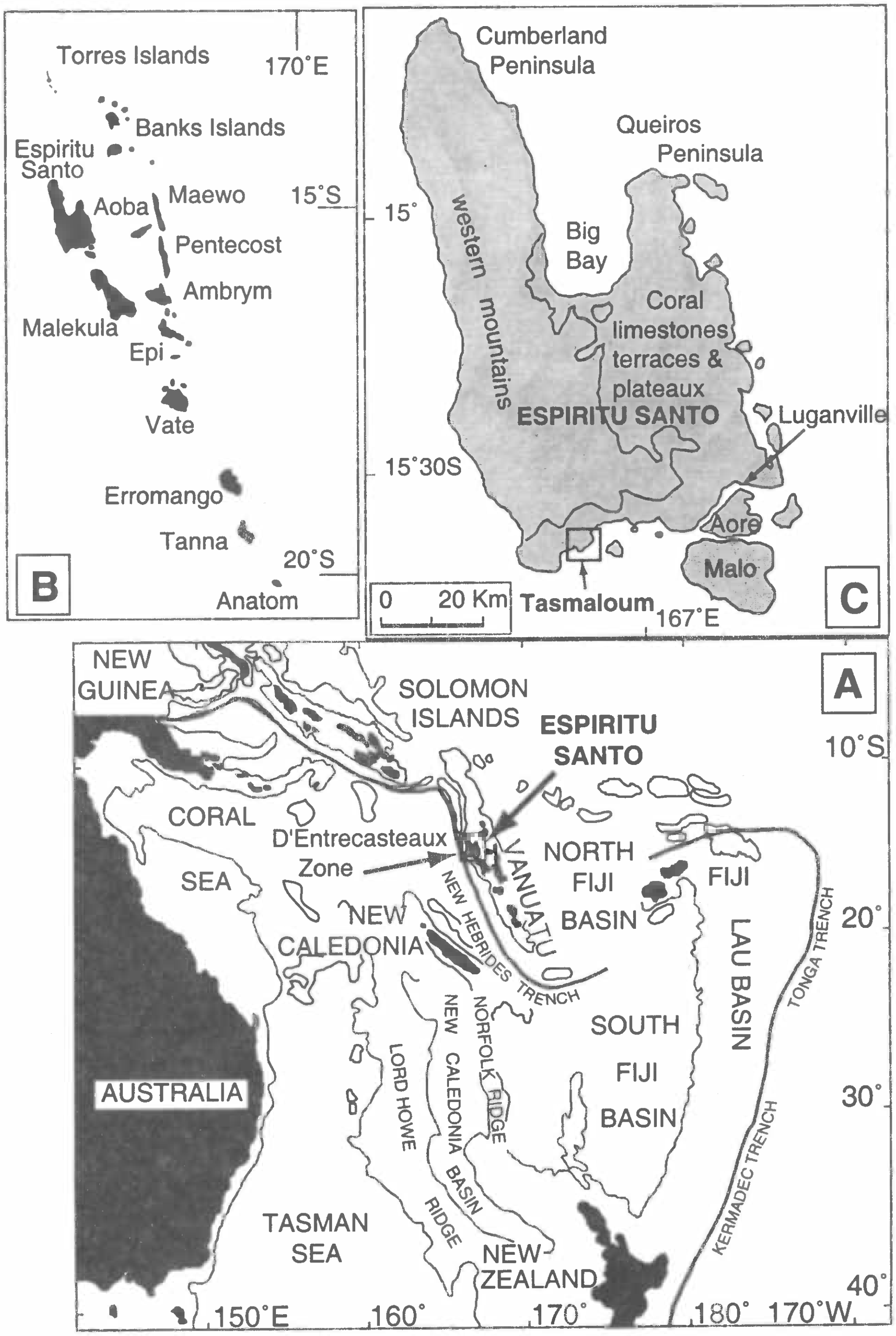

Fig. 1. Map showing the location of Vanuatu. A. Regional view; B. major islands of Vanuatu; C. Espiritu Santo Island with Tasmaloum peninsula (drill site).

To calculate reservoir-corrected fraction of modern values (F_{RC}), we define the relationship

$$^{14}\mathrm{C\ age}_{RC} \equiv -\tau \ln F_{RC} \quad . \tag{4}$$

Combining equations 2, 3, and 4 yields the expression

$$F_{RC} = F\, e^{RC/\tau} \quad . \tag{5}$$

The uncertainty in F_{RC} depends on the uncertainty in F and on the uncertainty in RC. Propagating these two sources of error yields the expression

$$\sigma_{F_{RC}} = \left\{ \left(e^{RC/\tau}\right)^2 (\sigma_F)^2 + \left[\left(\frac{F}{\tau}\right)\left(e^{RC/\tau}\right)\right]^2 (\sigma_{RC})^2 \right\}^{1/2} \tag{6}$$

where the σ's represent the uncertainties in F_{RC}, F, and RC.

$\Delta^{14}C$ values were computed from F_{RC} values. $\Delta^{14}C$ is a relative measure of the $^{14}C/^{12}C$ (or $^{14}C/^{13}C$) content of the atmosphere, as compared with the assumed value for 1950. Positive values indicate an excess relative to 1950 and negative values indicate a relative ^{14}C deficit. $\Delta^{14}C$ values were computed with the expression

$$\Delta^{14}C = (F_{RC}\, e^{\lambda t} - 1)\ 1000‰ \tag{7}$$

where λ is the decay constant for the 5730-yr half-life, and t is the calendar age of the sample in years BP (before 1950), determined with the ^{230}Th technique. This value for $\Delta^{14}C$ is equivalent to the age-corrected value for Δ given in Stuiver and Polach (1977).

The total uncertainty of $\Delta^{14}C$ includes uncertainties in F_{RC} and ^{230}Th ages. Propagating these yields the expression

$$\sigma_\Delta = 1000 e^{\lambda t}\left[(F_{RC}\lambda)^2 \sigma_t^2 + \sigma_{F_{RC}}{}^2\right]^{1/2} \tag{8}$$

where σ_Δ is the total uncertainty in $\Delta^{14}C$, t is the calendar age of sample in years BP, σ_t is the standard deviation reflecting the uncertainty in the age (uncertainty in the ^{230}Th date) and $\sigma_{F_{RC}}$ is the uncertainty in F_{RC}.

^{230}Th Technique

^{230}Th dating of corals relies on the decay of ^{234}U (half-life 244.5×10^3 yr) to ^{230}Th (half-life 75.4×10^3 yr). Both isotopes accumulate in the coral as relatively long-lived intermediate daughter products from ^{238}U decay. Initial ^{230}Th in modern corals is negligible due to the extreme low solubility of Th in seawater. The amount of ^{230}Th dissolved in seawater is approximately equivalent to the amount produced by one year of ^{234}U decay (Edwards, Chen and Wasserburg 1987). Uranium is more soluble than thorium, and dissolved uranium becomes incorporated into a coral's skeleton as it grows. Typical uranium concentrations for the coral samples analyzed here are *ca.* 3 ppm.

Assuming a closed system and assuming zero initial ^{230}Th, the ^{230}Th age of the coral can be calculated using the equation (Broecker 1963; Broecker and Thurber 1965):

$$\left[{}^{230}\mathrm{Th}/{}^{238}\mathrm{U}\right] - 1 = -e^{-\lambda_{230}T} + \left(\delta^{234}\mathrm{U}_m / 1000\right)\left[\lambda_{230}/\left(\lambda_{230} - \lambda_{234}\right)\right]\left(1 - e^{(\lambda_{234}-\lambda_{230})T}\right) \tag{9}$$

where the value [^{230}Th/^{238}U] is the ^{230}Th/^{238}U activity ratio, λ_{230} and λ_{234} are the decay constants for ^{230}Th and ^{234}U, T is the sample age in years, and $\delta^{234}U_m$ is the measured δ^{234}U value, defined as

$$\delta^{234}U_m = \{[(^{234}U/^{238}U)_{measured} / (^{234}U/^{238}U)_{se}] - 1\} \times 1000 \qquad (10)$$

where $(^{234}U/^{238}U)_{se}$ is the ^{234}U/^{238}U ratio at secular equilibrium (Edwards, Chen and Wasserburg 1987).

The initial ^{234}U/^{238}U ratio of the corals reflects that of seawater, which is presently in excess of the secular equilibrium value by *ca.* 150‰. This value has not varied by more than 2‰ over the last 13,000 yr (Edwards *et al.* 1993). This means that significant deviations from observed initial ^{234}U/^{238}U values can be used to identify samples that may have been altered.

The weighted average initial δ^{234}U value for these corals is 148.8 ± 0.5 (2σ). This mean value is within errors of that determined for deglacial New Guinea corals (Edwards *et al.* 1993). No ^{230}Th age reversals were seen in the 13 age determinations along the core, and we observed a 1:1 relationship between the ^{230}Th ages and growth bands determined by counting layers (see below).

Coral ^{230}Th ages reported in this study were measured using thermal ionization mass spectrometry (TIMS) following the method of Edwards, Chen and Wasserburg (1987) and Edwards *et al.* (1993). ^{230}Th concentrations were measured using a ^{229}Th spike; uranium concentrations were measured using a mixed ^{233}U/^{236}U spike. Uranium measurements were made with a double zone-refined Re filament. Th measurements were made on a single zone-refined Re filament with a graphite substrate.

Results and Discussion

^{230}Th and ^{14}C Results

The chronology of the *Diploastrea heliopora* core is shown diagrammatically in Figure 2. It consists of four continuous sections, punctuated by three hiatuses. The hiatuses represent times when the coral died off for some period and later recolonized. The durations of the hiatuses were determined by combining the ^{230}Th dates with growth band counts. The thorium results are given in Table 1. Differences in the ages of specific growth bands along continuous sections of coral were determined by counting bands and by computing differences between ^{230}Th dates. These two methods agree perfectly within quoted uncertainties. To obtain the most precise age estimate possible for a given piece of coral, the ^{230}Th ages were averaged after adjusting the ages of measured growth bands to the first year of growth for each piece (Table 1B). These average ages of each section were combined with the growth band counts to complete the calendar chronology of the entire core (Fig. 2). The total number of years computed in this manner is 720. The duration of all of the growth hiatuses is *ca.* 100 yr for all three hiatuses and the total number of growth years is *ca.* 400.

The ^{14}C results from the *Diploastrea* core (Table 2) are plotted in Figure 3 along with the tree ring ^{14}C data of Kromer and Spurk (1998). The two data sets overlap and the overall trend between the two sets of measurements is in good agreement. Both sets of data are plotted with 2σ uncertainties. For the coral data these are less than 1%. This uncertainty is computed as the larger of the internal or external variance in the population of annual measurements that contribute to the decadal average. The uncertainty in each annual measurement includes contributions deduced from counting statistics, machine random error and the reservoir correction.

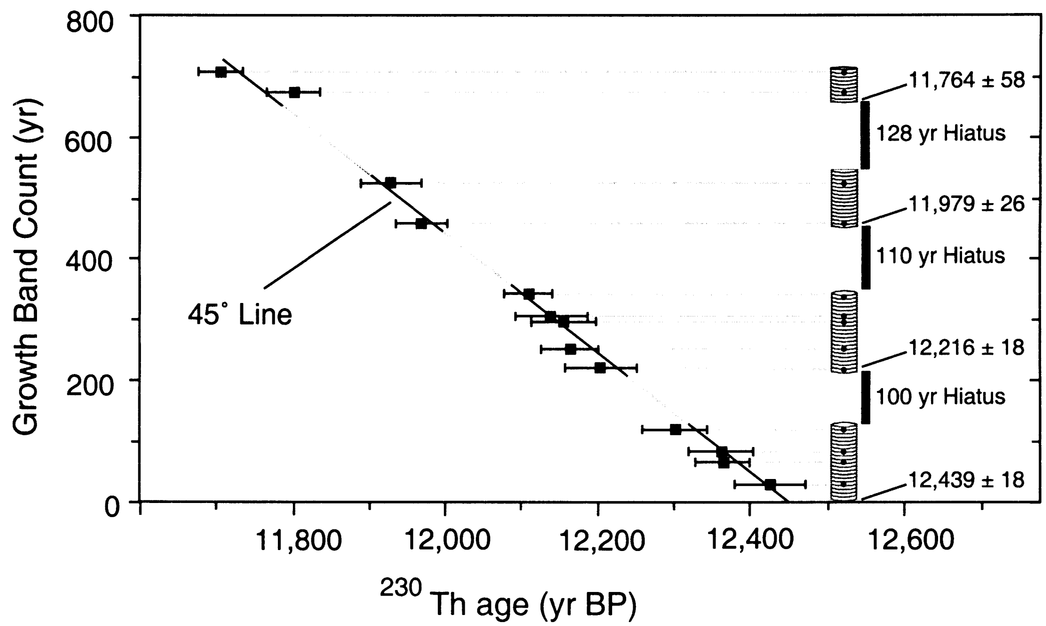

Fig. 2. Diagrammatic representation of the *Diploastrea heliopora* core showing the deduced chronology in yr BP

Fine Structure in the Record

The precision of these measurements permits our first look into the fine structure of the ^{14}C record during portions of the Younger Dryas climatic event. Significant variations (wiggles) are evident in the record. This is not surprising, as the Younger Dryas period is known to be a period of rapid change in atmospheric $\Delta^{14}C$ (Edwards *et al.* 1993). $\Delta^{14}C$ values are plotted in Figure 3B. The earliest part of this core shows a steady rise in $\Delta^{14}C$ followed by a hiatus. The second segment shows a distinct oscillation culminating in a sharp rise and a second hiatus. The third segment shows a modest rise followed by a sudden sharp rise and a hiatus; the final segment records a 50-yr period of large rapid $\Delta^{14}C$ variations. The initial sharp rise in $\Delta^{14}C$ is consistent with the global marker described by Hajdas *et al.* (Hajdas and Bonani 1997) for the onset of the Younger Dryas. The peak in the *Diploastrea* curve observed in the first section of core is also temporally coincident with the beginning of a distinct pause in sea level rise documented in the New Guinea sea level reconstruction (Edwards *et al.* 1993).

Of particular interest are the two sharp increases in $\Delta^{14}C$ prior to the death of the organism at the second and third hiatuses. Possible causes of death include 1) burial by volcanic debris or flooding, 2) sudden emergence resulting from tectonic activity or sea level variations, and 3) a rapid change in water temperature that exceeded the tolerance limits of the coral. The observed changes in $\Delta^{14}C$ prior to the second and third hiatuses cannot be explained by burial. Emergence accompanied by some recrystallization could raise the $\Delta^{14}C$ value of the coral, but the X-ray powder diffraction data and $\delta^{234}U$ results do not show any evidence of recrystallization. A rapid change in water temperature could result from changes in paleocirculation. In this case the water would be expected to have an elevated $\Delta^{14}C$ value and be either too cold or too hot for the coral to survive. This possibility can be tested using coral paleothermometry.

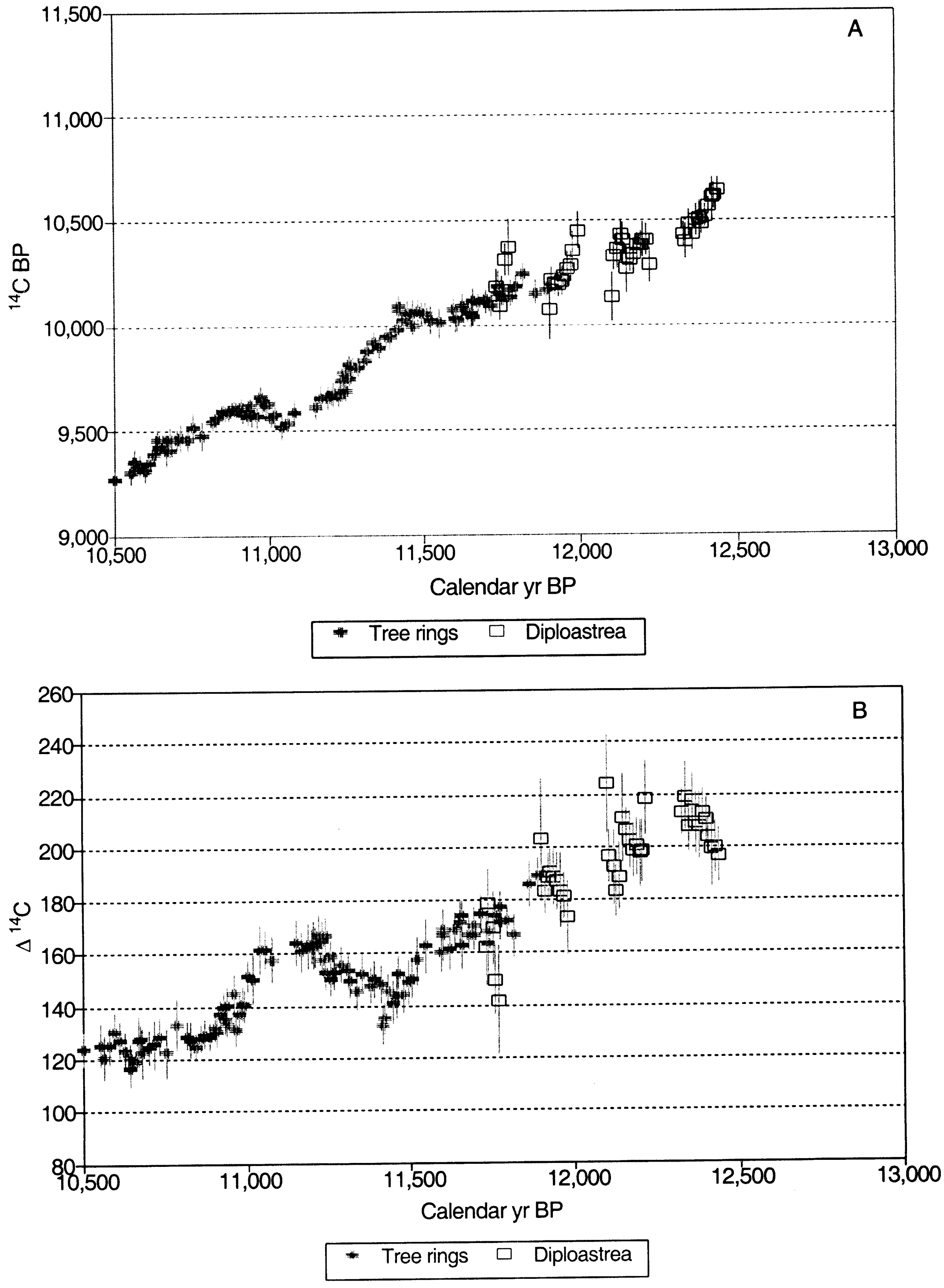

Fig. 3. Comparison of the coral data from this study with the tree ring data of Kromer and Spurk (1998, revised from Kromer and Becker 1993). All uncertainties are 2σ. A. ^{14}C ages; B. $\Delta^{14}C$ values.

TABLE 1A. ^{230}Th Results for Individual Years

Sample	^{230}Th age ± 2σ (yr BP)	$\delta^{234}U_{initial}$ ± 2σ	^{238}U (ppm)	^{232}Th (ppt)	Growth band (year number)
Top growth band	Section 4				720
9-11-12.5-b	11,705 ± 29	149.3 ± 1.0	2.357	597.0	710
9-11-12.5	11,800 ± 35	148.8 ± 1.1	2.792	800.0	675
Growth hiatus					**128 ± 64 (2σ)**
Top growth band	Section 3				549
9-12.5-14.0-1	11,928 ± 39	149.3 ± 1.0	2.970	131.0	526
9-12.5-14.0-2	11,968 ± 34	150.7 ± 1.5	2.598	28.2	460
Growth hiatus					**110 ± 32 (2σ)**
Top growth band	Section 2				350
9-12.5-14.0-3a	12,108 ± 32	146.6 ± 1.2	2.542	55.0	345
9-12.5-14.0-3b	12,138 ± 47	148.0 ± 1.1	2.590	1925	306
9-12.5-14.0-3c	12,154 ± 42	152.3 ± 1.5	2.543	49.6	297
9-12.5-14.0-4	12,163 ± 37	148.9 ± 1.3	2.691	104.0	251
9-12.5-14.0-5	12,204 ± 47	146.1 ± 1.2	2.570	1015	223
Growth hiatus					**100 ± 26 (2σ)**
Top growth band	Section 1				123
9-12.5-14.0-6a	12,301 ± 43	150.5 ± 1.0	2.520	83.0	121
9-12.5-14.0-6b	12,362 ± 30	150.5 ± 1.1	2.460	165.0	84
9-14.0-15.5-1	12,364 ± 34	149.9 ± 1.6	2.733	674.0	67
9-14.0-15.5-2	12,425 ± 46	147.4 ± 1.3	2.613	1386	31
Basal growth band					1

TABLE 1B. ^{230}Th ages of Continuous Sections of Coral Based on Weighted Mean Values

Section number	Number of years	Nominal age of oldest year in section (±2σ)
Section 4	45	11,764 ± 58
Growth hiatus	**128**	
Section 3	87	11,979 ± 26
Growth hiatus	**110**	
Section 2	127	12,216 ± 18
Growth hiatus	**100**	
Section 1	123	12,439 ± 18

Comparisons with Other Calibration Data

Other sources of calibration information with which to compare the *Diploastrea heliopora* record include: 1) other published coral results from Barbados and Mururoa (Bard *et al.* 1990; Bard *et al.* 1993), Papua New Guinea (Edwards *et al.* 1993), and Tahiti (Bard *et al.* 1996); 2) European varved lakes (Wohlfarth 1996; Wohlfarth, Björck and Possnert 1995; Hajdas *et al.* 1993, 1995; Goslar *et al.* 1992, 1995); and 3) marine varved sediments from the Cariaco basin (Hughen *et al.* 1998).

TABLE 2. Radiocarbon results. Decadal averages; weighted means from multiple measurements. The number of annual bands averaged for each result is given as n. Uncertainties are 2σ (see text).

^{230}Th age (yr BP)	^{14}C age (yr BP)	Δ^{14}C (‰)	n
11,730	10,189 ± 82	162 ± 14	4
11,740	10,086 ± 69	179 ± 13	10
11,750	10,161 ± 76	169 ± 14	10
11,760	10,308 ± 77	149 ± 13	10
11,770	10,370 ± 138	142 ± 21	2
11,900	10,077 ± 151	203 ± 23	8
11,910	10,219 ± 59	184 ± 9	10
11,920	10,195 ± 58	189 ± 9	10
11,930	10,192 ± 58	190 ± 9	10
11,940	10,213 ± 70	189 ± 11	9
11,950	10,234 ± 70	187 ± 11	10
11,960	10,268 ± 88	184 ± 14	10
11,970	10,290 ± 59	182 ± 9	10
11,980	10,357 ± 89	173 ± 14	4
12,100	10,134 ± 122	224 ± 19	6
12,110	10,327 ± 65	196 ± 10	10
12,120	10,364 ± 95	192 ± 14	10
12,130	10,435 ± 66	183 ± 10	10
12,140	10,407 ± 84	189 ± 13	10
12,150	10,268 ± 112	211 ± 17	10
12,160	10,311 ± 59	206 ± 9	10
12,170	10,342 ± 71	203 ± 11	10
12,180	10,379 ± 66	199 ± 10	10
12,190	10,379 ± 71	200 ± 11	9
12,200	10,407 ± 84	197 ± 13	10
12,210	10,410 ± 78	198 ± 12	10
12,220	10,286 ± 89	219 ± 14	6
12,330	10,429 ± 60	213 ± 9	8
12,340	10,398 ± 84	219 ± 13	10
12,350	10,483 ± 66	208 ± 10	10
12,360	10,429 ± 72	218 ± 11	10
12,370	10,495 ± 78	209 ± 12	10
12,380	10,511 ± 85	208 ± 13	10
12,390	10,486 ± 54	213 ± 9	10
12,400	10,517 ± 55	210 ± 9	10
12,410	10,568 ± 43	204 ± 7	10
12,420	10,610 ± 92	199 ± 14	10
12,430	10,616 ± 61	200 ± 10	10
12,440	10,645 ± 61	197 ± 10	9

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Comparisons with previously published coral data are given in Figure 4. The agreement is within errors for all years of overlap. A comparison with European varved lakes (Fig. 5) is less definitive than the comparison with other corals, but the revised Swedish record (Wohlfarth 1996) and Lake Gościąż record (Goslar *et al.* 1995) both agree with our results, within errors. Other varved lake records from Soppensee (Hajdas *et al.* 1993) and Lake Holzmaar (Hajdas *et al.* 1995) do not agree with our coral chronology, but these European records are currently being revised (I. Hajdas, personal communication). A comparison with the marine varve record from the Cariaco basin (Hughen *et al.* 1998) is shown in Figure 6. The agreement is within errors for all points, but the two records appear to begin to diverge *ca.* 12.5 ka BP. This apparent trend could reflect a real shift in the relative reservoir ages of the two sites. More data from the two records should clarify the extent of the deviation.

CONCLUSION

This study extends the high-resolution ^{14}C calibration beyond the current dendrochronological limit and covers most of the period between *ca.* 11.7 and 12.4 calendar ka BP with decadal resolution. It is the first coral study to achieve routine 1% (2σ) age uncertainties with coral and the first study to exploit growth bands in coral for the purpose of ^{14}C calibration. The relatively high precision and resolution of this calibration permits a look into the fine structure of the curve during the Younger Dryas climatic episode. The data show that this was a period of large, rapid variations in $\Delta^{14}C$ superimposed on the drop in $\Delta^{14}C$ identified by Edwards *et al.* (1993). The data agree with the existing dendrocalibration, European varved records, the marine varved record and existing coral data over this time period.

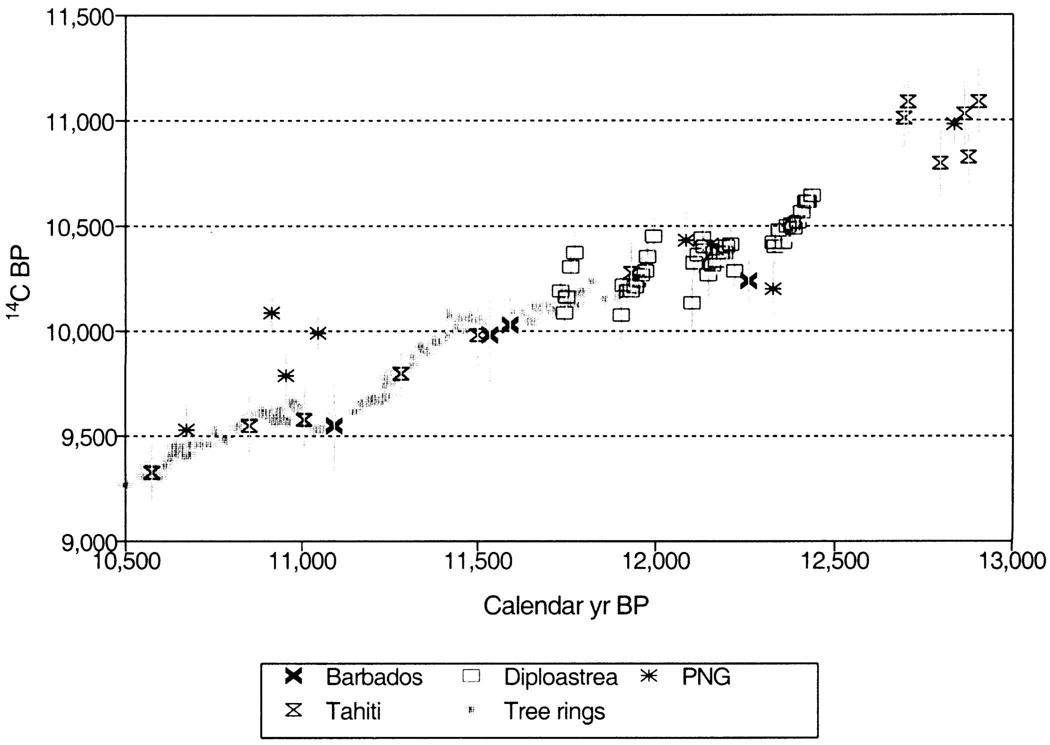

Fig. 4. Comparison of the coral data from this study with the coral data from Barbados and Mururoa (Bard *et al.* 1993), Papua New Guinea (Edwards *et al.* 1993), and Tahiti (Bard *et al.* 1996). All uncertainties are 2σ.

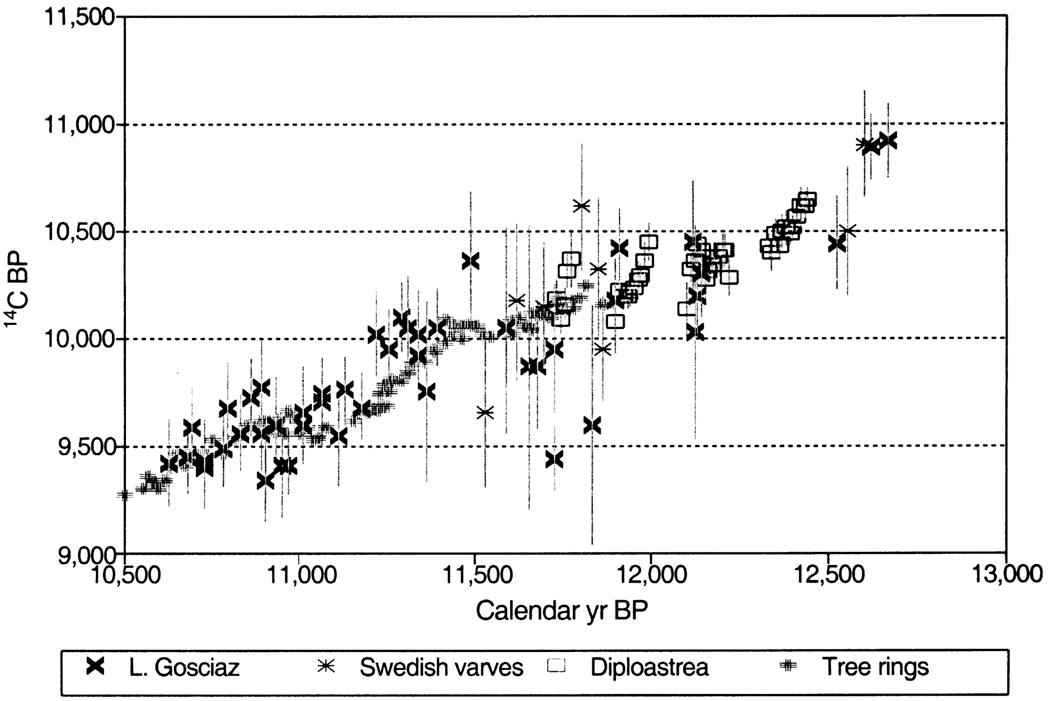

Fig. 5. Comparison of the coral data from this study with European varve data from Sweden (Wohlfarth 1996), and Lake Gościąż, Poland (Goslar *et al.* 1995). All uncertainties are 2σ.

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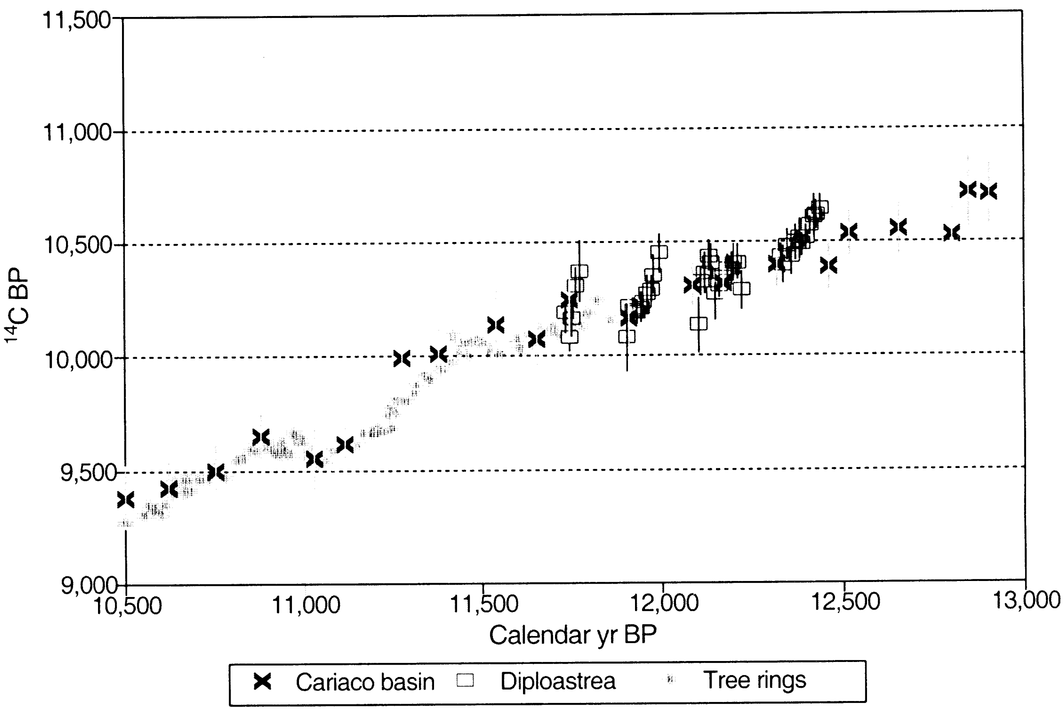

Fig. 6. Comparison of the coral data from this study with Cariaco basin marine varve data (Hughen *et al.* 1998). All uncertainties are 2σ.

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REVISIONS AND EXTENSION OF THE HOHENHEIM OAK AND PINE CHRONOLOGIES: NEW EVIDENCE ABOUT THE TIMING OF THE YOUNGER DRYAS/PREBOREAL TRANSITION

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ABSTRACT. Oak and pine samples housed at the Institute of Botany, University of Hohenheim, are the backbone of the early Holocene part of the radiocarbon calibration curve, published in 1993 (Becker 1993; Kromer and Becker 1993; Stuiver and Becker 1993; Vogel *et al.* 1993). Since then the chronologies have been revised. The revisions include 1) the discovery of 41 missing years in the oak chronology and 2) a shift of 54 yr for the oldest part back into the past. The oak chronology was also extended with new samples as far back as 10,429 BP (8480 BC). In addition, the formerly tentatively dated pine chronology (Becker 1993) has been rebuilt and shifted to an earlier date. It is now positioned by ^{14}C matching at 11,871–9900 BP (9922–7951 BC) with an uncertainty of ±20 yr (Kromer and Spurk 1998). With these new chronologies the ^{14}C calibration curve can now be corrected, eliminating the discrepancy in the dating of the Younger Dryas/Preboreal transition between the proxy data of the GRIP and GISP ice cores (Johnsen *et al.* 1992; Taylor *et al.* 1993), the varve chronology of Lake Gościąż (Goslar *et al.* 1995) and the pine chronology (Becker, Kromer and Trimborn 1991).

INTRODUCTION

After Bernd Becker's death in February 1994, we tried to close the so-called "Hallstatt gap", which was a gap in Hohenheim chronology as it existed in 1993. To accomplish this, the authors at Hohenheim checked the correctness of each single sample of the Hohenheim chronology, using modern methods to check their dating. If there was reason to doubt the correctness of the ring-width pattern originally measured, the samples were measured anew. This task was supplemented by an identification of trees with growth disturbances caused by insect damage; such trees were excluded from the chronology. This triple check, and a comparison with the Göttingen oak chronology, confirmed Becker's work for the most part but also located two weak points in the oak chronology, and one in the Preboreal pine chronology. These minor revisions in the two long Hohenheim chronologies, and the collection of new samples that enabled the backwards extension of the oak chronology by almost 500 yr, resulted in a new link to the Preboreal pine chronology. Both the extension and the revisions are explained in this paper.

COMPARISON OF HOHENHEIM AND GÖTTINGEN CHRONOLOGIES: THE 41-YR SHIFT AT 5242 BC

The two South German oak chronologies from Hohenheim and Göttingen were constructed based on wood collected during the last 30 years (Leuschner 1992; Becker 1993). Most of the wood for both chronologies comes from gravel in the bed of the Main River, near the Franconian town of Bamberg. The chronologies were established independently of one another in most parts. A comparison of both chronologies revealed a 41-yr offset in the pre-5242 BC part. Detailed investigations showed that these 41 years were missing between 5242 and 5283 BC (7191 and 7232 BP)[4] from the Hohenheim chronology as published in 1993. The difficulty was caused by two samples labeled Sand 29 and Sand 33, which had been measured erroneously. After renewed measurements of these samples and the reestablishment of the pre-5100 BC section independently from the Göttingen chronology, formerly undated tree sections covering the missing years were located and inserted into the

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[4]Conversion from BC-age to BP-age: BP-age = BC-age + 1950 − 1. (The 1 must be subtracted due to the lack of the year zero in the BC time scale.) All BP ages in this paper represent real calendar years unless otherwise indicated.

Hohenheim chronology. This resulted in a perfect ring-width synchronization of the Hohenheim to the Göttingen oak chronologies back to the end of the absolute Göttingen chronology at 7197 BC (9147 BP) (Leuschner 1992) (Fig. 1). The pre-7197 BC part of the Hohenheim chronology also displays perfect synchronization to a 578-yr-long floating sequence in the Göttingen chronology. Both long oak chronologies from Germany are now, for the first time, mutually corroborative back to 7736 BC (9685 BP).

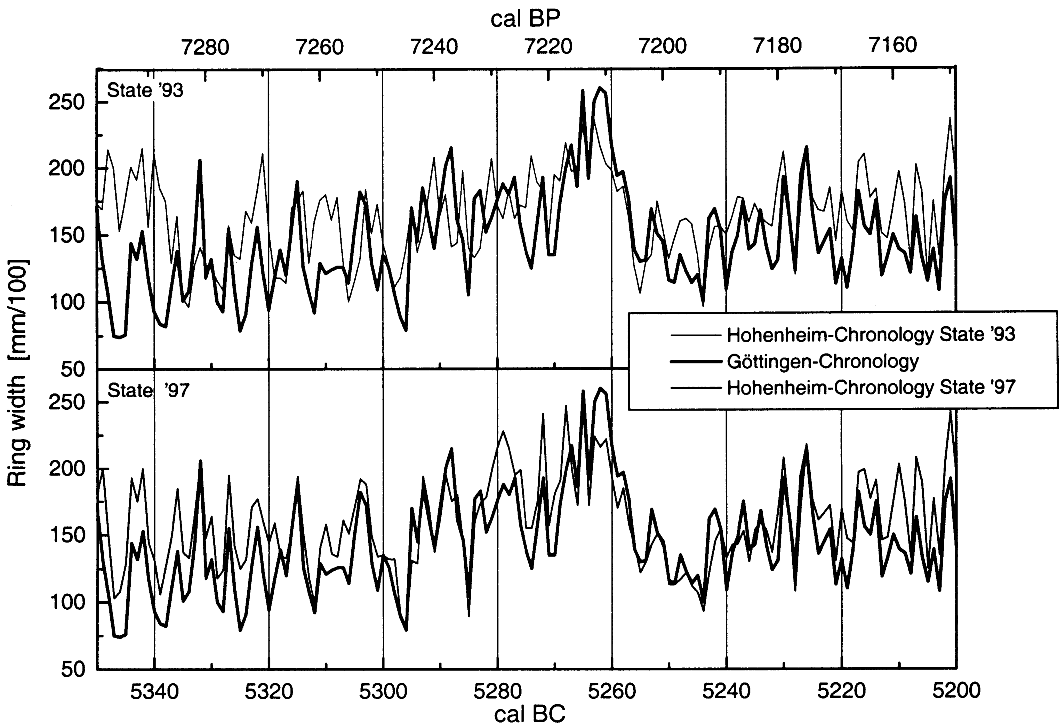

Fig. 1. Similarity of the Göttingen and Hohenheim chronologies in 1993 (State '93) and in 1997 (State '97) after the correction of the Hohenheim chronology. The statistical parameters after the correction are: Gleichläufigkeit = 77.9%, t-value$_{Baillie}$ = 82.0.

BRIDGING THE WEAK POINT AT 7800 BC: THE 54-YR SHIFT

All samples from the rivers Main, Regnitz and Naab (Main River chronology) were reexamined, disclosing a weak point at 7800 BC. During this period, the overlap was too short and the number of samples too low to qualify as a dendromatch. The overlap of the older "floating" part with the younger absolute oak chronology was only 35 yr long. Becker (1993) tried to improve this situation using the tree sample "Stettfeld 181", but this synchronization was not convincing and the tree was removed from the chronology. As a consequence, the pre-7792 BC section of the chronology, which had formerly been absolutely dated, was declared to be a floating 230-yr-long oak section (Kromer *et al.* 1996).

During the work reported here, four trees were found bridging this gap. The 210-yr-long chronology of these trees, labeled "bridging section", displays convincing similarity to the absolute part of the chronology and to the floating section, when the floating section is shifted back 54 yr (Fig. 2). The combination of the 41-yr and the 54-yr shifts pushes the oldest samples of the previously published

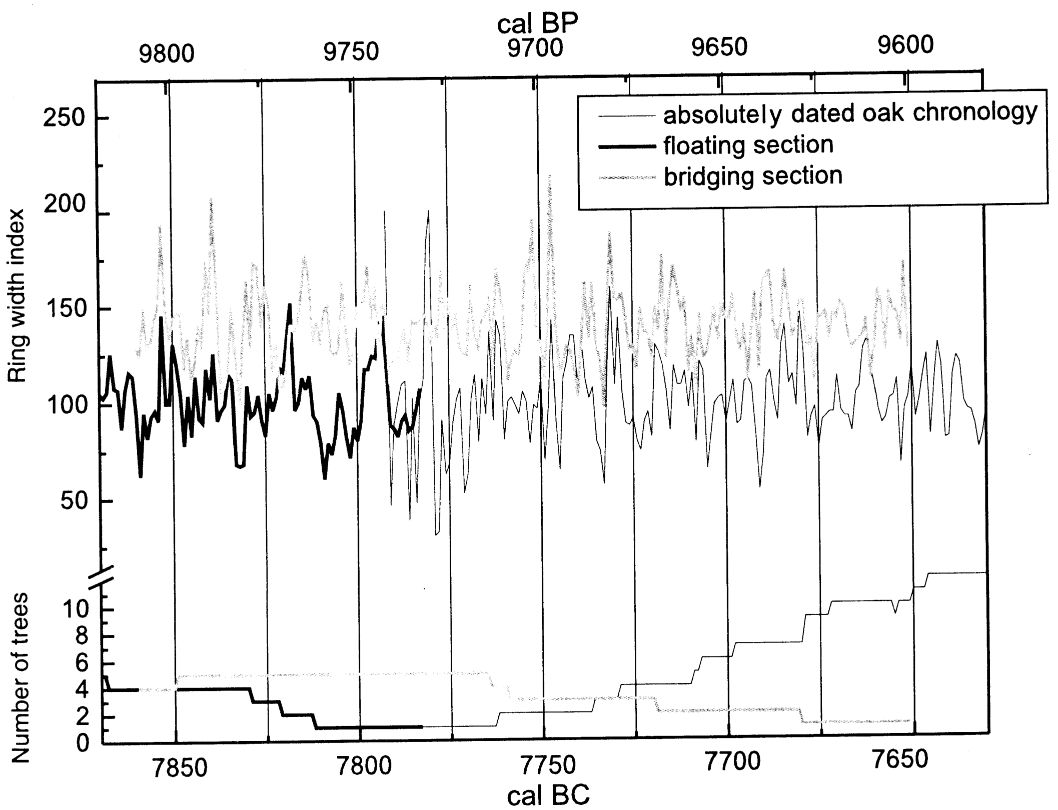

Fig. 2. Bridging the weak point at 7792 BC with a group of four trees (bridging section). The floating section has to be shifted by 54 yr to older ages (95 yr if the 41-yr shift at 5242 BC is included). Statistical parameters: bridging section/floating section, Gleichläufigkeit = 72%, t-value$_{Baillie}$ = 5.2; bridging section/absolutely dated oak-chronology, Gleichläufigkeit: 68%, t-value$_{Baillie}$: 6.6.

oak chronology back to 8117 BC. Accordingly, the absolute oak chronology started at 8117 BC (10,066 BP).

With these errors recognized, the dendroscale of the Hohenheim oak chronology and consequently the ^{14}C calibration curve has to be revised. The previously published pre-5242 BC (pre-7191 BP) ^{14}C calibration must be shifted by 41 yr (Kromer *et al.* 1996) and the pre-7792 BC (pre-9741 BP) ^{14}C calibration must be shifted by 95 yr (41 + 54) to older ages. Both corrections solved hitherto existing problems in the ^{14}C calibration described in Kromer and Spurk (1998). Newly dated samples with shifts differing from the 41-yr or 54-yr shifts are labeled in Table 1.

TABLE 1. Numbers of the Oak Samples with Shifts Differing from the 41-yr or 54-yr Shifts

Heidelberg Lab No.	Shift to older ages
8510, 8511, 8518, 8519, 8524, 8525, 8544	11 yr
8141, 8140, 8144, 8244	30 yr

Extension of the Oak Chronology Back to 8480 BC

Besides those already mentioned, new trees were found that enabled an extension of the absolutely dated oak chronology back to 8480 BC (10,429 BP). This was done in two steps. First, a tree was found that fitted onto the end of the absolute oak chronology and extended it back to 8239 BC (10,188 BP). Second, a 507-yr-long floating chronology from the upper Rhine valley (Rhine chronology 9b) was linked to the absolute part of the chronology, which was established primarily with wood from the Main River. Here, key positions are occupied by three trees (Rhine chronology 9a) showing perfect ring width synchronization to the absolute part, as well as to the Rhine chronology 9b (Fig. 3). As a result, the Rhine chronologies 9a and 9b were absolutely dated, extending the absolute oak chronology back to 8480 BC (10,429 BP).

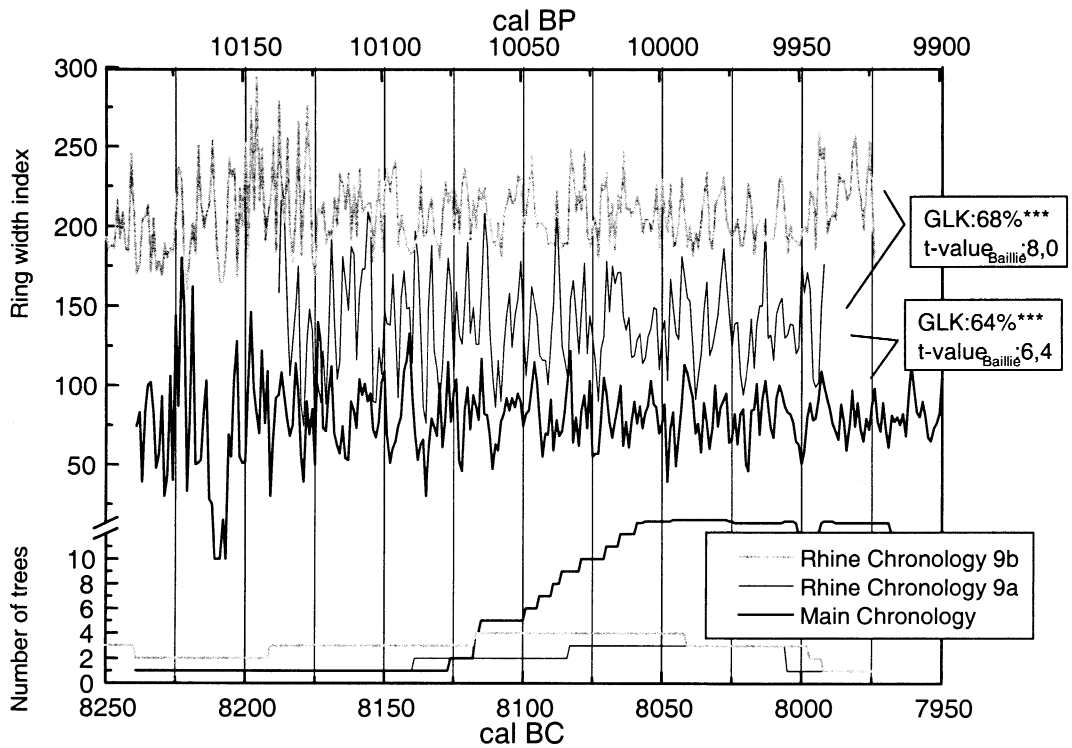

Fig. 3. Extension of the absolute oak chronology with samples from the Rhine River back to 8480 BC. A group of 3 trees (Rhine Chronology 9a) could be dated with the absolute Main chronology. This group perfectly matches the 507-yr-long floating sequence from the Rhine River (Rhine chronology 9b), thus anchoring this sequence.

Matching ^{14}C data of decadal samples from the oak extension to those of Preboreal pine resulted in a new, reliable ^{14}C link between the absolute oak chronology and the Preboreal pine chronology (see next section).

Linking the Preboreal Pine Chronology with the Oak Chronology

In 1993 the Preboreal pine chronology (PPC) was dated by ^{14}C and tentatively linked to the oak chronology by B. Becker (1993). In 1996 this tentative link was revised by the authors. Detailed investigation into the long-term ^{14}C trend and the absence of convincing dendrochronological similarity between the two chronologies resulted in a 120-yr backward shift of the PPC, with a confidence interval of *ca.* ±80 yr (Björck *et al.* 1996).

Now that the oak chronology starts prior to the ^{14}C plateau at 8800 ^{14}C yr BP, it displays the sharp ^{14}C age increase between 8900 and 9200 ^{14}C yr BP, which can be seen in the ^{14}C calibration curve of the PPC (Kromer and Spurk 1998). By wiggle-matching the ^{14}C pattern in both chronologies, the PPC can now be linked very reliably, resulting in a PPC interval of 9922–7951 BC (11,871–9900 BP)[5] with an uncertainty of ±20 yr only.

A dendrochronological linkage of the two chronologies is in preparation, but the realization is problematic due to the diversity of species originating from different rivers (the PPC is established mainly with wood from the Danube River). Even if this attempted linkage proves to be unfeasible, the Hohenheim chronologies provide a high-resolution time scale for nearly the last 12,000 years.

Revision of the Preboreal Pine Chronology

In 1997, when the PPC was established anew, a weak period between 9350 and 9250 BC (11,299 and 11,199 BP) became apparent, dividing the PPC into an older and a younger part. In the "weak" period the growth of the trees was very strongly disturbed, resulting in missing rings. In some trees no ring was formed for 3 to 5 consecutive years. The older part and the younger part of the PPC could be joined, however, by a tentative dendro-link. This required shifting the older part 31 yr to older ages with respect to the 1993 stage. In terms of dendrochronology this linkage is considerably better than the earlier link, but it still has to be confirmed by additional trees (Fig. 4). The younger part of the PPC reaches from 7951 BC to 9375 BC (9900 to 11,324 BP) and the older part from 9222 to 9922 BC (11,171 to 11,871 BP).

^{14}C measurements at Heidelberg support this tentative link. They connect the younger and the older part at exactly the position of the dendro-synchronization (Fig. 5). We therefore continue to use the PPC as a single chronology, based on the tentative link of the older and younger part (Fig. 6).

With respect to the absolute time scale of the PPC as previously published (Becker 1993; Kromer and Becker 1993), the internal revisions of the PPC result in time shifts of differing amounts, all to older ages (Table 2).

Timing of the Younger Dryas/Preboreal Transition

With the new dating of the PPC there is now evidence that the transition of the Younger Dryas to the Preboreal is reflected in the ring width of the pines (Björck *et al.* 1996). In the oldest part of the pine chronology the ring width is very narrow and the rings appear similar to those of pines from the alpine timberline, where summer temperature is the growth-limiting factor (Schweingruber, Briffa and Jones 1991). At 11,530 ± 20 BP the ring width suddenly doubles, indicating better growing conditions. The trees growing in this manner were found at six different sites spread over >70 km, excluding the possibility of a local event. Better growing conditions could be caused by better water supply or higher temperatures, or a combination of both. This implies a climatic change in South Germany at 11,530 ± 20 BP, which can be related to the Younger Dryas/Preboreal transition. In the

[5]At the 16th International Radiocarbon Conference in Groningen an age of 9952 to 8012 BC and a shift of 304 yr was presented. Both figures need to be corrected. In the first place, a change resulted when the PPC was newly established after the conference. Second, the incorrect labeling of some samples sent to Heidelberg entailed an incorrect shape for the ^{14}C curve of the PPC, which was used to create the linkage with the absolute oak chronology.

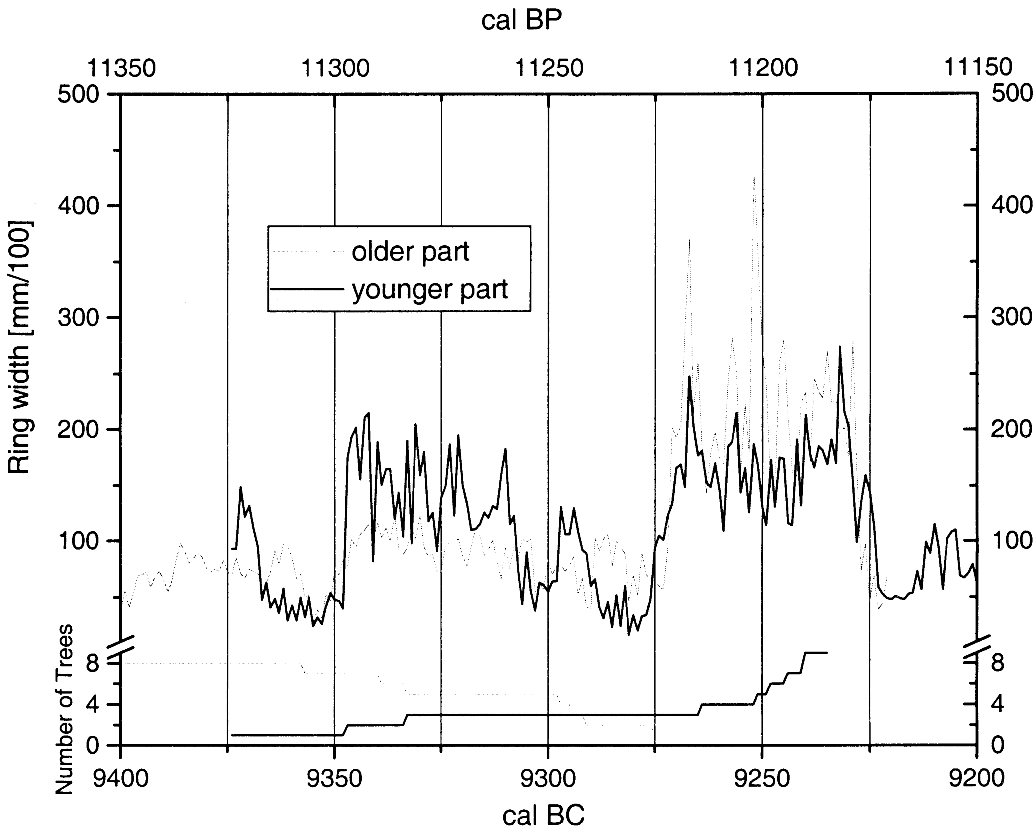

Fig. 4. Tentative ring-width linkage of the younger and the older part of the PPC. (Gleichläufigkeit = 62%, t-value$_{Baillie}$ = 3.0). This linkage needs to be confirmed by additional trees. The growth of the trees is disturbed and rings are missing, complicating the linkage of both parts. The synchronization is supported by the ^{14}C wiggle-matching.

Greenland ice cores the rapid transition of the $\delta^{18}O$ data took place at 11,550 ± 90 BP (GRIP: Johnsen *et al.* 1992) and 11,640 ± 240 BP (GISP2: Taylor *et al.* 1993), respectively. At 11,440 ± 120 BP there is an abrupt increase of $\delta^{18}O$ in the Lake Gościąż data record, combined with changes in terrestrial and lacustrine vegetation (Goslar, Arnold and Pazdur 1995). Furthermore, when the $\delta^{18}O$ record of the Lake Gościąż is related to the PPC by ^{14}C wiggle-matching, the increase of the $\delta^{18}O$ and the increase in ring width takes place at the same time (T. Goslar, personal communication). Records from Europe now match well, and taking into account the uncertainty of the time scales, it is possible that the Younger Dryas/Preboreal transition in Greenland and Europe occurred simultaneously.

Conclusion

The comparison of the two long South German oak chronologies entailed a revision of the pre-5242 BC part of the Hohenheim chronologies but also confirmed the time scale back to 7792 BC. The reexamination of the pre-5100 BC samples and the reestablishing of the Hohenheim oak chronology resulted, moreover, in an extension of the oak chronology back to 8480 BC. This enabled a ^{14}C linkage of the Preboreal pine chronology with an uncertainty of ±20 yr, whereby the pine chronology was shifted to older ages. The PPC was established anew resulting in a younger and an older part,

TABLE 2. Ages and the corresponding shifts of the PPC samples. "cal BC 1993" refers to the age from the previous publications (Becker 1993; Kromer and Becker 1993), "cal BC 1998" to that from 1998.

Lab code (Hd-)	cal BC 1993	Shift	cal BC 1998	Lab code (Hd-)	cal BC 1993	Shift	cal BC 1998
13511	−9439	−231	−9670	9005	−8728	−200	−8928
13512	−9429	−231	−9660	8826	−8723	−200	−8923
13525	−9409	−231	−9640	8835	−8708	−200	−8908
13526	−9389	−231	−9620	9865	−8855	−42	−8897
10567	−9385	−221	−9606	8836	−8693	−200	−8893
10568	−9355	−221	−9576	8867	−8678	−200	−8878
12888	−9323	−231	−9554	8868	−8663	−200	−8863
12945	−9309	−231	−9540	8876	−8648	−200	−8848
12959	−9304	−231	−9535	8877	−8633	−205	−8838
12960	−9289	−231	−9520	8889	−8618	−200	−8818
12964	−9279	−231	−9510	8890	−8603	−205	−8808
14220	−9254	−231	−9485	8911	−8573	−200	−8773
14159	−9229	−231	−9460	8904	−8558	−200	−8758
12999	−9219	−231	−9450	8905	−8543	−200	−8743
13000	−9199	−231	−9430	8977	−8525	−203	−8728
12967	−9194	−231	−9425	8957	−8508	−200	−8708
12968	−9184	−231	−9415	8978	−8495	−200	−8695
12981	−9174	−231	−9405	8970	−8473	−200	−8673
12982	−9159	−231	−9390	9026	−8468	−200	−8668
9097	−9159	−214	−9373	8971	−8458	−200	−8658
9098	−9144	−214	−9358	9007	−8453	−200	−8653
9118	−9127	−214	−9341	8989	−8435	−200	−8635
9119	−9107	−214	−9321	9064	−8433	−200	−8633
9126	−9087	−214	−9301	9154	−8418	−200	−8618
9127	−9067	−214	−9281	9160	−8403	−200	−8603
9134	−9047	−211	−9258	9161	−8388	−200	−8588
9810	−9042	−206	−9248	9191	−8373	−200	−8573
9969	−9038	−205	−9243	9192	−8358	−200	−8558
9135	−9022	−214	−9236	9199	−8345	−200	−8545
9811	−9026	−206	−9232	10001	−8335	−200	−8535
9970	−9015	−206	−9221	10002	−8315	−200	−8515
9153	−9002	−214	−9216	10191	−8305	−200	−8505
9807	−9007	−206	−9213	10003	−8295	−200	−8495
9808	−8991	−205	−9196	10191	−8285	−201	−8486
13009	−8989	−205	−9194	10004	−8275	−201	−8476
9836	−8983	−206	−9189	10010	−8255	−201	−8456
13010	−8974	−205	−9179	10011	−8235	−201	−8436
9837	−8972	−206	−9178	10035	−8215	−201	−8416
13059	−8954	−205	−9159	10036	−8195	−201	−8396
13087	−8936	−205	−9141	10090	−8175	−201	−8376
13088	−8866	−200	−9066	10091	−8145	−201	−8346
13094	−8844	−200	−9044	10097	−8135	−201	−8336
13016	−8829	−200	−9029	10098	−8115	−201	−8316
13017	−8809	−200	−9009	10115	−8095	−201	−8296
13018	−8794	−200	−8994	10337	−8085	−200	−8285
14231	−8784	−200	−8984	10116	−8075	−200	−8275
9844	−8925	−42	−8967	10338	−8065	−200	−8265
9853	−8911	−42	−8953	9769	−7833	−243	−8076
9864	−8891	−42	−8933	--	--	--	--

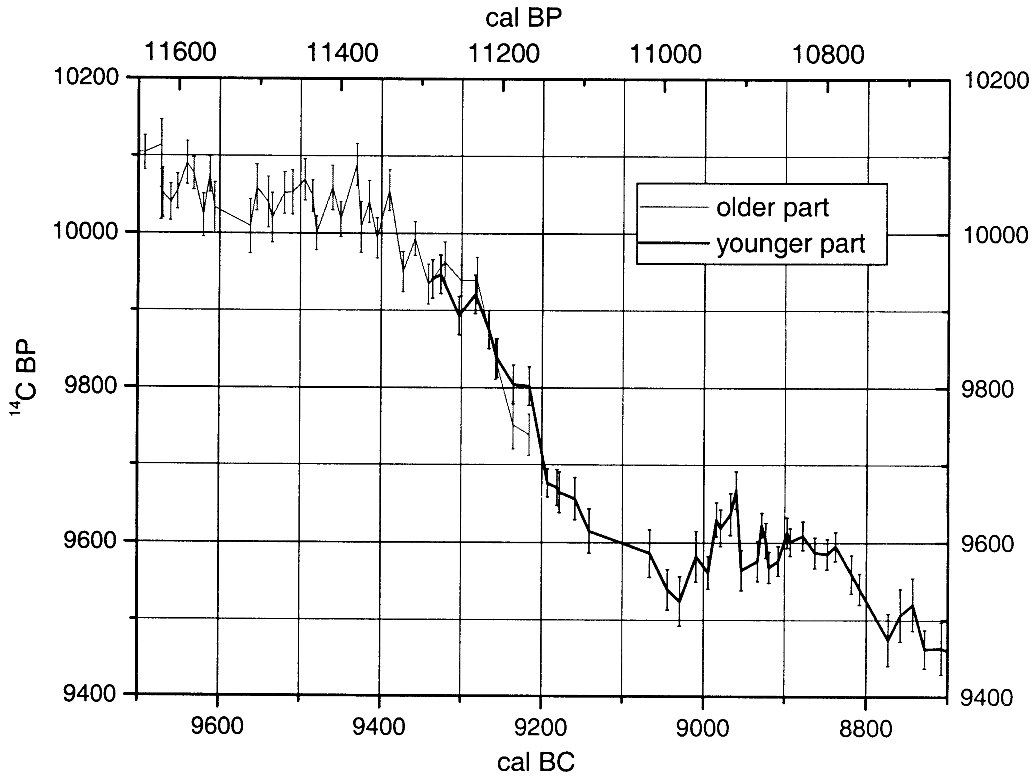

Fig. 5. ^{14}C measurements confirm the tentative linkage of the older and younger part of the PPC

which were tentatively linked together. As a consequence, the previously published ^{14}C calibration curve has to be revised prior to 5242 BC according to the corrections of the Hohenheim chronologies.

With these revisions, the Hohenheim chronologies provide a high-resolution time scale for nearly the last 12,000 years. The new situation has enabled the resolution of apparent discrepancies with other long data records involving the timing of the Younger Dryas/Preboreal transition.

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This paper is dedicated to Bernd Becker, who was sadly unable to complete his work during his lifetime. The dendrochronological research was supported by the European Commission (ENV4-CT95-0127–PL951087) and the BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, 07VKV/01A–21178.3/3). We also thank Sandra Hauser, Sabine Schmidt, Claudia Schuster and Silke Wurst for precise ring-width measurements.

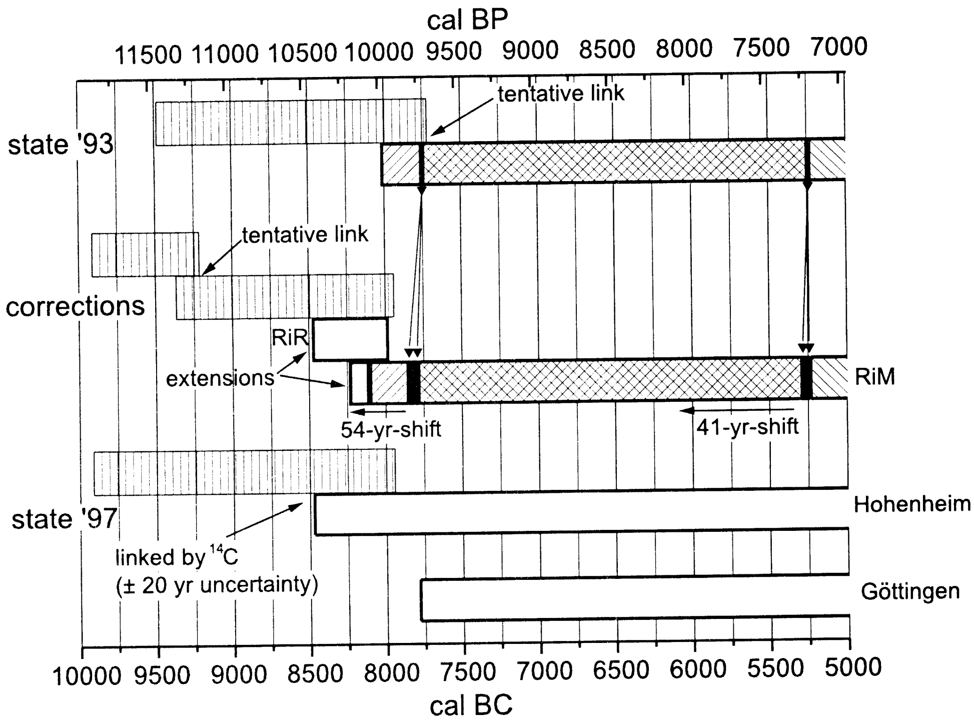

Fig. 6. Range of the Hohenheim chronologies before (state '93) and after (state '97) the revisions and extensions (thick-lined rectangles with various fill patterns = oaks, thin-lined rectangles with vertical fill = pines). The revisions of the oak chronology are shown in three segments. The youngest segment is shifted by 41 yr (crosshatched fill); the middle one by 54 yr (diagonal fill). As a result of these shifts the earliest segment is moved by 95 yr (diagonal fill). The chronologies from the Main River (RiM) and Rhine River (RiR) are synchronized, extending the oak chronology back to 8480 BC. The pine chronology is linked to the absolutely dated oak chronology by ^{14}C measurements with an uncertainty of ±20 yr. The PPC is divided into an older and a younger part that are synchronized tentatively. The Göttingen chronology and the Hohenheim chronology are mutually corroborative back to 7736 BC.

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REVISION AND TENTATIVE EXTENSION OF THE TREE-RING BASED ^{14}C CALIBRATION, 9200–11,855 CAL BP

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ABSTRACT. We report radiocarbon calibration data based on the revised German oak and pine series. The age range of the absolutely dated German oak series has been extended to 10,430 cal BP. The German pine series is tentatively linked to the oak series by ^{14}C, and now reaches back to 11,871 cal BP (±20 yr). The revisions of the tree-ring time scale of the German oak chronology solved long-standing apparent discrepancies in the mid-Holocene ^{14}C calibration data sets. The calibration data set based on the floating German pine is now in close agreement with the Preboreal part of ^{14}C calibration series obtained from most varve chronologies and corals.

INTRODUCTION

We previously published ^{14}C calibration data sets based on the German oak and pine series (Kromer and Becker 1993) reaching back to 11,500 cal BP. At that time the absolute time scale of the German pine chronology was based on a tentative tree-ring synchronization to the German oak master (Becker 1993). Since then, the tree-ring scale of both the German oak and the link to the pine has had to be revised (Spurk *et al.* 1998). We present the revised data sets for both series (Tables 1 and 2, following References) and discuss their implications for the atmospheric ^{14}C level at the transition from the Younger Dryas to the Preboreal and into the Boreal. Both chronologies were extended by findings made since 1993. For these intervals additional ^{14}C calibration dates are reported here.

^{14}C-DATED TREE-RING SERIES

German Oak

The tree-ring scale of the German oak chronology (Becker 1993) had to be revised at two intervals: at 7190 cal BP and 9740 cal BP (Spurk *et al.* 1998) rings were missing in the chronology. The corrections lead to shifts of 41 and 54 yr, respectively, to older ages. The error at 7190 cal BP has been noted already in the comparison of ^{14}C data sets (Stuiver and Pearson 1993; McCormac, Baillie and Pilcher 1995). Its correction also solved another apparent discrepancy: in 1986 the German oak in the 6th to the 8th millennia was floating but was wiggle-matched to the bristlecone pine (Linick, Suess and Becker 1985; Kromer *et al.* 1986; Stuiver *et al.* 1986), resulting in a zero-point range of 7190–7230 BC. When it was later synchronized dendrochronologically to the younger absolute oak chronology, the zero point became 7177 BC, raising suspicion of a true offset in the ^{14}C ages between the bristlecone pine and the German oak. After application of the 41-yr correction at 7150 cal BP, the two data sets are now fully compatible. The correction at 9740 cal BP solved an apparent offset in the German oak sections measured in Belfast (Pearson, Becker and Qua 1993) from those measured in Heidelberg (F. G. McCormac, personal communication).

Through new findings and synchronization of previously floating sections, the German oak chronology was extended by more than four centuries and now reaches back to 10,430 cal BP (Spurk *et al.*

absolute age scale is estimated at less than ±20 yr (see text).

1998). The ^{14}C calibration curve (Fig. 1) shows a pronounced and rapid transition from ^{14}C ages of 9200 BP to 8900 BP around 10,200 cal BP, which is now part of the oak chronology. This "marker" is used to constrain the absolute age of the floating German pine chronology with respect to the absolutely dated oak chronology.

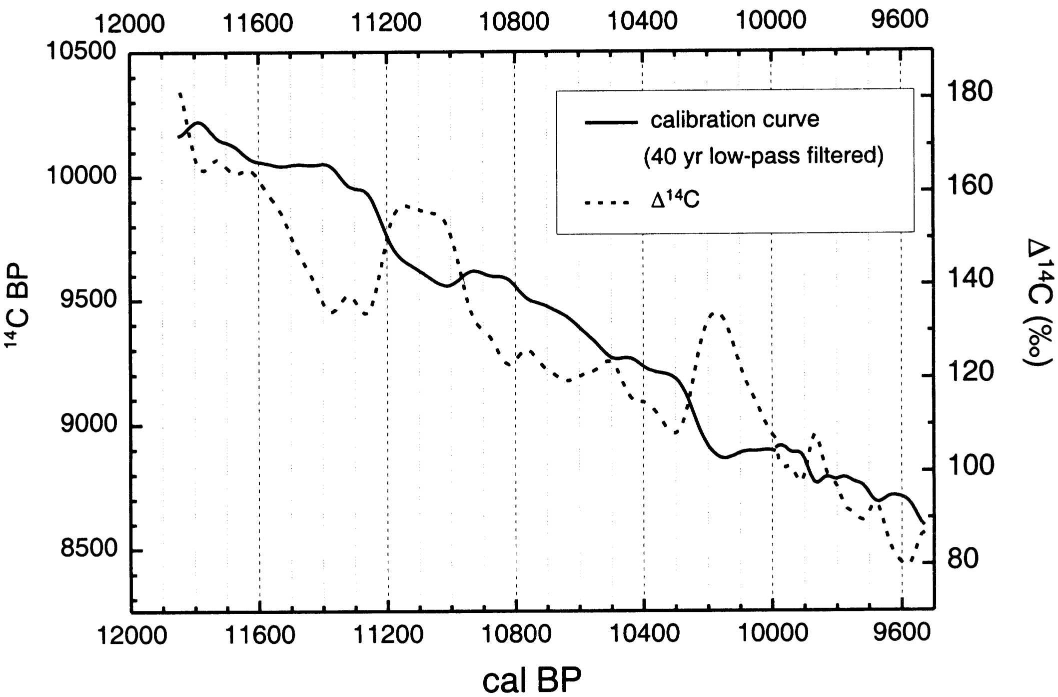


Fig. 3. Smoothed ^{14}C calibration curve (FFT filter, 40-yr low pass) and $\Delta^{14}C$ (- - -) (Stuiver and Pollach 1977) as derived from the German oak and pine series.

Obvious candidates for causes of the variable ^{14}C level are changes in ocean ventilation and ^{14}C production changes, *e.g.*, by solar activity variability (Stuiver and Braziunas 1993). The improved absolute age control and the high resolution of tree-ring based $\Delta^{14}C$ reconstruction will now allow a better discrimination among forcing and response mechanisms as seen in the atmospheric $\Delta^{14}C$.

^{14}C PATTERNS IN THE LATE YOUNGER DRYAS

We obtained ^{14}C data from two floating sections predating the German pine series. 1) At d'Olon, east of the Lake of Geneva, Switzerland, a 340-ring *Larix* section was found and submitted by J. P. Hurni, Moudon. The ^{14}C sequence (Fig. 4, Table 3)—overlapping in ^{14}C age with the German pine for the youngest rings—documents a straight relation between ^{14}C age and true years. 2) From the lignite area close to Cottbus, East Germany, we obtained a large quantity of pine sections. The ^{14}C

TABLE 3. ^{14}C ages of the floating VOD 505 chronology (Rhone River, Geneva, Switzerland)

Lab code (Hd-)	Center ring	^{14}C BP	Lab code (Hd-)	Center ring	^{14}C BP
16184	15	10309 ± 47	17325	150	10259 ± 28
16185	35	10342 ± 60	16779	230	10179 ± 21
16847	50	10335 ± 28	16812	270	10159 ± 24
16825	70	10281 ± 29	16866	328	10088 ± 37
16641	90	10290 ± 27	16824	330	10118 ± 24
16823	110	10218 ± 25			

we allow for additional error components, *e.g.*, arising from wood splitting or unequal spacing of the pine samples (most notable in the interval 10,200 to 10,230 cal BP), the German pine chronology is now fixed absolutely to the oak with an uncertainty better than ±20 yr. All ^{14}C pine data as reported below are based on this match.

Calibration Curve and Atmospheric ^{14}C Levels in the Age Range 9400 to 11,855 cal BP

The calibration curve based on the German pine is shown in Figure 2. Strong departures from a steady-state ^{14}C level are noted. A smoothed version of Figure 2 (FFT-smoothing with a 40-yr cut-off) and the $\Delta^{14}C$ level as calculated from the smoothed data are shown in Figure 3.

Superimposed on a continuously declining long-term trend are century-scale peaks of ^{14}C rising by up to 30‰ above the long-term mean. Following the end of the Younger Dryas (11,650–11,550 cal BP) we observe a decline of $\Delta^{14}C$, followed by a strong century-scale peak in the early Preboreal. This oscillation is synchronous to the evidence of Preboreal cooling documented in the stable isotope data of the Greenland ice cores and in mid-latitude archives, as discussed in detail elsewhere (Björck *et al.* 1996). The transition from the Preboreal to the Boreal chronozone, roughly coincident with the suppression of pine by oak in the river valleys of Southern Germany, is marked by another strong $\Delta^{14}C$ anomaly.

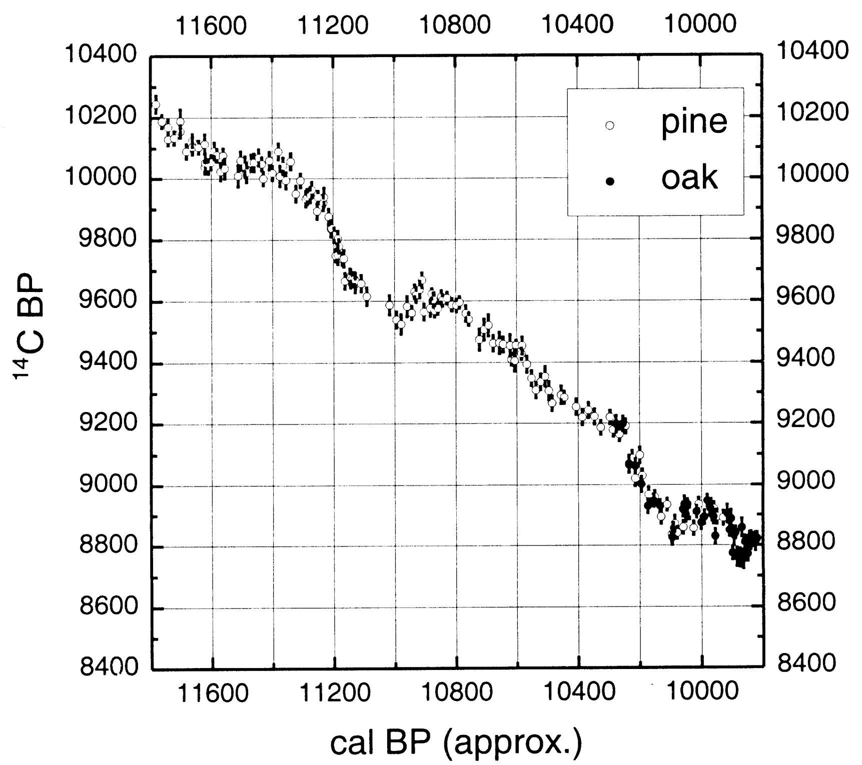
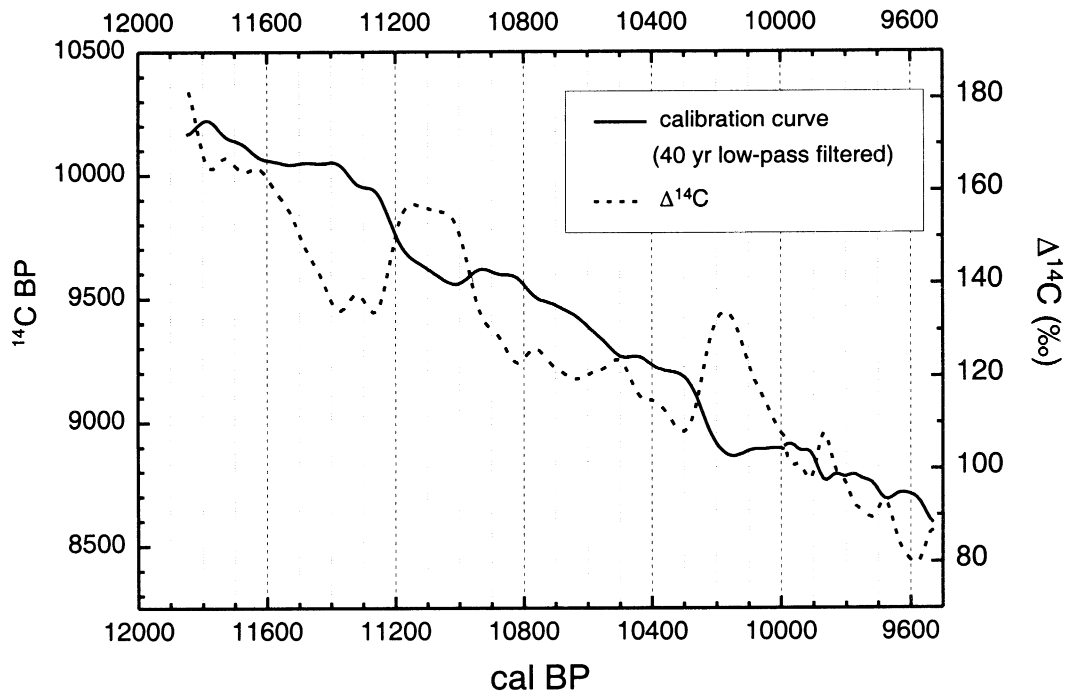


Fig. 2. ^{14}C calibration curve as derived from the German pine chronology. The uncertainty of the absolute age scale is estimated at less than ±20 yr (see text).



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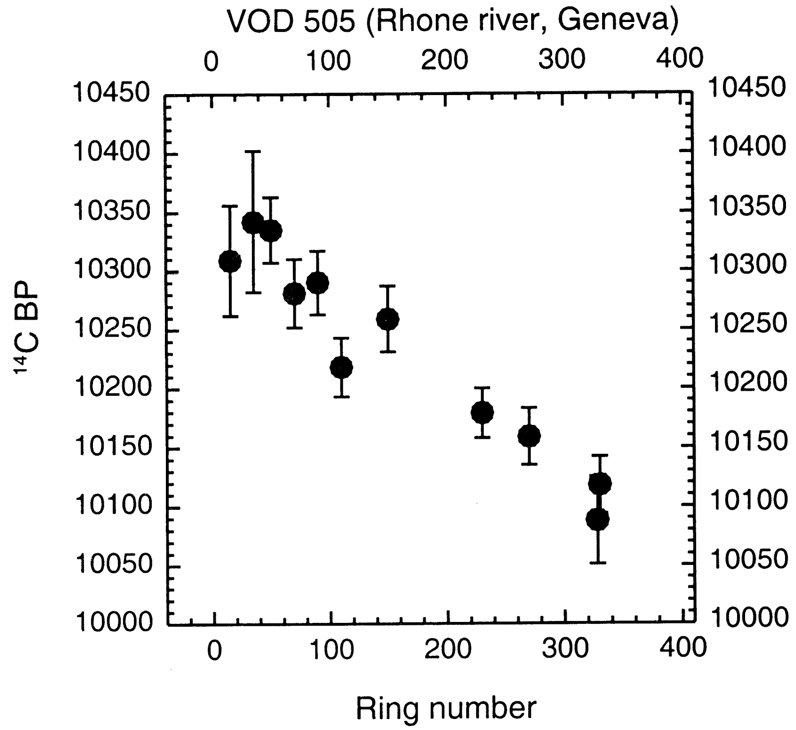

Fig. 4. ^{14}C dates *vs.* ring number of the floating *Larix* series VOD505 (Rhone River, Geneva, Switzerland). The sequence indicates an essentially "regular" age relation for this interval at the end of the Younger Dryas event.

ages of the samples analyzed so far cover the range 10,480 to 10,280 BP. From 7 sections we built a 296-ring chronology which is now being ^{14}C-dated. The oldest rings date to 10,280 ± 26 ^{14}C BP, raising hopes for a slight extension of the German pine chronology.

Conclusion

The revisions of the tree-ring time scale of the German oak chronology solved long-standing apparent discrepancies noted over the course of high-precision ^{14}C measurements. The extension of the German oak by more than 450 yr allows for a much improved ^{14}C link to the German pine chronology, constraining its absolute position with an error of less than ±20 yr. The calibration data set based on the German pine is now in close agreement with the Preboreal part of ^{14}C calibration series obtained from most varve chronologies and corals.

Acknowledgments

The main body of the German oak and pine chronologies was constructed by the late Bernd Becker. For the new extension of the chronologies we profited much from the work of Michael Friedrich, Jutta Hofmann and Sabine Remmele.

We thank Minze Stuiver and Paula Reimer for discussion and exchange during the course of ^{14}C analyses of the tree-ring series. Edouard Bard and Tomasz Goslar made us aware of the problems of the earlier oak-pine link. Svante Björck and Sigfus Johnson opened new vistas when the work on the tree-ring series seemed at a dead end.

The Cottbus pine sections were found and submitted by D. Neubauer-Saurer, Y. Gautier and C. Pasda. The *Larix* section was provided by J. P. Hurni, A. Orcel and C. Orcel, Laboratoire Romand de Dendrochronologie, Moudon, Switzerland.

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TABLE 1. Revised German oak data. Compared to the previous publication (Kromer and Becker 1993) data were added at the beginning of the chronology, and shifts of the dendroscale are included (see text).

Lab code (Hd-)	cal BC	cal BP	^{14}C BP
19079	8329	10278	9198 ± 27
19055	8307	10256	9199 ± 24
19054	8287	10236	9069 ± 27
19091	8267	10216	9062 ± 23
19175	8247	10196	9002 ± 25
19174	8227	10176	8930 ± 23
19179	8207	10156	8947 ± 20
19349	8187	10136	8930 ± 20
19415	8147	10096	8826 ± 24
15145	8113	10062	8918 ± 23
14904	8108	10057	8934 ± 28
19350	8107	10056	8923 ± 20
15889	8103	10052	8901 ± 23
15923	8098	10047	8935 ± 18
16046	8068	10017	8911 ± 20
15906	8053	10002	8874 ± 20
16632	8043	9992	8893 ± 23
16038	8033	9982	8947 ± 20
16587	8023	9972	8921 ± 20
16586	8018	9967	8901 ± 20
16585	8013	9962	8894 ± 23
19351	8007	9956	8830 ± 24
9513	7968	9917	8904 ± 30
14075	7961	9910	8850 ± 20
9502	7956	9905	8887 ± 30
14076	7951	9900	8774 ± 20
9501	7946	9895	8832 ± 30
14077	7941	9890	8842 ± 20
9492	7936	9885	8762 ± 30
14079	7931	9880	8764 ± 20
9491	7926	9875	8760 ± 30
14112	7921	9870	8858 ± 30
9486	7916	9865	8755 ± 30
16623	7911	9860	8810 ± 22
14274	7901	9850	8772 ± 23
16605	7896	9845	8823 ± 21
9264	8051	9840	8816 ± 30
14088	8046	9835	8818 ± 21
9258	7876	9825	8813 ± 30

Lab code (Hd-)	cal BC	cal BP	^{14}C BP
14106	7871	9820	8822 ± 21
14171	7851	9800	8820 ± 23
9255	7836	9785	8801 ± 30
14160	7831	9780	8791 ± 24
14172	7821	9770	8772 ± 21
8510	7717	9666	8721 ± 30
8511	7709	9658	8721 ± 30
8518	7701	9650	8648 ± 30
8519	7694	9643	8710 ± 30
8524	7679	9628	8733 ± 30
8525	7669	9618	8708 ± 30
8544	7659	9608	8735 ± 30
8141	7653	9602	8719 ± 30
8140	7637	9586	8727 ± 33
8091	7620	9569	8739 ± 30
8144	7613	9562	8696 ± 30
8286	7613	9562	8736 ± 30
8145	7603	9552	8746 ± 30
8295	7594	9543	8577 ± 30
8127	7588	9537	8528 ± 30
8244	7581	9530	8608 ± 30
8151	7578	9527	8474 ± 30
7758	7570	9519	8439 ± 30
8171	7558	9507	8509 ± 30
7759	7541	9490	8455 ± 30
8273	7523	9472	8458 ± 30
8304	7473	9422	8371 ± 30
7760	7460	9409	8279 ± 30
8086	7423	9372	8315 ± 30
7757	7421	9370	8300 ± 30
8306	7408	9357	8382 ± 30
8117	7390	9339	8380 ± 30
8689	7268	9217	8296 ± 30
8717	7261	9210	8251 ± 30
8718	7251	9200	8198 ± 30
8719	7241	9190	8239 ± 30
8720	7231	9180	8232 ± 30
8750	7221	9170	8277 ± 30
8751	7210	9159	8271 ± 30

TABLE 2. Revised German pine data. The absolute ages are tentative. They are based on matching the ^{14}C ages of the pine to the German oak. The uncertainty of the absolute age scale is estimated to be less than ±20 yr (see text).

Lab code (Hd-)	cal BC	cal BP	^{14}C BP
16342	9908	11857	10162 ± 23
16427	9878	11827	10156 ± 29
16251	9833	11782	10244 ± 28
17017	9813	11762	10188 ± 21
15586	9793	11742	10170 ± 24
16269	9793	11742	10130 ± 20
15591	9773	11722	10134 ± 22
15592	9753	11702	10156 ± 20
16328	9753	11702	10189 ± 38
15594	9733	11682	10090 ± 24
15731	9713	11662	10126 ± 21
16332	9713	11662	10105 ± 26
15730	9693	11642	10104 ± 22
16022	9673	11622	10114 ± 32
16502	9673	11622	10038 ± 21
13511	9671	11620	10052 ± 32
13512	9661	11610	10040 ± 24
16902	9653	11602	10054 ± 23
13525	9641	11590	10091 ± 28
16667	9633	11582	10077 ± 21
13526	9621	11570	10023 ± 28
16652	9613	11562	10076 ± 23
10567	9607	11556	10033 ± 33
10568	9563	11512	10009 ± 35
12888	9555	11504	10059 ± 30
12945	9541	11490	10040 ± 33
12959	9536	11485	10020 ± 32
12960	9521	11470	10052 ± 27
12964	9511	11460	10053 ± 29
12965	9496	11445	10069 ± 27
14220	9486	11435	10048 ± 21
14185	9481	11430	10000 ± 22
14159	9461	11410	10059 ± 29
12999	9451	11400	10018 ± 23
13000	9431	11380	10089 ± 27
12967	9426	11375	10008 ± 33
12968	9416	11365	10041 ± 27
12981	9406	11355	9994 ± 26
12982	9391	11340	10056 ± 27
9097	9374	11323	9950 ± 26
9098	9359	11308	9993 ± 22
9118	9342	11291	9934 ± 26
11647	9337	11286	9941 ± 25
11648	9327	11276	9947 ± 25
9119	9322	11271	9963 ± 26
11653	9304	11253	9893 ± 25
9126	9302	11251	9939 ± 20
11670	9284	11233	9921 ± 25
9127	9282	11231	9939 ± 30
11671	9267	11216	9875 ± 25
9134	9259	11208	9837 ± 26
11685	9257	11206	9838 ± 25
9810	9249	11198	9816 ± 23
9969	9244	11193	9749 ± 20
9135	9237	11186	9751 ± 31
11686	9237	11186	9804 ± 25
9811	9233	11182	9780 ± 22
9970	9222	11171	9738 ± 20
9153	9217	11166	9739 ± 27
9807	9214	11163	9665 ± 26
9808	9197	11146	9680 ± 26
13009	9195	11144	9673 ± 30
11715	9194	11143	9677 ± 18
9836	9190	11139	9670 ± 22
11729	9182	11131	9671 ± 23
13010	9180	11129	9656 ± 28
9837	9179	11128	9665 ± 26
13059	9160	11109	9657 ± 27
13087	9142	11091	9615 ± 29
13088	9067	11016	9586 ± 31
13094	9045	10994	9539 ± 26
13016	9030	10979	9524 ± 32
13017	9010	10959	9582 ± 33
13018	8995	10944	9561 ± 21
14231	8985	10934	9630 ± 22
13095	8980	10929	9619 ± 24
9844	8968	10917	9637 ± 27
14397	8961	10910	9668 ± 24
9853	8954	10903	9564 ± 26
9864	8934	10883	9576 ± 26
9005	8929	10878	9623 ± 16
8826	8924	10873	9603 ± 23
14375	8920	10869	9568 ± 20
8835	8909	10858	9576 ± 19
9865	8898	10847	9613 ± 20
8836	8894	10843	9601 ± 18
8867	8879	10828	9609 ± 19
8868	8864	10813	9587 ± 20
8876	8849	10798	9585 ± 20
8877	8839	10788	9595 ± 19
8889	8819	10768	9559 ± 25
8890	8809	10758	9540 ± 20
8911	8774	10723	9474 ± 34
8904	8759	10708	9506 ± 34
8905	8744	10693	9520 ± 34
8977	8729	10678	9462 ± 25
8957	8709	10658	9463 ± 34
8978	8696	10645	9458 ± 24
8970	8674	10623	9455 ± 34
9026	8669	10618	9410 ± 19

TABLE 2. *(Continued)*

Lab code (Hd-)	cal BC	cal BP	^{14}C BP
8971	8659	10608	9405 ± 34
9007	8654	10603	9456 ± 15
8989	8636	10585	9428 ± 18
9064	8634	10583	9454 ± 27
9154	8619	10568	9394 ± 26
9160	8604	10553	9348 ± 25
9161	8589	10538	9309 ± 25
9191	8574	10523	9336 ± 26
9192	8559	10508	9354 ± 32
9199	8546	10495	9307 ± 30
10001	8536	10485	9266 ± 24
10191	8506	10455	9293 ± 29
10003	8496	10445	9285 ± 20
10010	8457	10406	9254 ± 25
10011	8437	10386	9220 ± 25
10035	8417	10366	9243 ± 25
10036	8397	10346	9222 ± 25
10090	8377	10326	9186 ± 22
10091	8347	10296	9220 ± 22
10097	8337	10286	9179 ± 21
10098	8317	10266	9164 ± 21
10115	8297	10246	9191 ± 23
10337	8286	10235	9065 ± 25
10116	8276	10225	9086 ± 25
10338	8266	10215	9021 ± 25
10127	8251	10200	9097 ± 25
16081	8243	10192	9030 ± 21
16093	8223	10172	8967 ± 25
16100	8203	10152	8960 ± 20
16106	8183	10132	8894 ± 23
16110	8163	10112	8934 ± 20
16635	8148	10097	8835 ± 23
16068	8143	10092	8847 ± 23
16082	8143	10092	8850 ± 24
16595	8138	10087	8871 ± 27
16596	8131	10080	8841 ± 20
16290	8111	10060	8859 ± 21
16289	8091	10040	8907 ± 21
9769	8077	10026	8856 ± 22
16082	8061	10010	8935 ± 22
16216	8021	9970	8930 ± 23
16593	8011	9960	8921 ± 21
16594	8001	9950	8894 ± 24
16385	7981	9930	8890 ± 24

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HIGH-PRECISION RADIOCARBON AGE CALIBRATION FOR TERRESTRIAL AND MARINE SAMPLES

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ABSTRACT. Single-year and decadal radiocarbon tree-ring ages are tabulated and discussed in terms of ^{14}C age calibration. The single-year data form the basis of a detailed ^{14}C age calibration curve for the cal AD 1510–1954 interval ("cal" denotes calibrated). The Seattle decadal data set (back to 11,617 cal BP, with 0 BP = AD 1950) is a component of the integrated decadal INTCAL98 ^{14}C age curve (Stuiver *et al.* 1998). Atmospheric ^{14}C ages can be transformed into ^{14}C ages of the global ocean using a carbon reservoir model. INTCAL98 ^{14}C ages, used for these calculations, yield global ocean ^{14}C ages differing slightly from previously published ones (Stuiver and Braziunas 1993b). We include discussions of offsets, error multipliers, regional ^{14}C age differences and marine ^{14}C age response to oceanic and atmospheric forcing.

INTRODUCTION

Radiocarbon ages of dendrochronologically dated wood samples, mostly 10-yr segments, were previously reported for the interval 6000 cal BC–cal AD 1950. These ^{14}C measurements have now been extended back to 9668 cal BC. We also applied some minor corrections to a portion of the ^{14}C ages reported for decadal samples (Stuiver and Becker 1993), multiple-year samples (Stuiver and Reimer 1993) and single-year samples (Stuiver 1993; Stuiver and Braziunas 1993a). Our additional data (9668–6000 cal BC) are given here, together with corrected (when applicable) decadal and single-year ^{14}C ages for the intervals 6000 cal BC–cal AD 1950 and cal AD 1510–1954, respectively. The decadal data (Table 1, Appendix) altogether incorporate the 11,617–0 cal BP interval. Single-year data are given in Table 2 (Appendix) for the cal AD 1510–1954 interval.

As reported in the 1993 Calibration Issue (Stuiver, Long and Kra 1993), the measured ^{14}C activities of the samples dated between 1977 and 1987 were corrected for small amounts of radon (Stuiver and Becker 1993). The original ages, calculated without applying a radon correction, were reported in Stuiver and Kra (1986). Additional information, discussed in the next section, reduces the radon correction to one half the 1993 value. The 1993 ^{14}C age correction of ~10 to 20 ^{14}C yr for samples measured between 1977 and 1987 evidently was too large. For the 1998 calculations we halved the original radon correction to ~5 to 10 ^{14}C yr. The latest "correction of the 1993 correction" is small and its influence is usually limited to ~10 ^{14}C yr.

Adjustments of the German oak and pine chronologies have been included. Both chronologies were extensively reevaluated at the University of Stuttgart-Hohenheim (Spurk *et al.* 1998). Whereas the German oak series yields absolute cal AD/BC dates (through a continuous count from the present to the past), the latest part of the pine series is ^{14}C-matched with the earliest portion of the oak chronology. This yields a cal BP scale with a margin of error of about two decades (Kromer and Spurk 1998; Spurk *et al.* 1998).

The materials used here for the AD interval are mainly derived from U.S. Pacific Northwestern, Californian and Canadian trees. A few Northern German oak samples were used as well. The trees are described in Table 2 of Stuiver and Becker (1986).

For the BC portion a limited number of samples from the Irish oak chronology (Pilcher *et al.* 1984) were used near 500 cal BC. California trees overlap with the oak series from Southern Germany between cal AD 45 and 145 cal BC. The Seattle German Main-Donau oak and German pine samples cover the intervals 7748 cal BC–cal AD 45 and 9668–8007 cal BC, respectively. Cellulose (Stuiver, Burk and Quay 1984) was isolated from all decadal wood samples older than 150 cal BC.

After studying ring thickness patterns of individual tree sections, the Hohenheim group rejected the earlier absolute dating (relative to the master chronology) of some of these sections (*e.g.*, where beetle-induced damage was evident). Our previously measured ^{14}C ages of the rejected sections had to be withdrawn. Replacement wood will be used for new measurements, but in the meantime Seattle ^{14}C ages are missing for midpoints 7566–7498, 7876–7758, and 8827–8757 cal BC. An additional gap due to a 41-yr shift in the master chronology concerns the midpoints 5256–5215 cal BC. In some instances we did not receive wood (sections 6166–6053, 6386–6356, 7316–7206, 7996–7886, 9057–9027, 9258–9242 and 9358–9332 cal BC).

OFFSETS, "ERROR MULTIPLIER" AND RADON CORRECTION

The most recent Seattle (S), Belfast (B) and Heidelberg (H) results are reported in this issue. Belfast results, adjusted for the shifts in German oak chronology (McCormac, personal communication) are based on Pearson and Qua (1993) and Pearson, Becker and Qua (1993). Pretoria/Groningen (P/G) results were reported previously (Vogel and van der Plicht 1993). Average offsets between the ^{14}C ages of the different laboratories are relatively small for the complete date sets, with S − B = −13 ± 1 yr (n = 866), S − H = −25 ± 2 yr (n = 230) and S − P/G = −17 ± 2 yr (n = 194). The ± equals one standard deviation (σ) and n is the number of comparisons. Offsets for millennia are given in Table 3.

TABLE 3. Average and millennia offsets (in ^{14}C yr) between Seattle (S), Belfast (B), Heidelberg (H) and Pretoria/Groningen (P/G). σ_1 is the predicted average standard deviation in ^{14}C age differences. The variance beyond σ_1 is represented by σ_E (see text). Comparisons are based on decadal samples (see Stuiver *et al.* 1998).

	Offsets			σ_1	σ_E	σ_1	σ_E	σ_1	σ_E
Age AD/BC	S−B	S−H	S−P/G	S−B		S−H		S−(P/G)	
10–9 ka BC		−12 ± 5				34	17		
9–8 ka BC		−18 ± 4				32	24		
8–7 ka BC	10 ± 5	−26 ± 6		34	47	36	39		
7–6 ka BC	−17 ± 3	−34 ± 5		31	31	36	36		
6–5 ka BC	−34 ± 3	−56 ± 9		29	31	35	56		
5–4 ka BC	−11 ± 3	−28 ± 5		28	24	31	41		
4–3 ka BC	−17 ± 3		−18 ± 2	27	17			20	19
3–2 ka BC	−17 ± 2		−16 ± 3	25	27			23	13
2–1 ka BC	−1 ± 3		4 ± 9	26	21			23	8
1–0 ka BC	−6 ± 2			25	13				
AD 0–1 ka	−12 ± 3			27	11				
AD 1–2 ka	−15 ± 2			19	15				
10 ka BC–AD 2 ka	**−13 ± 1 yr**	**−25 ± 2 yr**	**−17 ± 2 yr**	**27**	**24**	**34**	**35**	**22**	**13**

For Seattle (S) we usually report a σ derived from the near-Gaussian counting statistics of the accumulated number of counts for the sample and standards. Additional information on the σ in the ^{14}C age is derived from the reproducibility of ^{14}C age determinations in the Seattle laboratory, and interlaboratory comparisons that provide information on the sum total of uncertainty tied to the processes of wood allocation, dendro-age determination, sample pretreatment, laboratory ^{14}C determination, regional ^{14}C differences and individual tree ^{14}C differences.

The reported age error can be used to predict the statistical variance in ^{14}C age differences when results of two laboratories are available for samples with the same cal age. The ^{14}C age differences of samples of identical cal age yield an offset (the average of the differences) and a (scatter) standard deviation σ_2. The σ_2 is compared to the standard deviation σ_1 predicted from the ^{14}C age errors reported by both laboratories. The increase in variance (excess variance) σ_E is derived from $\sigma_E{}^2 = \sigma_2{}^2 - \sigma_1{}^2$. The ratio σ_2/σ_1 yields the "error multiplier" k (Stuiver 1982).

The above statistical considerations are valid for comparisons of ^{14}C determinations of identical samples. However, the samples to be compared here are rarely fully identical in that the time over which the sample is averaged (*e.g.*, 10-yr *vs.* 3-yr samples) differs. Furthermore, the differences in cal age (time-midpoints) of the samples is usually variable. Different selection criteria (*e.g.*, should two samples be compared if one is a 20-yr and the other a 3-yr sample, and the difference in midpoints is 10 yr?) yield different σ_E (and k) estimates. Given these uncertainties, the following σ_E calculations (based on decadal sample files; see the INTCAL98 calibration (Stuiver *et al.* 1998) for the construction of the decades) are "order of magnitude" only.

The comparison of the S ^{14}C ages to those of B, H and P/G yields the σ_1 and σ_E values given in Table 3. For S–B (n = 859) and S–H (n = 230) comparisons, the σ_E and σ_1 are of the same order of magnitude; for S–P/G (n = 194), the σ_E is more like half σ_1. Expressed differently, average k values are in the 1.3–1.4 range. Other estimates yielded k = 0.7 (n = 44) when comparing S ^{14}C ages of single-year Pacific Northwest wood with S determinations of single-year Kodiak Island wood (Stuiver and Braziunas 1998), and k = 1.2 from evaluating counting stability in the Seattle laboratory over 4 years (Stuiver and Becker 1993).

Previously we discussed in much detail a small radon correction that had to be applied to measurements made between 1977 and 1987 (Stuiver and Becker 1993). An average count-rate difference of 0.279 ± 0.045 counts per minute (cpm) was used for this correction. Since 1987 we have remeasured many samples for which newly determined ^{14}C ages can be compared to 1977–1987 ones. The enlarged data set suggests a smaller radon correction, with a count-rate difference of 0.051 ± 0.023 cpm. The 1993 paper also reported first day *vs.* fourth day count-rate differences that were compatible with a radon contribution of 0.276 ± 0.016 cpm. When adding similar first day–fourth day baseline information for 1992–1996,the 0.276 ± 0.016 cpm radon excess estimate is lowered to 0.213 ± 0.016 cpm.

The radon corrections (0.051 and 0.213 cpm) suggested by the above calculations differ significantly (at the 5.8σ level). There is no obvious explanation for the difference but both methods suggest a smaller radon correction. The adjusted average count-rate difference (unweighted) for the two comparisons is 0.132 cpm, or 48% of the 1993 value. For the calculation of the ^{14}C ages listed in Tables 1 and 2 we used counting rate corrections of individual counters that average 0.132 cpm for samples measured between 1977 and 1987. This effectively halves the radon correction previously (Stuiver, Long and Kra 1993) applied to tree-ring ^{14}C determinations made in Seattle between 1977 and 1987.

Most of the cal age midpoints in Table 1 represent the midpoint of decadal (10 ring) wood samples. Occasional departures from 10-yr rings are noted in Table 1.

REGIONAL OFFSETS

Regional offsets, relative to Washington (W), were reported previously (Stuiver and Braziunas 1998). Trees grown in Alaska (A), Russia (R), Tasmania (T) and South Chile (C) were used (details can be found in Stuiver and Braziunas 1998). The reported offsets are A – W = 14 ± 3 yr (AD 1884–1932), R – W = –6 ± 6 yr (AD 1545–1615) and 2 ± 6 yr (AD 1615–1715), T – W = 25 ± 7 yr (estimated for the 19th century) and C – W = 38 ± 5 yr (AD 1670–1722) and 21 ± 5 yr (19th century). The 19th century "Southern Hemispheric" (Chile and Tasmania) offset is 23 ± 4 ^{14}C yr (reported incorrectly in Stuiver and Braziunas 1998 as 23 ± 9 yr).

The above regional offsets, which are not necessarily constant with time, are for "natural" conditions. During the first half of the twentieth century the ^{14}C levels were modified by fossil fuel CO_2 releases that depressed atmospheric ^{14}C levels to a greater extent in the Northern Hemisphere (Northern Hemispheric fossil fuel CO_2 emissions are much larger than Southern Hemispheric ones). Whereas 19th century Chile/Tasmania ^{14}C ages are *ca.* 23 ^{14}C yr older than those of Washington, this offset is reduced during the first half of the 20th century. There is even a switch to younger Southern Hemispheric ages *ca.* AD 1940 (Stuiver and Braziunas 1998; McCormac *et al.* 1998a,b).

Laboratory Offsets in Pine and Bristlecone Pine Data

The measurements of two laboratories, Seattle and Heidelberg, are now available for German pine samples (both this issue). In Figure 1 we compare the S and H ^{14}C dates of the German pine chronology. The cal ages reflect the latest reevaluation by the University of Stuttgart-Hohenheim tree-ring laboratory (Spurk *et al.* 1998). There is substantial agreement, with an S-H offset of –16 ± 3 yr (n = 101) and an error multiplier k = 1.20.

For the older samples, the German and Irish oak chronologies are of crucial importance. ^{14}C results of the independent bristlecone pine chronology (Linick *et al.* 1986), as established at Tucson, Arizona (A), cover the 6554–5350 cal BC interval. When comparing these data to Belfast and Heidelberg oak results (Pearson, Becker and Qua 1993; Stuiver *et al.* 1998; Kromer and Spurk 1998), the bristlecone pine ^{14}C ages are, respectively, 19 ± 4 (n = 75) and 17 ± 8 (n = 24) yr older. When comparing Seattle (Stuiver and Reimer 1993) measured bristlecone pine ^{14}C ages (1998 radon corrected) to bristlecone pine measured in Arizona (Linick *et al.* 1986), the offset is 25 ± 8 yr (n = 15) toward older Arizona ages. These offsets, on the order of one or two decades, fall within the range expected from laboratory measuring errors, cal age differences in midpoint and tree-ring length of the wood samples, and nonidentical regional ^{14}C.

The bristlecone pine ^{14}C age offset with Seattle oak ^{14}C ages (with minor offset corrections, see Stuiver *et al.* 1998) is a surprisingly large 48 ± 3 yr (n = 80). The reason for this "anomalous" result is, at present, unknown.

Single-Year Age Calibration

In the 1993 calibration issue, and also in Stuiver and Braziunas 1993a, a set of single-year ^{14}C results was reported for wood from the Pacific Northwest (Washington State). The data in Table 2 and Figure 2 are based on these ^{14}C results with two modifications: 1) adjustment of the ^{14}C determinations made between 1977 and 1987 for the minor change in radon correction, as discussed previously, and 2) the incorporation of single-year results from a Kodiak Island, Alaska, Sitka spruce tree.

The Alaskan Sitka spruce (58°N, 153°W) covers the cal AD 1884–1932 interval. Its ^{14}C ages are, on average, 14 ± 3 ^{14}C yr older than Washington State results (Stuiver and Braziunas 1998). To obtain a reduced standard deviation, the Alaskan and Washington ^{14}C data were averaged after normalizing on Washington State (by reducing the Alaskan results by 14 yr). As noted previously (Stuiver 1993),

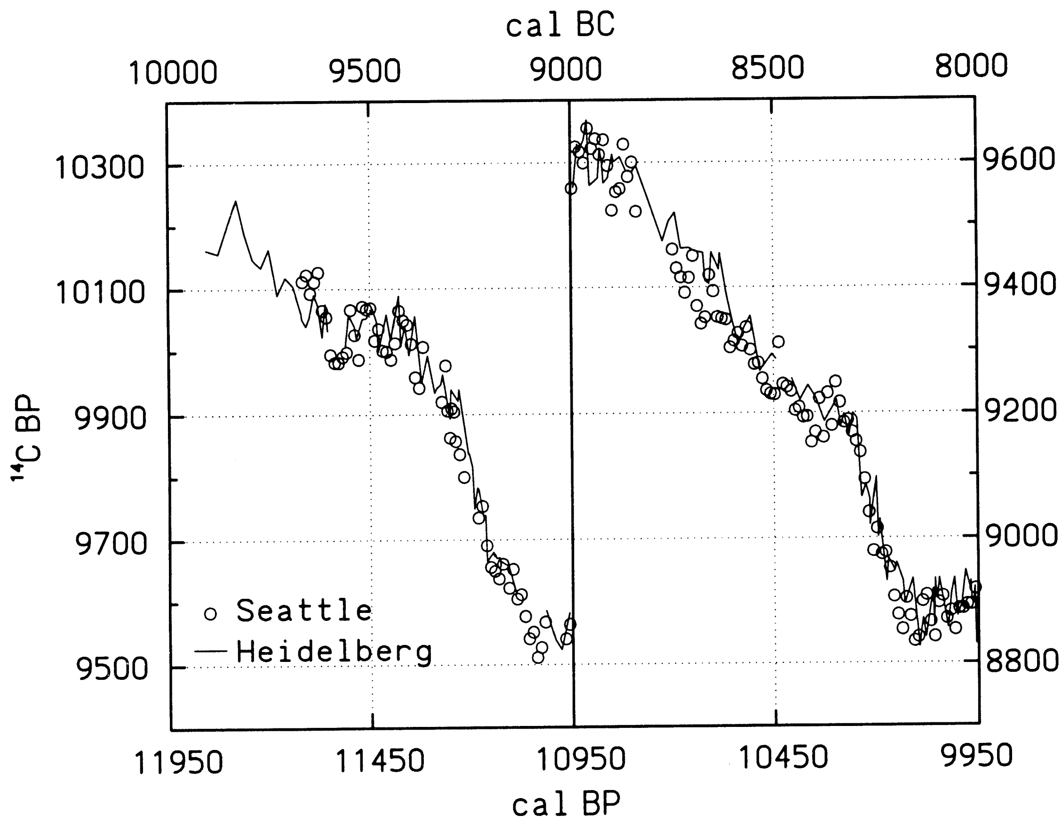

Fig. 1. A comparison of Heidelberg and Seattle German pine measurements. The solid line connects the Heidelberg points; the average standard deviation in a single measurement is 24 and 23 ^{14}C yr for, respectively, Heidelberg and Seattle.

the average standard deviation (for a 1.0 error multiplier) in the single-year calibration curve of 1993 was 12.8 ^{14}C yr. Adding Kodiak Island data reduces the average single-year standard deviation of the cal AD 1884–1932 interval to 10.2 ^{14}C yr.

MARINE ^{14}C AGE CALIBRATION

With INTCAL 98 based on decadal averages, we no longer provide a separate (terrestrial) decadal Seattle curve. A model calculated marine curve, however, is still relevant. Extensive discussion of marine age calibration was presented in Stuiver, Pearson and Braziunas 1986, and Stuiver and Braziunas 1993b.

The 19th century reservoir age $R_g(t)$ (t = time) of the global ocean, relative to the atmosphere, is usually estimated at 400 ^{14}C yr (its value prior to the industrial effect, or *ca.* AD 1850). Marine reservoir age $R_g(t)$ varies over time as a result of geomagnetic and solar-related changes in ^{14}C production rates. $R_g(t)$ calculations suggests changes on the order of ±100 ^{14}C yr for solar-mediated production rate change (Stuiver, Pearson and Braziunas 1986: Fig. 9A; Bard 1988).

The simple box diffusion global carbon cycle model employed here reproduces the expected history of global $R_g(t)$ in response to atmospheric ^{14}C production driven by solar and geomagnetic modulation of the ^{14}C production rate. To determine the variation in ^{14}C production rate required to produce

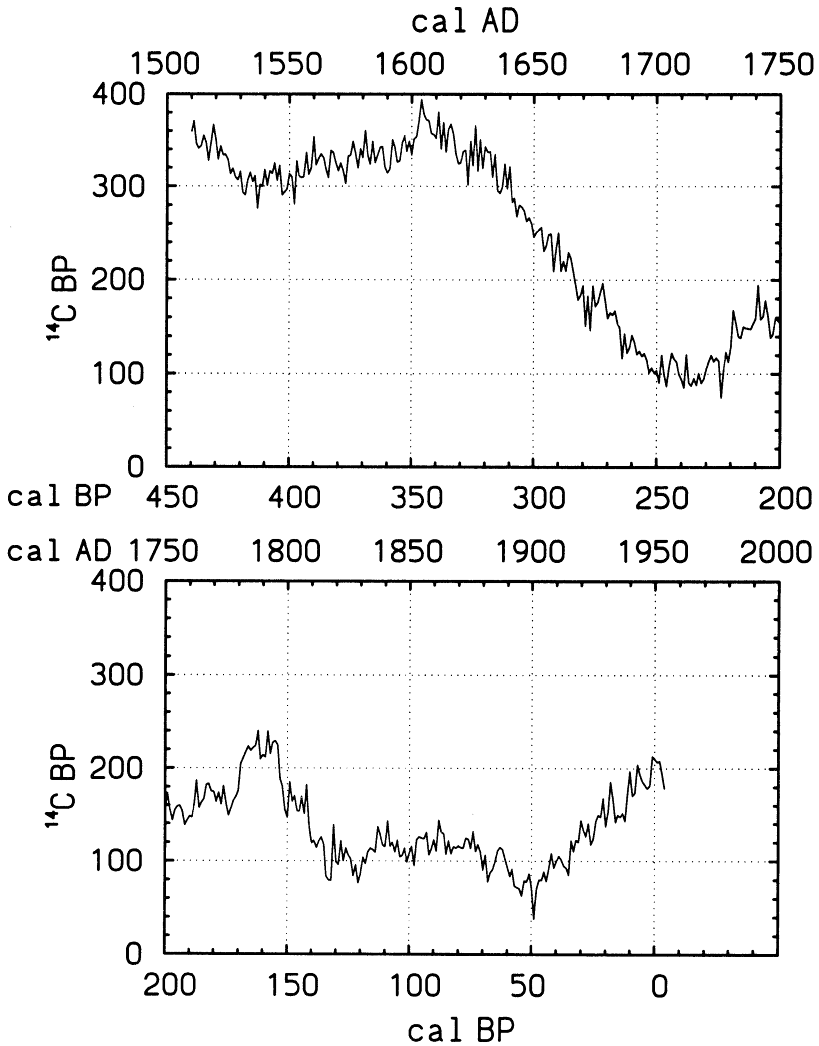

Fig. 2. ^{14}C age *vs.* cal age for single-year samples

the observed atmospheric record the model uses 1) the observed ^{14}C record from tree-rings; 2) a set of simple fixed parameters for ocean circulation, air-sea exchange, and atmosphere/terrestrial biosphere CO_2 fluxes; 3) a reservoir age R_g(AD 1850) = 400 ^{14}C yr; and 4) ^{14}C information derived from corals to fix the initial ^{14}C level at the start of the Holocene. Model parameterization is discussed in Stuiver and Braziunas (1993b: 140).

Ocean circulation may also have affected the ^{14}C partitioning between atmosphere and global ocean, resulting in $R_g(t)$ change. Our $R_g(t)$ model response to oceanic, or production rate, forcing is depicted in Figure 3A. Starting with an approximately 200-yr-long plateau (~9100–8900 cal BC) in atmospheric ^{14}C ages (dashed curve, constructed from a 200-yr moving average) we find substantial oceanic plateau smoothing ("surface ocean - 1" in Fig. 3A) for atmospheric forcing. However, when the ocean forces the atmosphere, both have similar plateau lengths ("surface ocean - 2" in Fig. 3A). Thus the presence or absence of ^{14}C age plateaus in marine sediment chronologies can be tied to the causative factors responsible for atmospheric ^{14}C change.

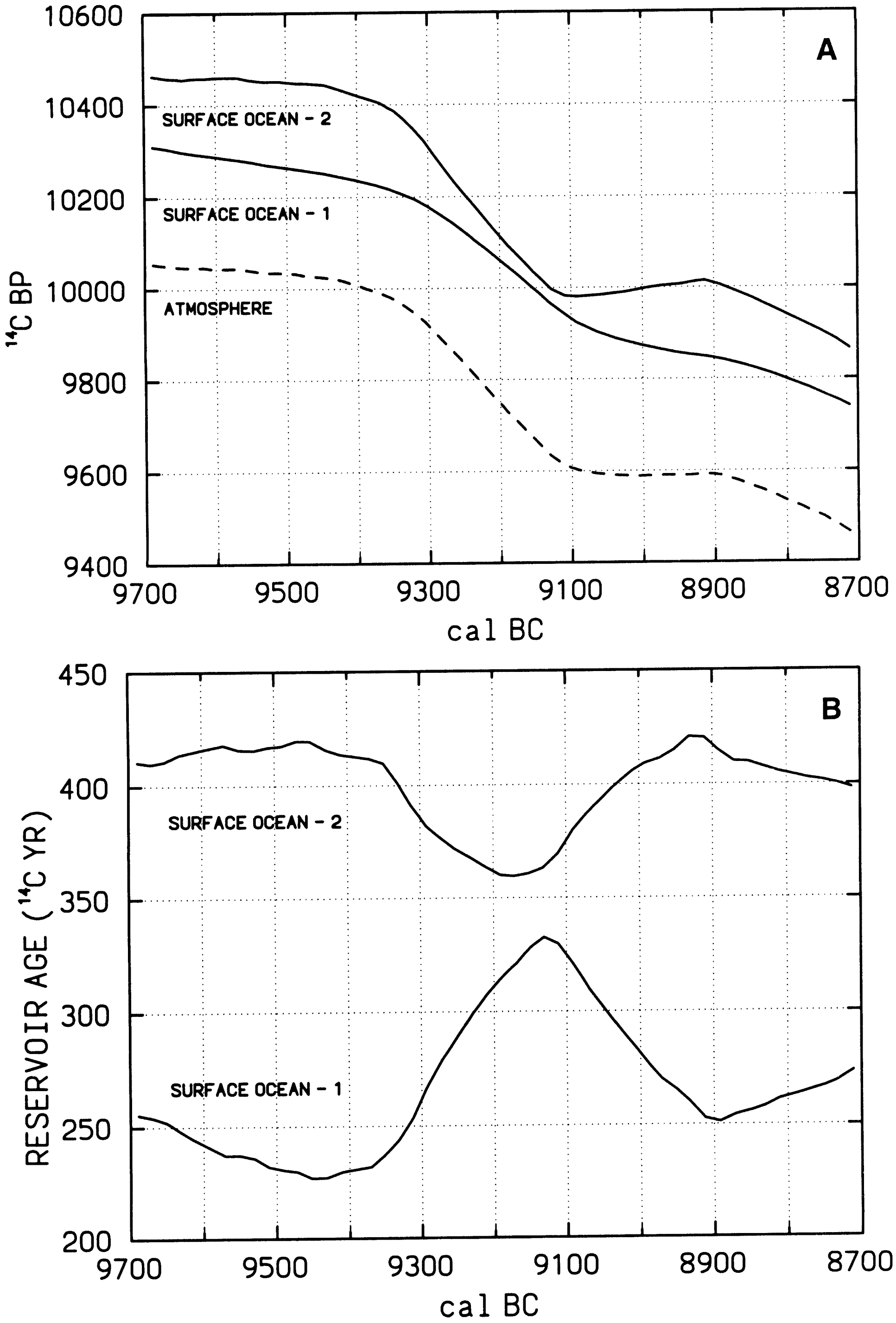

Fig. 3. **A**. Smoothed (200-yr moving average) ^{14}C age profiles for the atmosphere and surface ocean. Curve 1 was calculated from a carbon reservoir model assuming atmospheric ^{14}C production rate change to be responsible for the observed atmospheric ^{14}C change; curve 2 was calculated with ocean circulation change as the causal agent. **B**. Reservoir ages of the model ocean (mixed layer) for ^{14}C age plateaus generated by production rate change (curve 1) or oceanic circulation change (curve 2).

Surface ocean reservoir ages differ substantially between scenarios based on production rate *vs.* oceanic circulation (Fig. 3B). Production-related atmospheric ^{14}C supply to the surface ocean results in concurrent fluxes to the deep ocean, whereas the atmosphere, when forced by the ocean, does not sustain such major losses to other reservoirs. As a result, the change in reservoir age is larger for the production rate scenario. Reservoir age perturbations also are opposite in sign because the ocean lags the atmosphere for the production-rate scenario, whereas the atmosphere lags the ocean for a postulated oceanic increase.

The possibility of oceanic-induced $R_g(t)$ change, on a century time scale, cannot be excluded. But nonhypothetical calculations of oceanic-induced Rg(t) change are not possible because detailed information on century time scale oceanic circulation change is lacking. The simple box-diffusion global carbon cycle calculations used to generate the solid line in Figure 4 assume, of necessity, that Holocene century-scale atmospheric ^{14}C variations are production rate related.

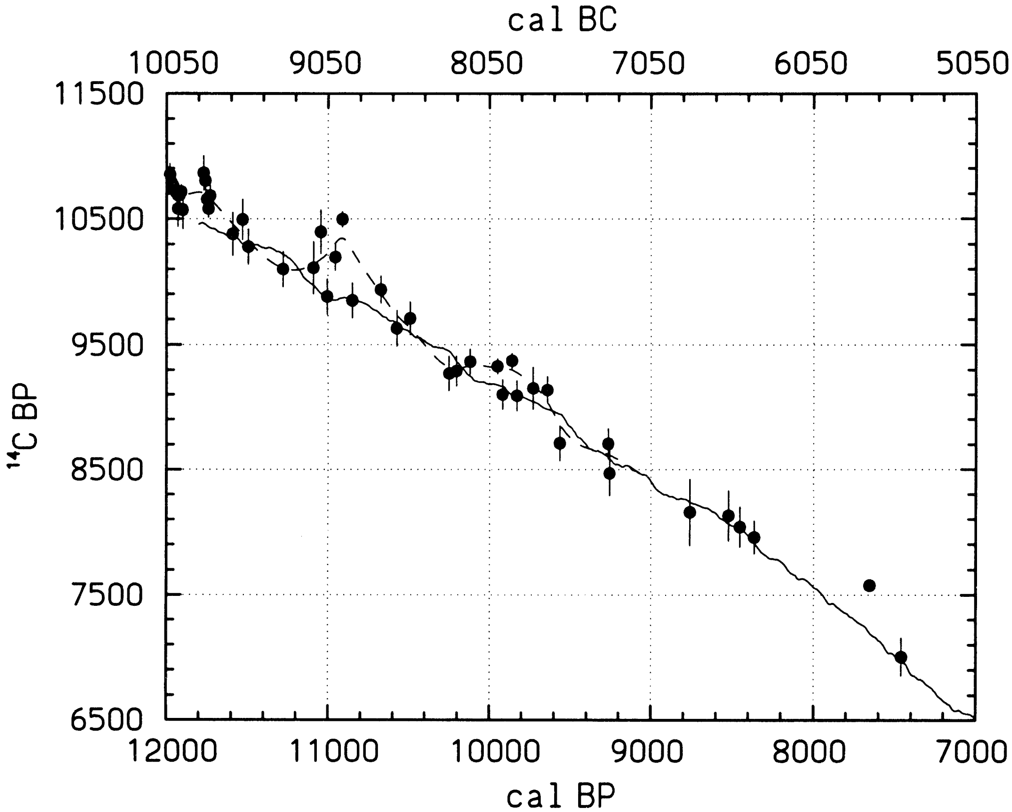

Fig. 4. A comparison of marine ^{14}C ages (solid line) derived from a carbon reservoir model (see text) and coral ^{14}C ages (Bard *et al.* 1998; Burr *et al.* 1998; Edwards *et al.* 1993; Stuiver *et al.* 1998: Fig. 2).

World ocean reservoir ages $R_g(t)$ increase (with a delayed response) when atmospheric ^{14}C increases and, conversely, are reduced when atmospheric ^{14}C levels drop. The reservoir ages $R_g(t)$ calculated for the world ocean are global averages only. Marine reservoir ages (R(t,s), with s = space) of the 19th century differ by up to 1000 ^{14}C yr from one oceanic region to another. The difference between regional reservoir age and the global average, R(t,s) – Rg(t), equals ΔR(s) (as defined in Stuiver and

Braziunas 1993b). Implied in this definition is the notion that the time-dependent changes of the local environment parallel those of the global ocean, thus yielding a time-independent $\Delta R(s)$. Our approach has been to supply a model-derived $R_g(t)$, and estimate $\Delta R(s)$ from the measured reservoir ages of 19th century shells (*e.g.*, $\Delta R(s) = R(\text{AD}1850,s) - R_g(\text{AD}1850)$). The measured ^{14}C age must be reduced by $\Delta R(s)$ when using the model-calculated marine calibration curves. We specifically note that the reservoir age $R(t,s)$ should not be subtracted but only $\Delta R(s)$ ($\Delta R(s) = 0$ when $R(\text{AD}1850,s) = 400$ yr). A short summary of regional ΔR can be found in Stuiver and Braziunas (1993). Recent ΔR determinations (partial list only) are those of Berkman and Forman (1996), Forman and Polyak (1997), Goodfriend and Flessa (1997), Heier-Nielsen *et al.* (1995), Higham and Hogg (1995), Ingram (1998), Ingram and Southon (1997), Kennett *et al.* (1997), Little (1993) and Southon, Rodman and True (1995).

Because the INTCAL98 tree-ring data for the 7000–0 cal BP interval are nearly identical to the data used previously, the 1993 marine calibration curves are still applicable (Stuiver and Braziunas 1993: Figs. 17A–N). Figure 4 compares the marine ^{14}C ages calculated from the INTCAL98 tree-ring record to those measured for INTCAL 98 corals (Bard *et al.* 1998; Burr *et al.* 1998; Edwards *et al.* 1993).

There is evidence for a marine ^{14}C reservoir deficiency change from 400 to 500 ^{14}C yr over the 12,000–10,000 cal BP interval (Stuiver *et al.* 1998: Fig. 2). This change, tied to ocean circulation change, is not simulated in the carbon reservoir model, where the ocean circulation parameters are fixed. This lack of ocean circulation change may have resulted in the slightly younger model-calculated ^{14}C ages of the 12,000–10,000 cal BP interval (Fig. 4).

The number of coral data points between 9500 and 7000 cal BP is limited, but the overall agreement is good for this interval. For the INTCAL 98 marine age calibration curve (see Stuiver *et al.* 1998) we used 1) a spline of coral and marine varve ^{14}C ages between 24,000 and 8800 cal BP and 2) a linear connection of ^{14}C ages derived from the tree-ring record *via* carbon reservoir modeling (8800–0 cal BP).

The latest 1998 version of the CALIB program (Stuiver and Reimer 1993) incorporates the single-year data given here (and also the decadal INTCAL98 data set for marine and terrestrial environments). The data sets can be downloaded from the Quaternary Isotope Laboratory World Wide Web site <http://depts.washington.edu/qil/>.

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APPENDIX: TABLES 1 AND 2

TABLE 1. ^{14}C age determinations made at the University of Washington Quaternary Isotope Lab (Seattle). The cal AD/BC ages (or cal BP) represent midpoints to the nearest year of wood sections (10 yr unless given in parentheses with the cal AD/BC age). Overlapping decadal samples with midpoints less than 1 yr apart were averaged. Single-year data were averaged with decadal data for the AD 1515–1935 interval. Single-year data only were used for the AD 1945 data point. Results of the few 20-yr samples were taken as two decadal samples (*) with the same ^{14}C age and with the standard deviation in the age and $\Delta^{14}C$ (defined in Stuiver and Polach 1977) increased by 1.4 times. No error multiplier has been included in the standard deviations.

TABLE 1. Decadal Measurements

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
AD 1945	−22.8 ± 0.5	190 ± 4	5
AD 1935	−17.4 ± 0.5	156 ± 4	15
AD 1925	−14.0 ± 0.4	138 ± 3	25
AD 1915	−9.2 ± 0.3	108 ± 3	35
AD 1905	−4.2 ± 0.4	78 ± 3	45
AD 1895	−2.8 ± 0.4	76 ± 3	55
AD 1885	−4.5 ± 0.4	100 ± 3	65
AD 1875	−5.2 ± 0.4	115 ± 4	75
AD 1865	−4.2 ± 0.5	117 ± 4	85
AD 1855	−3.5 ± 0.5	120 ± 4	95
AD 1845	−1.6 ± 0.5	115 ± 4	105
AD 1835	−0.5 ± 0.4	116 ± 3	115
AD 1825	2.8 ± 0.4	99 ± 3	125
AD 1815	3.2 ± 0.5	106 ± 4	135
AD 1805	−2.3 ± 0.5	159 ± 4	145
AD 1795	−6.2 ± 0.5	201 ± 4	155
AD 1785	−6.9 ± 0.6	216 ± 5	165
AD 1775	0.4 ± 0.4	167 ± 4	175
AD 1765	1.4 ± 0.5	169 ± 4	185
AD 1755	4.1 ± 0.4	156 ± 3	195
AD 1745	4.6 ± 0.5	163 ± 4	205
AD 1735	7.0 ± 0.5	153 ± 4	215
AD 1725	13.2 ± 0.4	114 ± 3	225
AD 1715	16.8 ± 0.3	95 ± 3	235
AD 1705	16.7 ± 0.3	105 ± 3	245
AD 1695	16.6 ± 0.3	115 ± 2	255
AD 1685	14.9 ± 0.4	139 ± 3	265

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
AD 1675	12.0 ± 0.5	172 ± 4	275
AD 1665	8.5 ± 0.5	209 ± 4	285
AD 1655	5.7 ± 0.5	241 ± 4	295
AD 1645	3.5 ± 0.5	268 ± 4	305
AD 1635	−0.2 ± 0.5	308 ± 4	315
AD 1625	−2.2 ± 0.5	333 ± 4	325
AD 1615	−3.2 ± 0.5	351 ± 4	335
AD 1605	−3.7 ± 0.5	365 ± 4	345
AD 1595	0.7 ± 0.5	340 ± 4	355
AD 1585	2.7 ± 0.5	333 ± 4	365
AD 1575	4.4 ± 0.6	329 ± 5	375
AD 1565	6.0 ± 0.5	326 ± 4	385
AD 1555	8.3 ± 0.6	319 ± 5	395
AD 1545	10.6 ± 0.5	309 ± 4	405
AD 1535	12.8 ± 0.4	301 ± 3	415
AD 1525	11.3 ± 0.5	322 ± 4	425
AD 1515	9.2 ± 0.6	349 ± 5	435
AD 1505	10.5 ± 1.0	349 ± 8	445
AD 1495	11.2 ± 1.3	353 ± 10	455
AD 1485	9.0 ± 1.7	380 ± 13	465
AD 1475	9.0 ± 1.8	390 ± 14	475
AD 1465	9.6 ± 1.8	395 ± 14	485
AD 1455	11.5 ± 1.2	390 ± 10	495
AD 1445	9.2 ± 1.5	418 ± 12	505
AD 1435	4.1 ± 1.8	468 ± 14	515
AD 1425	1.4 ± 1.7	500 ± 13	525
AD 1415	0.0 ± 1.7	520 ± 14	535

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
AD 1405	−4.3 ± 1.6	565 ± 13	545
AD 1395	−4.3 ± 1.8	575 ± 14	555
AD 1385	−10.3 ± 1.3	633 ± 11	565
AD 1375	−11.6 ± 1.4	653 ± 11	575
AD 1365	−4.4 ± 1.3	604 ± 11	585
AD 1355	−4.8 ± 1.4	617 ± 12	595
AD 1345	0.8 ± 1.4	582 ± 12	605
AD 1335	4.7 ± 1.2	560 ± 10	615
AD 1325	−0.6 ± 1.3	613 ± 11	625
AD 1315	−0.8 ± 1.2	625 ± 10	635
AD 1305	0.0 ± 1.0	627 ± 8	645
AD 1295	−3.0 ± 1.8	661 ± 15	655
AD 1285	−8.2 ± 1.7	713 ± 14	665
AD 1275	−13.7 ± 1.8	767 ± 15	675
AD 1265	−11.0 ± 1.8	755 ± 15	685
AD 1255	−16.7 ± 1.7	811 ± 14	695
AD 1245	−14.6 ± 1.8	803 ± 14	705
AD 1235	−13.4 ± 1.8	804 ± 14	715
AD 1225	−11.1 ± 1.2	795 ± 10	725
AD 1215	−14.5 ± 1.7	832 ± 14	735
AD 1205	−17.6 ± 1.7	867 ± 14	745
AD 1195	−15.2 ± 1.7	857 ± 14	755
AD 1185	−17.7 ± 1.6	887 ± 13	765
AD 1175	−15.7 ± 1.7	881 ± 14	775
AD 1165	−11.6 ± 1.2	857 ± 10	785
AD 1155	−16.5 ± 1.8	907 ± 15	795
AD 1145	−22.7 ± 1.2	967 ± 10	805
AD 1136	−12.9 ± 1.8	896 ± 15	814
AD 1135	−14.7 ± 2.0	911 ± 17	815
AD 1125	−13.9 ± 1.8	915 ± 15	825
AD 1116	−17.4 ± 1.8	952 ± 15	834
AD 1115	−15.5 ± 1.9	937 ± 16	835
AD 1106	−15.1 ± 1.7	943 ± 14	844
AD 1105	−15.8 ± 1.7	949 ± 14	845
AD 1096	−13.8 ± 1.9	942 ± 15	854
AD 1095	−13.4 ± 1.8	940 ± 15	855
AD 1086	−9.9 ± 1.8	920 ± 14	864
AD 1085	−9.2 ± 1.1	916 ± 9	865
AD 1076	−7.0 ± 1.1	907 ± 9	874
AD 1075	−5.7 ± 1.8	897 ± 15	875
AD 1066	−8.4 ± 1.4	928 ± 11	884
AD 1065	−6.7 ± 1.7	915 ± 14	885
AD 1056	−6.0 ± 1.4	918 ± 12	894
AD 1055	−8.2 ± 1.8	936 ± 15	895
AD 1046	−6.4 ± 1.8	931 ± 15	904
AD 1045	−4.7 ± 1.8	918 ± 14	905
AD 1036	−6.6 ± 1.7	942 ± 14	914
AD 1035	−8.2 ± 1.8	956 ± 15	915
AD 1025	−9.3 ± 1.8	974 ± 14	925
AD 1015	−14.8 ± 1.8	1029 ± 15	935
AD 1005	−10.3 ± 1.8	1002 ± 15	945
AD 995	−14.7 ± 1.6	1047 ± 13	955
AD 985	−15.8 ± 1.6	1066 ± 13	965
AD 975	−21.5 ± 1.8	1123 ± 15	975
AD 965	−19.5 ± 1.8	1116 ± 15	985
AD 955	−18.9 ± 1.9	1121 ± 16	995
AD 945	−17.5 ± 1.9	1119 ± 15	1005
AD 935	−19.7 ± 1.6	1147 ± 13	1015
AD 925	−18.1 ± 1.5	1143 ± 12	1025
AD 915	−10.9 ± 1.3	1094 ± 11	1035

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
AD 905	−9.4 ± 1.3	1091 ± 11	1045
AD 895	−14.5 ± 1.5	1143 ± 13	1055
AD 885	−16.3 ± 1.6	1167 ± 13	1065
AD 875	−17.3 ± 1.4	1186 ± 12	1075
AD 865	−17.1 ± 1.5	1194 ± 12	1085
AD 855	−16.9 ± 1.1	1201 ± 10	1095
AD 845	−15.5 ± 1.4	1200 ± 12	1105
AD 835	−12.2 ± 1.4	1183 ± 12	1115
AD 825	−12.8 ± 1.4	1197 ± 12	1125
AD 815	−10.6 ± 1.5	1189 ± 12	1135
AD 805	−10.3 ± 1.6	1197 ± 13	1145
AD 795	−11.2 ± 0.9	1213 ± 8	1155
AD 785	−4.4 ± 1.2	1168 ± 10	1165
AD 775	−12.9 ± 1.3	1247 ± 11	1175
AD 765	−16.0 ± 1.3	1282 ± 10	1185
AD 755	−16.5 ± 1.0	1296 ± 8	1195
AD 745	−11.4 ± 1.3	1263 ± 11	1205
AD 735	−8.2 ± 1.2	1248 ± 10	1215
AD 725	−7.8 ± 1.6	1254 ± 13	1225
AD 715	−9.0 ± 1.7	1273 ± 13	1235
AD 705	−10.4 ± 1.8	1294 ± 15	1245
AD 695	−5.2 ± 2.0	1262 ± 16	1255
AD 685	−12.5 ± 2.2	1331 ± 18	1265
AD 675	−10.5 ± 2.1	1324 ± 17	1275
AD 665	−11.5 ± 2.1	1342 ± 17	1285
AD 655	−13.9 ± 1.9	1371 ± 16	1295
AD 645	−15.9 ± 2.1	1397 ± 17	1305
AD 635	−22.4 ± 1.4	1460 ± 12	1315
AD 625	−19.2 ± 1.9	1444 ± 16	1325
AD 615	−17.8 ± 3.9	1442 ± 32	1335
AD 605	−17.8 ± 1.8	1452 ± 15	1345
AD 595	−21.2 ± 2.0	1489 ± 17	1355
AD 585	−18.3 ± 1.9	1475 ± 16	1365
AD 575	−19.7 ± 2.1	1497 ± 17	1375
AD 565	−17.8 ± 2.0	1491 ± 16	1385
AD 555	−18.8 ± 2.0	1509 ± 17	1395
AD 545	−16.3 ± 1.4	1497 ± 11	1405
AD 535	−22.6 ± 2.0	1559 ± 16	1415
AD 525	−25.3 ± 1.2	1591 ± 10	1425
AD 515	−21.9 ± 1.7	1573 ± 14	1435
AD 505	−21.5 ± 1.8	1580 ± 15	1445
AD 495	−18.1 ± 1.6	1561 ± 13	1455
AD 485	−16.9 ± 2.0	1561 ± 17	1465
AD 475	−15.5 ± 1.9	1560 ± 15	1475
AD 465	−16.6 ± 2.0	1578 ± 17	1485
AD 455	−15.6 ± 2.0	1580 ± 17	1495
AD 445	−11.5 ± 2.0	1556 ± 16	1505
AD 435	−10.8 ± 2.0	1560 ± 16	1515
AD 425	−16.8 ± 1.5	1618 ± 13	1525
AD 415	−18.1 ± 2.0	1639 ± 16	1535
AD 405	−20.2 ± 1.8	1666 ± 15	1545
AD 395	−19.0 ± 1.5	1666 ± 13	1555
AD 385	−19.7 ± 1.4	1681 ± 11	1565
AD 375	−22.0 ± 1.1	1710 ± 9	1575
AD 365	−16.5 ± 1.8	1675 ± 15	1585
AD 355	−18.4 ± 2.0	1699 ± 17	1595
AD 345	−17.0 ± 1.8	1698 ± 15	1605
AD 335	−19.6 ± 2.0	1729 ± 16	1615
AD 325	−17.6 ± 2.0	1723 ± 17	1625
AD 315	−22.9 ± 2.0	1775 ± 16	1635

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	Δ^{14}C (‰)	^{14}C BP	cal BP
AD 305	−21.4 ± 1.9	1773 ± 16	1645
AD 295	−14.5 ± 1.9	1726 ± 15	1655
AD 285	−17.7 ± 1.9	1762 ± 16	1665
AD 275	−10.5 ± 1.9	1713 ± 15	1675
AD 265	−8.1 ± 1.4	1703 ± 11	1685
AD 255	−15.3 ± 1.1	1773 ± 9	1695
AD 245	−14.5 ± 1.0	1774 ± 9	1705
AD 235	−18.0 ± 1.4	1813 ± 12	1715
AD 225	−17.6 ± 2.0	1819 ± 17	1725
AD 215	−18.1 ± 2.0	1834 ± 17	1735
AD 205	−19.0 ± 1.4	1852 ± 12	1745
AD 195	−14.1 ± 2.0	1820 ± 17	1755
AD 185	−11.4 ± 1.8	1808 ± 15	1765
AD 175	−13.0 ± 2.0	1831 ± 16	1775
AD 165	−13.1 ± 2.2	1841 ± 18	1785
AD 155	−11.9 ± 1.9	1841 ± 15	1795
AD 145	−10.2 ± 2.0	1837 ± 17	1805
AD 135	−8.6 ± 1.3	1833 ± 11	1815
AD 125	−15.7 ± 1.1	1901 ± 9	1825
AD 115	−14.6 ± 2.2	1902 ± 18	1835
AD 105	−13.4 ± 2.1	1902 ± 17	1845
AD 95	−8.9 ± 1.2	1874 ± 10	1855
AD 85	−9.3 ± 2.0	1888 ± 16	1865
AD 75	−11.4 ± 1.4	1915 ± 11	1875
AD 65	−12.9 ± 1.4	1936 ± 11	1885
AD 55	−13.4 ± 1.2	1951 ± 9	1895
AD 45	−16.8 ± 1.0	1988 ± 8	1905
AD 35	−9.8 ± 1.5	1940 ± 13	1915
AD 25	−13.9 ± 1.4	1983 ± 11	1925
AD 15	−14.6 ± 1.1	2000 ± 9	1935
AD 5	−11.3 ± 1.0	1982 ± 8	1945
5 BC	−18.0 ± 1.4	2046 ± 12	1954
6 BC	−18.3 ± 2.0	2049 ± 16	1955
15 BC	−11.1 ± 1.2	1999 ± 10	1964
16 BC	−11.5 ± 2.0	2003 ± 16	1965
25 BC	−12.7 ± 2.0	2022 ± 16	1974
26 BC	−14.2 ± 1.8	2035 ± 15	1975
35 BC	−10.4 ± 1.1	2012 ± 10	1984
36 BC	−8.7 ± 1.0	2000 ± 8	1985
45 BC	−14.6 ± 1.2	2056 ± 10	1994
46 BC	−9.9 ± 2.0	2019 ± 16	1995
55 BC	−13.7 ± 1.3	2057 ± 11	2004
56 BC	−17.3 ± 1.3	2089 ± 11	2005
65 BC	−15.7 ± 1.4	2085 ± 12	2014
66 BC	−16.0 ± 1.8	2088 ± 15	2015
75 BC	−14.5 ± 2.0	2085 ± 17	2024
76 BC	−13.1 ± 2.0	2075 ± 17	2025
85 BC	−8.9 ± 1.4	2049 ± 11	2034
86 BC	−13.1 ± 2.0	2084 ± 16	2035
95 BC	−13.5 ± 1.9	2096 ± 15	2044
96 BC	−12.6 ± 2.0	2090 ± 16	2045
105 BC	−8.6 ± 2.0	2066 ± 16	2054
106 BC	−12.3 ± 1.6	2097 ± 13	2055
115 BC	−8.2 ± 2.0	2073 ± 17	2064
116 BC	−13.0 ± 1.5	2113 ± 12	2065
125 BC	−10.1 ± 2.1	2097 ± 17	2074
126 BC	−13.8 ± 1.5	2129 ± 12	2075
135 BC	−7.1 ± 2.1	2083 ± 17	2084
136 BC	−9.4 ± 2.0	2102 ± 16	2085
145 BC	−5.6 ± 1.6	2080 ± 13	2094

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	Δ^{14}C (‰)	^{14}C BP	cal BP
146 BC	−9.6 ± 1.9	2114 ± 16	2095
156 BC	−5.4 ± 2.1	2090 ± 17	2105
166 BC	−6.0 ± 1.3	2104 ± 11	2115
176 BC	−11.8 ± 2.1	2161 ± 17	2125
186 BC	−10.4 ± 2.0	2159 ± 17	2135
196 BC	−5.4 ± 1.4	2128 ± 11	2145
206 BC	−10.2 ± 1.9	2177 ± 15	2155
216 BC	−15.4 ± 1.1	2229 ± 9	2165
226 BC	−7.8 ± 1.5	2177 ± 12	2175
236 BC	−14.7 ± 1.2	2243 ± 9	2185
246 BC	−12.3 ± 1.5	2233 ± 12	2195
256 BC	−9.3 ± 2.0	2218 ± 16	2205
266 BC	−13.6 ± 1.9	2263 ± 16	2215
276 BC	−7.7 ± 1.4	2225 ± 11	2225
286 BC	−8.6 ± 1.8	2242 ± 15	2235
296 BC	−3.9 ± 1.4	2212 ± 11	2245
306 BC	−0.1 ± 1.9	2192 ± 16	2255
316 BC	0.2 ± 1.9	2200 ± 16	2265
326 BC	5.2 ± 1.4	2169 ± 11	2275
336 BC	7.3 ± 1.9	2162 ± 16	2285
346 BC	6.9 ± 1.4	2176 ± 11	2295
356 BC	1.4 ± 1.4	2229 ± 11	2305
366 BC	−1.8 ± 1.4	2265 ± 11	2315
376 BC	0.1 ± 1.4	2260 ± 11	2325
386 BC	−1.0 ± 2.0	2278 ± 16	2335
396 BC	−5.7 ± 1.4	2324 ± 12	2345
406 BC	−10.8 ± 1.1	2377 ± 9	2355
416 BC	−16.8 ± 2.0	2434 ± 16	2365
426 BC	−13.6 ± 2.1	2418 ± 17	2375
436 BC	−16.5 ± 2.0	2452 ± 16	2385
446 BC	−15.7 ± 3.3	2455 ± 27	2395
456 BC	−19.1 ± 2.3	2493 ± 18	2405
466 BC	−11.8 ± 2.5	2443 ± 20	2415
476 BC	−6.1 ± 1.4	2406 ± 12	2425
486 BC	−8.5 ± 2.0	2435 ± 17	2435
496 BC	−6.3 ± 1.5	2428 ± 12	2445
506 BC	−5.7 ± 2.0	2432 ± 17	2455
516 BC	−4.7 ± 1.6	2433 ± 12	2465
526 BC	−8.6 ± 1.7	2475 ± 13	2475
536 BC	−2.5 ± 1.3	2436 ± 11	2485
546 BC	−6.7 ± 1.5	2479 ± 12	2495
556 BC	−5.9 ± 1.8	2482 ± 14	2505
566 BC	−5.8 ± 2.3	2491 ± 18	2515
576 BC	−4.3 ± 2.2	2489 ± 18	2525
586 BC	1.0 ± 2.2	2456 ± 18	2535
596 BC	−4.9 ± 1.7	2513 ± 14	2545
606 BC	−3.9 ± 1.8	2515 ± 15	2555
607 BC	−1.8 ± 2.1	2499 ± 17	2556
616 BC	0.1 ± 1.6	2492 ± 13	2565
617 BC	1.6 ± 1.5	2482 ± 12	2566
626 BC	−0.8 ± 1.7	2509 ± 14	2575
627 BC*	4.6 ± 2.9	2467 ± 23	2576
636 BC	2.9 ± 2.1	2489 ± 17	2585
637 BC*	5.8 ± 2.9	2467 ± 23	2586
646 BC	4.9 ± 2.0	2483 ± 16	2595
647 BC	6.3 ± 2.1	2472 ± 17	2596
656 BC	7.0 ± 1.4	2475 ± 11	2605
657 BC*	13.0 ± 2.8	2429 ± 22	2606
667 BC	14.2 ± 2.8	2429 ± 22	2616
697 BC	14.7 ± 3.3	2455 ± 26	2646

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
707 BC	15.5 ± 3.4	2458 ± 27	2656
717 BC	15.9 ± 3.4	2464 ± 27	2666
727 BC*	19.6 ± 2.0	2445 ± 16	2676
737 BC*	20.8 ± 2.0	2445 ± 16	2686
747 BC*	21.3 ± 3.0	2451 ± 23	2696
757 BC*	22.5 ± 3.0	2451 ± 23	2706
767 BC*	11.3 ± 2.8	2550 ± 22	2716
777 BC*	12.5 ± 2.8	2550 ± 22	2726
787 BC	14.0 ± 1.6	2548 ± 12	2736
797 BC	7.6 ± 1.5	2608 ± 12	2746
807 BC	4.0 ± 1.6	2647 ± 13	2756
817 BC	2.2 ± 2.1	2670 ± 17	2766
827 BC	3.1 ± 1.6	2673 ± 13	2776
837 BC	−3.6 ± 1.6	2737 ± 13	2786
847 BC	−3.9 ± 1.6	2749 ± 13	2796
857 BC	−2.6 ± 2.1	2748 ± 17	2806
867 BC	−0.3 ± 2.0	2740 ± 16	2816
877 BC	1.1 ± 2.1	2738 ± 17	2826
887 BC	6.0 ± 2.1	2708 ± 17	2836
897 BC	3.2 ± 2.1	2741 ± 17	2846
907 BC	−0.3 ± 2.0	2778 ± 16	2856
917 BC	0.6 ± 2.1	2781 ± 17	2866
927 BC	0.5 ± 2.1	2791 ± 17	2876
937 BC	0.2 ± 1.6	2804 ± 13	2886
947 BC	−1.6 ± 1.5	2827 ± 12	2896
957 BC	0.1 ± 1.7	2824 ± 13	2906
967 BC	9.2 ± 2.1	2761 ± 17	2916
977 BC	0.0 ± 1.5	2844 ± 12	2926
987 BC	2.5 ± 2.0	2834 ± 16	2936
997 BC	5.6 ± 2.0	2818 ± 16	2946
1007 BC	4.7 ± 2.1	2836 ± 17	2956
1017 BC	1.4 ± 2.0	2871 ± 16	2966
1027 BC	0.4 ± 2.2	2889 ± 18	2976
1037 BC	2.8 ± 2.1	2880 ± 17	2986
1047 BC	7.7 ± 2.2	2850 ± 17	2996
1057 BC	−0.5 ± 2.0	2926 ± 16	3006
1067 BC	7.0 ± 2.3	2876 ± 18	3016
1077 BC	6.5 ± 2.2	2889 ± 18	3026
1087 BC	4.5 ± 2.2	2915 ± 18	3036
1097 BC	5.1 ± 1.4	2919 ± 12	3046
1107 BC	7.6 ± 1.5	2909 ± 12	3056
1117 BC	2.0 ± 2.4	2964 ± 19	3066
1127 BC	10.1 ± 2.1	2909 ± 17	3076
1137 BC	−0.3 ± 1.4	3002 ± 11	3086
1147 BC	11.8 ± 2.1	2915 ± 17	3096
1157 BC	8.9 ± 2.2	2947 ± 17	3106
1167 BC	10.3 ± 2.1	2946 ± 17	3116
1177 BC	11.2 ± 2.6	2949 ± 21	3126
1187 BC	18.5 ± 2.2	2901 ± 17	3136
1197 BC	6.6 ± 2.0	3005 ± 16	3146
1207 BC	18.7 ± 2.2	2918 ± 18	3156
1217 BC	10.4 ± 1.2	2992 ± 9	3166
1227 BC	10.6 ± 2.1	3002 ± 17	3176
1237 BC	16.5 ± 2.3	2965 ± 18	3186
1247 BC	14.5 ± 2.2	2990 ± 17	3196
1257 BC	16.4 ± 1.7	2985 ± 14	3206
1267 BC	11.0 ± 2.2	3038 ± 18	3216
1277 BC	13.0 ± 2.1	3032 ± 17	3226
1287 BC	18.9 ± 2.2	2994 ± 18	3236
1297 BC	15.1 ± 2.2	3035 ± 17	3246

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1307 BC	17.3 ± 2.3	3027 ± 18	3256
1317 BC	16.8 ± 2.2	3040 ± 18	3266
1327 BC	10.2 ± 1.9	3102 ± 15	3276
1337 BC	17.0 ± 2.2	3059 ± 17	3286
1347 BC	20.2 ± 2.2	3043 ± 18	3296
1357 BC	17.8 ± 2.2	3071 ± 17	3306
1367 BC	24.2 ± 2.1	3030 ± 16	3316
1377 BC	18.3 ± 2.0	3087 ± 16	3326
1387 BC	19.0 ± 2.1	3091 ± 16	3336
1397 BC	16.9 ± 1.5	3117 ± 12	3346
1407 BC	20.4 ± 2.0	3099 ± 16	3356
1417 BC	12.9 ± 2.0	3168 ± 16	3366
1427 BC	20.4 ± 2.2	3118 ± 17	3376
1437 BC	14.3 ± 1.5	3177 ± 12	3386
1447 BC	15.6 ± 1.5	3177 ± 12	3396
1457 BC	13.8 ± 1.4	3203 ± 11	3406
1467 BC	12.5 ± 1.5	3222 ± 12	3416
1477 BC	14.6 ± 1.5	3213 ± 12	3426
1487 BC	19.4 ± 1.7	3185 ± 13	3436
1497 BC	14.8 ± 2.3	3231 ± 18	3446
1507 BC	13.9 ± 2.0	3248 ± 16	3456
1517 BC	14.7 ± 2.2	3251 ± 17	3466
1527 BC	13.2 ± 2.0	3273 ± 16	3476
1537 BC	10.0 ± 2.1	3308 ± 17	3486
1547 BC	11.7 ± 2.2	3304 ± 17	3496
1557 BC	12.9 ± 2.1	3304 ± 17	3506
1567 BC	12.9 ± 3.6	3314 ± 29	3516
1577 BC	17.3 ± 3.6	3289 ± 29	3526
1587 BC	16.9 ± 2.2	3302 ± 18	3536
1597 BC	21.4 ± 1.7	3276 ± 14	3546
1607 BC	16.4 ± 1.6	3326 ± 13	3556
1617 BC	17.5 ± 1.7	3327 ± 14	3566
1627 BC	15.7 ± 1.7	3350 ± 13	3576
1637 BC	16.3 ± 2.2	3355 ± 18	3586
1647 BC	13.5 ± 1.3	3387 ± 10	3596
1657 BC	20.1 ± 1.7	3344 ± 13	3606
1667 BC	13.5 ± 2.3	3406 ± 18	3616
1677 BC	25.8 ± 2.2	3320 ± 17	3626
1687 BC	21.9 ± 2.2	3360 ± 17	3636
1697 BC	13.7 ± 1.5	3434 ± 12	3646
1707 BC	15.9 ± 2.2	3427 ± 18	3656
1717 BC	20.8 ± 2.2	3398 ± 17	3666
1727 BC	20.8 ± 2.2	3407 ± 17	3676
1737 BC	19.1 ± 2.2	3430 ± 17	3686
1747 BC	15.4 ± 2.2	3469 ± 18	3696
1757 BC	14.6 ± 1.6	3485 ± 13	3706
1767 BC	19.1 ± 1.7	3459 ± 14	3716
1777 BC	15.4 ± 1.7	3498 ± 13	3726
1787 BC	14.7 ± 1.5	3515 ± 12	3736
1797 BC	17.4 ± 1.5	3501 ± 12	3746
1807 BC	21.9 ± 1.5	3478 ± 12	3756
1817 BC	19.0 ± 1.5	3509 ± 12	3766
1827 BC	22.5 ± 2.2	3491 ± 18	3776
1837 BC	15.9 ± 2.1	3553 ± 17	3786
1847 BC	25.5 ± 2.2	3487 ± 18	3796
1857 BC	27.5 ± 2.2	3481 ± 18	3806
1867 BC	26.2 ± 2.2	3501 ± 18	3816
1877 BC	27.1 ± 1.6	3503 ± 12	3826
1887 BC	21.4 ± 2.1	3558 ± 17	3836
1897 BC	19.9 ± 2.2	3580 ± 18	3846

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1907 BC	24.2 ± 2.2	3555 ± 17	3856
1917 BC	25.2 ± 2.2	3557 ± 17	3866
1927 BC	21.1 ± 1.7	3599 ± 14	3876
1937 BC	22.9 ± 2.0	3595 ± 16	3886
1947 BC	22.4 ± 2.3	3609 ± 18	3896
1957 BC	23.2 ± 2.2	3612 ± 18	3906
1967 BC	23.5 ± 2.2	3619 ± 18	3916
1977 BC	22.3 ± 2.2	3638 ± 17	3926
1987 BC	19.5 ± 2.2	3670 ± 17	3936
1997 BC	28.8 ± 2.2	3607 ± 17	3946
2007 BC	32.1 ± 2.3	3591 ± 18	3956
2017 BC	26.4 ± 2.2	3645 ± 17	3966
2027 BC	28.8 ± 2.2	3636 ± 17	3976
2037 BC	24.3 ± 1.4	3681 ± 11	3986
2047 BC	22.6 ± 1.6	3704 ± 12	3996
2057 BC	22.1 ± 1.6	3717 ± 13	4006
2067 BC	28.4 ± 2.2	3678 ± 17	4016
2077 BC	21.5 ± 1.6	3742 ± 12	4026
2087 BC	32.4 ± 2.2	3666 ± 17	4036
2097 BC	30.2 ± 2.2	3693 ± 17	4046
2107 BC	35.2 ± 1.6	3664 ± 12	4056
2117 BC	32.2 ± 2.2	3697 ± 17	4066
2127 BC	35.1 ± 2.2	3684 ± 17	4076
2137 BC	32.2 ± 2.2	3716 ± 17	4086
2147 BC	27.5 ± 1.4	3762 ± 11	4096
2157 BC	29.6 ± 1.4	3756 ± 11	4106
2167 BC	32.6 ± 2.3	3743 ± 18	4116
2177 BC	34.7 ± 1.5	3736 ± 12	4126
2187 BC	36.6 ± 1.3	3730 ± 10	4136
2197 BC	36.0 ± 1.3	3745 ± 10	4146
2207 BC	30.2 ± 1.9	3800 ± 15	4156
2217 BC	30.2 ± 1.6	3811 ± 12	4166
2227 BC	34.3 ± 1.3	3787 ± 11	4176
2237 BC	28.9 ± 2.5	3839 ± 19	4186
2247 BC	31.3 ± 1.7	3830 ± 13	4196
2257 BC	37.2 ± 1.6	3793 ± 12	4206
2267 BC	40.0 ± 2.2	3782 ± 17	4216
2277 BC	36.4 ± 2.7	3820 ± 21	4226
2287 BC	37.7 ± 1.9	3820 ± 15	4236
2297 BC	34.7 ± 1.7	3852 ± 13	4246
2307 BC	38.4 ± 2.5	3833 ± 19	4256
2317 BC	35.7 ± 2.3	3865 ± 18	4266
2327 BC	39.3 ± 1.6	3846 ± 12	4276
2337 BC	38.9 ± 2.3	3859 ± 17	4286
2347 BC	38.0 ± 1.6	3876 ± 13	4296
2357 BC	36.5 ± 2.3	3897 ± 18	4306
2367 BC	37.5 ± 1.6	3899 ± 13	4316
2377 BC	39.1 ± 2.3	3896 ± 18	4326
2387 BC	44.8 ± 1.7	3864 ± 13	4336
2397 BC	50.1 ± 2.5	3832 ± 20	4346
2407 BC	42.4 ± 1.7	3900 ± 13	4356
2417 BC	41.8 ± 1.8	3914 ± 14	4366
2427 BC	47.3 ± 2.2	3882 ± 17	4376
2437 BC	46.3 ± 1.2	3900 ± 9	4386
2447 BC	48.4 ± 2.4	3893 ± 18	4396
2467 BC	47.9 ± 2.3	3916 ± 18	4416
2477 BC	37.2 ± 1.6	4009 ± 13	4426
2487 BC	41.2 ± 1.7	3987 ± 13	4436
2497 BC	35.8 ± 2.4	4039 ± 19	4446
2507 BC	33.3 ± 1.7	4067 ± 13	4456
2517 BC	40.9 ± 1.7	4018 ± 13	4466
2527 BC	44.6 ± 1.2	4000 ± 9	4476
2537 BC	48.1 ± 1.6	3983 ± 12	4486
2547 BC	48.6 ± 1.6	3988 ± 12	4496
2557 BC	47.9 ± 1.5	4003 ± 12	4506
2567 BC	46.4 ± 1.4	4024 ± 11	4516
2577 BC	43.9 ± 1.7	4053 ± 13	4526
2587 BC	40.8 ± 1.4	4088 ± 11	4536
2597 BC	47.1 ± 1.6	4049 ± 12	4546
2607 BC	40.3 ± 2.4	4110 ± 19	4556
2617 BC	49.8 ± 1.6	4047 ± 12	4566
2627 BC	45.5 ± 1.7	4089 ± 13	4576
2637 BC	44.3 ± 1.4	4108 ± 11	4586
2647 BC	39.1 ± 2.3	4159 ± 18	4596
2655 BC	50.6 ± 2.4	4078 ± 18	4604
2665 BC	49.9 ± 1.6	4093 ± 12	4614
2675 BC	47.8 ± 1.6	4119 ± 12	4624
2685 BC	48.7 ± 1.6	4122 ± 12	4634
2695 BC	48.2 ± 2.4	4136 ± 18	4644
2705 BC	47.5 ± 1.3	4150 ± 10	4654
2715 BC	45.4 ± 2.4	4177 ± 19	4664
2725 BC	51.9 ± 2.4	4137 ± 19	4674
2735 BC	49.9 ± 2.0	4161 ± 15	4684
2745 BC	54.1 ± 2.4	4139 ± 18	4694
2755 BC	54.5 ± 2.4	4145 ± 18	4704
2765 BC	47.4 ± 2.6	4210 ± 20	4714
2775 BC	54.4 ± 2.1	4166 ± 16	4724
2785 BC	57.4 ± 1.7	4153 ± 13	4734
2795 BC	55.6 ± 1.7	4176 ± 13	4744
2805 BC	53.7 ± 2.3	4201 ± 17	4754
2815 BC	66.5 ± 1.7	4114 ± 13	4764
2825 BC	72.3 ± 2.6	4079 ± 19	4774
2835 BC	67.6 ± 2.3	4124 ± 17	4784
2845 BC	65.1 ± 2.2	4153 ± 17	4794
2855 BC	66.7 ± 2.3	4151 ± 18	4804
2865 BC	66.3 ± 2.2	4163 ± 16	4814
2875 BC	65.1 ± 1.6	4182 ± 12	4824
2885 BC	61.3 ± 2.3	4220 ± 17	4834
2895 BC	55.1 ± 2.3	4277 ± 18	4844
2905 BC	54.5 ± 2.3	4292 ± 18	4854
2915 BC	53.4 ± 2.2	4310 ± 17	4864
2925 BC	47.9 ± 2.3	4361 ± 18	4874
2935 BC	46.9 ± 2.6	4379 ± 20	4884
2945 BC	45.3 ± 2.2	4401 ± 17	4894
2955 BC	52.7 ± 1.6	4355 ± 12	4904
2965 BC	52.2 ± 2.2	4367 ± 17	4914
2975 BC	50.2 ± 2.3	4392 ± 18	4924
2985 BC	56.8 ± 1.6	4352 ± 12	4934
2995 BC	59.7 ± 2.4	4339 ± 18	4944
3005 BC	58.4 ± 2.4	4359 ± 18	4954
3015 BC	57.5 ± 2.3	4376 ± 18	4964
3025 BC	59.2 ± 2.3	4372 ± 18	4974
3035 BC	59.2 ± 2.4	4382 ± 18	4984
3045 BC	55.7 ± 1.5	4418 ± 12	4994
3055 BC	54.8 ± 1.6	4435 ± 12	5004
3065 BC	56.5 ± 2.4	4432 ± 18	5014
3075 BC	63.2 ± 1.2	4390 ± 9	5024
3085 BC	58.8 ± 2.4	4434 ± 18	5034
3095 BC	60.8 ± 2.4	4428 ± 18	5044
3105 BC	52.3 ± 2.4	4503 ± 18	5054

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
3115 BC	56.5 ± 1.7	4481 ± 13	5064
3125 BC	53.7 ± 2.3	4512 ± 18	5074
3135 BC	55.1 ± 2.3	4510 ± 17	5084
3145 BC	51.9 ± 2.3	4544 ± 18	5094
3155 BC	58.9 ± 2.4	4501 ± 18	5104
3165 BC	64.7 ± 1.7	4467 ± 13	5114
3175 BC	58.9 ± 2.4	4520 ± 18	5124
3185 BC	63.0 ± 1.7	4500 ± 13	5134
3195 BC	61.5 ± 1.7	4520 ± 12	5144
3205 BC	61.7 ± 2.4	4528 ± 18	5154
3215 BC	67.0 ± 1.5	4497 ± 11	5164
3225 BC	68.7 ± 2.4	4495 ± 18	5174
3235 BC	74.5 ± 2.4	4461 ± 18	5184
3245 BC	79.3 ± 2.4	4435 ± 18	5194
3255 BC	77.9 ± 2.4	4455 ± 18	5204
3265 BC	75.1 ± 2.1	4486 ± 16	5214
3275 BC	77.2 ± 2.6	4480 ± 19	5224
3285 BC	80.0 ± 2.4	4469 ± 18	5234
3295 BC	81.4 ± 2.4	4468 ± 18	5244
3305 BC	81.0 ± 2.5	4480 ± 18	5254
3315 BC	78.4 ± 1.8	4511 ± 13	5264
3325 BC	84.2 ± 1.7	4476 ± 13	5274
3335 BC	78.9 ± 1.6	4525 ± 12	5284
3345 BC	78.8 ± 1.6	4535 ± 12	5294
3355 BC	74.9 ± 2.5	4575 ± 19	5304
3365 BC	72.0 ± 2.4	4606 ± 18	5314
3375 BC	68.2 ± 2.4	4644 ± 18	5324
3385 BC	63.7 ± 2.4	4688 ± 18	5334
3395 BC	60.8 ± 1.8	4718 ± 14	5344
3405 BC	66.8 ± 2.4	4684 ± 18	5354
3415 BC	65.6 ± 2.7	4703 ± 20	5364
3425 BC	70.9 ± 2.0	4673 ± 15	5374
3435 BC	73.4 ± 1.7	4664 ± 13	5384
3445 BC	73.8 ± 2.9	4670 ± 22	5394
3455 BC	74.0 ± 2.7	4679 ± 20	5404
3465 BC	80.0 ± 1.7	4643 ± 13	5414
3475 BC	86.6 ± 1.7	4604 ± 13	5424
3485 BC	87.1 ± 1.7	4611 ± 13	5434
3495 BC	86.1 ± 1.8	4628 ± 13	5444
3505 BC	79.9 ± 1.8	4684 ± 13	5454
3515 BC	76.3 ± 1.7	4720 ± 13	5464
3525 BC	77.2 ± 1.8	4723 ± 13	5474
3535 BC	78.4 ± 1.7	4725 ± 13	5484
3545 BC	73.1 ± 1.7	4773 ± 13	5494
3555 BC	74.9 ± 1.8	4769 ± 13	5504
3565 BC	79.7 ± 1.8	4743 ± 13	5514
3575 BC	79.5 ± 1.8	4755 ± 13	5524
3585 BC	82.7 ± 1.8	4741 ± 13	5534
3595 BC	85.0 ± 1.4	4734 ± 10	5544
3605 BC	88.1 ± 1.6	4719 ± 12	5554
3615 BC	91.3 ± 1.4	4706 ± 10	5564
3625 BC	89.4 ± 2.5	4730 ± 19	5574
3635 BC	82.5 ± 1.7	4790 ± 13	5584
3645 BC	77.4 ± 1.8	4837 ± 13	5594
3655 BC	73.4 ± 1.7	4878 ± 13	5604
3665 BC	75.2 ± 1.7	4874 ± 13	5614
3675 BC	69.7 ± 1.4	4925 ± 11	5624
3685 BC	75.0 ± 1.7	4895 ± 13	5634
3695 BC	77.3 ± 1.7	4888 ± 13	5644
3705 BC	74.8 ± 1.7	4916 ± 13	5654

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
3715 BC	71.4 ± 1.7	4951 ± 13	5664
3725 BC	71.4 ± 2.7	4961 ± 20	5674
3735 BC	75.9 ± 1.8	4937 ± 13	5684
3745 BC	76.0 ± 1.5	4946 ± 12	5694
3755 BC	76.9 ± 1.7	4949 ± 13	5704
3765 BC	72.8 ± 1.7	4989 ± 13	5714
3775 BC	73.2 ± 1.8	4995 ± 13	5724
3785 BC	74.9 ± 1.4	4992 ± 11	5734
3795 BC	75.8 ± 1.8	4996 ± 14	5744
3805 BC	65.4 ± 1.7	5083 ± 13	5754
3815 BC	65.5 ± 2.3	5092 ± 17	5764
3825 BC	71.4 ± 2.3	5058 ± 17	5774
3835 BC	73.1 ± 2.4	5055 ± 18	5784
3845 BC	71.5 ± 2.4	5077 ± 18	5794
3855 BC	71.9 ± 1.4	5084 ± 10	5804
3865 BC	78.1 ± 1.2	5046 ± 10	5814
3875 BC	73.9 ± 1.3	5088 ± 10	5824
3885 BC	87.1 ± 1.6	4999 ± 12	5834
3895 BC	82.5 ± 2.1	5044 ± 15	5844
3905 BC	82.6 ± 1.7	5052 ± 12	5854
3915 BC	81.9 ± 1.7	5067 ± 12	5864
3925 BC	84.0 ± 2.1	5062 ± 16	5874
3935 BC	85.1 ± 2.0	5063 ± 15	5884
3945 BC	81.1 ± 1.7	5102 ± 13	5894
3955 BC	82.0 ± 1.9	5105 ± 15	5904
3965 BC	76.1 ± 1.2	5159 ± 9	5914
3975 BC	74.5 ± 1.2	5181 ± 9	5924
3985 BC	70.3 ± 1.6	5221 ± 12	5934
3995 BC	69.5 ± 1.7	5237 ± 13	5944
4005 BC	69.0 ± 1.8	5251 ± 13	5954
4015 BC	72.1 ± 2.4	5237 ± 18	5964
4025 BC	77.2 ± 1.4	5209 ± 11	5974
4035 BC	78.5 ± 1.2	5209 ± 9	5984
4045 BC	73.7 ± 1.8	5255 ± 13	5994
4085 BC	73.0 ± 2.1	5298 ± 15	6034
4095 BC	74.6 ± 1.7	5296 ± 13	6044
4105 BC	78.4 ± 2.5	5278 ± 18	6054
4115 BC	69.5 ± 1.7	5354 ± 13	6064
4125 BC	80.2 ± 2.5	5284 ± 19	6074
4135 BC	82.0 ± 1.8	5280 ± 13	6084
4155 BC	85.6 ± 2.5	5273 ± 19	6104
4165 BC	80.1 ± 2.5	5323 ± 18	6114
4175 BC	75.3 ± 2.6	5369 ± 19	6124
4185 BC	81.4 ± 2.5	5333 ± 19	6134
4195 BC	84.8 ± 1.8	5318 ± 13	6144
4205 BC	92.6 ± 2.4	5270 ± 18	6154
4215 BC	94.1 ± 2.6	5269 ± 19	6164
4225 BC	81.5 ± 1.8	5372 ± 13	6174
4235 BC	81.5 ± 1.8	5381 ± 13	6184
4245 BC	86.3 ± 1.8	5355 ± 13	6194
4255 BC	79.0 ± 2.9	5419 ± 22	6204
4265 BC	74.8 ± 1.9	5460 ± 14	6214
4275 BC	79.7 ± 3.0	5433 ± 22	6224
4285 BC	81.2 ± 1.8	5433 ± 13	6234
4295 BC	85.5 ± 2.6	5409 ± 20	6244
4305 BC	91.6 ± 2.5	5374 ± 19	6254
4315 BC	92.1 ± 2.6	5380 ± 19	6264
4325 BC	86.7 ± 2.6	5430 ± 19	6274
4335 BC	80.7 ± 1.8	5484 ± 13	6284
4345 BC	78.2 ± 1.8	5513 ± 13	6294

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
4355 BC	74.0 ± 2.6	5553 ± 19	6304
4365 BC	73.8 ± 2.5	5564 ± 19	6314
4375 BC	73.4 ± 1.8	5575 ± 13	6324
4385 BC	78.7 ± 2.6	5547 ± 20	6334
4395 BC	75.4 ± 2.6	5582 ± 20	6344
4405 BC	77.7 ± 2.6	5574 ± 19	6354
4415 BC	73.4 ± 2.6	5616 ± 19	6364
4425 BC	84.7 ± 2.7	5542 ± 20	6374
4435 BC	87.9 ± 2.7	5527 ± 20	6384
4445 BC	83.6 ± 2.6	5569 ± 19	6394
4455 BC	79.7 ± 2.7	5608 ± 20	6404
4465 BC	71.5 ± 1.8	5679 ± 13	6414
4475 BC	73.4 ± 2.6	5675 ± 19	6424
4485 BC	76.3 ± 2.7	5663 ± 20	6434
4495 BC	75.5 ± 2.6	5678 ± 19	6444
4505 BC	76.5 ± 2.5	5681 ± 19	6454
4515 BC	77.3 ± 2.6	5684 ± 19	6464
4525 BC	78.7 ± 2.8	5684 ± 21	6474
4535 BC	79.1 ± 2.6	5690 ± 19	6484
4545 BC	72.6 ± 2.7	5748 ± 21	6494
4555 BC	72.9 ± 2.6	5756 ± 19	6504
4565 BC	72.7 ± 1.9	5767 ± 14	6514
4575 BC	76.0 ± 1.8	5753 ± 13	6524
4585 BC	77.2 ± 1.8	5753 ± 13	6534
4595 BC	76.5 ± 2.6	5768 ± 19	6544
4605 BC	78.0 ± 2.5	5767 ± 19	6554
4615 BC	79.7 ± 2.8	5764 ± 21	6564
4625 BC	74.8 ± 1.6	5810 ± 12	6574
4635 BC	79.0 ± 2.2	5788 ± 16	6584
4645 BC	82.0 ± 1.3	5775 ± 10	6594
4655 BC	82.2 ± 1.8	5784 ± 13	6604
4665 BC	87.5 ± 2.6	5754 ± 19	6614
4675 BC	87.4 ± 2.8	5764 ± 21	6624
4685 BC	86.3 ± 1.5	5782 ± 11	6634
4695 BC	80.3 ± 1.9	5837 ± 14	6644
4705 BC	83.7 ± 1.8	5822 ± 13	6654
4715 BC	79.9 ± 2.5	5859 ± 19	6664
4725 BC	78.5 ± 2.6	5879 ± 19	6674
4735 BC	80.1 ± 2.5	5877 ± 19	6684
4895 BC	86.6 ± 1.9	5985 ± 14	6844
4905 BC	88.1 ± 1.5	5984 ± 11	6854
4915 BC	85.1 ± 2.1	6015 ± 15	6864
4925 BC	83.9 ± 2.6	6033 ± 20	6874
4935 BC	90.0 ± 1.9	5999 ± 14	6884
4945 BC	84.5 ± 1.4	6048 ± 10	6894
4955 BC	86.6 ± 1.8	6042 ± 14	6904
4965 BC	84.9 ± 1.9	6066 ± 14	6914
4975 BC	87.8 ± 1.8	6053 ± 13	6924
4985 BC	88.5 ± 2.0	6058 ± 14	6934
4995 BC	85.2 ± 2.6	6092 ± 19	6944
5005 BC	83.4 ± 2.6	6115 ± 19	6954
5015 BC	88.5 ± 2.7	6087 ± 20	6964
5025 BC	85.8 ± 2.6	6117 ± 19	6974
5035 BC	87.3 ± 2.7	6115 ± 20	6984
5045 BC	85.5 ± 2.7	6138 ± 20	6994
5055 BC	89.4 ± 2.7	6119 ± 20	7004
5065 BC	83.5 ± 2.6	6172 ± 19	7014
5075 BC	82.5 ± 2.7	6189 ± 20	7024
5085 BC	80.4 ± 2.6	6215 ± 19	7034
5095 BC	87.0 ± 1.9	6176 ± 14	7044

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
5105 BC	83.0 ± 2.6	6215 ± 19	7054
5115 BC	92.7 ± 2.5	6153 ± 19	7064
5125 BC	85.1 ± 2.6	6219 ± 19	7074
5135 BC	94.9 ± 2.5	6157 ± 18	7084
5145 BC	95.7 ± 1.9	6160 ± 14	7094
5165 BC	92.7 ± 2.6	6202 ± 19	7114
5175 BC	99.1 ± 2.6	6164 ± 19	7124
5185 BC	106.8 ± 1.9	6119 ± 14	7134
5195 BC	106.7 ± 2.6	6128 ± 19	7144
5205 BC	109.0 ± 2.8	6122 ± 20	7154
5266 BC	95.2 ± 2.8	6281 ± 21	7215
5276 BC	103.6 ± 2.7	6230 ± 20	7225
5286 BC	101.5 ± 1.9	6255 ± 14	7235
5296 BC	102.7 ± 1.9	6256 ± 14	7245
5306 BC	97.9 ± 2.6	6300 ± 19	7255
5316 BC	96.4 ± 1.7	6321 ± 13	7265
5326 BC	88.5 ± 1.8	6389 ± 13	7275
5336 BC	94.9 ± 2.7	6352 ± 20	7285
5346 BC	92.2 ± 2.8	6381 ± 20	7295
5356 BC	96.2 ± 1.9	6361 ± 14	7305
5366 BC	94.8 ± 1.9	6383 ± 14	7315
5376 BC	90.6 ± 2.6	6422 ± 19	7325
5386 BC	91.2 ± 1.9	6427 ± 15	7335
5396 BC	88.0 ± 1.9	6462 ± 15	7345
5406 BC	96.5 ± 2.7	6408 ± 20	7355
5416 BC	100.3 ± 2.9	6390 ± 21	7365
5426 BC	98.7 ± 3.1	6412 ± 23	7375
5436 BC	101.5 ± 2.7	6400 ± 20	7385
5446 BC	100.7 ± 2.7	6416 ± 20	7395
5456 BC	106.5 ± 1.9	6384 ± 14	7405
5466 BC	105.4 ± 2.1	6402 ± 15	7415
5476 BC	95.2 ± 2.6	6485 ± 19	7425
5486 BC	85.4 ± 2.0	6568 ± 15	7435
5496 BC	87.2 ± 2.7	6564 ± 20	7445
5506 BC	92.6 ± 1.9	6534 ± 14	7455
5516 BC	89.2 ± 2.8	6568 ± 20	7465
5526 BC	92.5 ± 2.8	6554 ± 21	7475
5536 BC	88.5 ± 2.8	6593 ± 20	7485
5546 BC	87.3 ± 2.8	6612 ± 21	7495
5556 BC	92.5 ± 2.8	6583 ± 20	7505
5566 BC	81.0 ± 2.7	6678 ± 20	7515
5576 BC	84.9 ± 2.8	6659 ± 21	7525
5586 BC	83.3 ± 2.8	6680 ± 21	7535
5596 BC	98.3 ± 2.8	6580 ± 21	7545
5606 BC	97.4 ± 2.8	6596 ± 21	7555
5616 BC	90.6 ± 1.9	6654 ± 14	7565
5626 BC	82.9 ± 2.7	6722 ± 20	7575
5636 BC	81.0 ± 2.9	6746 ± 22	7585
5646 BC	78.2 ± 1.8	6777 ± 13	7595
5656 BC	85.7 ± 1.8	6731 ± 14	7605
5666 BC	79.4 ± 2.8	6787 ± 21	7615
5676 BC	78.3 ± 1.8	6805 ± 13	7625
5686 BC	81.6 ± 2.6	6790 ± 19	7635
5696 BC	84.0 ± 2.9	6782 ± 21	7645
5706 BC	85.1 ± 1.9	6784 ± 14	7655
5716 BC	82.6 ± 2.9	6812 ± 21	7665
5726 BC	78.7 ± 4.2	6850 ± 32	7675
5736 BC	74.4 ± 2.7	6892 ± 20	7685
5746 BC	74.0 ± 1.9	6905 ± 14	7695
5756 BC	73.6 ± 2.8	6917 ± 21	7705

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
5766 BC	76.9 ± 2.5	6903 ± 19	7715
5776 BC	76.3 ± 2.4	6917 ± 18	7725
5786 BC	77.5 ± 2.5	6918 ± 19	7735
5796 BC	77.4 ± 2.8	6928 ± 21	7745
5806 BC	80.0 ± 2.0	6918 ± 15	7755
5816 BC	76.5 ± 2.8	6955 ± 21	7765
5826 BC	81.7 ± 1.9	6926 ± 14	7775
5836 BC	85.5 ± 2.0	6906 ± 15	7785
5846 BC	77.7 ± 2.8	6975 ± 21	7795
5856 BC	78.3 ± 2.0	6980 ± 15	7805
5866 BC	82.5 ± 1.9	6958 ± 14	7815
5876 BC	82.5 ± 1.9	6968 ± 14	7825
5886 BC	83.6 ± 1.9	6969 ± 15	7835
5896 BC	76.1 ± 3.0	7035 ± 22	7845
5906 BC	81.5 ± 2.4	7005 ± 18	7855
5916 BC	81.8 ± 2.7	7012 ± 20	7865
5926 BC	74.4 ± 2.7	7077 ± 20	7875
5936 BC	73.4 ± 2.9	7094 ± 22	7885
5946 BC	80.3 ± 1.9	7053 ± 15	7895
5956 BC	90.5 ± 2.1	6987 ± 16	7905
5966 BC	92.5 ± 1.9	6982 ± 15	7915
5976 BC	87.0 ± 3.3	7032 ± 25	7925
5986 BC	80.8 ± 2.7	7088 ± 20	7935
5996 BC	80.8 ± 2.6	7097 ± 19	7945
6006 BC	79.3 ± 2.8	7118 ± 21	7955
6016 BC	75.7 ± 3.2	7155 ± 24	7965
6023 BC	70.8 ± 2.8	7198 ± 21	7972
6026 BC	74.8 ± 2.3	7171 ± 17	7975
6036 BC	70.6 ± 2.8	7212 ± 21	7985
6043 BC	81.1 ± 1.9	7142 ± 15	7992
6176 BC	82.5 ± 1.8	7259 ± 13	8125
6186 BC	80.4 ± 2.7	7285 ± 20	8135
6196 BC	86.6 ± 2.1	7248 ± 16	8145
6206 BC	84.0 ± 2.2	7278 ± 16	8155
6216 BC	82.4 ± 3.6	7299 ± 27	8165
6226 BC	79.5 ± 2.8	7331 ± 21	8175
6236 BC	67.1 ± 3.7	7433 ± 28	8185
6246 BC	74.3 ± 2.8	7389 ± 21	8195
6256 BC	70.6 ± 3.6	7426 ± 27	8205
6266 BC	73.7 ± 2.9	7412 ± 22	8215
6276 BC	66.7 ± 3.8	7475 ± 29	8225
6286 BC	79.1 ± 3.0	7392 ± 23	8235
6296 BC	77.7 ± 2.2	7412 ± 16	8245
6306 BC	74.9 ± 2.0	7442 ± 15	8255
6316 BC	83.6 ± 2.3	7388 ± 17	8265
6326 BC	84.4 ± 2.2	7391 ± 16	8275
6336 BC	85.0 ± 2.8	7397 ± 21	8285
6346 BC	83.4 ± 2.0	7418 ± 15	8295
6396 BC	80.4 ± 3.5	7489 ± 26	8345
6406 BC	79.9 ± 2.1	7501 ± 15	8355
6416 BC	81.5 ± 2.0	7500 ± 15	8365
6426 BC	80.2 ± 1.8	7520 ± 14	8375
6436 BC	75.6 ± 3.0	7564 ± 22	8385
6446 BC	75.2 ± 2.0	7576 ± 16	8395
6456 BC	75.2 ± 2.1	7586 ± 16	8405
6466 BC	70.7 ± 2.0	7629 ± 15	8415
6476 BC	68.7 ± 1.7	7655 ± 13	8425
6486 BC	63.5 ± 3.0	7703 ± 23	8435
6496 BC	70.1 ± 3.1	7663 ± 24	8445
(4) 6499 BC	68.3 ± 2.3	7679 ± 17	8448

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
6506 BC	71.6 ± 2.9	7662 ± 22	8455
(5) 6514 BC	60.4 ± 2.2	7753 ± 17	8463
6516 BC	68.7 ± 2.0	7693 ± 15	8465
6526 BC	70.5 ± 2.0	7690 ± 16	8475
6536 BC	65.5 ± 2.8	7736 ± 21	8485
(8) 6538 BC	61.8 ± 3.2	7766 ± 24	8487
6546 BC	73.4 ± 2.2	7687 ± 16	8495
(8) 6555 BC	75.8 ± 2.2	7677 ± 16	8504
6556 BC	73.1 ± 2.1	7699 ± 16	8505
6566 BC	76.8 ± 3.1	7681 ± 23	8515
6576 BC	69.6 ± 1.7	7745 ± 13	8525
6586 BC	79.7 ± 1.8	7679 ± 13	8535
6596 BC	72.3 ± 2.8	7743 ± 21	8545
(4) 6600 BC	68.2 ± 3.2	7778 ± 24	8549
6606 BC	70.4 ± 1.9	7767 ± 15	8555
6616 BC	68.2 ± 2.1	7792 ± 16	8565
6626 BC	76.5 ± 2.2	7742 ± 16	8575
6629 BC	65.5 ± 2.8	7826 ± 21	8578
6636 BC	74.9 ± 2.1	7763 ± 16	8585
6646 BC	67.2 ± 1.5	7830 ± 11	8595
6656 BC	64.6 ± 3.3	7860 ± 25	8605
(6) 6662 BC	60.0 ± 3.3	7900 ± 25	8611
6666 BC	68.0 ± 3.3	7844 ± 25	8615
6676 BC	69.8 ± 1.8	7841 ± 14	8625
6686 BC	69.3 ± 3.1	7854 ± 23	8635
(11) 6693 BC	62.7 ± 3.1	7910 ± 24	8642
6696 BC	69.8 ± 3.5	7859 ± 26	8645
(5) 6701 BC	60.5 ± 3.0	7934 ± 23	8650
6706 BC	64.4 ± 3.1	7910 ± 23	8655
6716 BC	64.2 ± 2.3	7921 ± 18	8665
(5) 6721 BC	63.5 ± 3.2	7932 ± 24	8670
6726 BC	71.5 ± 2.8	7876 ± 21	8675
6736 BC	67.6 ± 3.2	7915 ± 24	8685
(5) 6741 BC	68.8 ± 3.0	7911 ± 23	8690
6746 BC	72.6 ± 1.9	7886 ± 14	8695
6756 BC	69.2 ± 1.9	7922 ± 15	8705
(5) 6761 BC	69.3 ± 3.0	7927 ± 23	8710
6766 BC	73.1 ± 1.8	7903 ± 14	8715
(3) 6767 BC	67.6 ± 3.3	7945 ± 25	8716
6776 BC	71.4 ± 3.1	7925 ± 23	8725
6786 BC	71.1 ± 2.2	7937 ± 16	8735
(3) 6787 BC	70.3 ± 3.4	7944 ± 26	8736
6796 BC	74.4 ± 3.6	7922 ± 27	8745
(3) 6804 BC	73.2 ± 3.4	7939 ± 26	8753
6806 BC	75.7 ± 3.0	7922 ± 22	8755
6816 BC	76.2 ± 2.1	7927 ± 16	8765
6826 BC	74.9 ± 2.3	7948 ± 18	8775
(4) 6831 BC	64.8 ± 3.4	8028 ± 26	8780
6836 BC	77.5 ± 3.6	7938 ± 27	8785
6846 BC	69.4 ± 2.9	8009 ± 22	8795
(4) 6853 BC	68.3 ± 3.4	8023 ± 26	8802
6856 BC	80.4 ± 3.6	7936 ± 27	8805
6866 BC	69.6 ± 2.8	8026 ± 21	8815
(5) 6871 BC	66.8 ± 3.2	8052 ± 25	8820
6876 BC	75.5 ± 2.1	7992 ± 16	8825
6886 BC	81.6 ± 3.0	7956 ± 22	8835
6896 BC	83.5 ± 2.1	7952 ± 16	8845
(5) 6901 BC	78.6 ± 3.2	7993 ± 24	8850
6906 BC	86.8 ± 3.0	7937 ± 22	8855
6916 BC	88.3 ± 3.7	7936 ± 27	8865

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
(5) 6921 BC	82.0 ± 3.2	7988 ± 24	8870
6926 BC	78.7 ± 1.6	8016 ± 12	8875
(11) 6933 BC	86.3 ± 4.8	7967 ± 36	8882
6936 BC	89.6 ± 2.8	7946 ± 21	8885
(6) 6940 BC	87.6 ± 3.3	7964 ± 24	8889
6946 BC	93.1 ± 2.9	7930 ± 21	8895
6956 BC	86.9 ± 2.7	7984 ± 20	8905
(5) 6961 BC	88.8 ± 3.5	7976 ± 26	8910
6963 BC	85.9 ± 3.3	7999 ± 24	8912
6966 BC	90.5 ± 2.3	7969 ± 17	8915
6976 BC	97.6 ± 3.7	7925 ± 27	8925
6986 BC	91.7 ± 2.3	7978 ± 17	8935
6996 BC	98.2 ± 3.3	7941 ± 24	8945
(5) 7001 BC	95.7 ± 4.4	7964 ± 32	8950
7006 BC	94.6 ± 1.9	7976 ± 14	8955
(11) 7013 BC	93.8 ± 1.8	7989 ± 13	8962
7016 BC	99.5 ± 2.2	7950 ± 16	8965
7026 BC	96.8 ± 2.3	7981 ± 17	8975
(5) 7031 BC	88.3 ± 3.3	8048 ± 24	8980
7036 BC	94.4 ± 3.2	8007 ± 24	8985
7046 BC	98.4 ± 3.1	7988 ± 23	8995
(5) 7051 BC	91.8 ± 3.2	8041 ± 24	9000
7056 BC	98.6 ± 3.1	7996 ± 22	9005
(5) 7061 BC	83.4 ± 3.2	8113 ± 24	9010
7066 BC	84.1 ± 2.3	8113 ± 17	9015
7076 BC	86.7 ± 2.1	8103 ± 16	9025
7086 BC	79.2 ± 2.2	8168 ± 16	9035
7096 BC	81.4 ± 3.8	8162 ± 29	9045
7106 BC	90.3 ± 2.9	8105 ± 21	9055
(5) 7111 BC	78.7 ± 3.2	8196 ± 24	9060
7116 BC	91.8 ± 2.8	8104 ± 21	9065
7126 BC	86.9 ± 4.0	8150 ± 30	9075
7136 BC	90.4 ± 2.3	8134 ± 17	9085
7146 BC	84.1 ± 2.1	8191 ± 16	9095
7156 BC	96.4 ± 3.0	8109 ± 22	9105
7166 BC	90.9 ± 2.2	8159 ± 16	9115
7176 BC	92.0 ± 2.2	8161 ± 16	9125
7186 BC	83.8 ± 2.1	8232 ± 16	9135
(4) 7190 BC	88.5 ± 3.3	8200 ± 24	9139
7196 BC	84.2 ± 1.8	8238 ± 14	9145
(2) 7200 BC	79.6 ± 5.5	8275 ± 41	9149
7326 BC	96.7 ± 3.4	8272 ± 25	9275
7336 BC	95.5 ± 4.3	8291 ± 32	9285
7346 BC	97.1 ± 3.0	8289 ± 22	9295
7356 BC	93.6 ± 3.0	8324 ± 22	9305
7378 BC	97.7 ± 3.1	8315 ± 22	9327
7388 BC	89.5 ± 2.7	8385 ± 20	9337
7398 BC	104.0 ± 3.3	8289 ± 24	9347
7408 BC	96.2 ± 4.7	8356 ± 34	9357
7418 BC	111.0 ± 3.3	8258 ± 24	9367
7428 BC	97.4 ± 3.7	8366 ± 27	9377
7438 BC	106.3 ± 3.5	8311 ± 25	9387
7448 BC	118.8 ± 3.9	8230 ± 28	9397
7458 BC	95.7 ± 2.3	8408 ± 17	9407
7468 BC	108.6 ± 3.1	8324 ± 23	9417
7478 BC	109.3 ± 3.0	8328 ± 22	9427
7488 BC	101.9 ± 3.1	8392 ± 23	9437
7576 BC	98.2 ± 3.4	8504 ± 25	9525
7586 BC	94.3 ± 3.1	8543 ± 23	9535
7588 BC	85.9 ± 3.3	8607 ± 25	9537

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
7598 BC	88.5 ± 3.2	8597 ± 24	9547
7608 BC	81.0 ± 3.0	8663 ± 22	9557
7618 BC	73.6 ± 3.0	8727 ± 22	9567
7628 BC	88.7 ± 3.2	8625 ± 24	9577
7638 BC	82.1 ± 3.4	8683 ± 25	9587
7648 BC	88.9 ± 3.4	8643 ± 25	9597
7658 BC	83.5 ± 3.3	8692 ± 25	9607
7678 BC	97.4 ± 4.6	8609 ± 34	9627
7688 BC	81.1 ± 2.8	8739 ± 21	9637
7698 BC	86.0 ± 3.4	8712 ± 25	9647
7708 BC	89.8 ± 5.1	8694 ± 38	9657
7718 BC	86.6 ± 4.2	8728 ± 31	9667
7728 BC	89.4 ± 4.2	8716 ± 31	9677
7738 BC	82.9 ± 4.2	8774 ± 31	9687
7748 BC	97.4 ± 4.5	8677 ± 33	9697
8007 BC	99.0 ± 2.2	8917 ± 16	9956
8017 BC*	103.7 ± 3.1	8893 ± 23	9966
8027 BC*	105.0 ± 3.1	8893 ± 23	9976
8037 BC*	107.3 ± 4.4	8886 ± 32	9986
8047 BC*	108.6 ± 4.4	8886 ± 32	9996
8057 BC	114.6 ± 3.1	8853 ± 23	10006
8067 BC	111.9 ± 2.9	8883 ± 21	10016
8077 BC	114.8 ± 3.2	8871 ± 23	10026
8087 BC	111.2 ± 2.1	8906 ± 15	10036
8097 BC	114.0 ± 3.3	8896 ± 24	10046
8107 BC	122.9 ± 3.1	8842 ± 22	10056
8117 BC	120.9 ± 3.0	8866 ± 22	10066
8127 BC	116.4 ± 3.7	8908 ± 27	10076
8137 BC	119.1 ± 3.7	8898 ± 27	10086
8147 BC	128.4 ± 3.3	8841 ± 24	10096
8157 BC	130.6 ± 2.6	8835 ± 18	10106
8167 BC	126.5 ± 3.3	8874 ± 24	10116
8177 BC	123.8 ± 3.2	8903 ± 23	10126
8187 BC	132.1 ± 3.3	8854 ± 23	10136
8197 BC	130.2 ± 3.3	8877 ± 24	10146
8207 BC	127.6 ± 3.5	8905 ± 25	10156
8217 BC	122.4 ± 3.4	8952 ± 24	10166
8227 BC	120.3 ± 3.4	8977 ± 24	10176
8237 BC	122.1 ± 2.8	8974 ± 20	10186
8247 BC	117.7 ± 2.8	9015 ± 20	10196
8257 BC	124.1 ± 2.5	8978 ± 18	10206
8267 BC	116.9 ± 2.3	9041 ± 17	10216
8277 BC	110.8 ± 2.0	9094 ± 14	10226
8287 BC	106.2 ± 3.5	9137 ± 26	10236
8297 BC	105.1 ± 3.4	9155 ± 25	10246
8307 BC	104.4 ± 2.3	9170 ± 17	10256
8317 BC	103.2 ± 2.3	9189 ± 17	10266
8327 BC	104.9 ± 3.4	9185 ± 25	10276
8337 BC	101.9 ± 4.0	9216 ± 29	10286
8347 BC	98.9 ± 2.0	9247 ± 15	10296
8357 BC	109.7 ± 3.9	9180 ± 29	10306
8367 BC	104.0 ± 3.3	9231 ± 24	10316
8377 BC	115.0 ± 3.2	9161 ± 23	10326
8387 BC	107.9 ± 3.2	9222 ± 23	10336
8397 BC	116.5 ± 3.4	9169 ± 25	10346
8407 BC	120.1 ± 3.2	9153 ± 23	10356
8417 BC	115.7 ± 3.2	9194 ± 23	10366
8427 BC	117.2 ± 3.2	9194 ± 23	10376
8437 BC	116.4 ± 3.4	9209 ± 25	10386
8447 BC	118.4 ± 3.2	9204 ± 23	10396

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
8457 BC	115.6 ± 3.2	9234 ± 23	10406
8467 BC	116.0 ± 3.4	9241 ± 24	10416
8477 BC	116.8 ± 3.2	9245 ± 23	10426
8487 BC	109.0 ± 2.4	9311 ± 17	10436
8497 BC	121.8 ± 3.1	9229 ± 22	10446
8507 BC	122.9 ± 3.4	9230 ± 24	10456
8517 BC	123.6 ± 3.2	9235 ± 23	10466
8527 BC	122.3 ± 2.4	9254 ± 17	10476
8537 BC	120.1 ± 2.4	9280 ± 18	10486
8547 BC	121.8 ± 3.3	9277 ± 24	10496
8557 BC	119.9 ± 3.1	9300 ± 22	10506
8567 BC	116.3 ± 3.2	9336 ± 23	10516
8577 BC	121.8 ± 2.5	9306 ± 18	10526
8587 BC	120.3 ± 3.2	9327 ± 23	10536
8597 BC	123.4 ± 2.5	9314 ± 18	10546
8607 BC	126.2 ± 3.9	9304 ± 28	10556
8617 BC	121.3 ± 3.7	9349 ± 27	10566
8627 BC	122.4 ± 3.5	9350 ± 25	10576
8637 BC	123.5 ± 3.3	9352 ± 24	10586
8647 BC	119.1 ± 2.4	9394 ± 17	10596
8657 BC	116.9 ± 5.1	9419 ± 37	10606
8667 BC	127.6 ± 3.2	9352 ± 23	10616
8677 BC	130.4 ± 3.4	9342 ± 24	10626
8687 BC	127.8 ± 2.3	9371 ± 16	10636
8697 BC	118.0 ± 3.4	9450 ± 24	10646
8707 BC	124.3 ± 3.3	9415 ± 24	10656
8717 BC	128.9 ± 3.4	9391 ± 25	10666
8727 BC	126.9 ± 3.3	9416 ± 23	10676
8737 BC	126.1 ± 2.5	9430 ± 18	10686
8747 BC	123.3 ± 3.4	9460 ± 25	10696
8837 BC	126.9 ± 3.2	9522 ± 23	10786
8847 BC	117.4 ± 3.4	9600 ± 25	10796
8857 BC	121.9 ± 3.3	9578 ± 23	10806
8867 BC	116.1 ± 3.5	9629 ± 25	10816
8877 BC	127.3 ± 3.3	9559 ± 23	10826
8887 BC	129.2 ± 2.4	9553 ± 17	10836
8897 BC	134.9 ± 2.3	9525 ± 17	10846
8907 BC	126.2 ± 3.8	9595 ± 27	10856
8917 BC	121.8 ± 3.5	9636 ± 25	10866
8927 BC	126.5 ± 3.5	9613 ± 25	10876
8937 BC	124.3 ± 3.5	9638 ± 25	10886
8947 BC	127.8 ± 3.5	9623 ± 25	10896
8957 BC	124.7 ± 3.4	9655 ± 24	10906
8967 BC	133.8 ± 3.2	9599 ± 23	10916
8977 BC	132.7 ± 3.5	9617 ± 25	10926
8987 BC	132.9 ± 3.5	9625 ± 25	10936
8997 BC	143.6 ± 3.1	9560 ± 22	10946
9007 BC	144.4 ± 2.5	9564 ± 17	10956
9017 BC	149.1 ± 2.7	9541 ± 19	10966
9067 BC	152.2 ± 3.3	9568 ± 23	11016
9077 BC	159.3 ± 2.5	9528 ± 17	11026
9087 BC	163.1 ± 3.3	9511 ± 23	11036
9097 BC	158.7 ± 3.5	9552 ± 24	11046

TABLE 1. Decadal Measurements *(Continued)*

cal AD/BC	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
9107 BC	161.6 ± 3.3	9541 ± 23	11056
9117 BC	157.8 ± 3.5	9577 ± 24	11066
9127 BC	154.3 ± 3.3	9611 ± 23	11076
9137 BC	156.7 ± 3.5	9604 ± 24	11086
9147 BC	151.2 ± 3.3	9652 ± 23	11096
9157 BC	157.1 ± 2.4	9622 ± 17	11106
9172 BC	153.5 ± 3.2	9660 ± 23	11121
9182 BC	158.3 ± 3.6	9637 ± 25	11131
9192 BC	157.9 ± 3.4	9649 ± 24	11141
9202 BC	158.4 ± 3.5	9655 ± 25	11151
9212 BC	154.8 ± 3.4	9690 ± 24	11161
9222 BC	147.1 ± 3.4	9753 ± 24	11171
9232 BC	151.2 ± 3.3	9735 ± 23	11181
9268 BC	146.9 ± 3.6	9800 ± 25	11217
9278 BC	143.1 ± 3.4	9836 ± 24	11227
9288 BC	141.5 ± 3.6	9857 ± 25	11237
9292 BC	135.4 ± 3.6	9904 ± 26	11241
9298 BC	135.5 ± 3.4	9909 ± 24	11247
9302 BC	142.6 ± 2.5	9863 ± 17	11251
9308 BC	137.3 ± 2.1	9906 ± 15	11257
9312 BC	127.8 ± 3.5	9977 ± 25	11261
9322 BC	137.4 ± 3.6	9920 ± 26	11271
9368 BC	131.3 ± 2.4	10007 ± 17	11317
9378 BC	141.9 ± 3.5	9942 ± 25	11327
9388 BC	140.9 ± 3.5	9959 ± 24	11337
9398 BC	134.8 ± 2.3	10011 ± 17	11347
9408 BC	131.8 ± 3.6	10042 ± 25	11357
9418 BC	132.2 ± 3.5	10049 ± 25	11367
9428 BC	131.4 ± 3.3	10065 ± 24	11377
9438 BC	140.1 ± 2.7	10013 ± 19	11387
9448 BC	145.2 ± 3.2	9987 ± 22	11397
9458 BC	144.8 ± 3.2	9999 ± 22	11407
9468 BC	145.9 ± 3.1	10001 ± 22	11417
9478 BC	142.4 ± 4.0	10036 ± 28	11427
9488 BC	146.4 ± 3.6	10017 ± 25	11437
9498 BC	140.3 ± 4.1	10069 ± 29	11447
9508 BC	142.0 ± 3.2	10068 ± 22	11457
9518 BC	142.8 ± 2.8	10072 ± 20	11467
9528 BC	156.3 ± 3.5	9987 ± 25	11477
9538 BC	152.0 ± 3.5	10027 ± 25	11487
9548 BC	147.7 ± 3.4	10066 ± 24	11497
9558 BC	158.8 ± 3.6	9999 ± 25	11507
9568 BC	161.2 ± 3.5	9992 ± 24	11517
9578 BC	164.0 ± 3.5	9982 ± 25	11527
9588 BC	165.4 ± 3.5	9982 ± 24	11537
9598 BC	165.0 ± 3.5	9995 ± 24	11547
9608 BC	157.7 ± 3.4	10055 ± 23	11557
9618 BC	157.5 ± 2.7	10066 ± 19	11567
9628 BC	150.2 ± 3.8	10126 ± 26	11577
9638 BC	153.8 ± 3.8	10111 ± 27	11587
9648 BC	157.8 ± 2.2	10093 ± 16	11597
9658 BC	155.0 ± 3.5	10122 ± 24	11607
9668 BC	157.9 ± 3.4	10112 ± 23	11617

TABLE 2. ^{14}C age determinations made at the University of Washington Quaternary Isotope Lab (Seattle). The cal AD (or cal BP) ages represent determinations on single-year wood sections from one or more North American trees, with the exception that from AD 1890–1914 the ^{14}C ages were constructed from the average of single-year determinations on an Alaskan tree and 2- and 3-yr samples of a Pacific Northwest tree. For the latter tree the same ^{14}C age was used for each single year of the 2–3 yr sample, with the standard deviation in the age increased by 1.4 or 1.7 times. $\Delta^{14}C$ was calculated as defined in Stuiver and Polach (1977). No error multiplier has been included in the standard deviations.

TABLE 2. Single-Year Data

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1954	−22.5 ± 2.7	179 ± 23	−4
1953	−24.1 ± 1.8	193 ± 15	−3
1952	−25.8 ± 1.6	208 ± 14	−2
1951	−25.5 ± 1.7	207 ± 14	−1
1950	−25.8 ± 1.7	210 ± 14	0
1949	−26.0 ± 1.7	213 ± 14	1
1948	−22.1 ± 1.8	182 ± 15	2
1947	−21.6 ± 1.6	178 ± 13	3
1945	−22.4 ± 1.9	187 ± 16	5
1944	−23.1 ± 1.3	193 ± 10	6
1943	−24.3 ± 1.2	204 ± 10	7
1942	−20.4 ± 1.2	174 ± 10	8
1941	−19.9 ± 1.9	170 ± 16	9
1940	−23.0 ± 2.0	197 ± 16	10
1939	−20.1 ± 1.8	174 ± 15	11
1938	−16.2 ± 1.2	143 ± 10	12
1937	−17.2 ± 1.6	152 ± 13	13
1936	−16.5 ± 1.7	147 ± 14	14
1935	−16.7 ± 1.9	150 ± 15	15
1934	−15.6 ± 1.8	142 ± 15	16
1933	−18.6 ± 1.8	167 ± 14	17
1932	−20.7 ± 1.2	186 ± 10	18
1931	−16.6 ± 1.8	153 ± 15	19
1930	−14.5 ± 1.2	137 ± 10	20
1929	−18.2 ± 1.0	168 ± 8	21
1928	−15.5 ± 1.2	147 ± 10	22
1927	−15.7 ± 1.1	149 ± 9	23
1926	−14.7 ± 1.2	143 ± 9	24
1925	−12.3 ± 1.2	124 ± 9	25
1924	−11.4 ± 1.2	117 ± 10	26
1923	−14.1 ± 1.0	140 ± 8	27
1922	−12.2 ± 1.2	126 ± 10	28
1921	−12.9 ± 1.2	133 ± 10	29
1920	−14.1 ± 1.3	144 ± 10	30
1919	−11.1 ± 1.2	120 ± 10	31
1918	−11.3 ± 1.0	122 ± 8	32
1917	−9.7 ± 1.0	110 ± 8	33
1916	−11.0 ± 1.2	122 ± 10	34
1915	−6.3 ± 1.7	85 ± 14	35
1914	−7.1 ± 1.0	92 ± 8	36
1913	−7.3 ± 0.9	95 ± 7	37

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1912	−8.1 ± 1.1	101 ± 9	38
1911	−8.3 ± 1.2	105 ± 10	39
1910	−7.5 ± 1.2	99 ± 10	40
1909	−6.5 ± 1.3	92 ± 11	41
1908	−8.4 ± 1.4	108 ± 12	42
1907	−6.2 ± 1.3	92 ± 10	43
1906	−4.4 ± 1.2	78 ± 10	44
1905	−5.5 ± 1.4	88 ± 11	45
1904	−4.3 ± 1.4	79 ± 11	46
1903	−4.2 ± 1.3	80 ± 11	47
1902	−2.9 ± 1.1	70 ± 9	48
1901	1.2 ± 1.1	38 ± 9	49
1900	−2.9 ± 1.5	72 ± 12	50
1899	−4.5 ± 1.3	86 ± 11	51
1898	−3.4 ± 1.5	78 ± 12	52
1897	−3.4 ± 1.4	79 ± 11	53
1896	−1.3 ± 1.2	63 ± 10	54
1895	−2.1 ± 1.2	71 ± 10	55
1894	−2.2 ± 1.2	72 ± 10	56
1893	−2.2 ± 1.3	73 ± 10	57
1892	−4.4 ± 1.3	92 ± 10	58
1891	−3.2 ± 1.4	83 ± 11	59
1890	−4.3 ± 1.4	93 ± 11	60
1889	−5.4 ± 1.1	103 ± 9	61
1888	−6.5 ± 1.8	113 ± 15	62
1887	−6.6 ± 1.1	115 ± 9	63
1886	−6.1 ± 1.1	111 ± 9	64
1885	−4.5 ± 1.2	100 ± 9	65
1884	−3.3 ± 1.7	91 ± 14	66
1883	−2.7 ± 1.2	87 ± 10	67
1882	−1.5 ± 1.2	78 ± 9	68
1881	−4.9 ± 1.6	107 ± 13	69
1880	−2.7 ± 1.6	90 ± 13	70
1879	−5.1 ± 1.5	110 ± 12	71
1878	−5.9 ± 1.1	118 ± 9	72
1877	−4.9 ± 1.5	110 ± 12	73
1876	−7.4 ± 1.7	132 ± 14	74
1875	−5.0 ± 1.1	113 ± 9	75
1874	−6.1 ± 1.8	123 ± 14	76
1873	−6.2 ± 1.2	124 ± 10	77
1872	−4.7 ± 1.1	114 ± 9	78

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1871	−4.6 ± 1.4	114 ± 11	79
1870	−4.8 ± 1.3	116 ± 11	80
1869	−4.3 ± 1.3	114 ± 10	81
1868	−4.4 ± 1.3	115 ± 11	82
1867	−3.3 ± 1.0	108 ± 8	83
1866	−5.0 ± 1.8	122 ± 15	84
1865	−3.1 ± 1.5	107 ± 12	85
1864	−5.6 ± 1.6	129 ± 13	86
1863	−5.8 ± 1.7	131 ± 14	87
1862	−7.2 ± 2.0	144 ± 16	88
1861	−3.0 ± 1.7	110 ± 13	89
1860	−4.4 ± 1.7	123 ± 13	90
1859	−3.1 ± 1.8	113 ± 15	91
1858	−2.1 ± 1.9	106 ± 15	92
1857	−5.0 ± 1.6	131 ± 13	93
1856	−4.0 ± 1.2	124 ± 10	94
1855	−4.0 ± 1.6	125 ± 13	95
1854	−4.1 ± 2.6	126 ± 21	96
1853	−3.6 ± 1.3	123 ± 11	97
1852	0.1 ± 2.5	95 ± 20	98
1851	−2.5 ± 2.5	116 ± 20	99
1850	−1.4 ± 2.5	109 ± 20	100
1849	−0.5 ± 1.5	99 ± 15	101
1848	−1.9 ± 1.8	114 ± 15	102
1847	−0.7 ± 1.7	106 ± 14	103
1846	−0.4 ± 1.7	104 ± 14	104
1845	−2.5 ± 2.5	122 ± 20	105
1844	−0.8 ± 1.2	109 ± 10	106
1843	−2.0 ± 1.0	120 ± 8	107
1842	−1.3 ± 1.4	116 ± 11	108
1841	−4.7 ± 1.7	143 ± 14	109
1840	−1.0 ± 1.7	115 ± 14	110
1839	−1.2 ± 1.7	117 ± 14	111
1838	−2.5 ± 0.9	129 ± 8	112
1837	−3.4 ± 1.2	137 ± 10	113
1836	0.2 ± 1.2	109 ± 10	114
1835	0.0 ± 1.6	112 ± 13	115
1834	−0.1 ± 1.9	114 ± 16	116
1833	0.5 ± 1.4	110 ± 11	117
1832	2.2 ± 1.4	97 ± 11	118
1831	1.4 ± 1.2	104 ± 10	119
1830	3.8 ± 1.6	86 ± 13	120
1829	5.2 ± 1.6	76 ± 13	121
1828	2.8 ± 1.0	96 ± 8	122
1827	4.4 ± 1.2	84 ± 9	123
1826	2.2 ± 1.6	103 ± 13	124
1825	1.9 ± 1.6	107 ± 13	125
1824	1.0 ± 1.2	114 ± 10	126
1823	3.0 ± 1.7	100 ± 14	127
1822	0.3 ± 1.2	122 ± 10	128
1821	3.6 ± 1.0	96 ± 8	129
1820	3.4 ± 1.0	99 ± 8	130
1819	−1.4 ± 2.0	139 ± 16	131

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1818	6.1 ± 1.3	79 ± 10	132
1817	6.2 ± 1.9	80 ± 16	133
1816	5.8 ± 1.8	84 ± 14	134
1815	1.7 ± 1.8	118 ± 14	135
1814	0.8 ± 2.0	126 ± 16	136
1813	1.5 ± 1.2	121 ± 10	137
1812	2.5 ± 2.0	114 ± 16	138
1811	1.6 ± 2.0	122 ± 16	139
1810	2.1 ± 1.9	119 ± 15	140
1809	−0.1 ± 1.8	138 ± 15	141
1808	−5.5 ± 1.8	183 ± 14	142
1807	−1.4 ± 1.3	150 ± 11	143
1806	−3.7 ± 1.8	170 ± 14	144
1805	−1.6 ± 1.7	154 ± 14	145
1804	−1.5 ± 1.7	154 ± 14	146
1803	−3.4 ± 1.7	170 ± 14	147
1802	−2.5 ± 1.3	164 ± 10	148
1801	−5.0 ± 1.2	185 ± 10	149
1800	−0.1 ± 1.7	147 ± 14	150
1799	−1.0 ± 1.7	155 ± 14	151
1798	−4.1 ± 1.2	181 ± 10	152
1797	−5.0 ± 1.7	189 ± 14	153
1796	−9.3 ± 1.8	225 ± 14	154
1795	−9.7 ± 2.0	229 ± 16	155
1794	−9.4 ± 1.7	228 ± 14	156
1793	−7.8 ± 1.7	215 ± 14	157
1792	−10.7 ± 1.8	240 ± 15	158
1791	−7.1 ± 1.8	212 ± 15	159
1790	−7.3 ± 1.7	214 ± 14	160
1789	−6.6 ± 1.8	209 ± 14	161
1788	−10.2 ± 1.8	240 ± 15	162
1787	−8.2 ± 1.7	224 ± 14	163
1786	−7.8 ± 2.3	222 ± 19	164
1785	−7.2 ± 1.4	219 ± 12	165
1784	−7.7 ± 1.7	224 ± 14	166
1781	−5.1 ± 1.2	205 ± 10	169
1780	−1.4 ± 1.2	176 ± 10	170
1779	−0.4 ± 1.7	170 ± 14	171
1778	0.2 ± 1.7	165 ± 14	172
1777	1.4 ± 1.3	157 ± 10	173
1776	2.5 ± 1.2	149 ± 10	174
1775	1.1 ± 1.7	162 ± 14	175
1774	−1.3 ± 1.7	181 ± 13	176
1773	1.4 ± 1.2	161 ± 10	177
1772	−0.1 ± 1.3	174 ± 11	178
1771	1.3 ± 1.7	164 ± 14	179
1770	0.0 ± 1.7	175 ± 14	180
1769	0.1 ± 1.7	175 ± 14	181
1768	−0.8 ± 1.7	183 ± 14	182
1767	−0.6 ± 1.7	183 ± 14	183
1766	1.5 ± 1.7	167 ± 14	184
1765	2.1 ± 1.7	163 ± 14	185
1764	2.9 ± 1.7	157 ± 14	186

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1763	−0.7 ± 1.7	187 ± 13	187
1762	2.6 ± 1.7	162 ± 14	188
1761	4.6 ± 1.2	147 ± 10	189
1760	4.6 ± 1.3	148 ± 10	190
1759	5.3 ± 1.3	143 ± 10	191
1758	6.0 ± 1.0	138 ± 8	192
1757	4.3 ± 1.3	153 ± 11	193
1756	3.6 ± 1.1	160 ± 9	194
1755	3.8 ± 1.2	159 ± 10	195
1754	4.5 ± 1.8	155 ± 14	196
1753	6.0 ± 1.1	143 ± 9	197
1752	4.7 ± 1.7	155 ± 14	198
1751	2.5 ± 1.3	174 ± 11	199
1750	5.1 ± 1.2	154 ± 10	200
1748	4.5 ± 1.7	160 ± 14	202
1747	6.9 ± 1.7	142 ± 14	203
1746	7.4 ± 1.2	139 ± 10	204
1745	4.6 ± 1.3	162 ± 10	205
1744	2.8 ± 1.7	178 ± 14	206
1743	5.0 ± 1.1	161 ± 9	207
1742	5.5 ± 1.8	158 ± 14	208
1741	1.1 ± 1.3	195 ± 10	209
1740	5.6 ± 1.7	159 ± 14	210
1739	6.4 ± 1.3	154 ± 10	211
1738	7.2 ± 1.7	148 ± 14	212
1737	7.3 ± 2.0	149 ± 16	213
1736	7.4 ± 2.0	149 ± 16	214
1735	7.3 ± 1.8	150 ± 15	215
1734	8.9 ± 2.3	139 ± 18	216
1733	8.9 ± 1.8	140 ± 15	217
1732	7.1 ± 1.4	155 ± 12	218
1731	5.6 ± 1.4	168 ± 11	219
1730	10.6 ± 1.8	129 ± 15	220
1729	12.8 ± 1.8	113 ± 14	221
1728	11.6 ± 1.8	123 ± 15	222
1727	14.2 ± 1.8	103 ± 15	223
1726	18.0 ± 1.5	75 ± 12	224
1725	13.1 ± 1.1	114 ± 9	225
1724	12.8 ± 1.0	117 ± 8	226
1723	13.5 ± 1.3	113 ± 10	227
1722	12.7 ± 1.2	120 ± 9	228
1721	13.7 ± 1.2	114 ± 10	229
1720	14.8 ± 1.0	105 ± 8	230
1719	16.3 ± 1.0	94 ± 8	231
1718	17.0 ± 0.8	90 ± 7	232
1717	15.8 ± 1.0	101 ± 8	233
1716	17.5 ± 1.3	88 ± 10	234
1715	16.7 ± 1.2	95 ± 10	235
1714	17.9 ± 1.2	87 ± 10	236
1713	17.6 ± 1.2	90 ± 10	237
1712	13.9 ± 1.2	121 ± 10	238
1711	18.5 ± 0.9	85 ± 7	239
1710	17.5 ± 1.0	94 ± 8	240

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1709	16.9 ± 1.3	100 ± 10	241
1708	15.4 ± 1.2	113 ± 9	242
1707	15.0 ± 0.8	116 ± 7	243
1706	14.4 ± 1.3	122 ± 10	244
1705	16.5 ± 1.3	107 ± 10	245
1704	19.1 ± 0.9	87 ± 7	246
1703	17.7 ± 0.9	99 ± 7	247
1702	15.2 ± 0.8	120 ± 6	248
1701	19.0 ± 1.0	91 ± 8	249
1700	17.5 ± 0.9	104 ± 7	250
1699	18.0 ± 1.1	101 ± 8	251
1698	17.4 ± 1.1	107 ± 8	252
1697	18.2 ± 1.1	101 ± 8	253
1696	16.6 ± 1.0	115 ± 8	254
1695	15.8 ± 0.8	122 ± 6	255
1694	16.3 ± 0.9	119 ± 7	256
1693	15.7 ± 1.0	125 ± 8	257
1692	16.3 ± 1.0	121 ± 8	258
1691	14.7 ± 1.0	134 ± 8	259
1690	13.9 ± 0.9	142 ± 7	260
1689	15.7 ± 1.3	128 ± 11	261
1688	16.6 ± 1.3	122 ± 10	262
1687	14.1 ± 1.1	143 ± 9	263
1686	17.6 ± 0.9	116 ± 8	264
1685	13.5 ± 2.4	150 ± 19	265
1684	13.2 ± 1.8	154 ± 14	266
1683	11.5 ± 1.8	167 ± 14	267
1682	12.2 ± 1.9	163 ± 15	268
1681	12.0 ± 1.8	166 ± 14	269
1680	12.9 ± 1.7	159 ± 13	270
1678	8.5 ± 1.8	197 ± 14	272
1677	9.9 ± 1.2	186 ± 9	273
1676	11.3 ± 1.2	176 ± 10	274
1675	12.0 ± 1.7	172 ± 14	275
1674	9.3 ± 1.4	194 ± 11	276
1673	15.4 ± 1.3	147 ± 10	277
1672	10.9 ± 1.8	183 ± 14	278
1671	15.1 ± 1.3	151 ± 11	279
1670	9.8 ± 1.8	194 ± 14	280
1669	11.2 ± 1.9	184 ± 15	281
1668	12.0 ± 2.0	179 ± 16	282
1667	10.2 ± 1.9	194 ± 15	283
1666	8.3 ± 1.8	209 ± 14	284
1665	6.7 ± 1.4	223 ± 11	285
1664	6.1 ± 1.1	229 ± 9	286
1663	8.7 ± 1.9	209 ± 15	287
1662	7.5 ± 1.8	220 ± 15	288
1661	9.0 ± 1.9	209 ± 15	289
1660	3.9 ± 1.3	250 ± 10	290
1659	6.2 ± 1.9	233 ± 16	291
1658	9.4 ± 1.9	209 ± 15	292
1657	4.4 ± 1.5	249 ± 12	293
1656	4.6 ± 1.6	249 ± 13	294

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1655	6.3 ± 1.6	236 ± 13	295
1654	7.1 ± 1.3	231 ± 10	296
1653	4.0 ± 1.9	256 ± 15	297
1651	4.9 ± 1.9	251 ± 15	299
1650	5.7 ± 1.3	246 ± 10	300
1649	4.0 ± 1.3	260 ± 10	301
1648	3.3 ± 1.8	267 ± 14	302
1647	4.0 ± 1.9	263 ± 16	303
1646	2.6 ± 1.8	275 ± 14	304
1645	2.2 ± 1.7	279 ± 14	305
1644	2.2 ± 1.0	280 ± 8	306
1643	3.8 ± 1.8	268 ± 15	307
1642	1.5 ± 1.8	288 ± 14	308
1641	2.1 ± 2.2	283 ± 17	309
1640	−2.5 ± 1.3	321 ± 11	310
1639	0.6 ± 1.1	298 ± 9	311
1638	−2.6 ± 1.7	324 ± 14	312
1637	0.6 ± 2.2	299 ± 17	313
1636	1.5 ± 1.3	293 ± 10	314
1635	1.3 ± 1.2	295 ± 10	315
1634	−3.4 ± 1.8	334 ± 15	316
1633	−0.2 ± 1.8	310 ± 15	317
1632	−3.6 ± 1.8	338 ± 15	318
1631	−3.3 ± 1.8	337 ± 15	319
1630	−4.0 ± 1.8	343 ± 15	320
1629	−1.0 ± 1.2	319 ± 10	321
1628	−4.7 ± 1.8	351 ± 15	322
1627	−0.4 ± 1.8	317 ± 15	323
1626	−6.4 ± 1.8	366 ± 15	324
1625	−0.8 ± 1.1	322 ± 9	325
1624	−4.0 ± 1.4	349 ± 11	326
1623	2.0 ± 2.0	302 ± 16	327
1622	−2.6 ± 1.3	339 ± 10	328
1621	−2.3 ± 1.8	338 ± 14	329
1620	−0.6 ± 1.3	325 ± 10	330
1619	−0.3 ± 1.8	324 ± 14	331
1618	−1.5 ± 1.7	335 ± 14	332
1617	−4.1 ± 1.8	357 ± 15	333
1616	−5.4 ± 1.7	368 ± 14	334
1615	−4.5 ± 1.3	362 ± 10	335
1614	−1.3 ± 1.8	337 ± 15	336
1613	−5.2 ± 1.7	369 ± 14	337
1612	−1.5 ± 1.8	340 ± 15	338
1611	−6.4 ± 1.3	381 ± 11	339
1610	−2.7 ± 1.8	352 ± 15	340
1609	−3.1 ± 1.6	356 ± 13	341
1608	−3.1 ± 1.4	357 ± 12	342
1607	−4.8 ± 2.0	372 ± 16	343
1606	−4.7 ± 1.1	372 ± 9	344
1605	−5.3 ± 1.4	378 ± 11	345
1604	−7.2 ± 1.3	394 ± 10	346
1603	−4.3 ± 1.9	372 ± 15	347
1602	−2.0 ± 1.8	354 ± 15	348

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1601	−1.5 ± 1.3	351 ± 11	349
1600	0.8 ± 1.2	334 ± 10	350
1599	−1.0 ± 1.8	349 ± 14	351
1598	0.5 ± 1.7	338 ± 14	352
1597	−1.5 ± 1.8	355 ± 15	353
1596	−0.4 ± 1.7	347 ± 14	354
1595	2.2 ± 1.7	327 ± 14	355
1594	2.5 ± 1.8	326 ± 14	356
1593	0.5 ± 1.7	343 ± 13	357
1592	−0.3 ± 2.0	351 ± 16	358
1591	3.7 ± 1.7	319 ± 14	359
1590	4.4 ± 1.8	314 ± 14	360
1589	3.7 ± 1.7	321 ± 14	361
1588	1.1 ± 1.8	343 ± 14	362
1587	1.3 ± 1.7	342 ± 14	363
1586	2.5 ± 1.7	334 ± 14	364
1585	3.7 ± 1.8	325 ± 15	365
1584	0.8 ± 1.8	349 ± 14	366
1583	4.1 ± 1.7	324 ± 13	367
1582	3.1 ± 1.7	333 ± 14	368
1581	−0.2 ± 1.8	361 ± 14	369
1580	3.6 ± 1.7	331 ± 14	370
1579	2.5 ± 1.7	341 ± 14	371
1578	5.2 ± 1.7	320 ± 14	372
1577	3.4 ± 1.8	336 ± 15	373
1576	1.8 ± 1.8	349 ± 14	374
1575	3.9 ± 1.7	334 ± 14	375
1574	4.1 ± 1.8	333 ± 14	376
1573	7.9 ± 1.9	303 ± 15	377
1572	6.3 ± 1.8	317 ± 14	378
1571	5.4 ± 1.9	325 ± 15	379
1570	6.6 ± 1.8	317 ± 15	380
1569	5.6 ± 1.7	325 ± 14	381
1568	4.4 ± 1.8	336 ± 15	382
1567	4.1 ± 1.3	339 ± 10	383
1566	8.0 ± 1.2	309 ± 10	384
1565	7.0 ± 1.9	318 ± 15	385
1564	5.5 ± 1.9	331 ± 16	386
1563	5.1 ± 1.8	335 ± 14	387
1562	5.9 ± 1.7	330 ± 14	388
1561	6.9 ± 1.8	323 ± 15	389
1560	3.2 ± 1.8	354 ± 15	390
1559	7.6 ± 1.8	320 ± 14	391
1558	8.5 ± 1.7	313 ± 14	392
1557	5.7 ± 1.8	337 ± 15	393
1556	9.1 ± 1.8	310 ± 15	394
1555	9.3 ± 1.7	309 ± 13	395
1554	9.2 ± 1.8	311 ± 14	396
1553	7.3 ± 1.8	327 ± 14	397
1552	13.2 ± 2.1	281 ± 16	398
1551	9.7 ± 2.0	310 ± 16	399
1550	9.4 ± 1.1	314 ± 9	400
1549	11.6 ± 2.1	297 ± 17	401

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1548	12.1 ± 1.8	294 ± 14	402
1547	12.6 ± 1.8	291 ± 14	403
1546	8.8 ± 1.8	323 ± 15	404
1545	10.9 ± 1.8	306 ± 14	405
1544	8.6 ± 1.7	325 ± 14	406
1543	10.2 ± 1.6	314 ± 13	407
1542	10.0 ± 1.2	317 ± 10	408
1541	12.1 ± 1.2	301 ± 9	409
1540	10.0 ± 1.2	318 ± 10	410
1539	12.5 ± 1.3	300 ± 10	411
1538	12.3 ± 1.3	302 ± 10	412
1537	15.6 ± 1.2	277 ± 10	413
1536	11.4 ± 1.3	311 ± 10	414
1535	12.4 ± 1.2	305 ± 10	415
1534	11.1 ± 1.3	315 ± 10	416
1533	12.3 ± 1.2	307 ± 10	417
1532	14.5 ± 1.3	291 ± 10	418
1531	14.3 ± 1.7	293 ± 13	419
1530	11.5 ± 1.8	316 ± 14	420

TABLE 2. Single-Year Data *(Continued)*

cal AD	$\Delta^{14}C$ (‰)	^{14}C BP	cal BP
1529	12.8 ± 1.8	307 ± 14	421
1528	12.6 ± 1.6	310 ± 13	422
1527	11.5 ± 1.8	319 ± 14	423
1526	12.4 ± 1.8	313 ± 14	424
1525	10.6 ± 1.3	328 ± 10	425
1524	10.0 ± 1.8	334 ± 14	426
1523	10.2 ± 1.7	334 ± 14	427
1522	9.1 ± 2.0	344 ± 16	428
1521	11.0 ± 2.0	329 ± 16	429
1520	8.5 ± 1.8	350 ± 14	430
1519	6.4 ± 1.9	367 ± 16	431
1517	11.6 ± 1.8	328 ± 14	433
1516	9.2 ± 1.7	348 ± 14	434
1515	8.5 ± 1.6	355 ± 13	435
1514	10.0 ± 1.8	344 ± 14	436
1513	10.5 ± 1.8	341 ± 14	437
1512	10.0 ± 1.8	346 ± 14	438
1511	6.9 ± 1.7	371 ± 13	439
1510	8.5 ± 1.8	359 ± 14	440

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VARIATIONS OF RADIOCARBON IN TREE RINGS: SOUTHERN HEMISPHERE OFFSET PRELIMINARY RESULTS

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ABSTRACT. The Queen's University of Belfast, Northern Ireland and University of Waikato, Hamilton, New Zealand radiocarbon laboratories have undertaken a series of high-precision measurements on decadal samples of dendrochronologically dated oak (*Quercus patrea*) and cedar (*Libocedrus bidwillii*) from Great Britain and New Zealand, respectively. The results show a real atmospheric offset of 3.4 ± 0.6‰ (27.2 ± 4.7 ^{14}C yr) between the two locations for the interval AD 1725 to AD 1885, with the Southern Hemisphere being depleted in ^{14}C. This result is less than the value currently used to correct Southern Hemisphere calibrations, possibly indicating a gradient in $\Delta^{14}C$ within the Southern Hemisphere.

INTRODUCTION

A number of studies have demonstrated a measurable difference between the ^{14}C activities of dendrochronologically dated trees between the hemispheres (Lerman, Mook and Vogel 1970; Vogel *et al.* 1986; Vogel *et al.* 1993). Vogel *et al.* (1993) measured $\Delta^{14}C$ in fourteen pairs of dendrochronologically dated wood from South Africa and the Netherlands and calculated an offset of 5.15 ± 0.59‰ (41 ± 5 ^{14}C yr), with the Southern Hemisphere wood giving the older dates. This value is used to correct Southern Hemisphere radiocarbon determinations for age calibration. However, Sparks *et al.* (1995) found no hemispheric offset in New Zealand matai (*Prumnopitys taxifolia*) from a single, non-crossdated tree spanning AD 1335–1745. Barbetti *et al.* (1995) reported a negligible offset in Tasmanian wood compared with European oak at 10,000–9,500 cal BP and minimal offsets between AD 1600 and 1800, although the ^{14}C measurements for these series lack high levels of precision (Barbetti *et al.* 1992, 1995).

Recently, Damon, Cheng and Linick (1989), Damon *et al.* (1992) and Damon (1995a,b) have identified significant differences (*ca.* 4–7‰) between contemporaneous tree rings in the same hemisphere from Tucson, the Olympic Peninsula of Washington State and the Mackenzie Valley in the Arctic Circle. McCormac *et al.* (1995) have suggested location-dependent differences in ^{14}C from contemporaneous trees in Ireland and the United States; Stuiver and Braziunas (1998) and McCormac *et al.* (1998) have shown variations in the value of the interhemispheric ^{14}C offset. These authors have suggested that regional effects may not be temporally constant.

In this paper, we describe a research program designed primarily to verify the existence and magnitude of the hemispheric offset in ^{14}C between New Zealand and Great Britain. The program is a collaborative effort among the radiocarbon laboratories at The Queen's University of Belfast, Northern Ireland (QUB) and the University of Waikato in New Zealand (Wk) and the tree-ring laboratories at the Department of Plant Sciences at Lincoln University in New Zealand and the Palaeoecology Centre at QUB. We are in the process of measuring $\Delta^{14}C$ in successive decadal samples of dendrochronologically dated Irish/English oak and New Zealand cedar spanning the period AD 1000–1945 to investigate location dependence and the hemispheric offset. In this paper, we describe our methodology, provide the results of a preliminary intercomparison exercise designed to identify any interlaboratory differences and give preliminary results for the offset between Great Britain and New Zealand in the interval AD 1725 to 1885. Our preliminary measurements between AD 1885 and AD

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1935 (not discussed in detail here) indicate a hemispheric response to fossil fuel input in the Northern Hemisphere (McCormac *et al.* 1998).

METHODS

The intrahemispheric location-dependent differences in $\Delta^{14}C$ identified by McCormac *et al.* (1995) are small (on the order of 2.5‰) and may be time dependent. As a consequence, intercomparison of results from different regions tends to be difficult and laboratory offsets can easily mask real atmospheric variation. The only satisfactory way to determine the magnitude of regional offsets, should they exist, is to measure $\Delta^{14}C$ in contemporaneous sample pairs within a single laboratory and replicate the measurements in another laboratory. Duplication of the measurements by the two laboratories has enabled us to compare inter- and intralaboratory data sets and to obtain duplicate high-precision (HP; $\Delta^{14}C$ $\sigma \leq 2‰$) curves for the validation of results. The advantage of duplicate intralaboratory measurements is that there are no external offsets to consider, hence relative differences between the ^{14}C dates of wood from both hemispheres should be real.

Three components are critical to the success of the research program: dendrochronology, wood pretreatment and analytical reproducibility.

Dendrochronology

It is critical that the wood used in HP ^{14}C calibration comes from securely crossdated and well replicated tree-ring chronologies. Dendrochronological errors can easily create false offsets in the $\Delta^{14}C$ values between regions or between significant sections of the calibration chronologies (Kromer *et al.* 1996). In designing this study we have used oak from the long-established Irish oak master chronology (Pilcher *et al.* 1984) and the recently developed New Zealand cedar (*Libocedrus bidwillii*) chronology (Xiong 1995). The dendrochronology of the oak from the British Isles has been both externally and internally cross-linked and has provided the basis for previous calibration studies (Baillie 1995; Pearson and Stuiver 1986, 1993). The oak trees actually used for the measurements shown in this paper were obtained from parkland at Shane's Castle, County Antrim, Northern Ireland (54°44′N, 06°16′W) (AD 1935–1755) and Sherwood Forest, England (53°12′N, 01°04′W) (AD 1725–1745).

The New Zealand cedar chronology is now established for the period AD 1950 to AD 1140 and is derived from 11 different sites and over 200 trees (Xiong 1995). The specific tree selected for this study was one of 43 crossdated trees from the Hihitahi State Forest, near Waiouru in the central North Island of New Zealand (39°32′S, 175°44′E).

All wood samples were split into decadal blocks each weighing between 120 and 180 g.

Wood Pretreatment

By necessity, the tree species used for this study was different in each of the hemispheres. We therefore sought to pretreat the wood to a reliable fraction of cellulose that would reflect the ambient atmospheric conditions at the time of growth and would not be affected by variable lignin fractions or species-specific differences. A variety of methods have been applied to pretreat wood for radiocarbon calibration because of the possibility of translocation of resins and sugars across rings (Tsoumis 1969: 60–89; Olsson 1979). The de Vries method (Stuiver and Quay 1981) utilizes treatment with dilute NaOH and HCl to remove resins, sugars and some lignins. A full description is given in Stuiver, Burk and Quay (1984), detailing the method for pretreatment to α-cellulose used at the University of Washington, Seattle laboratory for the 1986 calibration measurements (Stuiver and Pearson 1986). The Belfast laboratory used a different method involving the bleaching of the wood using sodium chlorite and 0.018N HCl at 70°C followed by charring of the cellulose at 500°C to produce a carbon-rich residue (Pearson and Stuiver 1986). Linick *et al.* (1986) pretreated bristlecone pine to holocellulose using acetic acid and sodium chlorite. For this study we have pretreated both wood types to α-cellulose. The method used is described in detail in Hoper *et al.* (1998), where an investigation into the effectiveness of the sample pretreatment method is described.

Radiocarbon Analysis

Both Waikato and Belfast laboratories measure $\Delta^{14}C$ by liquid scintillation counting of benzene, using the same type of spectrometers (Wallac Quantulus 1220™) and similar benzene synthesis systems. The Wallac Quantulus 1220™ is an optimized spectrometer designed for low-level counting (Polach *et al.* 1988). For high-precision measurements, the stability and performance of the Quantulus for $\Delta^{14}C$ measurement may be further increased by manual control of the high voltage (HV) supply to the guard and sample photomultiplier tubes (McCormac 1992). The Waikato laboratory operates two factory-modified manual high-precision versions of the Quantulus using a similar system. One is set up using manual HV control, the other using automatic HV.

The Waikato and Belfast laboratories use different methods to obtain an analytical precision of *ca.* ±2‰. The Belfast laboratory uses single 15 mL aliquots of benzene to achieve high levels of precision (±2–3‰). Standard deviations at Belfast include the Poisson counting error and an error multiplier to account for replicate sample variability. The Waikato laboratory utilizes duplicate 7.5 g (*ca.* 8 mL) aliquots of benzene for each equivalent single HP measurement and then combines the two measurements, provided the results are statistically representative of the same mean value. This provides a continuous measure of internal reproducibility. The precision of each decadal measurement is *ca.* ±2.5‰, with a final mean precision for each decadal sample of *ca.* ±2‰.

Intercomparison

We have undertaken an intercomparison exercise to quantify Wk/QUB offsets, beginning by remeasuring multiple samples of the International Reference Materials HOxI and HOxII (Long 1995). The Belfast and Waikato HOxI/HOxII activity ratios are presented in Table 1.

TABLE 1. HOxI/HOxII Activity Concentration Ratios Measured at Waikato and Belfast (error-weighted mean)

Laboratory	Ratio HOxI/HOxII
Waikato mean	1.2887 ± 0.0013
Belfast mean	1.2895 ± 0.0008

The error-weighted mean calculated was statistically indistinguishable from the international weighted average reported by Mann (1983) of 1.2893 ± 0.0004.

Despite the consistency of these standards, the cedar and oak measurements made independently in Waikato and Belfast do show measurable differences. When we compare the measurements on identical oak and cedar samples, the laboratory differences are 9.1 ± 6.4 and 10.9 ± 5.6 yr, respectively. It seems likely that this difference may be explained in part by the use of different standards in the two laboratories (HOxII in Belfast and ANU Sucrose in Waikato).

Results

The results of both the QUB and Wk paired measurements on cedar and oak for the interval AD 1725 to 1935 are shown in Figures 1 and 2, respectively. The offsets between the cedar and oak determined independently in both laboratories are shown in Figure 3. By combining the results from both laboratories and calculating the error-weighted mean of the difference over the interval, we obtain an offset of 27.2 ± 4.7 ^{14}C yr. This is less than the value reported by Vogel *et al.* (1986, 1993) and may indicate a regional difference in the hemispheric offset because in both this study and that of Vogel *et al.* (1986, 1993) the offsets were determined by intralaboratory measurements. A recent publication by Stuiver and Braziunas (1998) shows data from Chile, Tasmania and the United States that give a hemispheric offset value of 23 ± 4 yr for the 19th century.

Conclusions

Intralaboratory ^{14}C measurements of Southern and Northern Hemisphere wood avoid laboratory biases and enable determination of the offset in $\Delta^{14}C$ between the hemispheres without reconciling interlaboratory differences. Using this protocol and producing replicate measurements in QUB and Wk of the $\Delta^{14}C$ content of α-cellulose derived from decadal samples of dendrochronologically

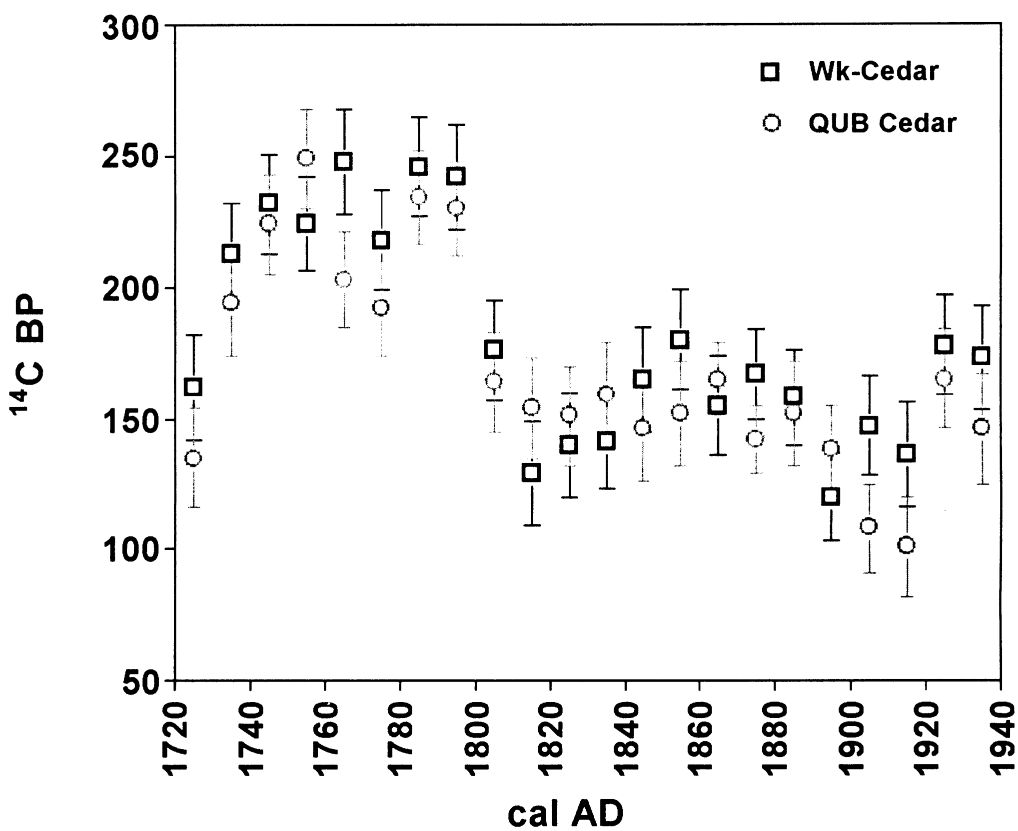

Fig. 1. ^{14}C measurements (yr BP) made at QUB and Wk on decadal blocks of cedar from New Zealand

dated oak from Northern Ireland and cedar from the North Island of New Zealand, we have found that an offset of 3.4 ± 0.6‰ (27.2 ± 4.7 ^{14}C yr) exists between the two locations for the interval AD 1725 to AD 1885.

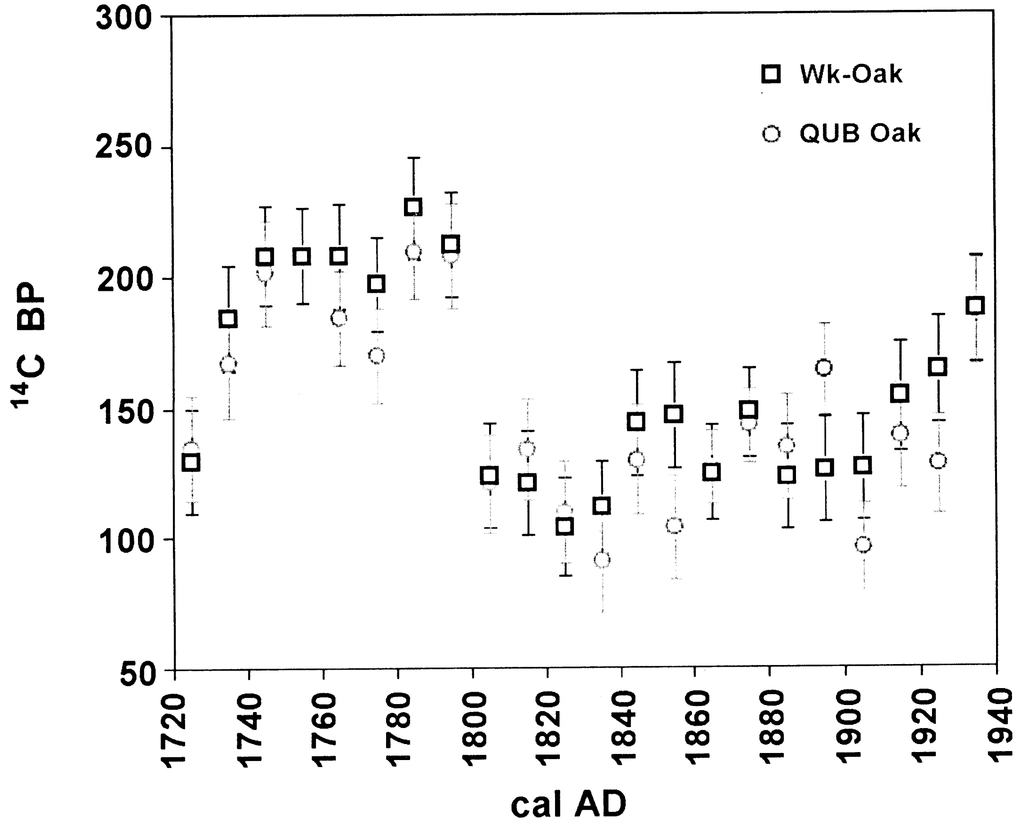

Fig 2. ^{14}C measurements (yr BP) made at QUB and Wk on decadal blocks of oak from England and N. Ireland

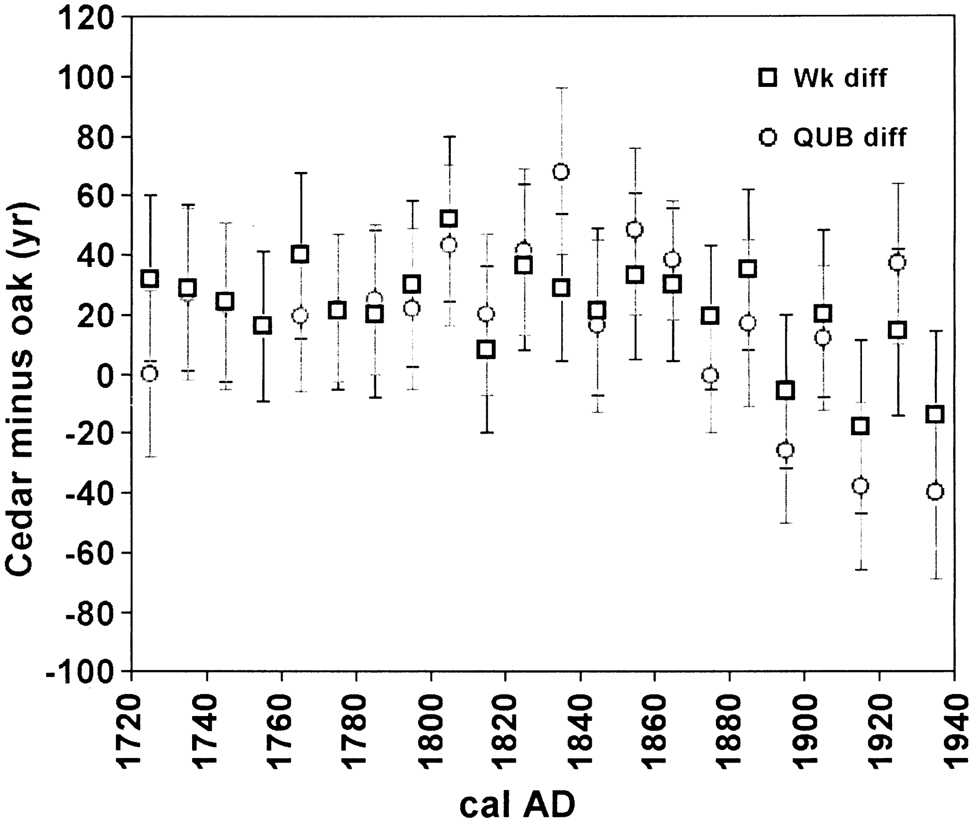

Fig 3. Hemispheric differences (yr) between individual decadal measurements of oak from the British Isles (~54°N) and cedar from New Zealand (~39°S) made at QUB and Wk

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RADIOCARBON UPDATES

Call for ^{14}C Calibration Data

RADIOCARBON is planning a "comparison issue" as a companion to INTCAL98. It will supplement and perhaps refine the calibration curve presented in this issue, derived primarily from tree-ring and coral data, with comparisons based on other chronologies such as varved sediments, ice cores and speleothems. If you are working on a record of this type and would be interested in contributing to this volume, you are encouraged to contact one of the project editors:

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Online Database of RADIOCARBON Articles

The *RADIOCARBON* World Wide Web server now has a full-text searchable database of articles published from Volume 36 (1994) to present. The archived articles are in text-only form (no graphics, equations, special characters, *etc.*), but we hope that they will prove a useful resource for researchers seeking to locate references to names, sites, locations and other features. Access is limited to *RADIOCARBON* subscribers (individual or institutional); for information, please refer to URL http://www.radiocarbon.org/Subscribers/search.html.

Award

Dr. Rodger Sparks, manager of the Rafter Radiocarbon Laboratory at the Institute of Geological and Nuclear Sciences, New Zealand, has received the 1998 Marsden Medal awarded by the New Zealand Association of Scientists. The Marsden Medal is awarded annually for "outstanding service to science and in recognition of services rendered to the cause or profession of science". (The full text of Dr. Sparks' citation can be found on the NZAZ website at http://nzas.rsnz.govt.nz/awardlst.html.)

New Laboratory

Uruguay now has a radiocarbon laboratory at the Universidad de la República in Montevideo. Counting is done using a Packard 1600TR liquid scintillation counter. The main research fields at present are Late Pleistocene and Holocene coastal conditions in Uruguay and the prehistoric mounds of the Laguna Merin basin of eastern Uruguay.

Laboratory information:

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Universidad de la República
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E-mail: radquim@bilbo.edu.uy

Laboratory Address Changes

The radiocarbon laboratory previously housed at the University of Leipzig has moved to the "Umweltforschungszentrum" (Centre for Environmental research) in Halle, Germany. The new address is:

LZ Dr. Achim Hiller
UFZ-Umweltforschungszentrum Leipzig-Halle GmbH
Sektion Hydrogeologie
Arbeitsgruppe Paläoklimatologie
Theodor-Lieser-Strasse 4
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E-mail: hiller@hdg.ufz.de

Please note the following corrections and updates to our laboratory listing for the Physical Research Laboratory in Ahmedabad, India:

PRL Dr. Sheela Kusumgar and Mr. M. G. Yadava
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Publication Received

Harkness, D. D., Miller, B. F. and Tipping, R. M. 1997 NERC radiocarbon measurements 1977–1988. *Quaternary Science Reviews* 16: 925–927. [This issue of *QSR* includes a CD-ROM containing all of NERC's ^{14}C age reports between 1977 and mid-1988. The reports may be searched by fields (submitter, location, etc.) or by full text using an included search engine.]

CORRECTIONS

We regret a textual error and poorly reproduced figure in one of the articles from the Groningen Conference proceedings. Please take note of the following corrections:

Bas van Geel, Johannes van der Plicht, M. R. Kilian, E. R. Klaver, J. H. M. Kouwenberg, H. Renssen, I. Reynaud-Farrera and H. T. Waterbolk. The sharp rise of $\Delta^{14}C$ *ca.* 800 cal BC: Possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* Vol. 40, No. 1 (1993): 535–550.

Abstract, p. 535, second line: for "paleological", read "paleoecological".

Figure 2, p. 593: please see the replacement figure on the following page.

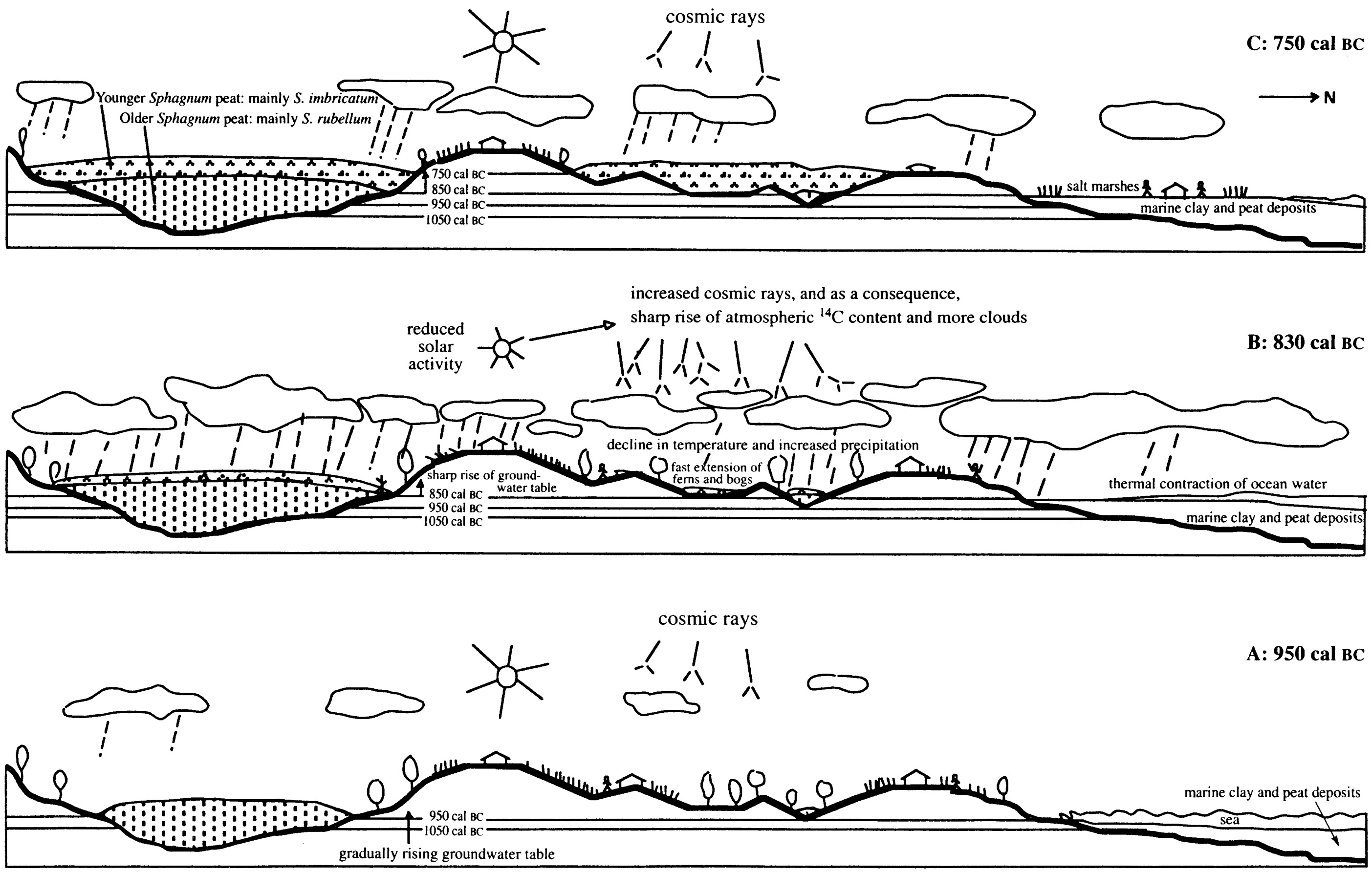

Fig. 2. Development of the landscape in the northern Netherlands during the older part of the first millennium BC under influence of climate change. Between phases A and B a decline of solar irradiance caused an increase in cosmic rays, resulting in a sharp increase in the atmospheric ^{14}C content and also in more clouds, more precipitation and lower temperatures (change of atmospheric circulation patterns). Consequently, there was a sharp increase of the groundwater level and enhanced bog growth. Farmers in hydrologically marginal areas had to move to drier sites. Salt marshes emerged, probably as a consequence of thermic contraction of ocean water, and these areas were colonized. When the solar irradiance changed again to the less extreme values, the atmospheric circulation patterns did not move to their earlier positions and, consequently, the relatively cool and wet climate persisted.

Jerusalem 2000 ירושלים

17th International Radiocarbon Conference

Preliminary Announcement

We have the pleasure to announce that the 17th International Radiocarbon Conference is scheduled to take place June 18–23 in the year 2000 in Israel.

The Conference will be held at a beautiful location, in the rural setting of *kibbutz* Ma'ale Hahamisha, which is just 15 km west of Jerusalem. The kibbutz offers an attractive self-contained arrangement of excellent accommodations and conference facilities, which will enable a high degree of interaction between the conference participants. The City of Jerusalem with its unique history and tourist attractions is nearby and can easily be reached by bus or taxi.

The scientific program will include a wide variety of topics in the tradition of past Radiocarbon Conferences, with a glance into a new millennium: *e.g.*, Archaeology, Environment past and present, Groundwater, Oceanography, Calibration and Measurement Techniques. More details will be given in the first circular, to be issued soon.

The social program of the conference will include an afternoon walking tour in the Old City of Jerusalem and a one-day tour in the unique Dead Sea area.

Suggestions about conference topics, as well as proposals for workshops, etc., are very much welcome and can be sent to the organizing committee by fax or e-mail.

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Jerusalem 2000 ירושלים

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NOTICE TO READERS AND CONTRIBUTORS

The purpose of *RADIOCARBON* is to publish technical and interpretive articles on all aspects of ^{14}C and other cosmogenic isotopes. In addition, we present regional compilations of published *and unpublished* dates along with interpretive text. Besides the triennial Proceedings of Radiocarbon Conferences, we publish special issues that focus on particular themes. Organizers interested in such arrangements should contact the Managing Editor for information.

Our regular issues include NOTES AND COMMENTS, LETTERS TO THE EDITOR, RADIOCARBON UPDATES and BOOK REVIEWS. Authors are invited to extend discussions or raise pertinent questions regarding the results of investigations that have appeared on our pages. These sections also include short technical notes to disseminate information concerning innovative sample preparation procedures. Laboratories may also seek assistance in technical aspects of radiocarbon dating. We include a list of laboratories and a general index for each volume.

Manuscripts. When submitting a manuscript, include three printed copies, double-spaced, and a floppy diskette, single-spaced. We will accept, in order of preference, FrameMaker, WordPerfect, Microsoft Word, or any standard word-processing software program on 3½" IBM disks, or high-density Macintosh diskettes. We also accept e-mail and ftp transmissions of manuscripts. Papers should follow the recommendations in INSTRUCTIONS TO AUTHORS (1994, Vol. 36, No. 1). Offprints of these guidelines are available upon request. Our deadlines for submitting manuscripts are:

For	*Date*
Vol. 41, No. 2, 1999	January 1, 1999
Vol. 41, No. 3, 1999	May 1, 1999
Vol. 42, No. 1, 1999	September 1, 1999

Half-life of ^{14}C. In accordance with the decision of the Fifth Radiocarbon Dating Conference, Cambridge, England, 1962, all dates published in this volume (as in previous volumes) are based on the Libby value, 5568 yr, for the half-life. This decision was reaffirmed at the 11th International Radiocarbon Conference in Seattle, Washington, 1982. Because of various uncertainties, when ^{14}C measurements are expressed as dates in years BP, the accuracy of the dates is limited, and refinements that take some but not all uncertainties into account may be misleading. The mean of three recent determinations of the half-life, 5730 ± 40 yr, (*Nature*, 1962, Vol. 195, No. 4845, p. 984), is regarded as the best value presently available. Published dates in years BP can be converted to this basis by multiplying them by 1.03.

AD/BC Dates. In accordance with the decision of the Ninth International Radiocarbon Conference, Los Angeles and San Diego, California, 1976, the designation of AD/BC, obtained by subtracting AD 1950 from conventional BP determinations is discontinued in *RADIOCARBON*. Authors or submitters may include calendar estimates as a comment, and report these estimates as cal AD/BC, citing the specific calibration curve used to obtain the estimate. Calibrated dates should be reported as "cal BP" or "cal AD/BC" according to the consensus of the Twelfth International Radiocarbon Conference, Trondheim, Norway, 1985.

Measuring ^{14}C. In Volume 3, 1961, we endorsed the notation Δ, (Lamont VIII, 1961), for geochemical measurements of ^{14}C activity, corrected for isotopic fractionation in samples and in the NBS oxalic-acid standard. The value of $\delta^{14}C$ that entered the calculation of Δ was defined by reference to Lamont VI, 1959, and was corrected for age. This fact has been lost sight of, by editors as well as by authors, and recent papers have used $\delta^{14}C$ as the observed deviation from the standard. At the New Zealand Radiocarbon Dating Conference it was recommended to use $\delta^{14}C$ only for age-corrected samples. Without an age correction, the value should then be reported as percent of modern relative to 0.95 NBS oxalic acid (Proceedings of the 8th Conference on Radiocarbon Dating, Wellington, New Zealand, 1972). The Ninth International Radiocarbon Conference, Los Angeles and San Diego, California, 1976, recommended that the reference standard, 0.95 NBS oxalic acid activity, be normalized to $\delta^{13}C = -19‰$.

In several fields, however, age corrections are not possible. $\delta^{14}C$ and Δ, uncorrected for age, have been used extensively in oceanography, and are an integral part of models and theories. Thus, for the present, we continue the editorial policy of using Δ notations for samples not corrected for age.

RADIOCARBON is indexed and/or abstracted by the following sources: *Anthropological Index; Anthropological Literature; Art and Archaeology Technical Abstracts; Bibliography and Index of Geology* (GeoRef); *British Archaeological Bibliography; Chemical Abstracts; Chemistry Citation Index; Current Advances in Ecological and Environmental Sciences; Current Contents* (ISI); FRANCIS (Institut de l'Information Scientifique et Technique – CNRS); *Geographical Abstracts; Geological Abstracts; Oceanographic Literature Review; Science Citation Index; Social Sciences Citation Index.*