VOLUME 31 / NUMBER 2 / 1989

Radiocarbon

An International Journal of Cosmogenic Isotope Research

4717 East Ft Lowell Road
Department of Geosciences
The University of Arizona
Tucson, Arizona 85712

ISSN: 0033-8222

RADIOCARBON
An International Journal of Cosmogenic Isotope Research

Editor: AUSTIN LONG
Managing Editor: RENEE S KRA
Published by
Department of Geosciences
The University of Arizona

Published three times a year at The University of Arizona, Tucson, AZ 85712.

Subscription rate $90.00 (for institutions), $60.00 (for individuals), available only in whole volumes. The Proceedings of the Thirteenth International Radiocarbon Conference, Vol 31, No. 3, 1989 are $60.00. The Proceedings of the Twelfth International Radiocarbon Conference, Vol 28, Nos. 2A and 2B, 1986 are $60.00. No. 2B, the Special Calibration Issue, is available separately for $30.00. The full subscription for 1986 which includes the Proceedings is $80.00 (institutions) and $60.00 (individuals). The Proceedings of the Eleventh International Radiocarbon Conference, Vol 25, No. 2, 1983 are $50.00, and the Proceedings of the Tenth International Radiocarbon Conference, Vol 22, Nos. 2 and 3, 1980 are $60.00.

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List of laboratories. Our comprehensive list of laboratories appears at the end of each volume. We ask all laboratory directors to provide their telephone, telex and fax numbers as well as their E-mail addresses. Changes in names or addresses, additions, or deletions should also be reported to the Managing Editor.

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FROM THE EDITOR

CARBON-14 PRODUCTION IN AIRPORT SECURITY DEVICES

A few of our colleagues, upon receiving a radiocarbon date younger than they expected, have wondered if X-rays in airport security devices might have increased their ^{14}C content. Unfortunately for them, our colleagues have been forced to find alternate explanations for the uncooperative dates. Airport X-rays simply cannot produce ^{14}C. However, a new security technology is almost ready for installation at Kennedy Airport for some international flights, and, according to the Wall Street Journal, 100 additional units are planned for other high-risk airports. The new device will detect high concentrations of nitrogen (a component in explosives) by thermal neutron activation (TNA). Since TNA on a global scale is the process by which nature produces virtually all ^{14}C in the atmosphere, some ^{14}C must be produced in high-nitrogen materials, such as bones, as they pass through a neutron activation airport security device. The question important to the radiocarbon dating community is how much effect can the ^{14}C thus produced have on the ^{14}C date?

According to Peter Ryge, of Science Applications International Corporation (SAIC), in Santa Clara, California, one pass through this TNA security device, developed by SAIC, will produce a maximum of 3.6×10^{-12} μCi (8.0×10^{-6} disintegrations per minute (dpm)) of ^{14}C in one gram of nitrogen. This is equivalent to adding about $3.4 \times 10^{+5}$ atoms of ^{14}C. In terms of calculated effects on actual samples, 10 grams of carbon from bone protein containing about 1 gram of nitrogen for every 3 grams of carbon, could thus increase its ^{14}C activity by 7.2×10^{-4} dpm (add $3 \times 10^{+6}$ atoms) in 3 passes through the airport nitrogen detector. This is 3 orders of magnitude below detection limit of virtually all radiocarbon dating systems. A bone specimen originally containing "no" ^{14}C before neutron activation, would acquire a hypothetical ^{14}C age of 116,000 years. Clearly, the airport nitrogen detector, with expected routine use, would have no measurable effect on the ^{14}C age of samples intended for dating. So goes another potential explanation for spurious dates.

Austin Long

TIMOTHY W LINICK

OCTOBER 29, 1946–JUNE 4, 1989

Timothy Weiler Linick died on June 4th, 1989. He was a dedicated researcher, and an important part of the NSF Accelerator Facility for Radioisotope Analysis at the University of Arizona. He will be remembered for his care and attention to details, especially in the calculation and reporting of radiocarbon dates. He made important contributions to the fields of oceanography and tree-ring calibration of the ^{14}C time scale.

Tim was born in Los Angeles, California in 1946. He lived most of his life in southern California, attending high school in Palm Springs. He attended the University of California, Riverside, and received his BA in 1968. His graduate work was done at Scripps Institution of Oceanography under the direction of Professor Hans Suess. He received his doctorate in 1975. He continued to work with Hans Suess until 1982, when he moved to Tucson to work on liquid scintillation counting, and more recently, accelerator mass spectrometry. His thesis work on "The Uptake of Bomb Radiocarbon by the Pacific Ocean" is one of the most important works on the radiocarbon content of the oceans. Tim's knowledge of this subject, as well as the intricacies of tree-ring calibrations of ages were often a great asset in our laboratory.

Tim is survived by his wife, Constance and his eight-year old son Gregor. His untimely death is a great loss to them and to his co-workers, both in Tucson and around the world.

AJT Jull

Timothy was my graduate student and later was a co-worker in my laboratory, mainly involved in data reduction and the interpretation of the results. He was an extremely mathematically gifted and careful worker. His death is a loss, not only to my personal research interests, but also to the whole radiocarbon research community.

Hans E Suess

[RADIOCARBON, VOL 31, NO. 2, 1989, P 105–116]

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1989

RADIOCARBON DATING OF DEEP-SEA SEDIMENTS: A COMPARISON OF ACCELERATOR MASS SPECTROMETER AND BETA-DECAY METHODS

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INTRODUCTION

Radiocarbon dating (Libby, 1955) has been an important tool in the marine sciences since the early 1950s (eg, Arrhenius, Kjellberg & Libby, 1951; Ericson *et al,* 1956; Broecker, Ewing & Heezen, 1960; Emery & Bray, 1962) and the basic principles and analytic procedures of the method have changed little. In the late 1970s, the Accelerator Mass Spectrometer (AMS) method of ^{14}C dating was developed (Bennett *et al,* 1977, 1978), the major advantages being that samples several thousand times smaller than needed for beta-decay counting can be dated, and analysis time is reduced to ca 1 hr from the 1–6 days needed for beta-decay methods.

The deep-sea sediment record is ideally suited for ^{14}C dating by AMS, as there is often insufficient material available for both dating by beta-decay methods and performing other sedimentologic analyses. In many regions of the ocean, there is a significant component of eolian or glacially transported detrital carbonate, or reworked fine-grained biogenic carbonate (*ie,* ^{14}C-dead material). This material is mixed with contemporaneously produced biogenic carbonates, resulting in erroneously old, and often uninterpretable, ^{14}C ages when bulk-sediment analyses are made.

Despite the wide acceptance and clear utility of AMS dating in the marine geological sciences (eg, Broecker *et al,* 1984; Duplessey *et al,* 1986; Bard *et al,* 1987; Andrée *et al,* 1986), there has been no direct comparison of this method with the well-established beta-decay method of ^{14}C dating deep-sea sediments.

Within the past three years, Woods Hole Oceanographic Institution has become one of the largest users of the National Accelerator Facility at the University of Arizona, submitting some 300–400 samples annually. Most of these samples are carbonates obtained from the various components found in deep-sea sediments. Before undertaking AMS studies, we conducted a study in 1984–1985 to compare directly AMS and beta-decay

methods of dating deep-sea sediments, as well as to compare the iron-carbide (Linick *et al*, 1986) and graphite (Jull *et al*, 1986; Slota *et al*, 1987) methods of target preparation for AMS. This was an empirical study designed to identify the potential problems and/or advantages of using either method for a wide range of deep-sea-sediment studies, and obtain a base line of intercompared AMS and beta-decay ^{14}C dates from the same deep-sea sediment core. Fourteen conventional and 21 AMS ^{14}C analyses are reported from Equatorial Atlantic core V30-41K.

METHODS

V30-41K Core Description

Kasten core V30-41K (00° 13′ N, 23° 4′ W; 3874m water depth,) was collected from the eastern flanks of the mid-Atlantic Ridge by Lamont-

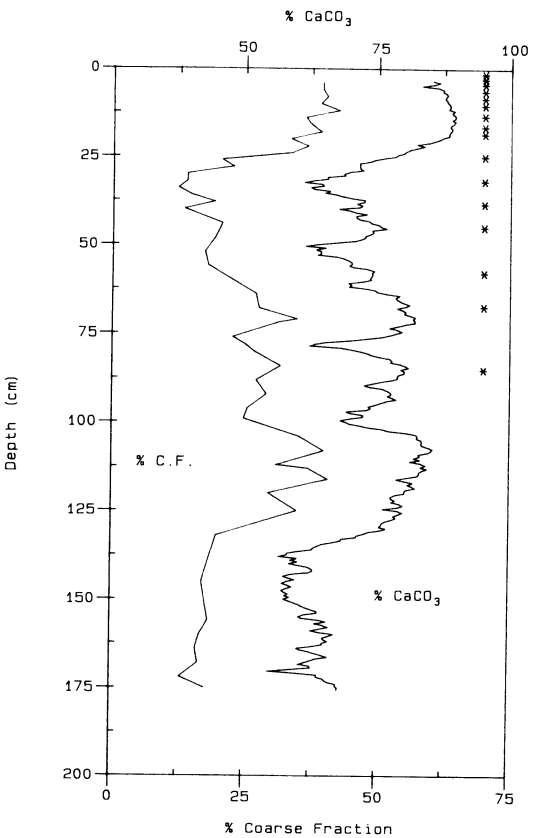

Fig 1. Coarse-fraction (>63μ) and $CaCO_3$ percentage determinations. $CaCO_3$ percentages were determined at 0.5cm intervals using the method of Jones and Kaiteris (1983). Coarse-fraction percentages were determined at ca 4cm intervals. Intervals sampled for ^{14}C determinations are marked with an asterisk (*). Exact depths of these analyses are given in Table 1.

Doherty Geological Observatory in 1973. This core is 176cm long and has been extensively studied (Jones & Ruddiman, 1982). It is an average Equatorial Atlantic core, with an approximately linear sedimentation rate over the past 35,000 years, no visible anomalous sediment features and no extensive carbonate dissolution. This core contains no evidence of downslope reworking, and is from a region relatively free of detrital carbonate (*ie,* ^{14}C-dead) input. Thus, V30-41K was chosen as a good direct test of beta-decay and AMS ^{14}C dating.

For this study, we have analyzed both the bulk (total) $CaCO_3$ and the $>150\mu$ fractions by AMS, and bulk $CaCO_3$ by beta-decay methods because these are the two most commonly used fractions for paleoceanographic studies. Most beta-decay ^{14}C dates from deep-sea sediment cores are obtained from the total carbonate fraction, while most paleoceanographic information is obtained from analyses of planktonic and benthonic foraminifera in the $>150\mu$ size fraction. Figure 1 shows the downcore profiles of coarse-fraction ($>63\mu$, entirely composed of planktonic and benthonic foraminifera) and total-sediment carbonate percentages for this core.

Beta-Decay Dating Techniques

With conventional methods of ^{14}C dating, ca 10–40g of carbonate (*ie,* ca 1–4g C) are acidified, and the CO_2 is most often converted to either acetylene (Suess, 1954) or benzene (Barker, 1953). Depending upon the age of the sample and the precision desired, a sample is counted from 1–6 days. On average, most ^{14}C laboratories achieve an analytical precision of ±4–7‰ for material of modern age. For a more thorough treatment of the principles of ^{14}C dating by the beta-decay method, see, eg, Libby (1955), Faure (1977) and Berger and Suess (1979).

We used 14 beta-decay analyses of bulk sediment (Table 1, Fig 2). Sample sizes ranged from 20–40g. The results are reported as conventional ^{14}C ages (Stuiver & Polach, 1977), and no reservoir corrections have been applied (Stuiver & Ostlund, 1980).

AMS Dating Techniques

For AMS ^{14}C dating of marine sediments, 10–30mg of carbonate (*ie,* 1–3mg of C) were used. CO_2 was produced by acidification with phosphoric acid *in vacuo.* The CO_2 was reduced to CO over hot Zn and further reduced over hot Fe to iron-carbide (Linick *et al,* 1986) or elemental carbon (Jull *et al,* 1986; Slota *et al,* 1987). The analytical precision obtained with the iron-carbide targets is ±20–30‰ for modern materials, and the background is ca 30,000 yr. This method was used by the US National Accelerator Facility in Tucson, Arizona from May 1982 to late 1984. Since late 1984, this facility has used graphite targets. The analytical precision of this method is ±5–10‰ for modern material, and the background is ca 45,000 yr.

We obtained 21 AMS ^{14}C dates from Equatorial Atlantic core V30-41K (Table 1, Fig 2). The results are reported as conventional ^{14}C ages (Stuiver & Polach, 1977), and no reservoir corrections were applied (Stuiver & Ostlund, 1980).

TABLE 1
Radiocarbon ages for Equatorial Atlantic core V30-41K

Depth (cm)	Beta-decay* (total sediment)	Graphite (total sediment)	Accelerator** Graphite (>150μ)	Iron-carbide (>150μ)
0–1	5800 ± 260†			
1–2			6170 ± 90	6510 ± 290
2.5–4	(2100 ± 120)†			
4–5	(2420 ± 200)†			
6–7	2490 ± 80‡	2500 ± 70	2760 ± 80	
8–9			2920 ± 70	
10–11	(3750 ± 230)†			
13–14	4490 ± 100‡	4340 ± 80	4830 ± 80	5610 ± 260
13–14			4520 ± 130	
18–19	(7890 ± 350)†			
24–26	(10,870 ± 360)†			
31–32	(12,610 ± 610)†			
32–33		12,860 ± 160	13,930 ± 170	14,400 ± 600
38–39	(15,230 ± 840)†			
44–46	(19,080 ± 920)†	18,150 ± 210	17,740 ± 190	18,200 ± 1000
57.5–59	22,100 ± 290§			
66–67.5	25,000 ± 310§			
68–69		30,450 ± 790	27,840 ± 480	29,600 ± 3900
84–85		36,120 ± 1380	33,970 ± 760	>30,000
84–87	25,040 ± 460‡			

* Dates in parentheses have been reported previously in Jones and Ruddiman (1982).

** Analyses made at University of Arizona, Tucson Accelerator Facility between 1984–85. Conventional ^{14}C ages are given with an assumed ^{13}C value of 0‰ used for $\delta^{13}C$ correction to −25‰.

† Analyses made at Lamont-Doherty Geological Observatory radiocarbon laboratory in 1978. Conventional ^{14}C ages are given with an assumed ^{13}C value of 0‰ used for $\delta^{13}C$ correction to −25‰.

‡ Analyses made at Beta Analytic between 1983–85. Conventional ^{14}C ages are given with measured ^{13}C values used for $\delta^{13}C$ correction to −25‰.

§ Analyses made at Beta Analytic between 1983–85. Conventional ^{14}C ages are given with an assumed ^{13}C value of 0‰ used for $\delta^{13}C$ correction to −25‰.

RESULTS AND DISCUSSION

Core-top Ages

Most deep-sea sediment studies assume that the sediment-water interface (*ie,* the "true" coretop) is either recovered infrequently or is disturbed by coring devices (*eg,* Wrath, 1936; Burns, 1963; Hopkins, 1964; Emery & Hulsemann, 1964; Weaver & Schultheiss, 1983; Blomqvist, 1985). Estimates range from no sediment to as much as lm missing due to this problem. V30-41K exhibits a different type of problem. The upper 2.0cm of this core was slightly darker than the underlying sediment but otherwise did not appear unusual. The 0–1cm level of this core yielded a beta-decay ^{14}C date of 5800 yr, which was clearly anomalous when compared to the ages of the underlying levels (Table 1). The 1–2cm level was AMS dated on the >150μ fraction. Both the iron-carbide and graphite targets revealed anomalously old ages (Table 1). Below the 2cm level, conventional and AMS dates yielded ages, and an age-depth profile, that would be expected for a core with a 2.40cm/1000 yr sedimentation rate and a bioturbated mixed layer of ca 4cm (Jones & Ruddiman, 1982; Peng *et al,* 1979).

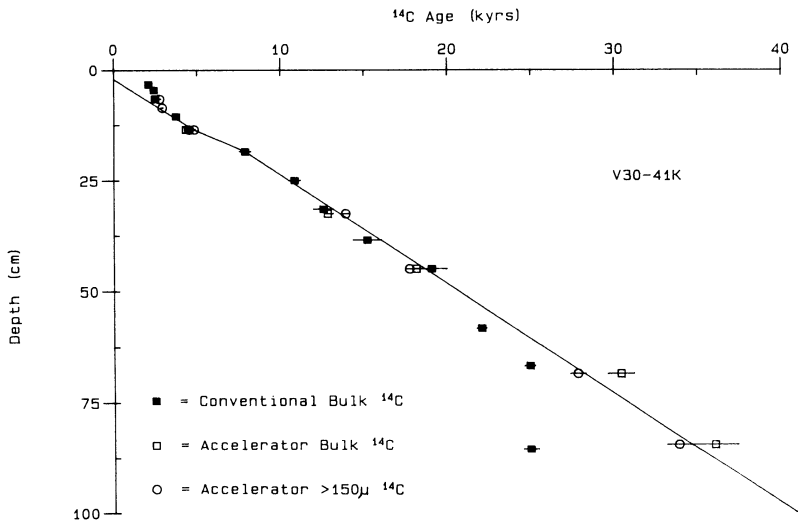

Fig 2. Age-depth plot for ^{14}C analyses listed in Table 1. Fit is based on a 2.4cm/1000 yr sedimentation rate from 2 (*ie*, true coretop) – 13.5cm, a 1.6cm/1000 yr sedimentation rate from 13.5–18.5cm; and a 2.45cm/1000 yr sedimentation rate from 18.5–85.0cm. 1σ errors are given by horizontal bars through each data point. Note 4–6cm-thick mixed layer at the coretop, and the increasingly divergent accelerator and conventional ^{14}C ages below 60cm.

We suspect that during core recovery and shipboard storage, dewatering of the core carried sediment upwards along the core liner and this sediment was redeposited onto the top of the core. This mechanism of dewatering and resedimentation was observed directly by the first author during a 1976 cruise to the Straits of Florida. During this cruise, piston cores with clear core liners were used to sample the foram-rich sediments from this region. Many of the recovered cores contained pockets of water between the sediment and the core liner. This sediment-laden water was observed migrating upwards along the coreliner-sediment boundary and the sediment was deposited as a new "coretop." At that time the effect was thought to be restricted to very coarse-fraction-rich sediments, but subsequent results on V30-41K and other cores indicate this may be more common than realized previously. In all subsequent discussions we consider the 2cm level to be the true coretop for V30-41 K.

Resedimented material at the coretop could explain many of the apparently old ^{14}C ages for coretops that previously were ascribed to a lack of true coretop recovery due to overpenetration of the coring device. Also, this mechanism could explain the anomalously thick mixed layers required by Peng *et al* (1979) to model many coretop ^{14}C ages.

Beta-Decay vs AMS Bulk ^{14}C Dates

The age-depth relationship of these analyses is shown in Figure 2. A distinct 4–6cm bioturbated mixed layer is observed, which agrees with the ca 4cm mixed layer estimated for this core by Jones and Ruddiman (1982).

From 2–42cm (*ie*, ca 20,000 BP), there is little difference at the 1σ level between these two methods. However, for sediments >20,000 yr, the beta-decay bulk ages increase more slowly than the accelerator bulk ages that continue to increase linearly (Fig 2).

Since both methods date the same material and are calibrated and checked through analyses of standards and blanks, we believe that one possible explanation for these results lies in the nature of the sampling. Samples for AMS dating were collected from the center of the Kasten core, whereas the ca 40g samples for the beta-decay analyses were slices of each dated level in the core. Despite removing all sediment from the outer edge of the sample that was in contact with the core barrel, and all sediment surfaces exposed during core storage, it is possible that these large samples may contain 1–2% of modern contamination (Fig 3).

This is an example, however, where accelerator ^{14}C dating of even bulk sediment can easily result in more realistic ages than the beta-decay methods for sediments >20,000–25,000 yr. The smaller sample size requirement results in greater freedom in selecting the exact location of the sample to be taken at a particular horizon. If one had used the beta-decay dates as obtained, the interpretation would have been that >18,000-yr-old glacial sediments had accumulated at higher rates than during the last 18,000 yr. The accelerator dates on both bulk sediment and the >150μ fraction suggest that, at this location, the ca 2.40cm/1000 yr sedimentation rate has changed little during the last 35,000 yr.

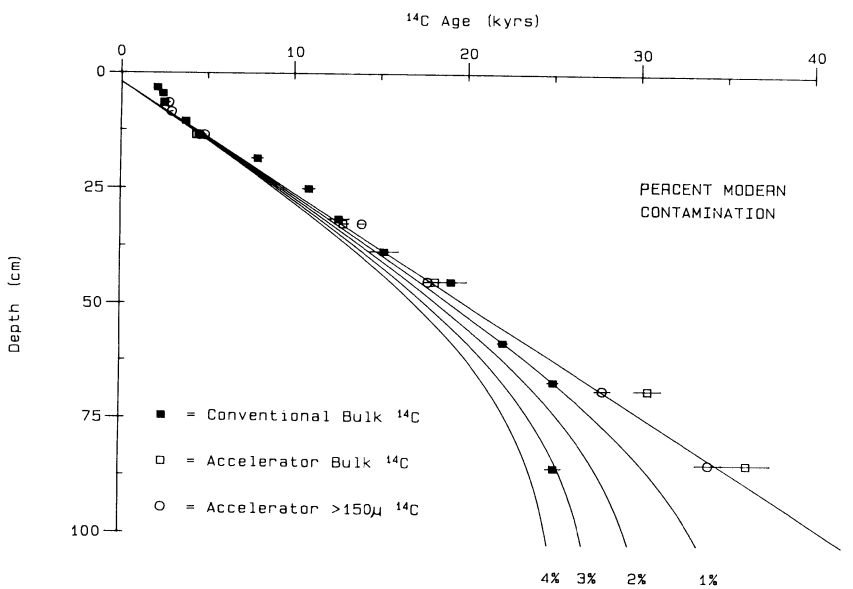

Fig 3. Age-depth plot for ^{14}C analyses listed in Table 1. Five curves are based on a uniform sedimentation rate of 2.4cm/1000 yr, and the effects of varying amounts (0–4%) of modern ^{14}C contamination on measured ^{14}C ages. 1σ errors are given as horizontal bars through each data point. Note increasingly divergent accelerator and conventional ^{14}C ages below 60cm.

There are many examples of apparent sedimentation rate increases, age reversals and ^{14}C ages that are inconsistent with other stratigraphic information in the 25,000–35,000 yr age range when dating organic carbon and carbonate materials (*eg,* Geyh, Krumbein & Kudrass, 1974; Geyh, 1979). This is one of the critical problems associated with ^{14}C dating older deep-sea sediments by beta-decay methods. It is well known that the sediment in contact with the core barrel is often contaminated with recent material as a result of the coring process. It is a standard procedure when sampling a deep-sea core to remove ca 0.25–0.5cm from this outer layer of potentially contaminated material. However, in trying to date older core material, larger sample sizes are required to insure sufficient beta decays for meaningful counting statistics within a reasonable time. Therefore, as sample size increases, either stratigraphically thicker samples must be taken, thus reducing the chronologic resolution that can be obtained, or more material is obtained from a given horizon by sampling closer to the outer layer of the core, thus increasing the chance of contamination with modern sediment found along the inner lining of the core barrel. The AMS samples were no larger than 40mg. Even for the oldest material, AMS requires only a very small segment of sediment (<1cm) from the central region of the core.

Iron-Carbide vs Graphite Targets

The Arizona Accelerator Facility was in the process of switching from iron-carbide to graphite targets at the time Woods Hole Oceanographic Institution was preparing to use AMS in marine sedimentologic studies. We chose six levels from core V30-41K to compare directly these two methods of AMS target preparation (Table 1). Iron-carbide targets yield ages that are systematically older than graphite targets, although still within the 1σ counting statistics. The significant improvement in both the analytical precision and the extended background ages with graphite targets is readily apparent from the data in Table 1. The Arizona Accelerator Facility had analyzed ca 1000 samples between May 1982 and late 1984 with the iron-carbide targets before switching to graphite targets. None of the Woods Hole sedimentologic or paleoceanographic studies were done with iron-carbide targets.

AMS Bulk vs AMS >150μ Fraction Ages

Several authors have discussed the problem of ^{14}C dating the carbonate fraction of marine sediments (*eg,* Emery & Bray, 1962; Olsson & Eriksson, 1965; Geyh, 1979; Erlenkeuser, 1979). Much of the problem involves incorporating reworked fine-grained detrital material (*ie,* ^{14}C dead), resulting in anomalously old ^{14}C ages, age reversals, and/or uninterpretable records (*eg,* Geyh, 1979; Stanley, Nelson & Stuckenrath, 1984; Stanley, 1985). The AMS method allows specific-size fractions and sediment components to be isolated and dated, thus offering a relatively straightforward method of eliminating the effects of detrital carbonate on ^{14}C ages.

As stated earlier, core V30-41K was collected from a region characterized by minimal detrital carbonate input. As such, this core offers a good

test of how bulk and coarse-fraction ^{14}C ages compare. The ages obtained from these two different fractions of the deep-sea sediment record reveal significant differences. For those sediments younger than the Holocene-Late Pleistocene transition (*ie*, ca 11,000 BP), the bulk sediment ages are younger than the coarse-fraction ages. For those sediments older than the Holocene-Late Pleistocene transition, the coarse-fraction dates are younger than the bulk sediment dates by as much as 2500 yr (Fig 4).

One possible explanation for these age differences is that they are an artifact of the bioturbation-abundance couple (Hutson, 1980; Andrée *et al*, 1984; Peng & Broecker, 1984). More Holocene coarse-fraction-rich sediment is mixed downward into the glacial-age sediments than glacial-age coarse-fraction material is mixed upwards into the Holocene sediments. This could result in glacial-age coarse-fraction dates younger than the true age for these sediments. The same would be true for the total $CaCO_3$ fraction dates. The coarse-fraction percentages range from ca 10% in the last glacial to ca 40% in the Holocene (Fig 1), for an "abundance" change of 4.0x. The carbonate percentages range from ca 60% in the last glacial to ca 90% in the Holocene (Fig 1), for an "abundance" change of 1.5x. The different magnitudes in abundance change across the glacial-Holocene transition will lead to differences in the ^{14}C ages of these two components.

Using the bioturbation model of Berger and Heath (1968), a 4cm mixed layer, a sedimentation rate of 2.40cm/1000 yr and the above-mentioned changes in carbonate and coarse-fraction percentages, the maximum model age difference between the two fractions occurs at the transi-

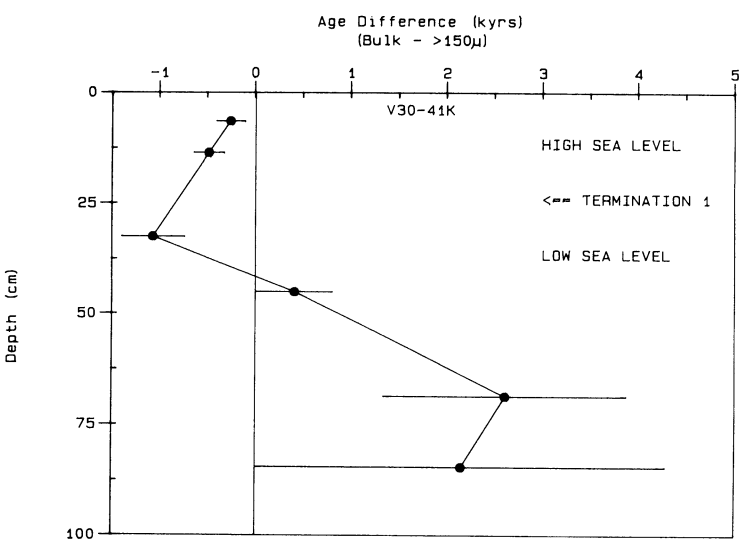

Fig 4. Age difference between the bulk (total) carbonate and the >150μ fraction AMS ^{14}C analyses. Note that for sediments shallower than 35cm (ca 14,000 yr), the bulk fraction is older than the >150μ fraction, whereas below this depth, the bulk fraction is younger than the >150μ fraction.

tion from glacial to Holocene values (*ie,* Termination 1) and is ca 300 yr. However, the model shows the coarse-fraction dates are younger than the bulk-carbonate dates at this transition. This result is the opposite of what is observed. Even using much thicker mixed layers, we could not duplicate the observed age differences between these two sediment components.

A second possible explanation for these age differences is that there is a significant component of reworked detrital carbonate in the fine fraction. The source of this material would be eolian dusts from the African continent (Prospero, Glaccum & Nees, 1981). Although it is difficult to determine quantitatively the detrital *vs* biogenic carbonate contributions to these sediments, we can estimate the detrital contribution from published data. Curry and Lohmann (1986) have determined the relationship of wet and dry bulk density to carbonate percentage for a series of cores from the nearby Sierra Leone Rise (ca 4°N, 21°W). Using the $CaCO_3$ percentages determined for V30-41K and the equation of Curry and Lohmann (1986) we can calculate the wet and dry bulk density for V30-41K.

Kolla, Biscaye & Hanley (1979) determined the accumulation rates of quartz for several Eastern Equatorial Atlantic cores. Core A180-73 (00° 10′ N, 23° 0′ W) 3749m water depth, is from the same location as V30-41K and has a Holocene quartz accumulation rate of 10mg cm^{-2} ky^{-1}. The quartz accumulation rate for the last glacial was 60mg/cm^{-2} ky^{-1}. The source of this material is wind-blown dusts from the African continent. Prospero, Glaccum & Nees (1981) showed that the mineralogy of dusts advected from Africa have a quartz/calcite ratio of ca 2.0. This dust composition is recorded in French Guiana, Barbados and Dakar, and remains seasonally little changed. We assume that the quartz/calcite ratio of African dusts has not changed between the last glacial and the Holocene.

Using these measurements, we can calculate that <0.2% of the carbonate in the Holocene interval of V30-41K is detrital, and for the last glacial, ca 2% is detrital carbonate. Using these estimates of detrital (*ie,* ^{14}C-dead) carbonate and the fact that the >150μ fraction of these sediments contains no detrital carbonate and should thus reflect a more realistic estimate of the "true" age of the sediments at each of the dated levels, we cannot reconcile the magnitude of the observed age differences. Although the effect is in the right direction to explain glacial bulk samples older than coarse-fraction samples, >20% of the glacial-age carbonate would have to be detrital in order to explain the observed age differences.

A third possible explanation is that carbonate dissolution could differentially affect the ^{14}C age of different size fractions and sediment components. Models have been developed to explain the dissolution effect on mixed-layer ages (Sundquist *et al,* 1977; Broecker & Peng, 1982; Berger & Killingley, 1982). If we assume that no dissolution occurred during the Holocene, and that the observed downcore variations in carbonate percentage are solely the result of carbonate dissolution (an extreme and unrealistic assumption), we can calculate the age of the Holocene mixed layer to be ca 1550 yr using the model of Broecker and Peng (1982). This age closely agrees with the measured value of 1700 yr (*ie,* the 2100-yr value reported in Table 1 minus the 400-yr ocean reservoir correction). Assum-

ing dissolution is the sole contributor to the observed carbonate percentage record, we would calculate a paleo-mixed-layer age for the last glacial as ca 75 yr. Thus, dissolution could cause a maximum 1500-yr shift in the age of a given horizon but does not explain the age difference between two different carbonate components from the same horizon.

We are unable to explain why bulk sediment ages are younger than coarse-fraction ages for the Holocene, but older than the coarse-fraction ages during the last glacial (Fig 4). We note that Andrée *et al* (1984) reported similar results for fine-fraction/coarse-fraction analyses from coretop and mid-Holocene levels in a core from the equatorial Pacific. In addition, Andrée *et al* (1984) showed a downcore trend of increasing age-differences for dissolution-resistant *vs* dissolution-susceptible foraminiferal species similar to that seen for coarse-fraction *vs* bulk-sediment ages. It is impossible at present to evaluate the role of dissolution in explaining the data presented here and in Andrée *et al* (1984).

The data we have obtained from core V30-41K points out how complicated even simple and potentially easily explained sedimentary environments can be. We suspect that bioturbation, detrital $CaCO_3$, dissolution and other factors all play a role in answering the up to 20% age differences observed between different components from the same horizon. This study was designed to compare the beta-decay and AMS methods of ^{14}C dating deep-sea sediments, and not to evaluate the depositional and post-depositional processes occurring on the sea floor. However, it is clear that AMS studies must be designed to evaluate the role of these processes if we are to be able to interpret and understand the deep-sea sediment ^{14}C record.

CONCLUSIONS

For chronostratigraphic purposes, there is no unambiguous method of determining precisely the "true" ^{14}C age for any horizon within a deep-sea-sediment core. Age differences of several thousand years have been obtained from different components collected from the same stratigraphic horizon. The overall sedimentation rate can be determined quite well with AMS and appears to be superior to the beta-decay method from the standpoint of sample size and the greater chance of routinely obtaining accurate ^{14}C dates from the interval 25,000–40,000 BP. Very thin horizons can be dated while, at the same time, leaving a substantial portion of the sediment from that horizon for other paleoceanographic and sedimentologic studies. This method eliminates much of the interpolation that has to be done with beta-decay methods where a horizon several cm thick from a core can be consumed for a single ^{14}C date.

On the other hand, the small sample-size requirements of the AMS method can cause problems. Inhomogeneities, such as burrows that are preserved in the sediment record, become important relative to the required sample size. With much larger sample sizes for conventional dating, these type of inhomogeneities are averaged and the measured ^{14}C age becomes a good approximation of the level dated.

The great interest in the AMS ^{14}C dating of deep-sea sediments is not in obtaining a routine chronostratigraphy, rather it is in using this method

for studying in detail the timing and duration of rapidly occurring climatic events, climatic lead-lags and regional temporal variability of climatic events. It is just these type of studies that must be evaluated very carefully before meaningful interpretations can be made.

ACKNOWLEDGMENTS

We thank L Toolin and A Hatheway for assistance in sample preparation and analysis, and A Gagnon for figure preparation. This research was supported by the Office of Sea Grant in the National Oceanic and Atmospheric Administration through grant NA-84AA-D-00033 (R/G-10) to G Jones, and NSF grants EAR-83-09448 and EAR-85-12761 to the Arizona Accelerator Facility. This is Woods Hole Oceanographic Institution contribution no. 6749.

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[RADIOCARBON, VOL 31, NO 2, 1989, P 117–120]

PROBLEMS ASSOCIATED WITH THE USE OF COAL AS A SOURCE OF ^{14}C-FREE BACKGROUND MATERIAL

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ABSTRACT. Many ^{14}C dating laboratories have established that coal samples exhibit a finite ^{14}C age, apparently caused by contamination of the specimens before any laboratory preparation is undertaken. In this work, the possibility that the contamination is due to microbial and fungal activity in the coal substrate is considered and some suggestions are made for alternative sources of background test materials for ^{14}C dating laboratories. Initial results indicate that geologically formed graphites contain little ^{14}C and are likely to be good background test materials, especially in ^{14}C AMS laboratories.

INTRODUCTION

The maximum age that can be determined reliably by the ^{14}C dating method is limited by several factors, amongst the most important of which is "background." In the case of ^{14}C dating by accelerator mass spectrometry (AMS), where extremely small samples are used, background problems caused by contamination are proportionally greater than for large samples. Three factors may contribute to the background observed during ^{14}C determinations using AMS:

1) the limit of detection or machine background
2) contamination of the sample during pretreatment and preparation
3) contamination of the sample prior to any laboratory preparation or analysis.

Vogel *et al* (1987) have provided an excellent analysis of 1) and 2) by separating out the components of contamination introduced during sample combustion and graphitization, as well as the contribution to background by the accelerator system. Some of the background samples tested by Vogel *et al* (1987) were specimens of anthracite coal which showed ^{14}C concentrations considerably higher than expected due to machine background ages and contamination during sample preparation. When background ages in the vicinity of 50 kyr were expected, the coal samples yielded 40–45 kyr. There are many other unpublished accounts by ^{14}C laboratories in which the use of coal as a background test material has been investigated. In many cases, the samples were found to contain ^{14}C, and further studies were discontinued. The AMS and gas counting facilities, DSIR, in Lower Hutt, New Zealand, eg, have observed apparent ages for coal specimens ranging from 25–40 kyr, and the NSF Accelerator Facility at Tucson, Arizona has determined ages of anthracite samples ranging from 30–40 kyr (AJT Jull, pers commun, 1988).

PROPERTIES OF COAL

Coal represents the accumulation of organic materials in sedimentary strata where it undergoes *in situ* compaction and induration to form various ranks. These vary from lignite, which is only moderately metamor-

* The National Center for Atmospheric Research is funded by the National Science Foundation.

phosed, plant residues still readily apparent, to anthracite, which is very hard and brittle (Wixson *et al,* 1980).

Because coal is formed over geological time scales at depths providing excellent shielding from cosmic rays, its ^{14}C content should be insignificant in comparison to the ^{14}C introduced by even the most careful sample preparation techniques used in ^{14}C dating laboratories. How is it then, that a material, which should show a ^{14}C age indistinguishable from that produced by a combination of machine background and contamination during careful sample preparation, routinely produces a finite ^{14}C age?

One suggestion is that radium, which is present in some coals at the sub ppm level, as a decay product of the uranium/thorium series, may produce ^{14}C during an extremely rare decay event (Rose & Jones, 1984). Jull, Barker and Donahue (1987) have detected ^{14}C from this process in uranium/thorium ores. Blendowski, Fliessbach and Walliser (1987) however, have shown that the ^{14}C decay mode of ^{226}Ra is only of the order of 10^{-11} of the preferred α decay channel to ^{222}Rn. Thus, the amount of ^{14}C produced by such events derived from radium in coal must be considered as insignificant.

MICROBIAL AND FUNGAL ACTIVITY IN COAL

I would like to suggest a simple explanation for the finite ^{14}C ages observed for many coal specimens, namely microbial and fungal action in coal substrates.

The action of various kinds of fungi and microbes in coal has been well documented (Paca & Gregr, 1977; Cohen & Aronson, 1987; Greenwell, 1987). Cohen and Gabrielle (1982) first reported that the fungi *Polyporus versicolor* and *Poria montiola* could degrade lignite. The fungus *Polyporus versicolor,* which is the common species involved in the rotting of wood, incorporates atmospheric CO_2 during its growth and thereby introduces ^{14}C into the coal substrate. Once the coal specimen is contaminated, fungi and microorganisms may be killed by conventional methods such as autoclaving, but the fungal hyphae and waste products, which contain ^{14}C derived from atmospheric CO_2, will be almost impossible to remove by standard chemical washing procedures. Assuming that a sample of coal contains no ^{14}C, microbial action only has to result in the deposition of ca 0.1% by weight of modern carbon in the coal to produce an apparent age of 45 kyr for the specimen.

Currently, the electric power industry is very interested in bacteria that can remove organic sulphur, pyrites and other potentially toxic substances from coal (Greenwell, 1987; Olson & Brinckmann, 1986). The bacteria studied so far are related to the microorganisms found feeding on sulphur deposits at submarine hydrothermal vents and obtain their energy by oxidizing reduced iron and sulphur compounds (Singer & Stumm, 1970; Ehrlich, 1981). In moist air, some of these autotrophic species including strains of thiobacillus-like bacteria, oxidize pyrites in coal, incorporate atmospheric CO_2 during their growth (Olson & Brinckmann, 1986; Ehrlich, 1981), and deposit products containing ^{14}C into the coal. The process is particularly prevalent in warm, damp coal in air, but will still occur at the

temperatures and lower relative humidities experienced in ^{14}C sample preparation laboratories where background coal test specimens have been stored.

CONCLUSION AND RECOMMENDATIONS

In order to try to prevent microbial and fungal activity in coal, only freshly mined coal, kept dry in a nitrogen atmosphere should be used. However, even with these precautions, considering the ubiquitous occurrence of fungi and microbes (bacteria have been found in a drill hole 3km underground apparently living on granite!), the use of coal samples as routine ^{14}C laboratory background test samples should probably be avoided.

A better background test material, particularly for ^{14}C AMS facilities, may be graphite. However, because industrial graphites, which include the synthetic and spectroscopic graphites routinely used in AMS laboratories as background test materials, are usually made by heating mixtures of coking coal and pitch of unknown provenance, these materials should probably also be avoided.

I suggest that a good source of ^{14}C-free materials for ^{14}C background and contamination tests is likely to be found by investigating geological deposits of graphite. If these graphites are pure, sulphur-free and stored dry under nitrogen, the possibility of microbial or fungal action should be remote. I recommend that such sources of graphite be evaluated in future studies of factors contributing to ^{14}C background in dating facilities. Graphite offers the advantage that it can be used directly without laboratory preparation in an accelerator sputter ion source to produce beams of negatively charged carbon ions. The same material can also be combusted, unfortunately with difficulty, to CO_2 and regraphitized to provide an unambiguous test of contamination introduced by laboratory target preparation procedures. Initial tests made recently at the New Zealand AMS facility, have shown a 51 kyr background for a geologically formed flake graphite which confirms that "natural graphites" are likely to be a good basis for further study into ^{14}C-free background materials.

I also suggest that freshly mined dry coal samples be tested for ^{14}C content and that the ^{14}C activity be monitored routinely after the samples are stored in laboratory air. The Argonne National Laboratory, eg, maintains a premium coal bank containing eight grades of coal, all of which are stored in an inert atmosphere since mining (Haggin, 1988). Such samples could be used as standards to check for the introduction of ^{14}C due to microbial activity after exposure of the coal specimen to moisture and air.

ACKNOWLEDGMENTS

My sincere thanks go to Ralph Cicerone and John Vogel for extremely helpful comments and criticisms during the preparation of this manuscript.

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[RADIOCARBON, VOL 31, NO. 2, 1989, p 121–145]

CHRONOMETRIC DATING AND LATE HOLOCENE PREHISTORY IN THE HAWAIIAN ISLANDS: A CRITICAL REVIEW OF RADIOCARBON DATES FROM MOLOKA'I ISLAND

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INTRODUCTION

The importance of chronometric dating in archaeology cannot be overemphasized. Indeed, most chronologies developed throughout the world during the past three decades have depended on radiocarbon age determinations to provide a temporal framework for examining change over time in cultural sequences during the late Pleistocene and Holocene. With the advent of legislation in the mid-1960s designed to protect archaeological sites in the United States threatened by increased urban development or government sponsored projects, archaeological surveys and excavations were mandated as a means for preserving information otherwise destroyed. As a result, thousands of projects have contributed to a growing body of "gray literature," *ie,* unpublished proprietary or manuscript reports with very limited circulation. Within these reports are hundreds, if not thousands, of ^{14}C age determinations, most of which are not accessible in published form. One objective of this paper is to present all the ^{14}C age determinations for the island of Moloka'i, Hawai'i as of December 1988, including 41 dates never before published with stratigraphic details.

Despite Polach's treatise on the limitations of ^{14}C dating in archaeology written over 10 years ago (Polach, 1976), the validity and utility of ^{14}C "dates" are most often accepted by researchers at face value. However, several recent critical examinations of ^{14}C data have produced some unsettling evaluations. Of fundamental concern is the relationship of the dated material to the actual archaeological event of interest (Butler & Stein, 1988; Dean, 1978; Grayson, in press; Mead & Meltzer, 1985). Other objectives of this paper are to critically review the significance of ^{14}C age determinations for Moloka'i, and to use these dates to outline the prehistoric sequence of the island. Although Kirch (1985) has provided a general summary of the prehistory of the Hawaiian Islands, the discussion that follows focuses on the ^{14}C data from the island of Moloka'i and critically evaluates their relation to stratigraphic context and archaeological significance.

Forty-eight age determinations are presented of samples collected and submitted for analysis between 1959 and 1988 (Fig 1). Forty-five are from archaeological sites, two from geologic contexts, and one is of modern marine shell dated to provide a correction factor for the ocean reservoir effect. Forty-three samples were charcoal (36 wood, 7 unspecified); other samples included marine shell (2), and one each of fishbone, coral and land snail. Most ^{14}C measurements were analyzed by Beta Analytic, Inc (41), 6

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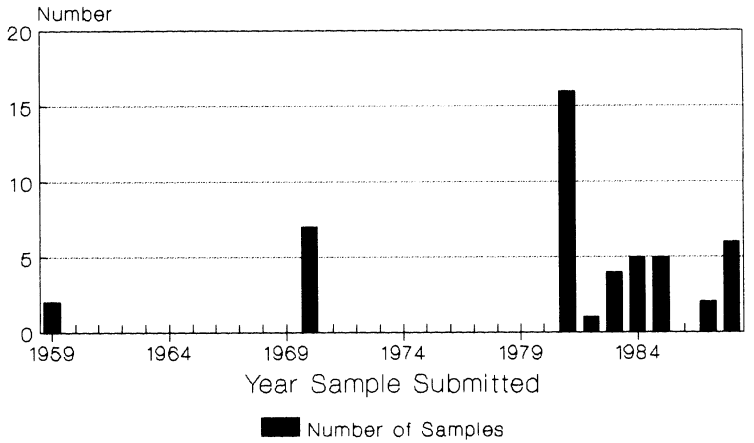

Fig 1. Bar graph of ^{14}C age determinations for the island of Moloka'i plotted by year submitted.

samples by Gakushuin, and 1 by Geochron Laboratories. The samples processed at the Gakushuin labs were dried and powdered, rootlets were removed by flotation, and the samples were boiled with 1 N HCl solution for ca 1 hr and washed with distilled water. No alkaline pretreatments were done (K Kigoshi, pers commun, 1988). As reported by Beta Analytic, all charcoal samples were given an extensive hot acid pretreatment to eliminate carbonates. After rinsing to neutrality, the pretreatment procedures were continued by submitting charcoal to hot alkali solution to extract humic acids. Again rinsing to neutrality, another acid treatment followed and another neutralization. Benzene syntheses followed and the dating proceeded normally in all cases. "Less than" dates are reported at 2 σ. All age determinations from Gakushuin and Beta Analytic were reported as ^{14}C years BP (before AD 1950) with the half-life of ^{14}C 5568 years. Calibrations for secular and marine reservoir effects were made on an updated microcomputer software program provided to the author by M Stuiver (Stuiver & Reimer, 1986; Stuiver, Pearson & Braziunas, 1986). Lab error multiplier factors are not available from any labs (*cf* Otlet, 1979; Stuiver, 1982). However, a recent detailed repetition study on a group of samples analyzed by Beta Analytic, in the 2000-yr range, indicated the error multiplier was close to 1 (J Stipp, pers commun, 1988).

Prior to 1984, isotopic fractionation adjustments were not made on ^{14}C samples from Moloka'i. A conventional ^{14}C date (Stuiver & Polach, 1977), however, must include a correction for isotope fractionation. Therefore, all samples are presented in Table 1 with $^{13}C/^{12}C$ data and conventional ^{14}C ages are used for calibrations when available. It is interesting to note that the $^{13}C/^{12}C$ corrections range from -55 to $+435$ yr and exhibit no consistent pattern. This alone should suggest caution when using any "^{14}C age" determinations analyzed prior to 1984 for archaeological sites from Moloka'i and probably all the Hawaiian Islands. It is also suggested

TABLE 1
Isotopic fractionation adjustments for Moloka'i ^{14}C determinations

Beta no.*	Site/Locality	"^{14}C age" BP	$^{13}C/^{12}C$ ‰	Conventional ^{14}C age	$^{13}C/^{12}C$ correction **	Reference
9275	03-312/Kalawao	<120	−28.71	<120	N/A	Somers, pers commun, 1984
9276	03-312/Kalawao	900 ± 70	−26.44	880 ± 70	−25	Somers, pers commun, 1984
9962	03-312/Kalawao	460 ± 180	−23.28	490 ± 180	+30	Somers, pers commun, 1984
11168	03-800/Kalama'ula	220 ± 60	−20.44	300 ± 60	+75	Athens, ms, 1985
11169	03-800/Kalama'ula	<120	−18.81	70 ± 50	+100	Athens, ms, 1985
11170	03-800/Kalama'ula	<190	−23.92	<190	N/A	Athens, ms, 1985
11171	03-800/Kalama'ula	170 ± 70	−10.81	400 ± 60	+230	Athens, ms, 1985
11172	03-800/Kalama'ula	1000 ± 60	+2.31	1450 ± 60	+435	Athens, ms, 1985
13743	02-24/ Mo'omomi	160 ± 50	−12.65	360 ± 50	+200	Dye, Weisler & Riford, ms, 1985
13744	02-85/'Amikopala	170 ± 50	−19.58	260 ± 50	+85	Dye, Weisler & Riford, ms, 1985
20881	01-1610/Kawakiu Nui	160 ± 60	−24.4	170 ± 60	+10	Weisler, ms, 1987
20906	02-21/Kawa'aloa Bay	1100 ± 60	−13.7	1290 ± 60	+180	Weisler & Collins, ms, 1988
27115	03-885/Kipu	540 ± 70	−24.4	500 ± 70	+10	Weisler, ms, 1989
27116	03-885/Kipu	640 ± 60	−26.6	610 ± 60	−25	Weisler, ms, 1989
27390	03-886/Kaunakakai	370 ± 70	−28.3	320 ± 70	−55	Weisler, ms, 1989
27391	03-887/Kaunakakai	600 ± 110	−27.4	560 ± 110	−40	Weisler, ms, 1989
27392	03-887/Kaunakakai	30 ± 60	−17.5	160 ± 60	+120	Weisler, ms, 1989
27393	03-888/Kaunakakai	380 ± 80	−26.6	350 ± 80	−25	Weisler, ms, 1989

* All wood charcoal samples except Beta-11172 (marine shell) and -20906 (marine fishbone).
** $^{13}C/^{12}C$ correction calculated with $(\delta^{13}C\text{-}25)16$ (Stuiver, pers commun, 1988).

that solid carbon age determinations (Browman, 1981; Taylor, 1987) should be eliminated entirely from analysis of archaeological chronologies.

After a brief outline of Moloka'i prehistory, archaeological samples are reviewed from seven regions of Moloka'i beginning from the east end at Halawa Valley and working west (Fig 2). Within each region, oldest dates are generally discussed first. Figure 3 illustrates all the archaeological ^{14}C determinations for Moloka'i grouped by region and plotted at 1 σ.

A BRIEF OUTLINE OF MOLOKA'I PREHISTORY

Centrally located in the Hawaiian archipelago, the elongated island of Moloka'i exhibits a striking array of ecological contrasts. Consisting of two broad shield volcanoes that overlap in the central saddle region, the eastern summit at Kamakou rises to 1244m and hosts dense rain forests and extensive bogs which drain into large amphitheater-headed valleys along the windward coast. Halawa Valley typifies the windward coastal setting where fertile alluvial soils on broad floodplains were supplied with ample water for agriculture, and inhabitants had easy access to a range of marine resources. In this "ecologically favored" setting, the oldest habitations are found. The majority of Moloka'i, however, lies within a leeward rain shadow dominated by the 421m high Maunaloa volcano, the summit of which lies amongst gently rolling grass-covered hills descending to moderately dissected slopes that terminate at rocky coastlines. Prehistoric settlements on West Moloka'i are located primarily at the summit region and around sheltered embayments along the coast. Unlike its windward coun-

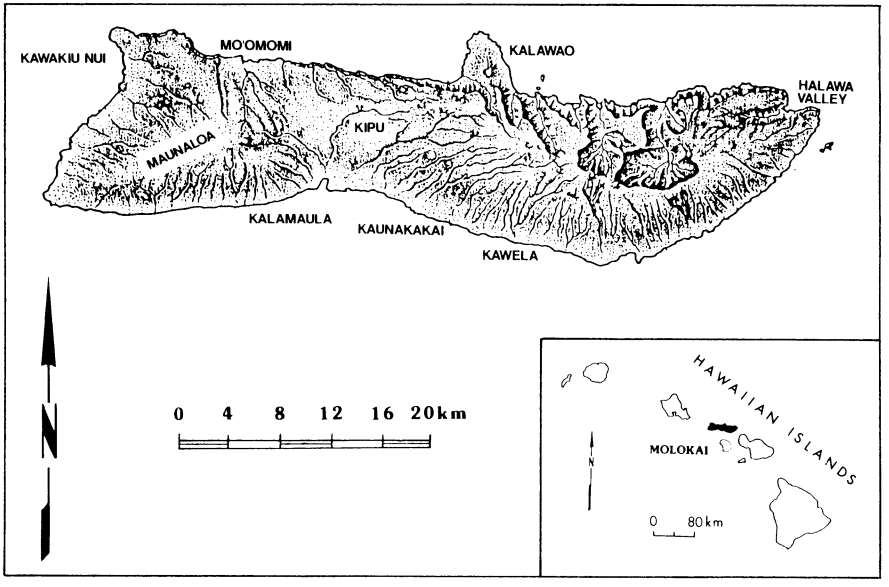

Fig 2. Map of the Hawaiian Islands showing the location of Moloka'i. Placenames on relief map refer to regions, discussed in the text, where ^{14}C age determinations are available.

terpart, population densities were much lower in the western, drier region of the island.

The discussion of Moloka'i prehistory that follows is modeled after historical periods proposed by Kirch (1985, p 298–308) for the archipelago as a whole, except that I have divided Kirch's Expansion period into an Early (AD 1100–1400) and late Expansion period (AD 1400–1650) to reflect the addition of much new data for the longest period in the Hawaiian cultural sequence (Kirch, 1985, p 303). My discussion focuses primarily on temporal patterns of settlement to the exclusion of subsistence, economy and socio-political change throughout the cultural-historical sequence. Age determinations were grouped in historical periods by using the oldest cal AD date at 1 σ.

Colonization Period (AD 300–600). Only eight sites throughout the archipelago contain cultural deposits dating to the earliest period of Hawaiian prehistory (Kirch, 1985, p 67–88). The data from these sites are from small excavated samples and are very incomplete. The composite picture documents settlement locations along the coastal, windward sides of the main islands. Halawa Dune, located on windward Moloka'i, is the only site on the island dating to this period. Marked by a sandy mound adjacent to the south bank of Halawa Stream and just inland from the boulder beach, portions of the lowest cultural stratum of the site date to the 6th century AD (Gak-2743) and contain postmolds, a pit and several amorphous hearths. Based on this scant evidence, house shape could not be discerned. Stone technology included adzes, percussion flaked basalt and volcanic glass. Fishing gear, as well as a range of faunal material, indicate a broad-based diet focused on marine subsistence and agriculture. The resident

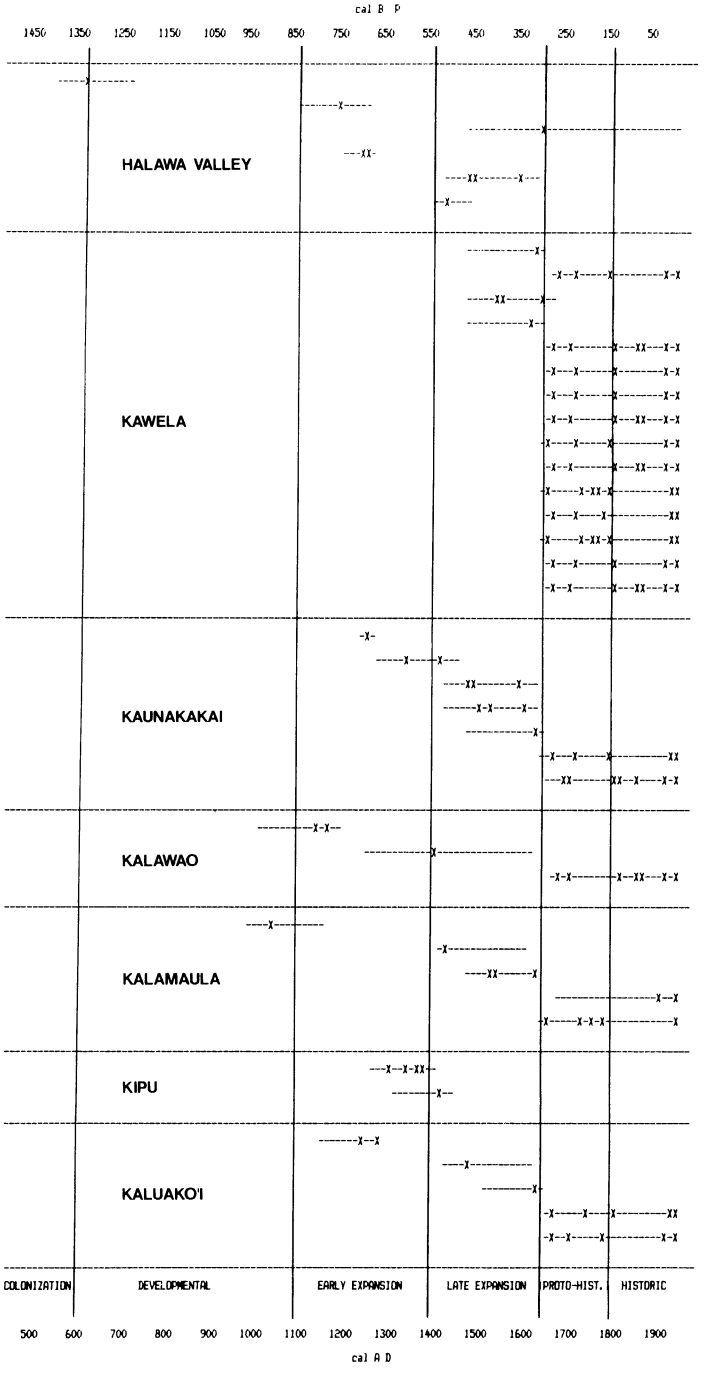

Fig 3. Archaeologic ^{14}C age determinations grouped by region and plotted at 1 σ by cultural-historical periods. Intercept points are marked with an "X."

population is believed to have consisted of, at most, a few dozen inhabitants.

Developmental Period (*AD 600–1100*). Kirch (1985, p 302–303) describes this period as one in which distinctive patterns of Hawaiian material culture and economic adaptation were firmly established throughout the archipelago. Few settlements were established but population continued to increase. The first clear evidence of house types is present and the expansion of agricultural systems in windward settings may have occurred. Three sites from different regions of Moloka'i have been dated to the Developmental period. Occupations at the Halawa Valley dune locale seem to have been mainly in the form of small, round-ended houses of pole and thatch construction with internal stone-lined fireplaces. A permanent population was established with a broad-based economic pattern similar to older occupation levels (Kirch, 1975a).

At Kalawao on the windswept Kalaupapa Peninsula, a collapsed lava tube shelter (Kaupikiawa) was initially occupied by the 11th century (Beta-9276). Numerous hearths, dense concentrations of marine shellfish and the remains of coastal fish suggest temporary occupation of the shelter by small groups engaged in collecting invertebrates and fishing along the nearby rocky coast.

Situated in leeward central Moloka'i, 1.5km from the south shore, is a complex of habitation structures and associated gardening features at Kalama'ula. A shell lens of food refuse from a large terrace was dated to the early 11th century (Beta-11172) and 400 yr earlier than four wood charcoal samples from the same complex (Beta-11168 to -11171). If the early end of the age range is accepted, temporary gardening areas may have been established on the leeward slopes of Moloka'i ca 100 yr before current archipelago-wide settlement models suggest (*cf,* Hommon, 1986; Kirch, 1985).

Early Expansion Period (*AD 1100–1400*). The Expansion period, as defined by Kirch (1985, p 303–306; AD 1100 to 1600), is the best archaeologically documented temporal period for the Hawaiian cultural sequence. During this time, population levels increased at an unprecedented rate, expanding from their windward locales into the most arid, leeward environments. Dryland and irrigated agricultural systems were expanded and elaborated. The first kinds of aquacultural production (walled fish ponds built over broad, shallow reefs along the south coast) were invented, though few additions were added to the tool inventory which, by this time, was fairly standardized. For this period, 7 ^{14}C dates from Moloka'i are available from 6 sites throughout the island.

Beginning in the early 13th century, burning for shifting cultivation on the colluvial slopes of Halawa Valley was first practiced and with it began localized human-induced environmental degradation (Gak-2744). The first evidence of temporary occupation along the leeward coast has been found in a sandy midden on the alluvial plain, east of Kaunakakai Stream and just inland from the shore (Beta-7564). From this locale, the broad reef-flat and its abundant marine resources were easily accessible, as were the inland expanse of fertile alluvial soil for agriculture. Dates for shifting cultivation above the flood plain begin by cal AD 1280 (Beta-27391), which currently is the oldest date for any dryland agricultural complex on the island.

The first evidence for exploitation of marine resources (shellfish, fish and turtle) and land birds along the western half of the N coast date to the end of the 12th century. Many middens along the N coast, between the Kalaupapa Peninsula and Mo'omomi, were probably occupied during this time. The Kaupikiawa shelter at Kalawao continued to be used by small groups.

At about the same time as the beginning of shifting cultivation in Halawa Valley, the upland forests at Kipu (335m asl) were cleared for dryland agriculture probably to feed an expanding population.

In sum, the Early Expansion period provides evidence for marine exploitation along the north and south coasts in leeward regions, and agricultural expansion into previously unoccupied areas such as Kaunakakai and Kipu.

Late Expansion Period (AD *1400–1650*). Whereas the Early Expansion period is marked by temporary use of the remote leeward regions for resource acquisition, archaeological evidence suggests the occupation of these areas on a permanent basis during the Late Expansion period.

In Halawa Valley, permanent settlements were located 1.5km inland from the coastal mound and the first residential complexes were inhabited (Gak-2740). The large-scale manufacture of adze blanks and preforms began by the mid-15th century (Beta-13743) at the Mo'omomi Adze Quarry on West Moloka'i, probably in response to the need for large adzes necessary for forest clearance for shifting cultivation. Permanent occupation of the Maunaloa summit region at the 'Amikopala Quarry complex was established by the early 16th century (Beta-13744), but the association of this date with adze production is unclear. The 'Amikopala Quarry complex was unusual in Hawai'i as there was a full-time resident population engaged in agriculture and maintaining numerous house structures, field shelters and religious features spread over nearly 1500ha of the summit region. Only temporary use of distant quarries has been documented for other Hawaiian Islands (McCoy, 1977).

Firm evidence of intermittent dryland gardening was found on the leeward slopes of central Moloka'i above Kalama'ula. Several habitation terraces, a small shelter and numerous stone mounds resulting from field clearance are evident. Along the south coast at Kaunakakai, occupation continued at a sandy mound. Permanent residential complexes were located just inland from the coast, but these were destroyed during construction of the nearby town. On the slopes just above the flood plain, small field shelters were occupied in the mid-15th century (Beta-27390, -27393) for tending dryland crops east of Kaunakakai Gulch.

East of Kaunakakai at Kawela, a similar sandy habitation mound was adjacent to the seaward edge of a broad alluvial plain. Occupation of this area for exploitation of marine foods and birds began by the late 15th century AD. Permanent occupation of the Kawela uplands was indicated by evidence from two residential complexes.

During the Late Expansion period, a pattern of permanent occupation in the most arid regions of leeward Moloka'i and inland expansion within the windward valley of Halawa were documented by 14 ^{14}C dates at 12 sites.

Proto-Historic Period (AD *1650–1795*). The remaining 145 yr of Hawaiian prehistory prior to European contact were documented during this period. Most archaeological age determinations from Moloka'i (18 of 44) dated to the Proto-Historic period and come from 14 sites, all in leeward areas. The Kawela area provided most of the data where a late prehistoric (17th and 18th centuries AD), nearly synchronic settlement pattern was intensively studied (Weisler & Kirch, 1985). More than a dozen residential complexes were situated along ridge lines on either side of Kawela Gulch below the 40m contour. Five of these, as well as a dryland agricultural complex and a rock shelter, dated to the Proto-Historic period.

Another sandy mound west of Kaunakakai Stream was also used at this time. Earlier occupation levels exist, but they have not been dated. The use of upland areas for shifting cultivation continued at Kaunakakai and Kalama'ula as well as exploitation of marine resources along the north coast at Kalawao and Mo'omomi. This was undoubtedly a sampling problem and earlier deposits must surely exist. However, the first documented use of the west coast was during this period at Kawakiu Nui (Beta-20881).

In summary, the oldest occupation on Moloka'i dates to the late Colonization period and is situated in a windward valley with easy access to inland and coastal marine resources. By the Developmental period, all the windward valleys were probably occupied, but the only documented occupation is a small, temporarily used shelter on the windswept Kalaupapa Peninsula. As population increased during the Early and Late Expansion periods, the leeward regions of the island were explored for food resources and fine-grained basalt for manufacture of adzes. Permanent occupation was established in leeward regions at the summit of Maunaloa, along the south coast at Kaunakakai, and in the interior of Halawa Valley. By the final centuries before European contact, all regions of the island were permanently occupied.

The prehistoric settlement of Moloka'i corresponds well to the model proposed by Kirch (1985) for the archipelago as a whole, although, based on present evidence, Kirch's Expansion period (AD 1100–1650) was divided here into Early (AD 1100–1400) and Late (AD 1400–1650) periods to reflect temporary, short-term use of the leeward regions of the island in the earlier period with permanent settlement in leeward regions not documented until the Late Expansion period (*cf,* Kirch, 1985, p 303). When ^{14}C chronologies for other islands are evaluated, further refinements in the Hawaiian cultural-historical sequence may be possible and our understanding of Hawaiian prehistory enhanced.

ARCHAEOLOGIC SAMPLES

Hawai'i

Moloka'i Island

A1–3, Halawa Dune site series

Three wood charcoal samples coll from prehistoric cultural stratum (St IV, ca 60cm thick) of sandy habitation dune (A1–3; 05-315) adjacent to S bank of Halawa Stream and immediately inland from boulder beach at 5m

asl (21° 9′ 42″ N, 156° 44′ 33″ W). Site consists of two small, low mounds, erosional remnants of more extensive deposits (Kirch, 1975a, p 18). In 1969 and 1970, 53m^2 was excavated, revealing in lowest cultural stratum, house foundations with internal slab-lined fireplaces, basalt adzes, abrading tools, bone fishhooks and other artifacts; also faunal material indicating broad-based diet based on marine subsistence and agriculture.

Gak-2743. Halawa Valley **1380 ± 90**

Wood charcoal from coastal midden Site A1–3 (05-315), Feature 57, Sq G3, Layer IV, 5cm above Layer V, stratigraphically lowest date for site; charcoal concentration 5cm thick. Coll Aug 1969 and subm Jan 1970 by P Kirch (PK). Cal AD 582 (648) 759 at 1 σ; cal BP 1368 (1302) 1191 at 1 σ. *Comments:* beginning of Halawa Valley occupation sequence (Kirch, 1975b) and oldest habitation date for island. Weight of sample not reported.

Gak-2741. Halawa Valley **820 ± 80**

Wood charcoal, 13.0g, from Site A1–3 (05-315), Feature 48, Sq F5, assoc with structural foundation 2, 15–25cm deep, Layer IV; from fireplace outlined with water-rounded stones containing charcoal, ash, marine shell and bone. Coll Aug 1969 and subm Jan 1970 by PK. Cal AD 1131 (1219) 1277 at 1 σ; cal BP 818 (731) 673 at 1 σ. *Comment:* terminal occupation of Layer IV.

Gak-2742. Halawa Valley **230 ± 120**

Wood charcoal, 8.0g, from Site A1–3 (05-315), Feature 58, Sq G5, intrusive from top of Layer IV; earth oven filled with vesicular basalt, concentrated charcoal and ash. Coll Aug 1969 and subm Jan 1970 by PK. Cal AD 1494 (1656) 1955 at 1 σ; cal BP 456 (294) 0 at 1 σ. *Comment:* dates period of use at or after abandonment of site (Kirch, 1975a, p 32).

General Comment: A1–3 (05-315) coastal mound series provides initial occupation and abandonment dates for this important archaeological site and clearly identifies lower levels of St IV as earliest identified occupation on Moloka'i. Halawa Valley dates (including those described below) were originally reported by Kirch (1975b) and document one of only a few occupation sequences for Hawaiian Islands.

Gak-2744. Halawa Valley **750 ± 90**

Wood charcoal, 8.0g, from taluvial fan site, A1–4 (05-315), geol Unit B, 32.5cm thick, stratum of hard-packed clay with charcoal and terrestrial gastropods (Kirch, 1975a, p 58). Coll Aug 1969 and subm Jan 1970 by PK. Cal AD 1211 (1264, 1268, 1276) 1284 at 1 σ; cal BP 739 (686, 682, 674) 666 at 1 σ. *Comments:* dates initial burning of valley slopes and beginning of human-induced erosion. Correlates with upper St IV occupation (Gak-2741).

Gak-2739. Halawa Valley **350 ± 80**

Wood charcoal, 9.0g, from rock shelter and habitation terrace Site A1–770 (05-315), Feature 3, mainly in Sq 4, intrusive to St III, 20–90cm below surface; sample from refuse pit filled with discrete ash lenses, char-

coal, silty sediment, volcanic glass flakes, adze fragments and marine invertebrates. Coll 1969 by G Hendren and subm Jan 1970 by PK. Cal AD 1441 (1494, 1502, 1506, 1605) 1645 at 1 σ; cal BP 509 (456, 448, 444, 345) 305 at 1 σ. *Comments:* average date for use of refuse pit and temporarily occupied shelter 1.3km from coast (Hendren, 1975). Possible assoc with primary flexed human burial.

Gak-2740. Halawa Valley **440 ± 80**

Wood charcoal, 40g, from habitation terrace Site A1–790 (05-315), Feature 2, Sq F7 and G7, intrusive to St III, capped by St I, 50–60cm below surface; earth oven filled with fire-cracked basalt, ash, charcoal, some marine shell, bone and one discrete ash lens. Coll Aug 1969 by Hendren and subm Jan 1970 by PK. Cal AD 1414 (1439) 1491 at 1 σ; cal BP 536 (511) 459 at 1 σ. *Comment:* site interpreted as a cookhouse and formed part of a residential complex situated 1.5 km from the coast (Hendren, 1975).

General Comment: temporary, inland occupation of the interior of Halawa Valley beginning during the Early Expansion period (AD 1100–1650; Kirch, 1985) is indicated by Site A1–770 (Beta-2739), while cookhouse Site A1–790 (05-315; Beta-2740), part of residential complex, suggests permanent occupation by early 15th century.

04-144, Kawela Mound series

Kawela Mound is situated adjacent to seaward edge of broad alluvial plain and, at time of occupation, immediately W of Kawela Stream (21° 4′ 5″ N, 157° 0′ 0″ W). Site is marked by low sandy dune 15m in diam and 1.5m elev. From 8 major cultural and geol strata, total depth >235cm, early human use of Kawela area, centered on exploitation of marine resources and birds, was documented (Weisler & Kirch, 1985, p 150). Later strata correlate with upland sites occupied primarily during 17th and 18th centuries AD.

Beta-2278. Kawela **290 ± 60**

Wood charcoal, 20.5g, from coastal midden Site 04-144, Feature 17, Tr 2, St VB, ca 235cm below surface; earth oven filled with ashy sediment, charcoal, fire-cracked vesicular basalt, marine and brackish water mollusks and bone. Coll Oct 1980 by M Weisler (MW); subm Jan 1981 by PK and MW. Cal AD 1494 (1640) 1656 at 1 σ; cal BP 456 (310) 294 at 1 σ. *Comment:* although this is not lowest habitation level of site, it is earliest date of occupation for Kawela area. While dates, cal AD 1673, 1678 and 1739 were obtained for St III (Beta-2273), St VB date, at ca 235cm below surface, is >110cm deeper, making cal AD 1494 likely age of occupation. Bones of endemic Hawaiian goose (*Nesochen sandvicensis;* id by S L Collins), historically unknown from Moloka'i, were recovered from this level and may have been culturally deposited.

Beta-2273. Kawela **<160**

Wood charcoal, 9.1g, from Site 04-144, Tr 7, St III; scoop hearth filled with charcoal and ash. Coll Oct 1980 by MW; subm Jan 1981 by PK

and MW. Cal AD 1673 (1678, 1739, 1804, 1938, 1955) 1943 at 1 σ; cal BP 277 (272, 211, 146, 12, 0) 7 at 1 σ. *Comment:* date for St III which contains densest concentrations of cultural material in site and correlates with settlement of inland residential complexes (*cf,* Beta-2274 to -2277, -2279, -3362 to -3369). Due to depth of St III (105–160cm below surface) and lack of any historic artifacts, cal AD dates of 1673, 1678, and 1739, assigned to Proto-Historic period (AD 1650–1795), are best age estimates of occupation.

General Comment: two cultural strata were dated from Kawela Mound, one near base of site, providing age for early use of area, the other ca 100–150cm below surface which correlates with occupation of upland settlements.

Upland Kawela series

Thirteen dates document late prehistoric (17th and 18th centuries AD), nearly synchronic settlement pattern during Proto-Historic period. Samples coll during intensive survey of 7.7 km^2 of leeward, s-central Moloka'i, including 442.5m^2 surface collection and excavation from 72 of 499 architectural features (Weisler & Kirch, 1985). Ten samples are from residential complexes (Weisler & Kirch, 1985, p 132). Two dates are from a dryland agric complex, and 1 sample was from an inland rock shelter. Eleven dates were originally reported as modern, *ie,* within 2 σ on the old side of modern standard (M Tamers, pers commun, 1986). Because no early historic artifacts were found in Kawela settlement area (aside from occasional late historic whiskey or wine bottle), all "modern" ages, reported here as "less than" (<) yr BP at 2 σ, are considered prehistoric.

Beta-3364. Kawela **300 ± 80**

Wood charcoal, 7.2g, from U-shaped enclosure Site 03-722 (Feature 408), architectural component 1, Sampling St D, NE ¼ of Cell 8, intrusive to St IVA; earth oven filled with fire-cracked vesicular basalt, dense ash, charcoal, marine invertebrates and bone. Coll Mar 1981 and subm Sep 1981 by MW. Cal 1476 (1532, 1541, 1637) 1659 at 1 σ; cal BP 474 (418, 409, 313) 291 at 1 σ. *Comment:* near base of ridge, ca 175m inland from coast at 21m contour, residential complex 03-722 has only three structures. Complex may be distant extension of another residential complex located upslope, remnant of larger complex that was partially destroyed by bulldozing or small residential unit. Beta-3364 is slightly older than most upland residential complexes at Kawela.

Beta-3365. Kawela **290 ± 60**

Wood charcoal, 22.1g, from C-shaped shelter Site 03-724 (Feature 431), architectural component 1, Units 1 to 4, St II, 12–30cm below surface; slab-lined oven filled with fire-cracked vesicular basalt, dense ash and marine invertebrates. Coll Mar 1981 and subm Sep 1981 by MW. Cal AD 1494 (1640) 1656 at 1 σ; cal BP 456 (310) 294 at 1 σ. *Comment:* date for cook-house and assoc residential complex. Feature 431 is 1 of 5 small shelters which surround large primary house structure. Residential complex,

along with assoc shrine, 37m E of main group, is situated along narrow ridge just inland from coast. Younger range of date, within Proto-Historic period, is probably more precise for occupation, considering ages of other residential complexes at Kawela.

Beta-2274. Kawela **<120**

Wood charcoal, 25.2g, coll from Site 04-730 (Feature 119), from architectural component 1, Units J41 and J42, St I, 0–9cm below surface; earth oven filled with dense ash, dispersed charcoal, fire-cracked vesicular basalt, bone and marine invertebrates. Coll Oct 1980 by MW; subm Jan 1981 by PK and MW. Cal AD 1689 (1694, 1722, 1812, 1859, 1869, 1921, 1955) 1926 at 1 σ; cal BP 261 (256, 228, 138, 91, 81, 29, 0) 24 at 1 σ. *Comment:* date for use of cook-house.

Beta-2275. Kawela **<140**

Wood charcoal, 11.8g, from habitation terrace 04-730 (Feature 121), dispersed through Units J23, J24, K23, K24, E22 and F22, St I, 0–15cm below surface. Coll Oct 1980 by MW; subm Jan 1981 by PK and MW. Cal AD 1680 (1685, 1730, 1808, 1931, 1955) 1937 at 1 σ; cal BP 270 (265, 220, 142, 19, 0) 13 at 1 σ. *Comment:* provides second date for residential complex 04-730.

General Comment: 2 of 5 habitation structures comprising residential complex 04-730, C-shaped shelter (Feature 119) and habitation terrace (Feature 121), were situated along E rim of Kawela Gulch at 95m contour overlooking gulch and S coastline. It was only residential complex in Kawela settlement with evidence of stone adze production. Beta-2274 and -2275, which overlap at 2 σ, suggest that separate structures comprising residential complex were occupied contemporaneously during Proto-Historic period. Site was subsequently destroyed by modern construction.

Beta-2276. Kawela **<140**

Wood charcoal, 11.1g, from habitation terrace Site 03-720, (Feature 321), architectural component 1, Unit 1, St I, 13–26cm below surface, coll from earth oven filled with ashy sediment, fire-cracked vesicular basalt, marine shellfish and bone. Coll Nov 1980 by MW; subm Jan 1981 by PK and MW. Cal AD 1680 (1685, 1730, 1808, 1931, 1955) 1937 at 1 σ; cal BP 270 (265, 220, 142, 19, 0) 13 at 1 σ. *Comment:* nearly 1 km W of Kawela Gulch is largest residential complex in Kawela study area consisting of 33 habitation and religious structures, burial platforms and gardening mounds spread along 260m of broad ridge. Sample coll from habitation terrace dated use of structure and, by assoc, residential complex.

Beta-3363. Kawela **<120**

Wood charcoal, 19.1g, from habitation terrace Site 04-142 (Feature 110), architectural component 1, Sampling St A, Cell 6, 22–25cm below surface; scoop hearth filled with marine invertebrates, fishbone, ash and dense charcoal lens at base. Coll Apr 1981 and subm Sep 1981 by MW. Cal AD 1689 (1694, 1722, 1812, 1859, 1869, 1921, 1955) 1926 at 1 σ; cal BP 261 (256, 228, 138, 91, 81, 29 0) 24 at 1 σ. *Comment:* date for structure,

substantial habitation terrace situated seaward of main residential complex.

Beta-3366. Kawela **150 ± 50**

Wood charcoal, 13.7g, from habitation terrace Site 04-142 (Feature 114), architectural component 1, Unit 1, below St I and above St V, 4–12cm below surface; slab-lined fireplace containing ashy sediment with marine and freshwater invertebrates, fishbone, *Aleurites* sp seed endocarp and evidence of two separate firings. Coll Apr 1981 and subm Sep 1981 by MW. Cal AD 1665 (1681, 1735, 1806, 1936, 1955) 1955 at 1 σ; cal BP 285 (269, 215, 144, 14, 0) 0 at 1 σ. *Comment:* date for lowest of two firings in fireplace. Dates use of food preparation area as well as residential complex (*cf,* Beta-3363, -3367).

Beta-3367. Kawela **<120**

Wood charcoal, 21.5g, from terrace Site 04-142 (Feature 113), architectural component 2, Sampling St D, Cell 24, between St I and IV, 5–20cm below surface; earth oven filled with fire-cracked vesicular basalt in ashy matrix. Coll Apr 1981 and subm Sep 1981 by MW. Cal AD 1689 (1694, 1722, 1812, 1859, 1869, 1921, 1955) 1926 at 1 σ; cal BP 261 (256, 228, 138, 91, 81, 29, 0) 24 at 1 σ. *Comment:* dates use of house structure as well as residential complex (*cf,* Beta-3363, -3366).

General Comment: situated along E ridge of Kawela Gulch at 81m contour is cluster of 6 habitation structures with another terrace 20m downslope. Environmental setting, overlooking agricultural area with commanding view of S coastline and across to Lana'i, Maui and Kaho'olawe, and "impressive" architecture of structures, suggests high status residence. Older portions of Beta-3363, -3366 and -3367, which overlap at 2 σ, are in Proto-Historic period. Site complex is illustrated in Weisler and Kirch (1985, p 147).

Beta-3368. Kawela **<180**

Wood charcoal, 2.4g, from compound structure Site 03-717 (Feature 248), N ½, Sampling St A, Cell 1, St I, 3–12cm below surface; dispersed through St I. Coll Apr 1981 and subm Sep 1981 by MW. Cal AD 1667 (1671, 1747, 1761, 1770, 1799, 1944, 1955) 1948 at 1 σ; cal BP 283 (279, 203, 189, 180, 151, 6, 0) 2 at 1 σ. *Comment:* sample given extended counting time to reduce statistical error. Residential complex 03-717, consisting of 21 structural features, is W of Kawela Gulch, ca 600m from coast at average elev of 35m. Beta-3368 provided date for largest, most impressive house feature not only in complex, but in entire Kawela settlement. Large quantities of marine shellfish, lithic debitage from tool manufacturing and artifacts are assoc with many structures. Occupation of site assigned to Proto-Historic period.

Beta-3369. Kawela **<170**

Wood charcoal, 6.6g, from rectangular enclosure Site 03-732 (Feature 414), architectural component 1, Unit 1, St II, 2–16cm below surface; slab-lined fireplace with fire-cracked vesicular basalt. Coll Mar 1981 and subm

Sep 1981 by MW. Cal AD 1670 (1674, 1743, 1801, 1941, 1955) 1945 at 1 σ; cal BP 280 (276, 207, 149, 9, 0) 5 at 1 σ. *Comment:* date for use of house feature, which was 1 of 6 structural features that comprised residential complex. Located ca 200m from coast between 18–29m elev, only sparse shellfish and lithic scatters are assoc with structures suggesting short-term use.

Beta-2277. Kawela **<180**

Wood charcoal, 9.9g, from square enclosure Site 03-731, (Feature 297), architectural component 1, Unit 11, St I, 2–12cm below surface; scoop hearth filled with dense ash. Coll Nov 1980 by MW; subm Jan 1981 by PK and MW. Cal AD 1667 (1671, 1747, 1761, 1770, 1799, 1944, 1955) 1948 at 1 σ; cal BP 283 (279, 203, 189, 180, 151, 6, 0) 2 at 1 σ. *Comment:* dates use of shelter and assoc dryland agricultural complex.

Beta-2279. Kawela **<140**

Wood charcoal, 8.3g, from square enclosure Site 03-731, (Feature 296), architectural component 1, Unit 2, St I, 2–13cm below surface; scoop hearth filled with ashy sediment and charcoal concentration at base. Coll Nov 1980 by MW; subm Jan 1981 by PK and MW. Cal AD 1680 (1685, 1730, 1808, 1931, 1955) 1937 at 1 σ; cal BP 270 (265, 220, 142, 19, 0) 13 at 1 σ. *Comment:* provides 2nd date for use of dryland agricultural complex 03-731 and shelter (*cf,* Beta-2277).

General Comment: major dryland agricultural complex, Site 03-731 covers ca 0.4ha along 2nd major ridge W of Kawela Gulch at ca 90m asl. Dryland crops, such as sweet potato (*Ipomoea* sp) and gourd (*Lagenaria* sp), may have been cultivated in rocky terrain. Complex consisted of >400 stone mounds from field clearance and 2 substantial temporary habitation shelters which yielded occupation dates (Beta-2277, -2279) from Proto-Historic period.

Beta-3362. Kawela **<120**

Wood charcoal, 15.4g, from rockshelter Site 04-710, (Feature 51), architectural component 2, SW ¼ of Unit 13, St I, 6–9cm below surface; scoop hearth filled with ashy sediment, dispersed charcoal, marine invertebrates and fishbone. Coll Apr 1981 and subm Sep 1981 by MW. Cal AD 1689 (1694, 1722, 1812, 1859, 1869, 1921, 1955) 1926 at 1 σ; cal BP 261 (256, 228, 138, 91, 81, 29, 0) 24 at 1 σ. *Comment:* date for use of upland rockshelter, 1.4km inland, and assoc barkcloth (*tapa*) found throughout upper layers and surface of cultural deposit.

Coastal Kaunakakai series

Three charcoal samples were coll from two coastal middens along broad alluvial flat E and W of Kaunakakai Stream. Sites 03-630 and 03-631 were used as bases for exploiting rich coastal flats and adjacent broad alluvial plain. Short-term occupation is documented by numerous scoop hearths, ovens and pit features assoc with marine invertebrates, fishbone and few artifacts. No evidence of permanent occupation, such as post molds and house foundations, were present. Beta-7564 dates earliest use of

any coastal dune along S coast and establishes date prior to inception of drastic environmental degradation initiated by burning adjacent uplands for agriculture. Beta-3802, -7563 and -7564 span Expansion period through early Proto-Historic period and fit well within expected age ranges for occupation of leeward Moloka'i. Upper cultural strata of both sites were disturbed and portions removed during expansion of nearby town. Sites were buried under alluvium deposited by adjacent stream and were discovered by backhoe trenching.

Beta-3802. Kaunakakai **110 ± 50**

Wood charcoal from Site 03-631, Tr 6, St VII, 73–93cm below surface, from pit(?) in cultural stratum containing small amounts of marine invertebrates, fishbone, possible fire-cracked basalt and carbonized *Aleurites moluccana* seed endocarp. Coll and subm Nov 1981 by K Shun. Cal AD 1677 (1706, 1719, 1814, 1829, 1879, 1917, 1955) 1955 at 1; cal BP 273 (244, 231, 136, 121, 71, 33, 0) 0 at 1 σ. *Comment:* coastal dune midden Site 03-631 is W of Kaunakakai Stream, 120m from shoreline at 2m asl. Sample was coll below water table and seawater percolation may have effected accuracy of dates (Shun, 1982). Older end of age range is not unusual for stratigraphic position of sample. Sample weight not reported.

Beta-7563. Kaunakakai **290 ± 60**

Charcoal, 27.3g, from Site 03-630, Tr 2, Test Pit 4, Layer IIc, Level 5, 55–62cm below surface, Feature 1 from small oven filled with dense charcoal, marine shell and fire-cracked vesicular basalt in calcareous sand matrix. Coll and subm Sep 1983 by J S Athens, Archaeol Consultant, Honolulu. Cal AD 1494 (1640) 1656 at 1 σ; cal BP 456 (310) 294 at 1 σ. *Comment:* this coastal dune is ca 250m from shoreline at 2m contour. Sample documents temporary use of coastal midden.

Beta-7564. Kaunakakai **710 ± 50**

Charcoal, 22.5g, from Site 03-630, Tr 16, Layer IIc, 60–65cm below surface, Feature 1 from small oven filled with charcoal and fire-cracked vesicular basalt in calcareous sand matrix. Coll and subm Sep 1983 by JSA. Cal AD 1262 (1280) 1285 at 1 σ; cal BP 688 (670) 665 at 1 σ. *Comment:* dates temporary use of site.

Upland Kaunakakai series

Four wood charcoal samples were coll from three sites in dryland agricultural zone 1.1km from coast. Zone, from 40–70m asl, is situated on both sides of Kaunakakai Gulch on gently sloping, weakly dissected uplands. Ca 37.5ha on E side of gulch contains several field shelters and thousands of stone mounds (which resulted from prehistoric field clearance) (Weisler, 1989). This site complex is largest, securely dated, prehistoric dryland agricultural zone on Moloka'i. Results from three field shelters are assumed to date use of adjacent agric features. All samples coll and subm Aug 1988 by MW.

Beta-27390. Kaunakakai **320 ± 70**

Wood charcoal, 6.4g, from agricultural Site 03-886, C-shaped shelter Feature B, W ½ of slab-lined fireplace, 15–20cm below surface. Fireplace contained fire-cracked vesicular basalt, charcoal and two layers of dense ash (representing individual firings) separated by culturally sterile sediment. Cal AD 1455 (1525, 1563, 1628) 1650 at 1 σ; cal BP 495 (425, 387, 322) 300 at 1 σ. *Comment:* sample consisted of charcoal pieces <7mm max length. Date from lowest firing in fireplace and use of field shelter. Shelter is in middle of agric field; date suggests use of this portion of complex.

Beta-27391. Kaunakakai **560 ± 110**

Wood charcoal, 2.6g, from agricultural Site 03-887, Tr 2, W face, St II, 6–14cm below surface; dispersed throughout stratum. Cal AD 1280 (1334, 1338, 1403) 1440 at 1 σ; cal BP 670 (616, 612, 547) 510 at 1 σ. *Comment:* only 0.34g of carbon was left after pretreatment; thus, counting was extended to reduce statistical error. Sample consisted mostly of angular chunks of wood charcoal <5mm max length and few pieces of carbonized grass dispersed through St II, id as agric stratum. Culturally sterile subsoil is St III, while ca 5cm of silt (St I) accumulated after abandonment of site.

Beta-27392. Kaunakakai **160 ± 60**

Wood charcoal, 10.0g, from agricultural Site 03-887, circular enclosed shelter Feature A, W ½ of fireplace, filled with dense ash and dispersed charcoal, few pieces of marine shellfish. Cal AD 1658 (1678, 1739, 1804, 1938, 1955) 1955 at 1 σ; cal BP 292 (272, 211, 146, 12, 0) 0 at 1 σ. *Comment:* sample consisted of angular chunks of wood charcoal <7mm max length with some carbonized grass. Probable id by MW of native Hawaiian tree (*Erythrina sandwicensis; wiliwili*) from at least one charcoal piece. Date is 2nd from Site 03-887 (*cf,* Beta-27391) and suggested use of agricultural complex for perhaps 400 yr from late 13th century through Proto-Historic period.

Beta-27393. Kaunakakai **350 ± 80**

Wood charcoal, 5.1g, from agricultural Site 03-888, circular shelter Feature A, W ½ of slab-lined fireplace, 10–15cm below surface. Fireplace filled with ash, fire-cracked vesicular basalt and charcoal lens at base. Cal AD 1441 (1494, 1502, 1506, 1605) 1645 at 1 σ; cal BP 509 (456, 448, 444, 345) 305 at 1 σ. *Comment:* possible id of *Erythrina sandwicensis* from sample which included angular chunks of wood charcoal <5mm max length. Sample provided date for use of shelter and lowest extent of upland agricultural zone near 40m contour.

General Comment: precise dating of agricultural sites remain, by their very nature, problematic. For example, gardening strata were continually reworked over course of use by constant addition of new sources of ^{14}C from crop plants, mulch and successive burning of dryland fields (*cf,* Handy, 1940; Yen, 1974). Thus, charcoal dispersed through gardening stratum (eg., Beta-27391) more accurately represents average age of multiple periods of use. This is in contrast to dates from discrete, charcoal layers

within circumscribed slab-lined fireplaces, which were periodically cleaned and thus are more closely assoc with last use by inhabitants (Dean, 1978). This may, in part, account for difference in results between Beta-27391 (cal AD 1280, oldest end of range) which was dispersed through gardening stratum, and Beta-27390 (cal AD 1455), -27392 (cal AD 1658), and -27393 (cal AD 1441) each recovered from fireplace. It appears that agricultural zone on E side of Kaunakakai Gulch (Sites 03-886, -887, -888) was used as early as late 13th century (Early Expansion period) and into beginning of Proto-Historic period.

03-312, Kalawao, Kalaupapa Peninsula, series

Kaupikiawa Cave (Site 03-312), is near NE extent of Kalaupapa Peninsula, 0.5km W of rocky coast at 15m asl. Dense shellfish scatter with historic and prehistoric artifacts are found on surface of collapsed lava tube and extend to ca 45cm below surface. Total site area is ca 300m^2. Site was test excavated for four days in 1966 and 1967 by Univ of Hawai'i field school (Pearson *et al*, 1974; Somers, 1985, p 42–43). Few excavation records exist and no stratigraphic profiles were drawn (R Pearson, pers commun, 1983). However, site was re-examined by MW and GF Somers, Natl Park Service, Honolulu, in 1984 and provenience of ^{14}C samples were considered accurate. Whether samples were from well-defined hearths or from other charcoal concentrations within deposits is uncertain. Three wood charcoal samples were subm for radiometric dating and document intermittent occupation of shelter beginning in 11th century AD (Beta-9276 and -9962) to well into Historic period.

Beta-9276. Kalawao **880 ± 70**

Wood charcoal, 25.5g, from Site 03-312, Sq 7, Layer D, 23–30cm below surface, possibly from hearth or dispersed through dense midden. Coll Nov 1966 by RP. Subm Apr 1984 by GFS. Cal AD 1031 (1161, 1185) 1225 at 1 σ; cal BP 919 (789, 765) 725 at 1 σ. *Comment:* 2nd oldest date for Moloka'i; suggests use of Kalaupapa Peninsula during late Developmental (AD 600–1100) to early Expansion period (AD 1100–1650) for exploitation of coastal marine resources.

Beta-9962. Kalawao **490 ± 180**

Wood ash and wood charcoal, 38.1g, from Site 03-312, Sq 7, Layer D, 35.5cm below surface, "top of reddish somewhat sterile level 5" (Pearson, 1966, note on sample label); probably from hearth. Coll Nov 1966 by RP. Subm July 1984 by GFS. Cal AD 1280 (1426) 1635 at 1 σ; cal BP 670 (524) 315 at 1 σ. *Comment:* only 0.17g of carbon obtained after pretreatment; thus, counting was extended to reduce statistical error (M Tamers, pers commun, 1984). Sample subm to corroborate age of Beta-9276 which overlaps at 2 σ. Beta-9962 dates occupation at or near base of cultural deposit.

Beta-9275. Kalawao **<120**

Wood charcoal, 21.3g, from Site 03-312, Sq 3, Layer 5, 30–38cm below surface, possibly from hearth or dispersed through dense midden deposit. Coll Nov 1966 by RP; subm Apr 1984 by GFS. Cal AD 1689 (1694,

1722, 1812, 1859, 1869, 1921, 1955) 1926 at 1 σ; cal BP 261 (256, 228, 138, 91, 81, 29, 0) 24 at 1 σ. *Comment:* considered excellent sample composed of relatively large chunks of wood charcoal. Young age and relatively deep stratigraphic position seem incongruous, but charcoal may be intrusive into this level, possibly as part of pit feature. No historic artifacts were recovered at this level suggesting older range of dates is reliable.

03-801, Kalama'ula series

Site 03-801 consists of several habitation structures and assoc gardening features covering ca 1ha of leeward slopes of central Moloka'i, 1.5km from coast at 45m contour. Site was probably used intermittently for gardening (Athens, 1985) during Early and Late Expansion periods (AD 1100–1650). One shell and 4 wood charcoal samples were coll and subm 1984 to 1985 by JSA.

Beta-11172. Kalama'ula **1450 ± 60**

Marine shell (*Tellina palatam*), 77.7g, from Site 03-800, Feature 12, Feature B (habitation terrace contiguous to Feature A discussed below), Test Pit 8, St III, 32–43cm below datum; shell lens of whole bivalves resting on non-cultural subsoil. Cal AD 1011 (1059) 1172 at 1 σ; cal BP 939 (891) 778 at 1 σ. *Comment:* ΔR of 115 ± 50 used to calibrate shell sample (Stuiver, Pearson & Braziunas, 1986) as sample derived from marine reservoir. (See also section on geologic samples for discussion of modern shell date.)

Three samples were subm from Feature 12, Terrace A, structure with three contiguous terraces at S extent of Site 03-800.

Beta-11171. Kalama'ula **400 ± 60**

Charcoal, 8.1g, from Test Pit 7, St I, 22–29cm below datum, base of cultural deposit; oven filled with abundant fire-cracked vesicular basalt in matrix of ash and silt. Cal AD 1434 (1450) 1619 at 1 σ; cal BP 516 (500) 331 at 1 σ. *Comment:* date for probable, short-term occupation of habitation terrace.

Beta-11168. Kalama'ula **300 ± 60**

Charcoal, 34.6g, from Test Pit 3, St III/2, 68–88cm below datum; oven with abundant charcoal chunks, grayish sediment and fire-cracked vesicular basalt. Cal AD 1490 (1532, 1541, 1637) 1653 at 1 σ; cal BP 460 (418, 409, 313) 297 at 1 σ. *Comment:* date for short-term occupation of habitation terrace.

Beta-11169. Kalama'ula **70 ± 50**

Charcoal, 10.5g, from Test Pit 4, St IIb, 38–51cm below datum; possible post hole or pit filled mostly with coral and charcoal chunks, some marine shell and bone in silt matrix. Cal AD 1692 (1903, 1905, 1955) 1955 at 1 σ; cal BP 258 (47, 45, 0) 0 at 1 σ. *Comment:* date for feature which may be post hole or pit.

General Comment: three dates, discussed above, document short-term use of habitation terrace from 15th-17th centuries of Late Expansion period.

Results fit Kirch's (1985) model of cultural evolution in Hawai'i, *ie,* less agriculturally productive areas of Hawaiian Islands (eg, leeward Moloka'i) were not utilized until relatively late in prehistoric sequence.

Beta-11170. Kalama'ula **<190**

Charcoal, 14.7g, from Site 03-800, C-shaped shelter (Feature 9), Test Pit 5, N extension, St II/I, 23–29cm below datum; Feature 1 probable hearth with oval lens of dark sediment with charcoal chunks. Cal AD 1663 (1668, 1751, 1758, 1777, 1796, 1947, 1953) 1955 at 1 σ; cal BP 287 (282, 199, 192, 173, 154, 3, 0) 0 at 1 σ. *Comment:* dated construction and use of shelter.

03-885, Kipu series

Two wood charcoal samples were acquired from buried site in uplands of central Moloka'i. Site 03-885, at base of unnamed gluch at 335m asl, lies 1.5km from sheer and inaccessible sea cliffs of N coast.

Beta-27115. Kipu **500 ± 70**

Wood charcoal, 20.3g, from Site 03-885, Tr 2, W face, St V, 130–155cm below surface, dispersed throughout an oven feature containing marine shell, fishbone, fire-cracked vesicular basalt and few artifacts. Coll July 1988 and subm Aug 1988 by MW. Cal AD 1331 (1422) 1442 at 1 σ; cal BP 619 (528) 508 at 1 σ. *Comment:* along with Beta-27116 dates initial burning of forested uplands in Kipu area ostensibly to clear land for dryland agriculture. Also establishes approximate sedimentation rate for 120cm of overburden covering St V.

Beta-27116. Kipu **610 ± 60**

Wood charcoal, 52.1g, from Site 03-885, Tr 2, E face, St V, 120–135cm below surface, dispersed through sandy silt matrix, ca 200cm from oven (discussed above). Coll July 1988 and subm Aug 1988 by MW. Cal AD 1283 (1321, 1367, 1388) 1408 at 1 σ; cal BP 667 (629, 583, 562) 542 at 1 σ. *Comment:* overlaps with Beta-27115 at 2 σ and corroborates date for initial burning of Kipu forest.

General Comment: although depth of Beta-27115 and -27116 vary slightly, they provide independent support for initial burning of forested Kipu uplands during Early Expansion period.

Kaluako'i series

Land division of Kaluako'i encompasses ca 20,000ha of leeward W Moloka'i, approximately W ⅓ of island. Dominated by Maunaloa volcano, its two rift zones (trending NW and SW) descend gently towards rocky coastlines with sheltered embayments. One fishbone and 6 charcoal samples are discussed from 5 sites along coast and 1 atop Maunaloa.

Beta-20906. Kawa'aloa Bay **1290 ± 60**

Fishbone (*Kuhlia sandvicensis*) 500g, from Site 02-21, pit feature containing predominately fishbone, with much lesser amounts of turtle and

birdbone. Site is atop sterile, strongly cemented coralline sand, exposed at ground surface. Coll Apr 1984 by MW and S Collins. Subm Apr 1987 by MW. Cal AD 1176 (1255) 1296 at 1 σ; cal BP 774 (695) 654 at 1 σ. *Comment:* feature is probably part of midden extending from rockshelter located to NW. Pit clearly documents bones of endemic Hawaiian goose (*Nesochen sandvicensis*), historically unknown on Moloka'i, and prehistoric cultural material. Ocean reservoir effect was calculated as sample material derived from marine environment. A ΔR factor of 115 ± 50, suggested for Hawaiian samples (Stuiver, Pearson, & Braziunas, 1986, p 995), was used for calibration.

Beta-13743. Mo'omomi **360 ± 50**

Wood charcoal, 27.7g, from Site 02-24, Sq E6, 41–46cm below surface, in extremely dense stratum of basalt debitage, 15–30cm thick; sample probably dispersed through level. Coll Aug 1952 by WJ Bonk, Univ Hawai'i; subm Aug 1985 by MW and T S Dye, formerly Bishop Mus. Cal AD 1445 (1490) 1635 at 1 σ; cal BP 505 (460) 315 at 1 σ. *Comment:* Site 02-24, 0.5km S of coast at 15m asl, is natural shelter (ca 15m^2) in lithified dune excavated in 1952 (Bonk, 1954). Dates initial use of rock shelter occupied by persons for reducing fine-grained basalt into adze blanks and preforms. Provides indirect date for use of Mo'omomi Adze Quarry (02-29), ca 0.7km SW.

Beta-13744. 'Amikopala **260 ± 50**

Wood charcoal, 31.4g, from habitation Site 02-85, NE ⅓ of slab-lined fireplace, 10–28cm below surface; sample dispersed through stratum containing fire-cracked basalt in silt matrix. Coll July 1985 and subm Aug 1985 by MW and TSD. Cal 1528 (1648) 1662 at 1 σ; cal BP 422 (302) 288 at 1 σ. *Comment:* date for occupation of 'Amikopala summit region (Dye, Weisler & Riford, 1985). Although site is in 'Amikopala Quarry complex, assoc of this date with adze production is unclear.

Beta-5700. Kawa'aloa Bay **<160**

Charcoal, 17.1g, from Site 02-629, dispersed through Feature A (cultural stratum with few basalt flakes, marine invertebrates and fishbone). Coll Oct 1982 by MW and SC; subm 1983 by SC. Cal AD 1673 (1678, 1739, 1804, 1938, 1955) 1943 at 1 σ; cal BP 277 (272, 211, 146, 12, 0) 7 at 1 σ. *Comment:* site lies in large dune of loose, calcareous sand 225m SE of Kawa'aloa Bay at ca 6m asl. There was no evidence for historic use and 02-629 may represent series of late prehistoric occupations.

Beta-20881. Kawakiu Nui **170 ± 60**

Wood charcoal, 23.8g, from Site 01-1610, Feature A, St III, 45cm below surface at base of wave-cut exposure; sample dispersed through cultural stratum, 15cm thick, with dense marine shellfish, fishbone, fire-cracked vesicular basalt and basalt flakes in silty-sand matrix. Coll Feb 1987 and subm Apr 1987 by MW. Cal AD 1655 (1674, 1743, 1801, 1941, 1955) 1955 at 1 σ; cal BP 295 (276, 207, 149, 9, 0) 0 at 1 σ. *Comment:* site is on N

side of Kawakiu Nui Bay at end of eroding ridge. Sample provides 1st ^{14}C result for entire W coast of Moloka'i (Weisler, 1987) and from its depth and lack of historical material, older end of age range most accurately dates site use.

M-767. Kawa'aloa Bay **550 ± 300**

Charcoal from Rockshelter 02-21, Sq F12, lowest cultural level, ca 1.1m below surface. Coll Aug 1952 by WJ Bonk. Subm Jan 1959 by K P Emory, formerly Bishop Mus. Cal AD 1229 (1422) 1952 at 1 σ; cal BP 721 (528) 0 at 1 σ. *Comment:* Rockshelter 02-21 formed in lithified sand at W end of Kawa'aloa Bay, ca 15m from ocean, at 3m contour. Excavated by WJB Aug 1952 (Bonk, 1954). No other data available. Date was originally reported in Crane and Griffin (1959, p 195). See General Comment below.

M-1183. Kalani **425 ± 150**

Charcoal, 26.0g, from rockshelter 02-26, Sq F12, bottom of concentrated cultural deposit of marine shell and fishbone, 61–76cm below datum. Coll Aug 1952 by WJB; subm June 1959 by KPE. Cal AD 1330 (1442) 1640 at 1 σ; cal BP 620 (508) 310 at 1 σ. *Comment:* site located just before rocky coastline changes to precipitous cliffs, ca 15m from coast at 10m asl. Little data available. Solid carbon was probably used to analyze sample.

General Comment: according to Taylor (1987), solid carbon was used by W F Libby and other early researchers such as the Michigan lab, during the 1950s. These measurements resulted in "typical counting errors of 200 to 300 yrs for samples up to about 5000 yrs" (Taylor, 1987, p 82). Due to problems with sample contamination and detecting efficiency, results were often irreproducible. Determinations were frequently skewed toward too recent ages (Browman, 1981). Based on current knowledge of W Moloka'i settlement pattern chronology, age ranges of M-767 and -1183 *may* be correct, but must be omitted from any discussion of prehistoric chronology.

It is interesting to note that the first ^{14}C sample analyzed from any Pacific island, one that "opened up undreamed of possibilities for reconstructing the prehistory of (Hawai'i)" (Emory, Bonk & Sinoto, 1959, p vii), was analyzed by Libby at Chicago in 1951 using the solid carbon counting technique. Ironically, this important sample (C-540) should not be accepted as valid, although its reported long age span influenced a generation of archaeologists who had previously thought that Pacific archaeological sites were of much shorter duration and did not merit serious attention.

Four ^{14}C results for Kaluako'i span Early and Late Expansion periods (AD 1100–1650), and a 5th (Beta-5700) begins in the early Proto-Historic period. Two dates processed by the Michigan lab in the late 1950s (M-767, -1183) are considered invalid. Evidence for exploitation of coastal resources (shellfish, fish and turtle) and landbirds began toward the end of the 12th century and continues today. The Mo'omomi Adze Quarry, one of

the largest on the island, near the N coast, was in use as early as the 15th century. No sites were dated along the S coast, and only one midden found on the W shore at Kawakiu Nui Bay was dated. A habitation complex near the summit region of Maunaloa at 'Amikopala, yielded a date from the 16th–17th centuries. These dates conform to current models of Hawaiian settlement patterns (Hommon, 1986; Kirch 1985) in that settlements were dispersed through the windward regions in early prehistory, while the drier, leeward regions, such as W Moloka'i, were occupied relatively late, beginning in the Early Expansion period.

GEOLOGIC SAMPLES

Hawai'i

Moloka'i Island

Beta-5122. Kawela **3370 ± 70**

Two pieces of branch coral (*Porites* sp), 28.2g, from Site 04-143, Auger Hole 10, 40cm below top of St III (marine stratum, non-cultural), 300cm below surface. Coll Aug 1981 and subm Aug 1982 by MW. Cal BC 1255 (1122) 996 at 1 σ; cal BP 3204 (3071) 2945 at 1 σ. *Comment:* sample recovered from auger hole located ca 400m inland from present shoreline, near sea level, on broad alluvial plain. Kakahai'a Fishpond lies immediately seaward. Coral sample was sharp, with no evidence of water-rounding, and assumed contemporaneous with deposition of marine stratum. Sample was pretreated by etching away outer layer with dilute acid; benzene synthesis and counting proceeded normally. ΔR of 115 ± 50 yr (Stuiver, Pearson & Braziunas, 1986) was used to calculate marine reservoir effect. Age of sample documented when present marsh surrounding Kakahai'a Pond was open to sea (Weisler, 1983). During Proto-Historic period (AD 1650–1795), Kawela area was intensively occupied (Weisler & Kirch, 1985) and this coincided with human-induced shoreline progradation and later infilling of Kakahai'a Pond in 19th century.

Beta-12903. Puko'o **410 ± 60**
$\delta^{13}C = -1.12‰$

Marine shell (*Tellina palatam*), 34.6g, "from Moloka'i: Puko'o, from sandy mud, 6 inches to 2 feet down" (Athens, 1983, p 89). Coll 1905 by Langford and Thaanum. Subm 1983 by JSA. Cal AD 1955 (1955) 0 at 1 σ; cal BP 0 (0) 1950 at 1 σ. *Comment:* sample subm to provide ΔR for marine reservoir effect for cultural sample Beta-11172, above (Kalama'ula). This sample varies considerably from L-576J (Stuiver, Pearson & Braziunas, 1986, p 1020) as 629 ± 51, or Beta-14024.

GX-2672. Kalani **27,000**

Fossil landsnail shells from lithified reddish fine-grained soil bed, 15–30cm thick, lying unconformably on lower eolianite (Stearns, 1973, p 160). Soil layer is 1km W of Kaiehu Point, 2m asl at top of coralline sand beach. Stratum contains abundant calcareous root casts indicating soil bed supported dense vegetation. Coll by J Aidem ca 1970; subm ca 1970 by H T Stearns, formerly U S G S. *Comments:* ca 10g of sample remained after ultra-

sonic cleaning and dilute HCl leach (H Krueger, pers commun, 1988); (HTS): date is consistent with similar fossil land snails 61 cm above. Age and position of stratum suggest climatic and environmental conditions vastly different from present.

ACKNOWLEDGMENTS

In 1980, Patrick Kirch (formerly, B P Bishop Museum) provided the initial opportunity to begin what has developed into a long-term involvement with Moloka'i archaeology. Many of the ^{14}C samples submitted during 1980 to 1985 were collected from field projects conducted under the auspices of the B P Bishop Museum, Honolulu, while the author was on the staff of the Department of Anthropology. Much of the archival data were collected at this time. Federal Grants-in-Aid support to the author (and P Cleghorn) provided funds, in 1985, through the Bishop Museum for dating two samples from West Moloka'i. Gary Somers (National Park Service, Honolulu) arranged travel expenses to visit sites at the Kalaupapa Peninsula and funds for dating three samples from Kaupikiawa Cave. Through archaeological contracts with the author and Randolf Moore (Moloka'i Ranch Ltd), Jim Kingzett (Moloka'i Golf Inc), and Phillip Boydston (Kaluako'i Corp), funding for many samples submitted during 1985 to 1988 was obtained.

Several contract reports and other site information were made available by Stephen Athens (Archaeological Consultant, Honolulu) and Annie Griffin, Historic Sites Division, Department of Land and Natural Resources, Honolulu. Requests for data on sample analyses were promptly answered by Kunihiko Kigoshi (Gakushuin), Harold Krueger (Geochron), and Jerry Stipp and Murry Tamers (Beta Analytic Inc).

At the University of Washington, comments on earlier versions of this paper were made by Patrick Kirch, Minze Stuiver, Donald Grayson, Robert Wenke and Kris Wilhelmsen. Minze Stuiver kindly provided an updated version of the microcomputer calibration program and answered several questions that archaeologists often confront while trying to interpret archaeological radiocarbon age determinations. I thank all of the above for their help and absolve them from any shortcomings found herein.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 145–149]

ACCURACY AND PRECISION IN DATING MICROGRAM CARBON SAMPLES

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ABSTRACT. The accuracy of AMS radiocarbon determinations on very small samples has been tested by measuring a suite of microgram-sized samples of a known-age material. The total measurement precision for the smallest sample (50μg) was found to be ±3% and the precision improved with larger sample size. The accuracies of the measurements were found to be within the measurement precisions.

Accelerator mass spectrometry (AMS) made possible the radiocarbon dating of samples containing only milligrams of carbon. As could be expected, pressure to develop methods for dating smaller amounts of carbon continued after the advent of AMS. We showed in 1986 that it was possible to date a 50μg sample of carbon using AMS to a precision which was not limited by the counting statistics of the measurement (Nelson *et al,* 1986b). We found that our total measurement system, from isolation of the carbon as CO_2 to final direct counting of the ^{14}C, was ca 1% efficient. Hence, it should be possible to measure the concentration of a modern sample to a counting-statistics precision of 1% using as little as 17μg of carbon. However, the graphite which is finally measured by AMS includes an unknown amount of ^{14}C which is introduced into the sample during processing. We researched the contribution of contamination to processing (Vogel, Nelson & Southon, 1987) and demonstrated that this places a limit on the ultimate precision possible in measuring very small samples. Since then, we have made use of samples containing 20–500μg of carbon in numerous studies in archaeology (Snow *et al,* 1986; Nelson *et al,* 1986a), paleo-climate (Peteet *et al,* ms), atmospheric science (Wahlen *et al,* ms), oceanography (Pedersen, Vogel & Southon, 1986), earth science (Vogel *et al,* 1989), and ecology (Bauer, Spies & Vogel, ms). We present here evidence that our measurement system can not only produce precise dates from very small amounts of materials, but that these dates are also accurate.

We tested our AMS system by dating several aliquots of an extracted cellulose provided by the Quaternary Isotope Lab of the University of Washington (Archaeology Comparison Test sample number 1, or ACT-1). These were processed in our usual manner as described in Vogel, Neslon and Southon (1987). The aliquots varied in size from 50 ± 4μg C to 6490 ± 4μg C (Table 1), as measured manometrically after combustion to CO_2 in sealed quartz tubes using CuO oxidant. These samples were processed without dilution by ^{14}C-free CO_2 as has been done by others (Verkouteren *et al,* 1987). The CO_2 was reduced to a filamentous graphite coating on cobalt powder using hydrogen in our usual reactors. The two largest CO_2 samples were divided and graphitized in 3 and 4 reactors, respectively, since each reactor is limited to a maximum of 2 mg of carbon. Most contamination arises from combustion (Vogel, Nelson, and Southon 1987), and graphitisation does not result in large isotope fractionation (Vogel,

TABLE 1
^{14}C concentrations and measurement parameters for various-sized samples

Size* (μgC)	$^{12}C^-$ (μA)**	N meas	Time (sec)	Total counts	^{14}C concentrations: Graphite† (pMC)	±	Bgnd‡ (pMC)	±	Sample (pMC)	±	Precision§ %	Accuracy# %
50	11.6	3	600	12424	75.64	0.95	3.00	2.00	72.64	2.21	3.0	2.2
90	14.0	4	800	20284	74.98	0.93	1.67	1.11	73.31	1.45	2.0	1.3
175	18.2	4	1000	33180	74.68	0.66	0.86	0.57	73.83	0.87	1.2	0.6
260	18.3	3	600	20194	75.35	0.78	0.58	0.38	74.78	0.87	1.2	0.7
420	22.7	4	800	33178	74.32	0.70	0.35	0.15	73.97	0.72	1.0	0.4
840	20.6	7	1600	60877	76.77	0.69	0.35	0.15	76.42	0.71	0.9	2.9
4700	23.3	22	3700	153373	74.42	0.46	0.35	0.15	74.13	0.47	0.6	0.2
6490	22.4	24	5100	202405	74.50	0.24	0.35	0.15	74.14	0.26	0.4	0.2

*Amount of CO_2 from combustion. Two largest samples analyzed using 4 separate aliquots of prepared graphite.

**Current is the average for the total time of the N measurements.

†^{14}C concentration calculated from the measured $^{14}C/^{13}C$ ratio using the measured $\delta\,^{13}C$ value of $-20.5‰$. Final concentrations corrected to a $\delta\,^{13}C$ of $-25‰$.

‡Background calculated as (1.5 ± 1.0μg modern equivalent) divided by the sample size in μg. Large sample (>400μg) background was 0.35 ± 0.15 pMC.

§Precision is the quadratic combination of the uncertainty in the background and the standard deviation of the set of N measurements.

#Accuracy calculated as the percentage difference from the value determined by a high-precision counting lab. The material was ACT-1 cellulose provided by M Stuiver (A = 74.27 ± 0.18 pMC, 2390 ± 20 BP).

Southon & Nelson 1987). Thus, the graphite from the separate reactions of the large samples was mixed and then considered as a single quantity. The cobalt powder to carbon weight ratios ranged from 15 for the smallest sample to 3 for the larger ones. This variation does not affect these measurements to the desired precision (Vogel, Southon & Nelson, 1987). No special handling (*ie,* argon atmosphere or closed systems) was used, despite the known presence of a "hot," organic, airborne contaminant. (Spent biomedical scintillants are stored in a room below our laboratory.)

Portions containing 300–500μg carbon of the large graphites were pressed into individual sample holders for measurement. The smaller samples were pressed into identical holders above a layer of pure silver powder so that all samples were recessed in the holes by a similar distance. The ion currents from these smaller samples were initially more than half the current from the larger samples, as is expected solely from carbon dilution by the cobalt (Vogel, Southon & Nelson, 1987). Once the relatively thin layer of graphite/cobalt over the silver base was sputtered through for the smallest samples, the ion output decreased with time. The beam shape also changed to that of a "doughnut," causing differential transmission effects between the ^{14}C and the ^{13}C. This was observed for only the 50μg sample, the $^{14}C/^{13}C$ ratio of which abruptly changed by 5% after 10 minutes of measurement. Even so, the 10 minutes of usable beam produced over 12,000 counts of ^{14}C, a total system efficiency of 0.6% from CO_2 to counted ^{14}C.

Table 1 gives the ^{14}C concentration results for the 8 sample sizes. The total measurement times and the total ^{14}C counts refer to the sum of all the measurements on each sample. No measurement was limited by statistics by >0.9%. The ^{14}C concentrations of the graphites are given in percent modern carbon (pMC), and the quoted uncertainties are the observed reproducibility (at 1σ) of the 3 to 24 different measurements made on each graphite sample. These isotope ratios were measured to precisions between 0.4 and 1.3%. The method for determining the background to be subtracted from these measured concentrations was discussed in Vogel, Nelson and Southon (1987). However, since that publication, we have taken steps to reduce our processing contamination. Our background has been reduced from the 0.48 ± 0.16pMC reported for large coal samples to 0.35 ± 0.15pMC as measured on amber and 45Myr (sic!) wood. The small sample background is now calculated to arise from 1.5 ± 1.0μg C modern-equivalent contamination during processing. This value was used to calculate the background subtracted from these small samples. We attribute our improvements to using cobalt rather than iron catalyst (Vogel, Southon & Nelson, 1987) and to storing our quartz combustion tubes in water vapor prior to use to dislodge adsorbed CO_2 (Zumbrunn, Neftel & Oeschger, 1982). The resultant final sample ^{14}C concentrations are shown in Table 1 and Figure 1. The total measurement precision for the sample includes the precision of the graphite measurement and the background uncertainty. This precision, in percent form, ranged from 3.0% for the 50μg sample to 0.4% for the largest sample.

An indication of the accuracy (in distinction to the precision) of these measurements is found by comparing them to the value obtained by the

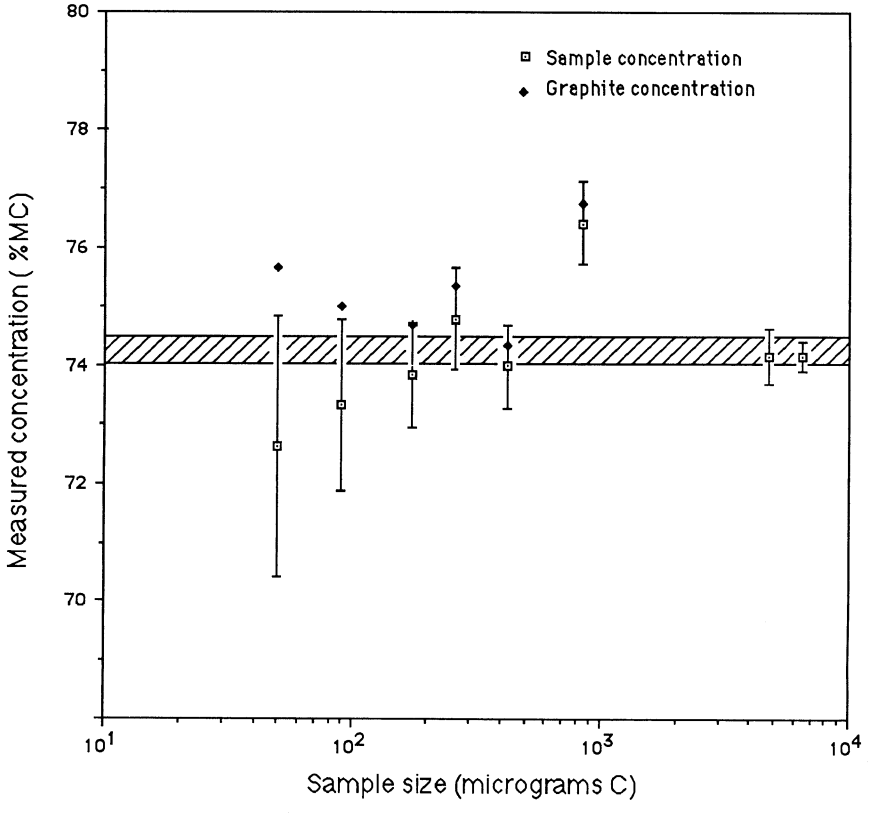

Fig 1. ^{14}C concentration *vs* processing size for 8 samples of ACT-1 cellulose. The 1σ width obtained by the University of Washington Quaternary Isotope Lab is shown as the hatched bar (74.27 ± 0.18 pMC, 2390 ± 20 yr BP). The graphite ^{14}C concentration, without any background subtraction, is also shown for the 6 smaller samples.

laboratory that provided the test material. Stuiver (pers commun, 1988) has determined this material to have an activity of 74.27 ± 0.18 pMC, corresponding to an age of 2390 ± 20 BP. The weighted average for all determinations in this test is 74.30 ± 0.19 pMC, or 2386 ± 20 BP. The very good agreement indicates that, on average, our results are accurate within our stated measurement precision.

However, it is the accuracy of individual determinations, and the effect of sample size on accuracy that is of greatest interest. The relative differences between our determinations and that of Stuiver are given in the last column of Table 1. With one exception, these differences are all smaller than the measurement precisions, indicating that our quoted uncertainties may be too conservative. An examination of the data suggests that we have over-estimated the uncertainty of the measurement background. However, given the very small amounts of contaminating material involved, we believe this caution is justified. A very large amount of experience on ultra-

small samples will be required before we can predict with confidence that processing contamination varies by $<1\mu$g C. The single sample that is apparently discrepant is large (840μg C) and is 3σ away from the mean, which would not be statistically unusual for this number of determinations. A later remeasurement of the remaining graphite from this sample gave a concentration of 74.33 ± 0.97pMC. The error in the initial determination probably arose from sample presentation in the ion source and was not inherent to the graphite. Even with this possible outlier, the spread of results is about that expected for replicative determinations on a single sample:

$$(\chi^2 = 11.3 < \chi^2_{.05} = 14.07; \text{n} = 8).$$

The results for the smallest aliquots are accurate within their measurement precisions. While the measurements for the small samples are not as precise as those for the larger samples, there is no bias in the results obtained: measurement accuracy reflects measurement precision. It is clear that, with the methods used here, reliable ^{14}C determinations can be directly made on samples containing only a few tens of micrograms of carbon.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 151–155]

HIGH-RESOLUTION ^{14}C DATING OF ORGANIC DEPOSITS USING NATURAL ATMOSPHERIC ^{14}C VARIATIONS

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ABSTRACT. The occurrence of atmospheric ^{14}C variations complicates calibration, *ie*, the translation of ^{14}C ages into real calendar ages. The procedure of wiggle matching, however, allows very precise calibration, by matching known ^{14}C variations with wiggles in the floating chronology. In principle, wiggle matching can also be applied to a series of ^{14}C dates from organic (peat) deposits. Where, in general, ^{14}C ages are required at short distances and on small samples, dating by ^{14}C accelerator mass spectrometry (AMS) is required.

INTRODUCTION

Variations in the $^{14}C/^{12}C$ ratio of CO_2 in the atmosphere are well established. Possible causes for the fluctuations were mentioned by Damon, Lerman & Long (1978). Medium-term atmospheric variations are evident from measurements of tree rings (Suess, 1970; de Jong, 1981; Klein *et al,* 1982; Becker, 1983). The so-called Suess wiggles are evident when conventional ^{14}C ages of tree rings are plotted *vs* tree-ring number (each tree ring representing one year). Pronounced wiggles may amount to changes in conventional ^{14}C ages of 120–180 yr within a historical period of 40–50 yr.

Presently, computer programs exist to transfer individual conventional ^{14}C ages into real calendar ages, using the known calibration curves. However, because of the irregular shape of these curves, the Gaussian distribution of an individual date of organic material ofter corresponds to a rather irregular real calendar age probability distribution, which in some cases encompasses a relatively long period (van der Plicht, Mook & Hasper, 1987). By using a series of ^{14}C ages of stratigraphically consecutive samples, we can, however, obtain a much better age assignment of a profile.

Overlapping chronologies can be matched using the method of wiggle matching (Ferguson, Huber & Suess, 1966) because separate wiggles often show particular and individual features. For curve matching, both sets must contain sufficient dates. In order to avoid ambiguity in the wiggle match, the peat section must be long enough to cover more than merely one wiggle. The matching procedure can in principle be done by computer.

The European Hohenheim master chronology is extended back to 7237 BC (Becker & Schmidt, in press) and the North American bristlecone pine chronology is extended back to 6700 BC (Ferguson & Graybill, 1983).

WIGGLE MATCHING IN ORGANIC DEPOSITS

The variations of atmospheric ^{14}C of the past that are reflected in the wiggles of the tree-ring calibration curves will certainly also be present in the organic material of lake sediments and bog deposits. Bioturbation, contamination and reservoir effect (Olsson, 1986) may have smoothed or dis-

turbed the original fluctuations, but in most sites selected for detailed palynological studies, these phenomena will not have played an important role.

In raised bog deposits (*Sphagnum* bogs) or other deposits with similar high accumulation rates (Aaby, 1986), high-resolution dating combined with wiggle matching may be successful. The application of tandem accelerators used as ^{14}C mass spectrometers allows ^{14}C dating of very small samples so that (non-aquatic) plant remains such as mosses, fruits and seeds can be selected at very short vertical distances (*eg*, a sample in every 2 or 3mm of sediment). In that way, contamination by (younger) roots can be totally avoided and an optimal correspondence of the date with the pollen spectrum can be achieved.

Following this strategy, the uncertainties of separate ^{14}C dates due to the natural atmospheric variations can be avoided and the disadvantage of these variations can be turned into an advantage: a more exact orientation in calendar ages of a stratigraphic sequence becomes possible. Application of "pollen density dating" (Middeldorp, 1982) in the same sediment sequence can provide an extra check on changes in the sediment accumulation rate.

Carbonate of relatively old age in lake deposits can be excluded from the sample by using fossil pollen for ^{14}C dating (preparation according to Faegri & Iversen (1975) using noncontaminating chemicals and ending the procedure with pollen in distilled water). In Holocene lake deposits, this pollen often is almost completely of non-aquatic origin (trees and herbaceous plants of upland sites). The application of ultrasonic filtration (Caratini, 1980; Tomlinson, 1984) on a 10μm sieve can be useful in eliminating fine organic particles from the pollen samples.

In the same way, pollen of subsequent layers in soils can be used for dating to avoid contamination by decomposed younger roots and fine vertically transported organic material. ^{14}C wiggle reconstruction cannot be used in soil studies because of the low time resolution and mixing as a consequence of the mobility of the various chemical fractions, and of activities of the soil fauna. The method outlined here may be useful to pinpoint with high precision floating chronologies in annually laminated sediments (Saarnisto, 1986; Ralska-Jasiewiczowa, Wicik & Wieckowski, 1987), especially when pollen can be used for dating. Even the possible presence of hiatuses may be studied (wiggles or part of one wiggle may be missing). In case of laminated sediments with questionable annual lamination, the present technique may also be of practical value.

DISCUSSION

The possibilities for the proposed high-resolution dating (recognition of Suess wiggles in sediments and curve matching with the dendro-calibration curve) depend on sediment accumulation rates. Apart from the demands related to little mixing during the formation of the deposit, there is also the need for minimal time resolution for each ^{14}C sample in a continuous series. In order to recognize separate Suess wiggles with individual characteristics, each sediment or peat sample should represent $\leq$ca 25 yr.

Peat accumulation rates in NW European bogs were calculated by Aaby and Tauber (1975). The mean rates vary between ca 0.2 and 0.9mm/yr, with a tendency for younger peat layers to higher accumulation rates (up to 1.8mm/yr) as a consequence of diminished autocompaction in the upper layers. Thus, for a successful application of wiggle matching, we should aim for ^{14}C dating 5–10mm of peat.

For matching a "floating" peat chronology with the calibration curve, wiggles are not always required. If the conventional ^{14}C age period is limited to a steep part of the calibration curve, matching is straightforward and requires 3–4 stratigraphically consecutive samples. An example is shown in Figure 1. Assuming constant peat growth, *ie,* a linear relation between sample depth and time, a series of ^{14}C ages (four in our example) may be stretched and shifted in real time (horizontally) to match the calibration curve.

If, however, the ^{14}C age range obtained coincides with a relatively horizontal part of the calibration curves, or extends over a long period of which only part of the calibration curve is steep—which is generally the case—we depend entirely on the occurrence of wiggles in this part. In these cases, more ^{14}C age determinations over a longer time period are required. At present, computer programs exist for determining the best (wiggle) match between the calibration data and a floating tree-ring chronology (Pearson,

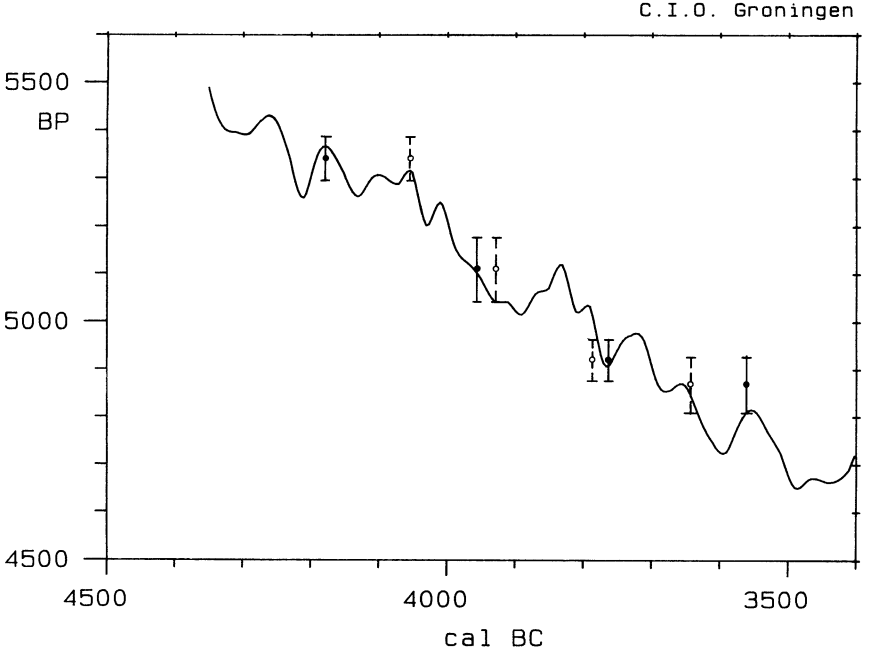

Fig 1. Part of the calibration curve based on the data of Pearson *et al* (1986). A series of ^{14}C ages from a peat section (subm by M O'Connell, Univ College, Galway, Ireland) from Loch Sheeauns is fitted for two different (constant) growth rates: filled circles refer to small peat accumulation. The relative position on the horizontal scale is proportional to sample depth.

1986), in which case, however, the growth period is known. In dating peat or lake deposits of unknown accumulation rates, this method cannot be applied simply.

There is one additional complication in wiggle matching organic deposits as compared to tree rings, for which the year-to-year true-age distribution is known, although absolute ages are not (floating chronology). For organic deposits, the sedimentation rate is unknown. Thus, computer matching should also make the proper adjustment for this. With constant accumulation rate, the real-age *vs* depth relationship is proportional, however, with an unknown proportionality constant. This amounts to stretching the calendar age chronology of the stratigraphical sequence until a best fit is obtained (Fig 1). This option will be inserted in the Groningen fitting program. With varying rates, matching becomes more complicated and additional information is required, *eg*, from variations in pollen concentration (Middeldorp, 1982).

The large number of dates (several wiggles have to be recorded) makes the method very expensive so that careful selection of deposits is necessary. In combination with high-resolution pollen analysis and the study of macrofossils, the estimation of the approximate duration (in calendar years) of the recorded vegetational and climatic changes can be improved.

The combination of detailed studies of raised bog and lake deposits with the above-mentioned high-resolution dating may lead to detecting a direct relationship between ^{14}C variations and short-term climatic fluctuations caused by solar and/or geomagnetic variations recorded in lake or bog ecosystems. Fluctuations in the concentrations of ^{14}C may help explain the very palaeoclimatic events to which ^{14}C dating has been applied. Using this dating strategy, it will be possible to compare, with maximal precision, the detailed palaeoecological and partly palaeoclimatic reconstructions based on raised bog studies (Middeldorp, 1982; Aaby, 1975; Barber, 1981; van Geel, 1978; Dupont, 1986) and densitometric and isotope (dendro) climatic reconstructions (Dupont & Mook, 1987; Bradley, 1985). Even cyclic climatic effects related to the causes of the ^{14}C wiggles may be recorded and subsequently interpreted in organic deposits.

For the application of the present idea, it would be useful to identify each wiggle in the tree-ring calibration curve by an identification number (*cf* the stages in the isotope curves from oceanic records (Emiliani, 1955)).

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 157–162]

ANOMALOUS AMS RADIOCARBON AGES FOR FORAMINIFERA FROM HIGH-DEPOSITION-RATE OCEAN SEDIMENTS

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ABSTRACT. Radiocarbon ages on handpicked foraminifera from deep-sea cores are revealing that areas of rapid sediment accumulation are in some cases subject to hiatuses, reworking and perhaps secondary calcite deposition. We present here an extreme example of the impacts of such disturbances. The message is that if precise chronologies or meaningful benthic planktic age differences are to be obtained, then it is essential to document the reliability of radiocarbon ages by making both comparisons between coexisting species of planktonic foraminifera and detailed down-core sequences of measurements.

INTRODUCTION

In a previously published paper (Broecker *et al,* 1988) we document that systematic differences exist between ^{14}C ages for *G sacculifera* and *P obliquiloculata* from sediments in the South China Sea. In that paper, a case is made against three of the obvious causes for such differences, *ie,* calcification depth, abundance changes and dissolution effects. In an attempt to come to grips with this problem, we made measurements on planktonic foraminifera pairs from two other cores from this region: V24-135 from the Sulu Sea (7° 21′ N, 120° 21′ E, 4276m) and V33-88 from the western Pacific Ocean (2° 42′ N, 127° 50′ E, 3237m). Both cores have sufficiently high sedimentation rates ($\approx$10cm/10^3 yr) so that impacts associated with bioturbation are minimized.

The results listed in Tables 1 and 2 were obtained on targets prepared by the cobalt catalyzed reduction method (Vogel *et al,* 1987) and measured by accelerator mass spectrometry (AMS) at the ETH/AMS Facility in Zürich, Switzerland. No correction for the air-sea $\Delta^{14}C$ difference has been made. To do this, 400 years should be subtracted.

SULU SEA CORE V24-135

We chose core V24-135 because carbon and oxygen isotope records are available (Lindsley *et al,* 1985) allowing us to select glacial age horizons. Although nearby core V28-322 (7° 58′ N, 120° 11′ E, 4102m) is reported to contain mud turbidites, no mention is made of similar layers in V24-135 (Lindsley *et al,* 1985). Nor could we find evidence for such layers in our examination of the core.

The results (see Table 1) came as such a shock that we immediately repicked and redated the two samples from the 101–102cm horizon. As agreement with the first set was achieved, we are convinced that the differences are geological rather than experimental in origin.

It is clear that neither abundance changes nor growth effects can account for the bizarre pattern of ages. As the foram shells are well preserved and deposition rate is high, we doubt whether dissolution is the villain, especially in a core with such a high deposition rate.

One way to look at the results is to assume the process creating the age

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TABLE 1
AMS ^{14}C ages for handpicked planktonic foraminifera from Sulu Sea core V24-135 (7° 21′ N, 120° 21′ E, 4276m)

Depth (cm)	Coarse fraction (%)	Species	Abundance (mg/gm)	^{14}C age (yr)
101–102	22.9	*G sacculifera*	13.6	14,010 ± 160
				14,550 ± 130
		P obliquiloculata	2.1	10,660 ± 130
				10,390 ± 100
110–111	31.3	*G sacculifera*	6.2	17,870 ± 150
		P obliquiloculata	1.2	16,320 ± 150
119–120	5.6	*G sacculifera*	1.0	13,940 ± 140
		P obliquiloculata	0.5	11,670 ± 100
131–133	10.4	*G sacculifera*	2.7	20,670 ± 200
		P obliquiloculata	0.4	21,060 ± 220
141–142	27.2	*G sacculifera*	3.6	19,220 ± 200
		P obliquiloculata	0.7	18,750 ± 170

biases acts in only one direction. For example, were secondary calcification responsible, the ages would be shifted toward younger values, and were reworking of previously deposited forams the reason, the ages would be shifted toward older values. These extreme interpretations are shown in Figure 1.

Oxygen isotope results (see Fig 2) on *G sacculifera* (Oppo & Fairbanks, pers commun) and on *G ruber* and benthics (Lindsley *et al,* 1985) show that

TABLE 2
^{14}C ages on western Pacific core V33-88 (2° 42′ N, 127° 50′ E, 3237m)

Depth (cm)	Method	Material	^{14}C age (yr)
0–6	Decay* LDGO	Bulk $CaCO_3$	1,700 ± 150
28–32	Decay* LDGO	Bulk $CaCO_3$	3,900 ± 150
50–52	Decay* LDGO	Bulk $CaCO_3$	5,510 ± 200
102–110	Decay* LDGO	Bulk $CaCo_3$	11,050 ± 400
126–132	Decay* LDGO	Bulk $CaCO_3$	12,600 ± 500
135–136	AMS Zürich	*G ruber*	13,040 ± 110
	AMS Zürich	*P obliquiloculata*	13,360 ± 140
155–156	AMS Zürich	*G ruber*	14,270 ± 120
	AMS Zürich	*P obliquiloculata*	14,310 ± 150

* Measured by scintillation counting at Lamont-Doherty Geological Observatory (LDGO)

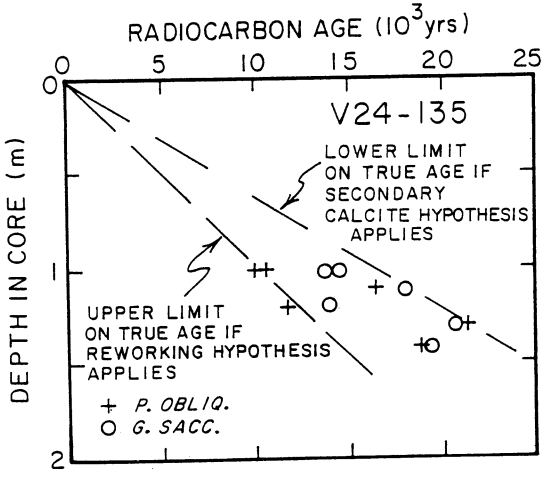

Fig 1. Plot of ^{14}C age *vs* depth in Sulu Sea core V24-135. The dashed lines show limits on the true age *vs* depth trend if, on the one hand, reworking (*ie,* resuspension coupled with lateral transport) and on the other, secondary calcite deposition is the cause of the scatter in the ages.

planktonic shells from the 100cm level have glacial oxygen isotope ratios. The youngest age that shells with full glacial $\delta^{18}O$ could have is ca 13,000 yr. This suggests that the ≃14,000-yr age for *G sacculifera* from the 101–102cm horizon is to be preferred over the ≃10,400-yr age for *P obliquiloculata.* If this logic is accepted, then we would have to conclude that the villain is a process such as secondary calcite deposition, which lowers the age of the calcite. If so, then all the ages in Table 1 are lower limits. However, it is also possible that resuspension of old foraminifera shells (coupled with lateral transport) created this hodge-podge of ages. However, the *P obliquiloculata* age of 10,400 yr at 101–102cm and of 11,700 yr for the 121–122cm horizon appear to be inexplicable if reworking is the major factor.

EQUATORIAL PACIFIC CORE V33-88

Fortunately, the disaster of the Sulu Sea was not repeated for core V33-38 from the equatorial Pacific (see Fig 3). This core, chosen because reconnaissance ^{14}C measurements made by the conventional decay counting method showed it to have a high deposition rate, yielded concordant *G ruber* and *P obliquiloculata* ages. Unfortunately, this core had too few *G sacculifera* to permit measurement, hence, the substitution of *G ruber.* Also, benthics are so rare so that we could not be able to use this otherwise very promising core in our attempt to document the surface to deep $^{14}C/C$ ratio difference for the glacial Pacific.

CONCLUSIONS

Our purpose in publishing this note is to emphasize that high deposition rate cores are full of surprises. Table 3 presents a summary of the AMS ^{14}C results on 14 high deposition rate cores made by our group and by JC

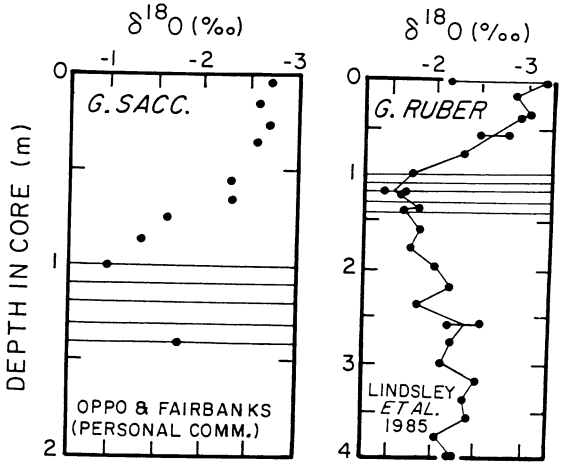

Fig 2. Plots of $\delta^{18}O$ *vs* depth for planktonic foraminifera from core V24-135. The levels at which samples were picked for ^{14}C analysis are shown by horizontal lines.

Duplessy and coworkers at the Gif-sur-Yvette Tandetron AMS Facility in France. In one core we have studied and one the French have studied a hiatus exists. In one core we have studied and in one core the French have studied an age reversal is found. In four cores we have studied unexplainable differences between coexisting planktonic foraminifera have been found. None of these deficiencies would have been picked up by conventional methods (*ie*, lithology, fauna and stable isotope) of studying deep-sea cores. AMS ^{14}C measurements are revealing that, at least in areas of high deposition rate, the assumptions of ideal accumulation and preservation often do not apply.

On the other hand, cores have been found which do appear to fulfill

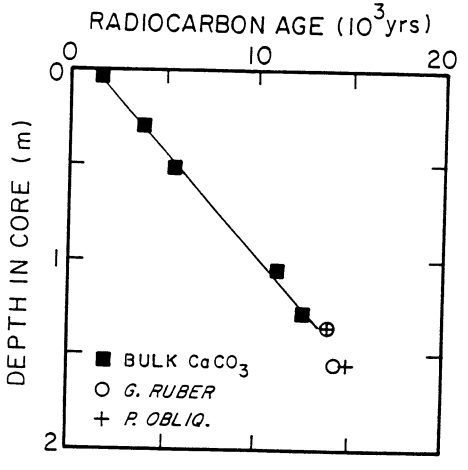

Fig 3. ^{14}C age *vs* depth in core V33-88 from the western equatorial Pacific.

TABLE 3
Summary of AMS ^{14}C results on high-deposition-rate deep-sea cores

Core	Location	Lat	Long	Depth (km)	Sed rate (cm/10^3 yr)	Hiatus	Age reversal	Planktonic *vs* planktonic age difference*	Reference
V23-81	N Atlantic	54.2° N	16.8° W	2.39	≈13	No	Yes	Yes	Broecker *et al*, 1988a,b
CH73–139C	N Atlantic	54.6° N	16.4° W	2.21	≈11	Perhaps	No	—	Duplessy *et al*, 1986
SU81-18	Off Portugal	37.8° N	10.2° W	3.14	≈25	No	No	—	Bard *et al*, 1987
SU81-14	Off Portugal	36.8° N	9.8° W	2.80	≈20	No	Yes	—	Bard *et al*, 1989a
EN32-PC6	Gulf of Mexico	27.0° N	91.4° W	2.28	≈40	Yes	Yes	—	Broecker *et al*, 1988a
V28-122	Caribbean Sea	11.9° N	78.7° W	3.62	≈7	No	No	No	Broecker *et al*, 1988a
KN110–82GGC	W Equat Atlantic	4.3° N	43.5° W	2.82	≈5	No	No	No	Broecker *et al*, 1988a
KET-8216	Mediterranean	41.5° N	18.0° W	1.17	≈10	No	No	—	Fontugne *et al*, 1989
MD84-527	Antarctic	43.8° S	51.3° E	3.26	≈20	Yes**	No	—	Bard *et al*, 1989b
TR163-31B	E Equat Pacific	3.6° S	84.0° E	3.21	≈10	No	No	—	Shackleton *et al*, 1988
V33-88	W Equat Pacific	2.7° N	127.8° E	3.24	≈11	No	No	No	This paper
V35-5	S China Sea	7.2° N	112.1° E	1.95	≈20	No	Yes	Yes	Broecker *et al*, 1988a
V24-135	Sulu Sea	7.3° N	121.4° E	4.28	≈13	—	Yes	Yes	This paper
CH84-14	Off Japan	41.6° N	142.5° E	0.98	≈60	No	No	No	Kallel *et al*, 1988

* Unexplainable by bioturbation
** May be due to low rate of sedimentation during stage 2

our expectations. Cores in which coexisting planktonics yield concordant ages and smooth age *vs* depth profiles are as common as those containing anomalies. Unfortunately, to find one such good core we may have to look at and discard one which is subject to disturbance. The message of the results now in hand is that where accurate chronologies are required, it is necessary to prove the validity of the core by making ^{14}C measurements on more than one species of planktonic foraminifera and by making detailed down-core ^{14}C age profiles.

ACKNOWLEDGMENTS

Discussions with Edouard Bard proved helpful in preparing Table 3. Funds for this research were provided by NSF grant ATM86-05372 and NASA grant NAGW 895, LDGO contribution #4509.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 163–168]

TEMPORAL ^{10}BE AND ^{14}C VARIATIONS: A TOOL FOR PALEOMAGNETIC RESEARCH

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ABSTRACT. Temporal variations of cosmogenic radionuclide atmospheric concentrations can be caused by such global phenomena as solar activity and geomagnetic field changes as well as atmospheric circulation processes. These causes can be distinguished by the comparison of several isotope records corresponding to the same time period. We discuss a possibility for reconstructing the geomagnetic moment during the last 30,000 years from the comparison of ^{10}Be and ^{14}C concentrations in terrestrial archives. The results agree with conventional paleomagnetic data and promise to enrich our knowledge of geomagnetic field variations and reversals.

INTRODUCTION

Cosmogenic isotopes such as ^{10}Be and ^{14}C are produced in the atmosphere mainly by galactic cosmic ray (GCR) particles. Their production rate is directly related to the primary GCR flux. Three main causes of the production rate variations are known:

1) *Primary GCR variations.* As discussed earlier (Konstantinov & Kocharov, 1984; Sonett, Morfill & Jokipii, 1987), they can result from a supernova explosion, though such an event is very rare.

2) *Solar activity modulation.* This complex process is manifested in the periodic depression of a low-energy part of a GCR spectrum which results in decreased atmospheric cosmic ray flux.

3) *Geomagnetic shielding.* The geomagnetic field prevents the low-energy GCR particles from penetrating into the atmosphere. The geomagnetic cut-off energy strongly depends on the moment of the near-dipole geomagnetic field.

Concentrations of the cosmogenic isotope in the specific archive depend on atmospheric transport and sample formation conditions. Basically, cosmogenic isotope production provides information on all the phenomena mentioned above. The main aim of this paper is to determine the geomagnetic moment in the past. A more detailed description of the cosmogenic isotope production model was published previously (Kocharov *et al,* 1985).

THE PRIMARY PRINCIPLES

Our paleomagnetic research is based on two ideas: the influence of the geomagnetic field on the abundance of cosmogenic nuclei in several archives and some specific features of isotope atmospheric transport. As recently shown (Siegenthaler & Beer, 1988) ^{10}Be and ^{14}C records demonstrate similar long-term variations that can be attributed to a variable sun. ^{10}Be and ^{14}C are similarly dependent on the GCR flux at the top of the

atmosphere, which is confirmed by model calculations (Konstantinov & Kocharov, 1984).

What are the reasons for their different sensitivity to the geomagnetic field? Investigations of the transport of radionuclides from nuclear tests through the atmosphere show that the precipitation of the aerosol-bound nuclides has a strong latitude dependence on the altitude of their injection (Lal & Peters, 1967). Isotopes injected into the troposphere are removed not far from the site of injection (the tropospheric residence time is about one month) but the stratospheric fallout mainly occurs in mid-latitudes. Thus, precipitation mainly contains the isotope component of tropospheric origin in polar regions. This type of latitude-fallout-dependence holds also for cosmogenic isotopes, which is confirmed by experimental research on ^{7}Be and ^{10}Be atmospheric transport (Raisbeck *et al,* 1981b). Latitude fallout distribution calculated on the basis of ^{10}Be concentrations measured in polar glaciers agrees with the fallout curve by Lal and Peters (1967). Thus, we used this curve for ^{10}Be atmospheric production rate reconstruction.

As the earth's magnetic field is basically a dipole, the geomagnetic cutoff energy (rigidity) is strongly latitude-dependent. The dependence of cutoff rigidity on the geomagnetic latitude, f, is given by

$$R(f) = R_{\circ} * M/M_{\circ} * \cos^4 (f) \tag{1}$$

where $R_{\circ}$ is the modern cutoff rigidity on the geomagnetic equator and $M/M_{\circ}$ is the ratio of the current geomagnetic dipole moment to its modern value. Near the geomagnetic pole is an area where the magnetic field has no influence on the cosmogenic isotope production rate as the geomagnetic cutoff energy becomes less than the threshold energy of the corresponding nuclear reactions. For the modern geomagnetic field, this region for ^{10}Be production is located on geomagnetic latitudes higher than 68°, whereas, for varying $M/M_{\circ}$ from 0.5–1.5, the boundary is moved from 64°–70°, respectively. Thus, there are areas near both poles where precipitation contains almost only isotope components of tropospheric origin insensitive to geomagnetic field variations. The tropospheric production rate in such an area is given by

$$Q_{tr} = \pi \int_{E_t}^{\infty} dN/dE * W_{tr} (E) * dE \tag{2}$$

where dN/dE is the GCR differential energy spectrum, W_{tr} is the isotope production rate in the troposphere per primary proton with energy E, and E_t is the threshold energy of the nuclear reaction. The isotopes that are mixed in the atmosphere (eg, ^{14}C or stratospheric ^{10}Be) and thus lose their production-rate latitude dependence are sensitive to magnetic field variations. The mean global ^{10}Be stratospheric production rate is described by

$$\langle Q_{str} \rangle = 1/4 * \pi \iint df * dl * \sin (f) \int_{E(f)}^{\infty} dN/dE * W_{str}(E) * dE \tag{3}$$

where W_{str} is the stratospheric isotope production rate per primary proton with energy E, E(f) is the energy corresponding to the cutoff rigidity R(f) in equation (1), and l is the longitude.

Thus, there is an opportunity for paleomagnetic investigations based on comparative analysis of cosmogenic isotope data independent of the magnetic field influence, which include ^{10}Be in polar ice and those containing a geomagnetic record, eg, ^{14}C and ^{10}Be from areas of significant stratospheric aerosol precipitation. We developed a method for calculating hadronic cascades in the atmosphere, through which we obtained the quantity W(E) (Levchenko & Blinov, 1984) and ^{10}Be production rates for the stratosphere and troposphere. The method enables us to account for the influence of solar modulation and obtain numeric data on the paleomagnetic field. We reconstruct magnetic-field intensity of the past in the following manner: we find the level of solar activity from the high-latitude ^{10}Be record, and with ^{14}C or ^{10}Be records from the lower latitude archives and the determined level of solar modulation, we reconstruct the magnetic field variations (M/M_o). This method differs from that of Beer, Siegenthaler and Blinov (1988).

THE GEOMAGNETIC FIELD OVER THE LAST 30,000 YEARS

In search of verification of this proposed method, we reconstructed the geomagnetic field variations for the 14th–18th centuries AD. We used ^{10}Be abundance data from the Milcent and Camp Century ice cores (Beer *et al*, 1984). According to Raisbeck and Yiou (1987), we suggested that ^{10}Be in the Camp Century core was "not sensitive" to the magnetic field. The geographical position of Milcent ice core is not the best for our purposes but it was the most detailed ^{10}Be record available for the last ca 500 years. The results of the calculations are shown in Figure 1. We compare them with the most detailed uniform series of archeomagnetic data for Moscow (Archeomagnetic determinations, 1977). Agreement with our results is satisfactory, eg, for the 16–17th centuries. It should be noted that this increase is also pronounced in other archeomagnetic series. Some discrepancies may be caused by local geophysical conditions, such as ice deposition rate variations, that were not taken into account. We suggest only general agreement in the data time profile.

Using the data of the ^{10}Be abundance in Greenland: Dye-3 (Beer *et al*, 1983), Milcent and Camp Century (Beer *et al*, 1984); Antarctic glaciers: Dome C (Raisbeck *et al*, 1981) and Vostok (Raisbeck *et al*, 1987); ^{14}C con-

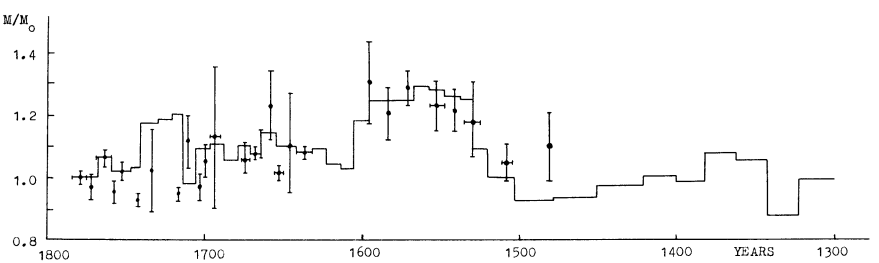

Fig 1. Temporal geomagnetic field variations during the 14th–18th centuries AD. ♦ = uniform series of archeomagnetic data (Archeomagnetic determinations, 1977); — = our geomagnetic field reconstruction.

centrations in tree rings (Suess, 1970) and stalactites (Vogel, 1983), we reconstructed the temporal variations of the geomagnetic dipole moment value over the last 30,000 years. The data from Camp Century, Dome C and Vostok stations were considered free from geomagnetic influence. Ice accumulation rate variations were determined using ^{18}O data and accounted for in the ^{10}Be production rate calculations. The results are plotted in Figure 2. The discrepancies in our results and the paleomagnetic data (Fig 2) and also in the results plotted in Figures 1 and 2 could be caused by: 1) the location of the sampling sites. Apparently, the stratospheric fallout contribution occurs at Camp Century station. It would be better to use the pair, Vostok-Dye 3, for paleomagnetism; 2) the difference in averaging and time scales between Figures 1 and 2; 3) different approaches to calculating ice accumulation rates.

Unfortunately, the paleomagnetic data for the period, 16–30,000 years ago bear such large uncertainties (up to 50%), that there is no reason to compare them with our results.

THE GEOMAGNETIC FIELD REVERSALS

The ^{10}Be concentrations in deep-sea sediments corresponding to the Brunhes-Matujama reversal (~730,000 yr BC) were measured by Raisbeck *et al* (1985), who determined the increased ^{10}Be concentration in the layers of the reversal. Using the method developed in accord with the geomagnetic nature of this phenomenon, we have reconstructed the temporal variation of the geomagnetic moment during this period (Fig 3). We cannot say anything about the minimum magnetic moment value because the ^{10}Be production rate is not sensitive to the M changes near zero. It is interesting that the magnetic moment decreases to its minimum 3–4000 yr after the

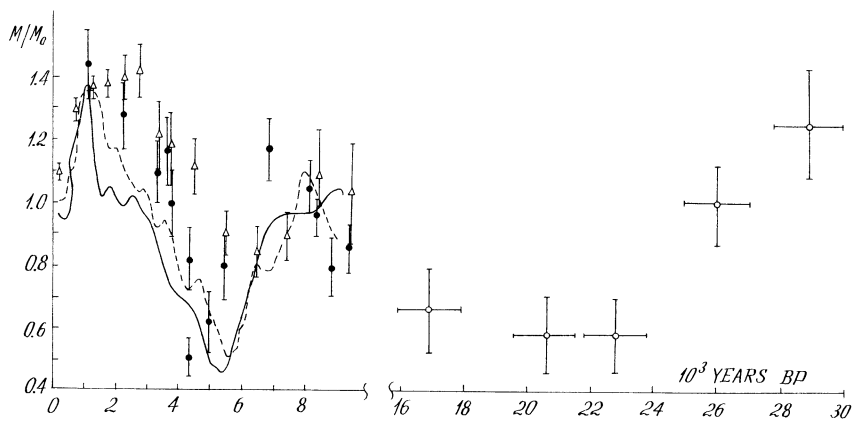

Fig 2. Temporal geomagnetic field variations over the last 30,000 yr. — = comparison of the ^{14}C record (Suess, 1970) with ^{10}Be (Camp Century) data; ⊣ = result of combined analysis of mixed ^{10}Be data; ⊣ = comparison of ^{14}C abundances in stalactites (Vogel, 1983) with ^{10}Be Vostok data; – – – = generalized archaeomagnetic data (Archeomagnetic determinations, 1977); ⊣ = compilation of data from Merrill and McElhinny (1983). The error bars are shown for the 95% confidence level.

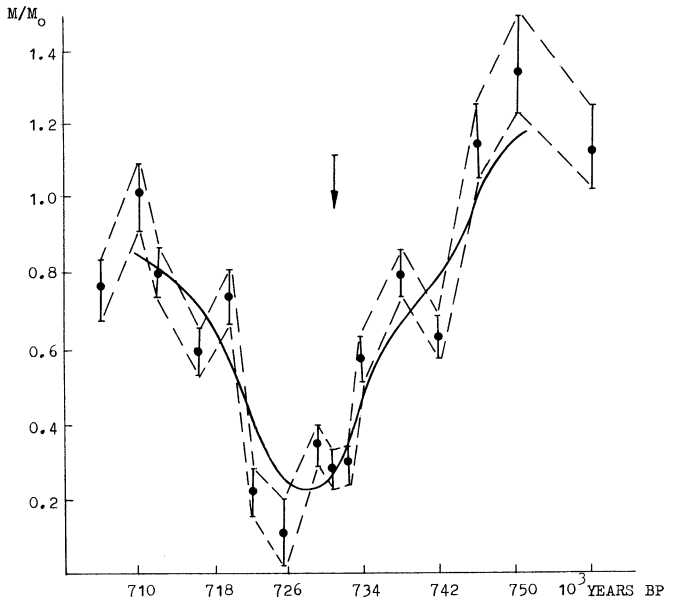

Fig 3. The time profile of the Brunhes—Matuyama magnetic reversal reconstructed from ^{10}Be concentrations in deep-sea sediments measured by Raisbeck *et al* (1985). The arrow marks the reversal position.
--- = uncertainties in M/M_o ratio value; — = result of smoothing.

reversal. This shift can be real (related to the magnetic field behavior) or it can be due to the ^{10}Be transport through the ocean and/or bioturbation in the upper layer of deep-sea sediments (Raisbeck *et al,* 1985). Besides the comparatively slow geomagnetic field variations, we can see, in Figure 3, the quasiperiodic variations in the 10,000-yr period and an amplitude ca (0.1–0.2) M_o. A conclusion about the nature of the variations is premature as similar variations were also found for the concentration of the stable isotope, ^9Be.

CONCLUSIONS

We have presented evidence that variations in the geomagnetic field moment, reconstructed from isotope data values, agree with conventional archeomagnetic and paleomagnetic results on a time scale of ca 10,000 yr. The methods we use extend the period of investigations up to 10^6 yr. Our calculations also offer a value of mean global geomagnetic moment instead of local values strongly influenced by the nondipole component. Further improvement in understanding cosmogenic isotope production and transport can result in more detailed knowledge not only of paleomagnetic intensities, but also the movement of magnetic pole positions.

We consider these results a demonstration of the promising method that needs not only theoretical improvement but also special experimental support, eg, measurements on ice samples from sites with specific time resolution and accuracy.

ACKNOWLEDGMENTS

We wish to thank P E Damon and C P Sonett for valuable discussions and fruitful comments during the preparation of this paper.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 169–178]

CORRECTING ^{14}C HISTOGRAMS FOR THE NON-LINEARITY OF THE RADIOCARBON TIME SCALE

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ABSTRACT. Large numbers of ^{14}C dates of the base and top of Holocene peat layers may be plotted in ^{14}C histograms in order to establish statistically a chronology of periods of essentially clastic sedimentation and peat formation. Due to the non-linearity of the ^{14}C time scale in terms of calendar years, clustering of ^{14}C dates on random peat growth may occur. This seriously hampers the interpretation of histograms. A quantitative method and computer program were developed to correct the histograms for this effect. The correction factor that has to be applied depends on the calibration curve and the interval width of the correction parameter dy. For peat samples, an interval width of 100 ^{14}C yr and a calibration curve based on a 100-yr moving average seems to be a reasonable choice.

INTRODUCTION

In the Holocene coastal lowland of The Netherlands, clastic marine sediments alternate with peat. The observed alternation is generally attributed to an alternation of transgressions (periods in which the sea invaded the land) and regressions that occurred presumably more-or-less synchronously along the coasts of northern Germany, The Netherlands, Belgium and northern France (Bakker, 1954; Bennema, 1954; Jelgersma, 1961; Brand *et al,* 1965; Geyh, 1966; Hageman, 1969; Roeleveld, 1974; Griede, 1978).

Large numbers of ^{14}C dates of the base and top of peat layers in these coastal lowlands have been used to establish statistically a chronology of alternating periods of essentially clastic sedimentation and peat formation, which is in geological terms explained by an alternation of (marine) transgressions and regressions. However, no single stretch of coast is likely to have documented and preserved a complete record of Holocene transgressions and regressions. Non-concordance of chrono-stratigraphic and litho-stratigraphic levels in the Holocene sedimentary sequence renders it difficult to determine, even if large numbers of borehole data are available, whether geological events like transgressions occurred synchronously over large areas. With many ^{14}C determinations available, the danger lies in the selection of dates that accord with preconceptions of Holocene geologic evolution. To overcome these problems, ^{14}C histograms (Fig 1) have been constructed by many authors (eg, Geyh, 1966; Roeleveld, 1974; Griede, 1978; Mulder & Bosch, 1982; Berendsen, 1982; Zagwijn, 1983; Berendsen, 1984; van de Plassche, 1985). The validity of this approach was accepted as early as 1955 in a discussion at the Royal Statistical Society.

However, the non-linearity of the ^{14}C time scale, in terms of calendar years, may result in clustering of ^{14}C dates on random peat growth (Fig 2). This seriously hampers the interpretation of histograms, because ^{14}C histograms may show maxima or minima that are not at all related to geologic events (de Jong & Mook, 1981). On the other hand, the danger exists that maxima and minima may be erroneously attributed only to the non-linearity of the ^{14}C time scale. Until now, there was no universal method to correct the histograms quantitatively.

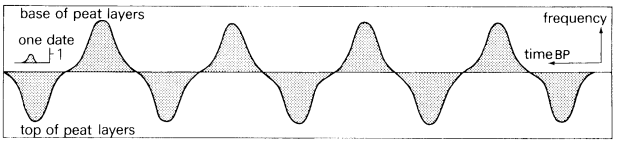

Fig 1. Idealized ^{14}C histogram of a coastal lowland, with a clear alternation of transgressions and regressions. Dates of the top of peat layers are plotted under the horizontal time axis, dates of the base of peat layers above it. Standard Gaussian curve indicates frequency 1.

We now present a method to correct ^{14}C histograms quantitatively for the non-linearity of the ^{14}C time scale. In a second paper attention will be focused on the interpretation of corrected ^{14}C histograms and on how transgressions and regressions may be defined.

CONSTRUCTION OF ^{14}C HISTOGRAMS

A ^{14}C histogram is obtained by graphic superposition of individual ^{14}C dates. Each date is represented by a Gaussian distribution of equal area (in some earlier publications rectangles or polynomes were used instead of Gaussian distributions, eg, Roeleveld, 1974; Shennan, 1979). The width of each Gaussian curve depends upon the standard deviation of the ^{14}C date. A date with a large standard deviation is represented by a Gaussian distribution with a low height, and thus contributes less to the histogram peaks. A date with a standard deviation of ± 45 yr has been chosen to represent frequency 1. All dates are expressed in conventional ^{14}C yr BP.

Roeleveld (1974, p 21) has shown that dates taken from the base and the top of peat layers should be represented in separate histograms. Thus, dates from the top of peat layers are often plotted under the horizontal time axis; dates from the base of peat layers, above it. Peaks in the "base of peat" histogram then represent maxima in the occurrence of the beginning of peat formation. Likewise, peaks in the "top of peat" histogram represent maxima in the ending of peat formation. Thus, in an ideally simple situation

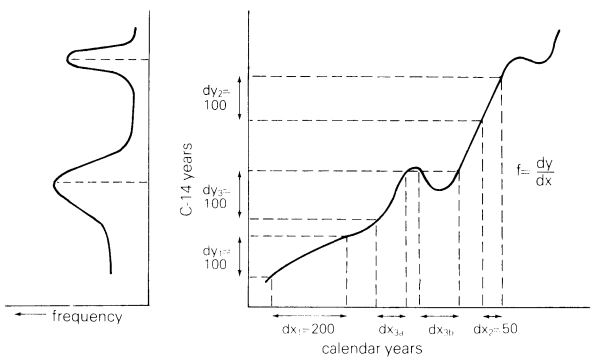

Fig 2. The influence of the ^{14}C calibration curve on histograms and the principle of the correction method

in which transgressions and regressions of equal time span alternate, the histogram could be expected to take the form shown schematically in Figure 1.

GENERAL PROBLEMS OF ^{14}C HISTOGRAMS

In interpreting and comparing histograms, care should be taken that all periods and areas are equally well represented by ^{14}C dates. Over- or under-representation may occur because certain areas or peat layers are less accessible or because researchers deliberately focus interest on certain areas and/or periods (Geyh, 1980). A similar problem arises from the non-linearity of the ^{14}C time scale.

Because the atmospheric ^{14}C content has not been constant in the past, ^{14}C ages expressed in years on the basis of a half-life of ^{14}C of 5568 yr, are different from astronomical ages (solar or calendar years). By carrying out ^{14}C measurements on dendrochronologically dated wood, various calibration curves have been created (Suess, 1970; Damon, Long & Wallick, 1972; Ralph, Michael & Han, 1973; Klein *et al*, 1982). At the 12th International Radiocarbon Conference in 1985, the more accurate curves constructed by Stuiver and Pearson (1986) and Pearson and Stuiver (1986), that span AD 1950–2500 BC, were accepted as an international standard of reference. In the same calibration issue, Pearson *et al* (1986) extended the limit to 5210 BC.

Clustering of ^{14}C dates on random peat growth may occur in ^{14}C histograms due to non-linearity of the ^{14}C time scale in calendar years (Fig 2). This effect has not yet been evaluated quantitatively (de Jong & Mook, 1981), and thus it is often underestimated (eg, Berendsen, 1982; Berendsen, 1984). Only Geyh (1971, 1980) attempted correction for part of the ^{14}C time scale.

CORRECTION OF ^{14}C HISTOGRAMS

In principle, there are two possibilities for correcting histograms for the non-linearity of the ^{14}C time scale: 1) calibrating the dates first, and successively plotting them in a histogram; 2) plotting the dates in a histogram and correcting the histogram. Although both methods should give similar results, we have chosen method 2 for several reasons. Calibrated ^{14}C dates cannot simply be described as a Gaussian curve (Renfrew & Clark, 1974; Warner, 1975; van der Plicht & Mook, 1989); this makes the plotting procedure of method 1 mathematically more complicated. Geologists are used to the ^{14}C time scale. With method 2, the ^{14}C time scale is maintained which enables direct comparison with histograms in the literature. Another advantage of method 2 is that, together with the corrected histogram, an uncorrected version is available for comparison. Also, if necessary, correction based on other calibration curves is possible.

Figure 2 shows the principle of correcting a histogram, eg, 100 ^{14}C yr at dy_1 equal 200 calendar yr. This means that peat formed in a time span of 200 yr will be represented by dates that fall within a time span of 100 ^{14}C yr, *ie,* clustering occurs. The frequency in the ^{14}C histogram will be

twice as high as in a histogram based on calendar years. In the case of dy_3 the equivalent time span on the calendar (solar) time axis is: $dx_3 = dx_{3a} + dx_{3b}$ (Fig 2).

To correct the histogram, the frequency at all points should be multiplied by a factor f = dy/dx (dy = number of years on the ^{14}C time scale, dx = number of years on the calendar time scale). The factor, f, depends on the calibration curve and the interval width, dy. For both, a choice has to be made.

Mook, de Jong and Geertsema (1979) and Mook (1983) have shown that a calibration curve should be used that is in accordance with sample time width. ^{14}C dates of peat samples represent a weighted average of plant materials grown over a range of time. This time range is difficult to quantify, but is likely to be greater than the ± figure on the ^{14}C date. According to Berendsen (1984), peat samples in the Netherlands coastal lowland generally cover 50–200 yr. Thus, the use of a smoothed calibration curve is necessary. Based on the data of Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986), a calibration curve based on a 100-yr moving average was constructed, by spline-smoothing with σ = 40 yr for the period 120–6150 BP (Fig 3). For every calendar year, the equivalent number of ^{14}C yr is calculated. From this, a data set has been selected with, for every fifth ^{14}C year, the equivalent number of calendar years. This data set has been used to calculate the correction factors.

If the interval, dy, is very small, f will closely follow the slope of the calibration curve at any point. Such detail in correcting a histogram made up of peat samples is unnecessary, and even meaningless. If dy is too large, irregularities in the calibration curve will be smoothed too much. Figure 4 shows the correction factor for dy = 50, dy = 100, dy = 150 and dy = 200 ^{14}C yr. An interval of 100 yr seems a reasonable choice for peat samples. Geyh (1980) proposed an interval width, dy = 2σ, which leads to comparable results.

The variation of the correction factor with time is shown in Figure 5. Periods in which a correction of >25% has to be applied to the original histogram are indicated on the time axis. In these periods, the non-linearity of the ^{14}C time scale will result in major virtual maxima and minima.

The computer program, KORHIS, is written in BASIC and has been designed for use on an IBM or compatible personal computer. It is available on diskette, together with instructions for use. The program uses laboratory number, age and standard deviation as input. The output is a data file with values for ^{14}C yr BP (x) and frequency (y), that can be plotted into a histogram. The histogram can be corrected for the non-linearity of the ^{14}C time scale by multiplying all y values with the correction factor, f. At present, only a data file with correction factors based on dy = 100 yr is available on floppy disk. The file contains a correction factor for every fifth ^{14}C year from 300–6100 BP. The corrected data are also stored as a data file and can be plotted as a histogram. An example is given in Figure 6, which shows both the original and the corrected histograms of 117 dates of the base of peat layers in the western part of The Netherlands.

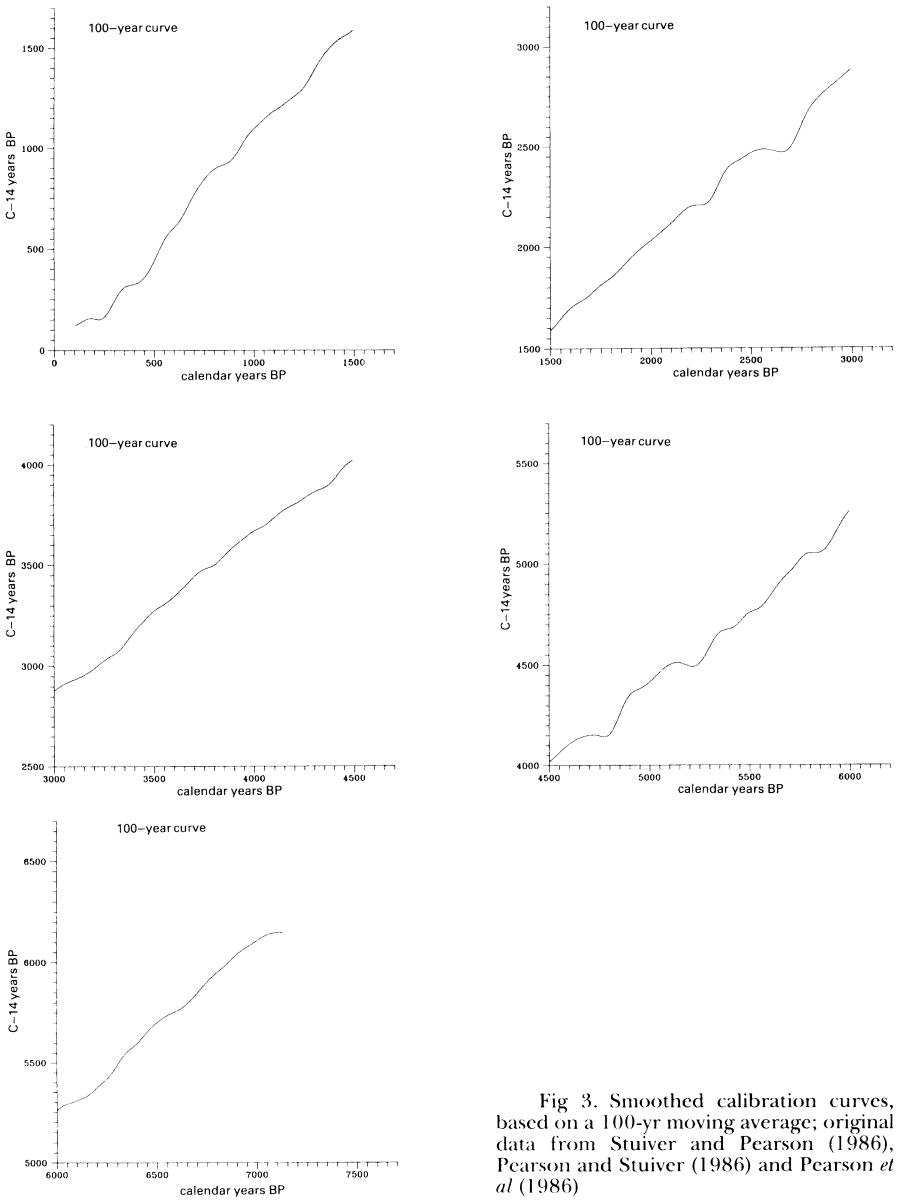

Fig 3. Smoothed calibration curves, based on a 100-yr moving average; original data from Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986)

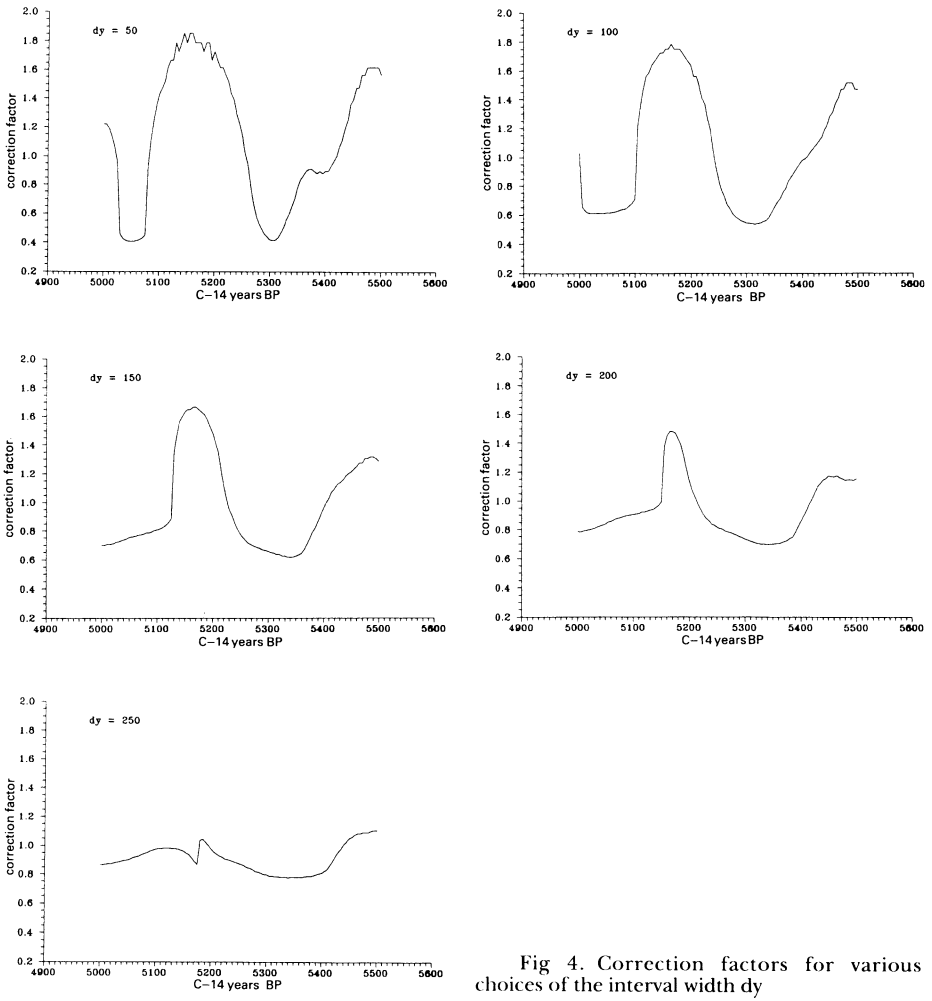

Fig 4. Correction factors for various choices of the interval width dy

NUMBER OF DATES REQUIRED

Many dates should be scattered over a large area to obtain reliable results. Not only the number of dates is important, but especially the "density" (no. dates/1000 yr). In a computer simulation, Shennan (1979) showed that histograms with >100 dates/1000 yr are reliable. Histograms with <40 dates/1000 yr must be considered unreliable.

According to Geyh (1980), the standard deviation should be considered in relation to the density. Per class (each class = twice the average standard deviation) there should be >25 dates in order to get reliable results. For a class of 100 yr, it follows:

reliable:	>250	dates/1000 yr
possibly useful:	40–250	dates/1000 yr
unreliable:	<40	dates/1000 yr

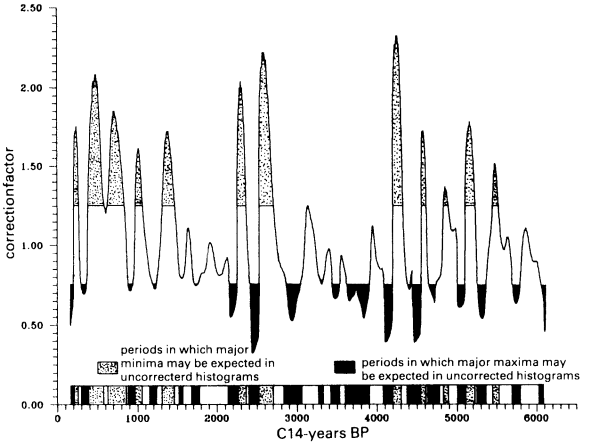

Fig 5. Variation of the correction factor with time, based on dy = 100 yr. Periods in which histograms have to be corrected by >25% are indicated on the ^{14}C time scale.

A ^{14}C histogram usually will not have the same reliability at all points. The KORHIS computer program gives not only the total number of dates used, but also the number of dates per millennium. An evaluation of histograms published so far shows that most histograms have to be classified as unreliable, or at best, possibly useful for only certain parts of the time scale (Stolk *et al*, ms). However, ^{14}C dates that lack statistical significance in histograms may well have geological significance. The geological evaluation of the data used in histograms therefore remains of primary importance.

CONCLUSIONS

^{14}C histograms are used for the statistical treatment of large numbers of ^{14}C dates, in order to establish a chronology of periods of essentially clastic sedimentation and peat formation. Histograms must be corrected for

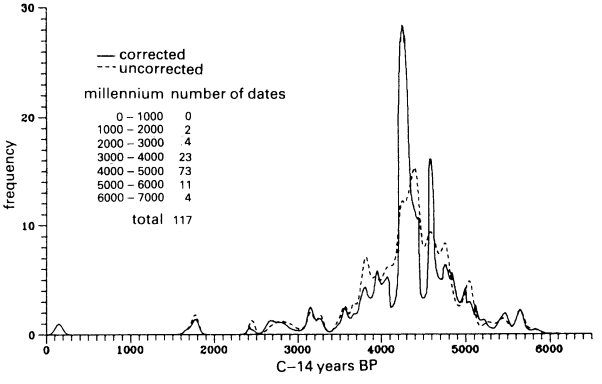

Fig 6. Corrected and uncorrected ^{14}C histograms of 117 dates of the base of peat layers in the western Netherlands

the non-linearity of the ^{14}C time scale; the KORHIS computer program offers a quantitative correction method. The correction factor used depends on the calibration curve and the interval width of the correction parameter. For correcting histograms, a smoothed version of the curves of Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986) based on a 100-yr moving average, is used. For peat samples, an interval width of 100 yr is appropriate. In order to get reliable results, >100 dates/1000 yr seem to be necessary.

ACKNOWLEDGMENTS

Joop Hoofd and Walter Roest were helpful in preparing the computer program.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 179–186]

RADIOCARBON DATES FOR LAVA FLOWS FROM NORTHEAST RIFT ZONE OF MAUNA LOA VOLCANO, HILO 7½′ QUADRANGLE, ISLAND OF HAWAII

J M BUCHANAN-BANKS*, J P LOCKWOOD** and MEYER RUBIN†

INTRODUCTION

Twenty-eight ^{14}C analyses are reported for carbonized roots and other plant material collected from beneath 15 prehistoric lava flows erupted from the northeast rift zone (NERZ) of Mauna Loa Volcano (ML) utilizing the recovery techniques of Lockwood and Lipman (1980). Most samples were collected from the Hilo 7½′ quadrangle during field work for a geologic map of that quadrangle (Buchanan-Banks, unpub data); a few sample sites are located in adjacent quadrangles: Piihonua to the west and Mountain View to the south. Altitudes are given in English units as well as metric to facilitate locating sites on USGS topographic maps.

The new ^{14}C dates establish ages for 13 previously undated lava flows, and correct or add to information previously reported by Kelley *et al* (1979) and Rubin, Gargulinski and McGeehin (1987). Limiting ages on other flows that lie either above or below the dated flows are also established. These dates help to unravel the eruptive history of ML's NERZ, and they extend that history back ca 24,000 yr. Although 9 eruptions have occurred from vents along the NERZ during the period of written history (the past 140 yr) (Peterson & Moore, 1987, Table 7.4), only lava flows from the 1880–81 eruption entered the Hilo quadrangle. During the past 2000 yr, at least 7 ML lava flows entered the quadrangle (averaging 1 lava flow about every 285 yr) and at least 1 reached the sea (Buchanan-Banks, unpub data). The recurrence interval is defined more poorly for earlier periods because more of the older flows are covered by younger eruptive material, and many of the few small outcrops that remain are commonly obscured by agriculture and construction projects.

The new ^{14}C ages also establish time constraints for tephra, probably mostly erupted from Mauna Kea Volcano, deposited in and near the quadrangle. The oldest documented ash deposit lies beneath a pahoehoe flow stratigraphically dated by W-5075 ca 24,000 yr; an ash also lies between a pahoehoe flow ca 24,000 yr old (W-4890) and another ca 14,000 yr old (W-4621, -4971, -4973, -4620, -4977); a more recent ash overlies a pahoehoe flow <ca 10,000 yr old (W-5072). These ash deposits likely represent all ash falling in a given area over a long time span rather than individual eruptive events. Although tephra occurs between other younger ML lava flows, it is difficult to tell if the deposits are airfall layers or have been reworked by wind and water.

All charcoal samples were analyzed at the USGS Radiocarbon Labora-

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tory at Reston. The samples were converted to acetylene gas and their ^{14}C activity was measured in 3 different proportional gas counters. Pretreatment of samples consisted of mechanical removal of carbonaceous contaminants by picking under magnification, heating in hydrochloric acid, heating in a basic (NaOH) solution, and heating in acid again. Distilled water rinses followed each stage. The NaOH treatment was omitted in the case of very small samples (<3g of charcoal) for fear of losing the entire sample. The error quoted is the standard 1 σ counting error and does not take into account other known laboratory uncertainties that could double this figure. No attempt was made to estimate the effect of juvenile, non-radiogenic carbon as none of the samples are believed to have been close to volcanic gas vents (Rubin, Lockwood & Friedman, 1987). The ages, given in yr BP (1950), were not corrected to a calendar date by the tree-ring calibrations presently available.

Only 3 of the 27 charcoal samples collected gave anomalous ages (indicated by sample number in parenthesis) and 2 of these ages were subsequently corrected through recollection of charcoal and new analyses (W-4535 by -5098, and W-4894 by -5072 and -5075). Charcoal could not be recollected for W-5081; hence, the remainder of the existing sample was re-analyzed as W-5604. No substantive decrease in the age was obtained.

SAMPLE DESCRIPTIONS

(W-4535). Pahoehoe flow of Kulaloa Rd **<200**

Charcoal roots at top of soil beneath finely crystalline pahoehoe flow; coll in drainage ditch 10m S of Ainaola Dr and 100m E of Kulaloa Rd junction, alt 1105ft (337m) Piihonua quad (19° 38.52′ N, 155° 07.58′ W). Coll 1979 by J P Lockwood (JPL). *Comment* (JPL): date is impossibly young, judging from degree of weathering and directions of remanent magnetization obtained on flow (Holcomb, Champion & McWilliams, 1986, site ID 9B061). See W-5098 for correct date.

W-5098. Pahoehoe flow of Kulaloa Rd **570 ± 60**

Charcoal fragments in thin ash pockets beneath pahoehoe flow at contact with underlying aa flow (picrite of Panaewa Forest Reserve, W-4981); coll 150m NW of S end of Kulaloa Rd, in dense thicket of guava and other exotic brush, alt 1580ft (482m), Piihonua quad (19° 37.62′ N, 155° 08.46′ W). Coll 1981 by J P and B M Lockwood. *Comment* (JPL): dates youngest prehistoric lava flow in Hilo quad.

W-4631. Pahoehoe flow of Kukuau ahupuaa **1110 ± 60**

Charcoal rootlets beneath pahoehoe flow of Kukuau ahupuaa (ahupuaa is Hawaiian land unit usually extending from uplands to sea) at top of thin stream deposit overlying aa flow of Ainaola Dr, W-5599; coll on NW side of Waiakea Stream, due W of Univ Hawaii, Hilo, alt 140ft (43m) Hilo quad (19° 42.38′ N, 155° 05.16′ W). Coll 1979 by J M Buchanan-Banks (JMBB). *Comment* (JMBB): sample dates second youngest and most exten-

sive prehistoric pahoehoe flow in NW part of quad. Flow originated from vents at ca 9000ft (2745m) elev (J P Lockwood, pers commun, 1986).

W-5597. Pahoehoe flow of Kukuau ahupuaa 1140 ± 300

Charcoal fragments dispersed in stream deposit under pahoehoe flow; coll in N tributary of Alenaio Stream, 400m E of Komohana St, alt 135ft (41m), Hilo quad (19° 42.99′ N, 155° 05.74′ W). Coll 1979 by J M Buchanan-Banks. *Comment* (JMBB): sparse charcoal scattered within stream deposit may have been reworked by floods. However, directions of remanent magnetization determined on samples coll from flow agree well with ^{14}C age. From same flow as W-4631.

W-4343. Pahoehoe flow of Kukuau ahupuaa 1280 ± 70

Charcoal rootlets and one large root of ca 2cm diam, coll at base of pahoehoe flow at contact with thin soil overlying aa rubble, 40m W of Ainaola Dr-Hoaka Rd intersection, N of Hoaka Rd and W along unpaved road, then N again at plant nursery entrance, on W side of road, alt 769ft (234m), Hilo quad (19° 40.18′ N, 155° 07.33′ W). Coll 1978 by J P Lockwood and J M Buchanan-Banks. *Comment* (JMBB): age agrees well with both W-4631 and -5597.

W-4981. Picritic aa flow of Panaewa Forest Reserve 1470 ± 50

Charcoal rootlets from unoxidized, coarse, grayish-black basal aa rubble surrounded by red oxidized aa; coll in new quarry cut on NW edge of Allied Aggregates Quarry, W of hwy 11, 1.6km N from Keaau turnoff, alt 360ft (110m), Hilo quad (19° 38.56′ N, 155° 03.39′ W). Coll 1981 by J P Lockwood. *Comment* (JPL): first reliable date for widespread surface flow in Hilo quad erupted from vents at 5200ft (1585m) elev on NERZ. Supersedes problematically old date of 2890 ± 70 yr (Kelley *et al,* 1979: W-4174) from beneath same flow.

W-5670. Pahoehoe flow of Waiakea Stream 1500 ± 200

Charcoal roots at top of ash deposit beneath hypersthene-bearing pahoehoe flow, alt 780ft (238m), 250m from W edge of Hilo quad (19° 39.90′ N, 155° 07.32′ W). Coll 1985 by J M Buchanan-Banks. *Comment* (JMBB): sample dates previously unrecognized young flow beneath pahoehoe flow of Kukuau ahupuaa (W-4631, -5597, -4343). At colln site, ash overlies another pahoehoe unit.

W-5278. Pahoehoe flow of Waiakea Stream 1740 ± 100

Carbonized twigs and roots, up to 2cm diam, coll from contact between thin outcrop of pahoehoe and top of thin ash unit; coll in NW bank of Waiakea Stream, alt 760ft (232m), 1.2km E of W edge of Hilo quad (19° 40.20′ N, 155° 06.85′ W). Coll 1983 by J M Buchanan-Banks. *Comment* (JMBB): comparison of thin section from this flow and from that dated by W-5670 suggests that they are same unit. Site destroyed by stream-widening work to reduce flood hazard.

W-4621. Pahoehoe flow of Punahoa ahupuaa **3140 ± 70**

Charcoal root, ca 2cm diam, beneath pahoehoe flow at top of ash layer ≧1m thick; coll on NW side of Kaumana Dr in front of house #698, alt 570ft (174m), 800m E of W edge of Hilo quad (19° 42.28′ N, 155° 07.02′ W). Coll 1979 by J M Buchanan-Banks and N G Banks. *Comment* (JMBB): probable S extension of flow dated 4050 ± 50 yr (Kelley *et al,* 1979: W-3803); sample helps distinguish this flow from younger pahoehoe of Kukuau ahupuaa that overlies it to E.

W-4629. Pahoehoe flow of Punahoa ahupuaa **3360 ± 80**

Abundant charcoal roots, some as much as 2cm diam, beneath pahoehoe flow at top of ash layer ≧3m thick; coll in Waipahoehoe Stream, alt 710ft (214m), W edge of Hilo quad (19° 41.87′ N, 155° 07.49′ W). Coll by J M Buchanan-Banks. *Comment* (JMBB): age agrees well with W-4621 and -4624 from beneath same flow. At colln site, flow is overlain by thin soil and by 1880-81 pahoehoe; flow also overlies thick ash and older pahoehoe dated by W-4890.

W-4624. Pahoehoe flow of Punahoa ahupuaa **3380 ± 80**

Carbonized part of trunk or root found in pahoehoe flow in sealed tree mold exposed during construction of Wailuku-Alenaio diversion canal; coll N of Waianuenue Ave, on E side of canal, alt 855ft (261m), Piihonua quad (19° 43.0′ N, 155° 08.15′ W). Coll 1979 by J M Buchanan-Banks and N G Banks. *Comment* (JMBB): age agrees well with W-4621 and -4629 from beneath same flow further E. Several units of this flow are exposed in canal, overlying ash of variable thickness and locally exposed pahoehoe probably dated by W-4971, -4973, -4620, -4977.

(W-5604). **3450 ± 200**

(W-5081). **3920 ± 80**

Charcoal roots and fragments distributed in vertical crack in pahoehoe flow and in pockets at contact with underlying alluvium; coll from S bank of Alenaio Stream, immediately W of Komohana St, alt 237ft (72m), Hilo quad (19° 42.83′ N, 155° 05.93′ W). Coll 1979 by J M Buchanan-Banks. *Comment* (JMBB): unusual location of charcoal in crack aroused skepticism about obtaining true age. Anomalously old age of W-5081 led to re-analysis of remainder of same charcoal as W-5604 but age still is considered too old. Charcoal was probably eroded from beneath older lava upstream and redeposited by flooding, as site is drainage bottleneck. Additional field mapping and determinations of remanent magnetization on overlying lava indicate it correlates with 1880-81 pahoehoe. Site now covered by masonry retaining wall.

W-5077. Pahoehoe flow of Wilder Rd **4410 ± 120**

Carbonized mat of vegetation coll at top of 2m-thick ash beneath and at edge of pahoehoe flow, S of Kaumana Dr, 800m SE along Edita Dr, 200 m E of rd along amorphous stream channel, alt 600ft (183m), Hilo quad

(19° 41.40′ N, 155° 07.18′ W). Coll 1983 by J M Buchanan-Banks. *Comment* (JMBB): sample dates relatively young prehistoric flow in W part of quad; flow is locally overlain by 1880-81 pahoehoe.

W-4536. Aa flow of Puna Sugar fields **5250 ± 100**

Large charcoal root at top of yellowish-red ash beneath picritic aa flow; coll 2.2km SE of Keaau, just NE of Keaau-Pahoa Rd, alt 320ft (98m), Mountain View quad (19° 36.66′ N, 155° 01.92′ W). Coll 1979 by J P Lockwood. *Comment* (JPL): sample dates extensive picritic aa flow with minor pahoehoe phases now under sugar-cane cultivation in Keaau area. Flow probably derived from Puu Makaala (Puu Makaala quad, 3700ft (1128m) elev). Contact, 5m below surface, was temporarily exposed by 1979 floodwater gullying.

W-5599. Aa flow of Ainaola Dr **7230 ± 230**

Charcoal in discontinuous pockets at top of ash layer beneath olivine-bearing aa flow; coll from N bank at E end of stream flowing through municipal golf course, W of bridge, 300m N of Haihai St and 400m W of Kinoole St, alt 225ft (69m), Hilo quad (19° 40.79′ N, 155° 04.50′ W). Coll 1984 by J M Buchanan-Banks and V C Taylor. *Comment* (JMBB): sample dates widespread olivine-bearing aa flow in W-central part of Hilo, and establishes min age for undated flows beneath it.

W-4975. Aa flow of Malaai Rd **9020 ± 130**

Charcoal rootlets in thin ash beneath picritic aa flow; coll in SE bank Waiakea Stream, alt 920ft (280m), 0.32km W of E edge of Piihonua quad (19° 39.62′ N, 155° 07.68′ W). Coll 1981 by J P Lockwood. *Comment* (JPL): sample dates picritic aa flow beneath aa of Ainaola Dr (W-5599); former is distinguished by its more abundant olivine. However, both flows may be part of same eruption cycle based on similarities of morphology and mineral content.

W-4884. Pahoehoe flow of Waiakea Homestead **9780 ± 140**

Charcoal tree root at top of ash beneath plagioclase-phyric pahoehoe flow; coll 1km S of Ainaola Rd along Alaloa Rd, to E in S bank of stream, alt 660ft (201m), Hilo quad (19° 39.52′ N, 155° 06.05′ W). Coll 1980 by J M Buchanan-Banks. *Comment* (JMBB): sample provides important date on previously unrecognized flow from NERZ; it also establishes min age for several underlying flows.

W-5072. Pahoehoe flow of Waiakea Stream, younger **10,320 ± 70**

Charcoal root at top of ash layer beneath pahoehoe flow; coll from N bank of S fork of Waiakea Stream between Hoaka and Alawaena Rds, alt 1000ft (305m), 650m W of E edge of Piihonua quad (19° 39.51′ N, 155° 07.85′ W). Coll 1982 by J M Buchanan-Banks. *Comment* (JMBB): sample dates uppermost of several pahoehoe flows exposed in stream and provides time constraints on ash deposits that overlie and underlie this pahoehoe. Re-analysis of W-4894: 21,900 ± 270 yr.

W-4623. Aa flow of Rainbow Falls **10,610 ± 150**

Carbonized reeds at top of 6m-thick ash dispersed beneath lower rubble of vitric, olivine-phyric aa flow where flow laps up on ash; coll in Wailuku R, alt 440ft (134m), 0.8km E of W edge of Hilo quad (19° 43.38′ N, 155° 07.00′ W). Coll 1980 by J M Buchanan-Banks and N G Banks. *Comment* (JMBB): sample provides new date that, with date for pahoehoe flow of Waianuenue Ave (W-4627, -4971, -4973, -4620, -4977), establishes age control on formation of present Wailuku R channel and Rainbow Falls.

W-4627. Pahoehoe flow of Waianuenue Ave **13,530 ± 180**

Crumbly carbonized root and rootlets at top of ash deposit beneath pahoehoe flow; coll 150m W of Kaumana Dr-Waianuenue Ave intersection, across from Carvalho Park on S side of ave under SW bridge abutment, alt 320ft (98m), Hilo quad (19° 43.20′ N, 155° 06.52′ W). Coll 1980 by N G Banks and J M Buchanan-Banks. *Comment* (JMBB): sample dates older, previously unrecognized, surface flow in Hilo, probably same flow as that dated by W-4971, -4973, -4620, -4977, although it contains higher percentage of olivine phenocrysts. Thin overlying ash deposit obscures stratigraphic relationships.

W-4971. Pahoehoe flow of Waianuenue Ave **14,080 ± 150**

Carbonized root or tree branch at top of ash layer beneath pahoehoe flow; coll on N side of ave at W end of First Protestant Church parking lot, alt 535ft (163m), 0.5km E of W boundary of Hilo quad (19° 43.23′ N, 155° 07.20′ W). Coll 1982 by J M Buchanan-Banks. *Comment* (JMBB): flow is characterized by surface that crumbles when struck with hammer. Date confirms this lobe to be same flow as that dated by W-4627, -4973, -4620, -4977.

W-4973. Pahoehoe flow of Waianuenue Ave **14,370 ± 190**

Charcoal tree root at top of thick ash deposit beneath pahoehoe flow; coll 200m N and 700m E of Ainako Ave, in N side of cut for driveway of pole house on Kaeokulani St, alt 610ft (186m), 100m E of W edge of Hilo quad (19° 42.95′ N, 155° 07.43′ W). Coll 1982 by J M Buchanan-Banks and V C Taylor. *Comment* (JMBB): date establishes min age for thick ash and Mauna Kea flows that underlie it. Site now covered by masonry retaining wall.

W-4620. Pahoehoe flow of Waianuenue Ave **14,500 ± 200**

Carbonized root and rootlets at top of thick ash beneath pahoehoe flow; coll in S bank of Wailuku R, N of Waianuenue Ave off Piikea St, alt 535ft (163m), 80m E of W edge of Hilo quad (19° 43.32′ N, 155° 07.45′ W). Coll by J M Buchanan-Banks and N G Banks. *Comment* (JMBB): flow, 12–14m above present river level, occupies channels cut by ancestral river into ash and underlying saprolitic deposits developed on Mauna Kea flows. Date establishes min age for development of this part of Wailuku R channel.

W-4977. Pahoehoe flow of Waianuenue Ave **14,530 ± 120**

Charcoal root and rootlets at top of ash layer beneath pahoehoe flow; coll 280m S of Waianuenue Ave, ca 300m W of Kaumana Springs, alt 480ft (146m), Hilo quad (19° 43.08′ N, 155° 07.02′ W). Coll 1982 by J M Buchanan-Banks. *Comment* (JMBB): age confirms this to be S lobe of flow dated by W-4627, -4971, -4973, -4620.

(W-4894). **21,900 ± 270**

Charcoal coll from two localities at contact between 1–1.5m-thick ash deposit and overlying pahoehoe flow, in Waiakea Stream between Hoaka and Alawaena Rds, Piihonua quad (19° 39.51′ and 39.68′ N, 155° 07.85′ and 07.65′ W). Coll 1982 by J M Buchanan-Banks. *Comment* (JMBB): invalid age as charcoal from two different sites, erroneously thought to be from beneath same flow, were combined. Anomalously old age led to recollection of charcoal for analysis as W-5072 and -5075.

W-4890. Pahoehoe flow of Waipahoehoe Stream **23,840 ± 600**

Charcoal root coll at top of thin ash layer beneath pahoehoe flow, near base of waterfall, alt 680ft (207m), 160m E from W edge of Hilo quad (19° 41.83′ N, 155° 07.43′ W). Coll 1980 by J M Buchanan-Banks. *Comment* (JMBB): sample dates one of oldest exposed Mauna Loa lava flows in quadrangle and establishes min age for much of ash deposited in quad. At coll site, flow is overlain by pahoehoe of 1880–81 eruption, thin ash, pahoehoe of Punahoa ahupuaa dated by W-4629, and 3–4m-thick section of ash; flow overlies thin ash layer and another undated pahoehoe from ML.

W-5075. Pahoehoe flow of Waiakea Stream, older **24,240 ± 500**

Charcoal roots and rootlets coll at top of thin ash layer beneath pahoehoe flow, between Hoaka and Alawaena Rds, alt 880ft (268m), 180m W of E edge of Piihonua quad (19° 39.68′ N, 155° 07.65′ W). Coll 1982 by J M Buchanan-Banks. *Comment* (JMBB): reanalysis of W-4894. Sample dates one of oldest pahoehoe flows exposed in Waiakea Stream; comparisons of thin sections establish this flow as distinct from that dated by W-4890. At colln site, flow is overlain by ash, which in turn is overlain by pahoehoe flow dated by W-5072.

ACKNOWLEDGMENTS

We are indebted to Lea Gargulinski and John McGeehin, USGS, Reston, for sample preparation and treatment. The manuscript's consistency and clarity were improved by the thoughtful reviews of D Dzurisin and D Yamaguchi, USGS, Vancouver.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 187–200]

INSTITUT ROYAL DU PATRIMOINE ARTISTIQUE RADIOCARBON DATES XIII

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This list contains the results of ^{14}C determinations obtained at the laboratory in 1986 and 1987. $\delta^{13}C$ was measured by the British Museum Research Laboratory or the Free University of Brussels: $*\delta^{13}C$ is estimated (Stuiver & Polach, 1977).

GEOLOGIC SAMPLES

Belgium

IRPA-754. Brussegem — **9490 ± 100**, $*\delta^{13}C = -25‰$

Organic material from Brussegem, Brabant (50° 55′ N, 4° 14′ E) at 2.11–2.13m depth. Coll and subm Feb 1986 by F Bogemans, Geol Service Belgium.

IRPA-756. Weerde — **28,730 ± 850**, $*\delta^{13}C = -24‰$

Wood from borehole at Weerde, Brabant (50° 58′ N, 4° 28′ E). Coll and subm Feb 1986 by F Bogemans.

Wintham series

The following results complete previously pub series (R, 1987, v 29, no. 2, p 197–208) of peat and wood from O Vlaanderen (51° 07′ 08″ N, 4° 18′ 15″ E). Coll and subm 1986 and 1987 by P Kiden, Univ Gent, Belgium.

IRPA-768. Zeesluis 4 — **5740 ± 70**, $\delta^{13}C = -27‰$

Base of peat at 2.80m depth. *Comment* (PK): with other dates from same location (IRPA-712, -740, -741) IRPA-768 shows gradual rise of local river level in Scheldt alluvial plain due to rising sea level. Based on other dates from Wintham and absolute alt of this sample, date ca 6000 BP was expected. Actual result is somewhat younger, probably due to compaction of underlying sandy-clayey sediments.

IRPA-816. Zeesluis 5 — **30,260 ± 1000**, $*\delta^{13}C = -25‰$

Wood from braided river deposits at 6.3m depth. *Comment* (PK): date may be too old due to reworking of older material (pers commun, Linda Huysmans, based on macrofossil analysis). Date is only max for these and overlying Pleistocene sediments.

Antwerpen series

Samples from Scheldt R alluvial deposit at Antwerpen, Antwerpen (51° 21′ N, 4° 16′ E). Coll and subm Jan 1986 by P Kiden.

IRPA-769. Berendrechtsluis 1 **6000 ± 70**
$\delta^{13}C = -27‰$
Peat at 11.0m depth.

IRPA-770. Berendrechtsluis 2 **4480 ± 70**
$\delta^{13}C = -27‰$
Peat at 9.38m depth.

IRPA-771. Berendrechtsluis 3 **4630 ± 70**
$\delta^{13}C = -27‰$
Peat at 8.50m depth.

IRPA-772. Berendrechtsluis 4 **3570 ± 60**
$\delta^{13}C = -27‰$
Peat at 7.65m depth.

General Comment (PK): age of IRPA-769 is as expected with respect to absolute height of sample. IRPA-770 is ca 500 yr younger than expected as result of decreased rate of rise of river level due to flood-basin effect in Lower Scheldt area. IRPA-771 and -772 are much older than expected (by at least 600 yr) and -771 even shows slight age reversal with -770. This is probably result of simultaneous peat growth at different levels of sloping Pleistocene subsoil due to groundwater seepage.

De Panne-Adinkerke series

Samples from De Panne-Adinkerke, W Vlaanderen (51° 04′ 30″ N, 2° 94′ 45″ E). Coll and subm 1980 by R De Ceunynck, Univ Gent, Belgium.

IRPA-792. DP stort 8/8/86 **2970 ± 70**
$\delta^{13}C = +0.4‰$
Shells (*Serobicularia plana*) at 1.8m depth. Diluted; 58.38% sample.

IRPA-793. DP stort 85 **3260 ± 60**
$\delta^{13}C = -6.7‰$
Shells (*Cerastoderma edule*) at 2.0m depth.

Bornem series

Samples in infilled paleochannel in Scheldt R alluvial plain at Bornem, Antwerpen (51° 06′ 40″ N, 4° 13′ 40″ E). Coll and subm Aug 1987 by P Kiden.

IRPA-850. Bornem-Buitenland 1 **9400 ± 190**
$\delta^{13}C = -31.1‰$
Marl at 5.68–5.72m depth.

9660 ± 110

IRPA-851. Bornem-Buitenland 2 $\delta^{13}C = -34.9‰$

Marl at 5.91–6.01m depth. Diluted; 81.29% sample.

9920 ± 200

IRPA-852. Bornem-Buitenland 3 $\delta^{13}C = -33.9‰$

Marl at 6.38–6.48m depth. Diluted; 70% sample.

General Comment (PK): dates of IRPA-851 and -852 are expected. Age of IRPA-850 is greater than initially expected but seems correct considering results of IRPA-851 and -852. Dates show gradual infilling of Late Glacial paleochannel and early onset of peat growth in deepest part of channel.

Western coastal plain of Belgium series

These results complete previously pub series (R, 1987, v 29, no. 2, p 197–199, R, 1986, v 28, no. 1, p 71–72) of peat and wood from W Vlaanderen. Coll by L Denys and subm 1987 by C Baetemen, Geol Service Belgium.

3830 ± 70

IRPA-825. Wolvenest $\delta^{13}C = -26.8‰$

Peat from base of intercalated clay layer in top peat layer, 2.92–2.95m below surface at Ramskapelle (51° 06′ N, 2° 46′ E).

3550 ± 60

IRPA-860. Wolvenest $\delta^{13}C = -27.3‰$

Peat from top of intercalated clay layer in top peat layer, 2.82–2.85m below surface at Ramskapelle (51° 06′ N, 2° 46′ E).

2710 ± 60

IRPA-859. Wolvenest $\delta^{13}C = -26.8‰$

Peat from top of top peat, 2.32–2.38m below surface at Ramskapelle (51° 06′ N, 2° 46′ E).

3800 ± 60

IRPA-864. Vliegveld $\delta^{13}C = 28‰$

Peat from clay level in top peat layer, 4.25–4.29m below surface at Leffinge (51° 10′ N, 2° 53′ E).

4700 ± 70

IRPA-865. Vliegveld $\delta^{13}C = -28.6‰$

Peat from top of intercalated clay layer in top peat layer, 4.78–4.82m below surface at Leffinge (51° 10′ N, 2° 53′ E).

4820 ± 70

IRPA-866. Vliegveld $\delta^{13}C = -27.6‰$

Peat from base of intercalated clay layer in top peat layer, 4.90–4.94m below surface at Leffinge (51° 10′ N, 2° 53′ E).

2200 ± 50

IRPA-867. Oostkerke $\delta^{13}C = -27.4‰$

Peat from top of top peat, 1.75–1.80m below surface at Oostkerke (51° 02′ N, 2° 42′ E).

4750 ± 70

IRPA-868. Oostkerke $\delta^{13}C = -28.5‰$

Peat from base of top peat, 3.82–3.85m below surface at Oostkerke (51° 02′ N, 2° 42′ E).

5050 ± 80

IRPA-869. Oostkerke $\delta^{13}C = -27.2‰$

Peat from second peat layer, 3.94–3.97m below surface at Oostkerke (51° 02′ N, 2° 42′ E). Diluted; 60.13% sample.

1610 ± 50

IRPA-872. Waterhoek $\delta^{13}C = -28.2‰$

Clay peat with reed from top of top peat, 1.43–1.48m below surface at Noordschote (50° 57′ N, 2° 49′ E).

4460 ± 60

IRPA-873. Waterhoek $\delta^{13}C = -29.4‰$

Wood from 4.37–4.43m below surface at Noordschote (50° 57′ N, 2° 49′ E).

4850 ± 80

IRPA-874. Waterhoek $\delta^{13}C = -28.1‰$

Peat from 5.53–5.58m below surface at Noordschote (50° 57′ N, 2° 49′ E). Diluted; 64.5% sample.

5400 ± 90

IRPA-875. Waterhoek $\delta^{13}C = -27.2‰$

Clay peat from 5.77–5.83m below surface at Noordschote (50° 57′ N, 2° 49′ E). Diluted 75;12% sample.

General Comment (CB): IRPA-872: top of upper peat layer. Age corresponds with IRPA-521 and -537, also from top of surface peat at more inland sites, showing that peat growth persisted considerably longer here than in coastal area.

IRPA-873 dates onset of dry conditions during peat growth as indicated by diatom analysis. IRPA-875, -874 date onset and termination of (relatively mild) saltwater influence at site. IRPA-825 peat at base of clayey intercalation in upper peat layer; -860 peat at top of same intercalation; -864 clayey intercalation in upper peat layer. Results agree with dates for clay layers of limited extension in same stratigraphic position (ANTW-316, -317, IRPA-527, -286, -287, -290) and other indications of increased

marine influence during this period (IRPA-529). IRPA-865 at base of upper peat layer and -866 at top of second peat layer immediately underlying upper layer date onset and end of increased marine influence and clay deposition. Relatively late start of rather continuous peat growth was expected because of proximity to present coastline; IRPA-865–866 closely agrees with IRPA-721 and -868, also from base of surface peat. IRPA-859 at top of upper peat and -867 at top of upper peat are expected dates for top of surface peat. IRPA-869 at second peat layer and -868 at base of first peat layer should be older. Generally, second peat layer yields considerably older results (IRPA-559, -561, -724, -515: R, 1986, v 28, no. 1, p 71–72), yet dates correspond with others for beginning of surface peat growth. IRPA-869 is possibly affected by root contamination, but it should probably be considered reliable, indicating discontinuity in peat growth shortly after initiation.

ARCHAEOLOGIC SAMPLES

Belgium

Maldegem series

Samples from Roman wells at Maldegem, O Vlaanderen (51° 13′ 22″ N, 3° 25′ 38″ E). Coll and subm 1986–1988 by H Thoen, Univ Gent, Belgium (Thoen & Vandermoere, 1986).

IRPA-673. Sample 1 — **1630 ± 50**; $*\delta^{13}C = -27‰$

Wood (*Quercus*).

IRPA-674. Sample 2 — **1810 ± 50**; $*\delta^{13}C = -27‰$

Wood (*Betula*).

IRPA-827. MAV 87/6/2/N3 — **1960 ± 50**; $\delta^{13}C = -27.6‰$

Wood (*Alnus*). Board from construction of well 2.

IRPA-828. MAV 87/6/a/f — **1840 ± 50**; $\delta^{13}C = -28.1‰$

Wood fragments (*Alnus, Corylus, Quercus*) from filling of well 2.

IRPA-829. MAV 87/6/d/f 3 — **1880 ± 50**; $\delta^{13}C = -23.7‰$

Wood (*Ilex*); pile from filling of well 3.

IRPA-830. MAV 87/6/d/N2 — **1800 ± 50**; $\delta^{13}C = -26.8‰$

Wood (*Alnus*) from construction of well 3.

IRPA-650. Oudenaarde **750 ± 50**
$\delta^{13}C = -16.3‰$

Mortar from St Elooi Church in Oudenaarde, O Vlaanderen (50° 51′ N, 3° 35′ E). Coll and subm 1986 by M Savko, IRPA. *Comment:* sample was first examined to separate fractions containing chalk carbonate from those containing carbonate formed after mortar preparation (van Strydonck, Dupas & Dauchot-Dehon, 1982). Dating methods are described in van Strydonck, Dupas and Dauchot-Dehon (1986). Date agrees with archaeol age; end of 13th century AD.

IRPA-651. Leffe Abdij **1070 ± 50**
$\delta^{13}C = -11‰$

Mortar from St Georges Church in Dinant, Namur (50° 16′ N, 4° 46′ E). Coll and subm 1986 by M Savko. *Comment:* sample was first examined to separate fractions containing chalk carbonate from those containing carbonate formed after mortar preparation. Sample was too small for dating, described in van Strydonck, Dupas and Dauchot-Dehon (1986). All carbonate was transformed to CO_2, which may explain non-concordance with archaeol date: 14th century AD.

Oudenaarde series

Organic material and wood from excavations of Donk in Oudenaarde, O Vlaanderen (50° 50′ 30″ N, 3° 35′ 30″ E). Coll 1985 by M van Strydonck and subm 1985 by P Vanderplaetsen, Univ Gent, Belgium.

IRPA-667. OD84/1 **4990 ± 70**
$*\delta^{13}C = -24‰$
Wood.

IRPA-743. OD85/V17 **5240 ± 70**
$*\delta^{13}C = -24‰$
Organic material.

IRPA-744. OD85/V31 **5050 ± 70**
$*\delta^{13}C = -24‰$
Wood.

IRPA-745. OD85/sl3/k1 **4670 ± 70**
$*\delta^{13}C = -24‰$
Wood.

IRPA-746. OD85 **3130 ± 60**
$*\delta^{13}C = -27‰$
Peat from first Neolithic settlement.

IRPA-748. OD85/25/s12 **4160 ± 65**
$*\delta^{13}C = -24‰$
Charcoal.

General Comment (JV): all but IRPA-748 are from same site which belongs to Michelsberg culture. IRPA-667 and -744 derive from archaeol layer covering some pits, which yielded IRPA-743 and -745. IRPA-743 is somewhat older and seems to agree with archaeol assessments as very large and deep pit from which it came was filled slowly and naturally. Somewhat later date of IRPA-745, from a smaller pit, does not necessarily indicate stratigraphic contradiction. This pit, although older than archaeol layer, may have had short duration. The 2σ ranges of these dates overlap and, even with 1σ there is only a very small gap. IPRA-746 is from peat layer overlying archaeol features. Date completely agrees with stratigraphic and geologic observations. IRPA-748 was from late Neolithic site. Date fits well with observed (late) Vlaardingen and Beaker influences on that site.

Zoniënbos series

Charcoal from pit in Uccle, Brabant (50° 46′ N, 4° 24′ E). Coll Jan 1986 and subm April 1986 by J Sanders, Univ Gent, Belgium. Results used to date furnace for metallurgy study in Zoniënbos (Sanders, Langohr & Cuyckens, 1985; Theon, 1983).

IRPA-763. 86/2/13-A **1020 ± 50**
$*\delta^{13}C = -24‰$
Top of pit.

IRPA-764. 86/2/13-B **1240 ± 50**
$*\delta^{13}C = -24‰$
Base of pit.

IRPA-765. 86/2/3/1 **1240 ± 50**
$*\delta^{13}C = -24‰$
Base of pit.

IRPA-766. 86/1/29/1.A **1150 ± 50**
$*\delta^{13}C = -24‰$
Top of pit.

IRPA-767. 86/1/29/1-B **1080 ± 50**
$*\delta^{13}C = -24‰$
Base of pit. *Comment:* difference between IRPA-766 and IRPA-768 has no signification. Results are statistically the same.

"Hogeweg" series

Samples from Hogeweg site at Gent, O Vlaanderen (51° 3′ N, 4° 47′ E). Coll April 1985 by J Vanmoerkerke and subm March 1986 by M C Laleman, Dienst Monumentenzorg en Stadsarcheologie, Gent, Belgium.

IRPA-773. HW85 level 26 **2710 ± 60**
$*\delta^{13}C = -24‰$
Oak leaves found in a pit.

IRPA-774. HW85 level 18 **3030 ± 90**
$\delta^{13}C = -24‰$
Charcoal in circular grave from Bronze Age.

Zerkegem series

Samples from boards of well at Zerkegem, W Vlaanderen (51° 10′ 27″ N, 3° 03′ 24″ E). Subm 1986 by A van Doorselae, Univ Leuven, Belgium. Early Middle Age expected.

IRPA-775. ZER86/5/k33/N3 **1790 ± 50**
$\delta^{13}C = -24‰$
Wood.

IRPA-776. ZER86/5/k39/N3bis **1350 ± 50**
$\delta^{13}C = -24‰$
Wood.

IRPA-777. ZER85/5/k26 **1580 ± 50**
$\delta^{13}C = 24‰$
Wood.

Mirwart series

Samples from blast furnace at Mirwart, Luxembourg (50° 02′ N, 5° 14′ 30″ E). Coll July 1985 by JP Weber and subm May 1986 by A Matthys, Natl Service Excavations, Belgium; 16th century expected (Weber, 1985).

IRPA-779. 85MA3.Fl.4 **350 ± 50**
$\delta^{13}C = -25‰$
Charcoal.

IRPA-780. 85MA9.Fl.5 **490 ± 50**
$\delta^{13}C = -15‰$
Charcoal.

Hastedon series

Samples from Hastedon, Namur (50° 28′ 59″ N, 4° 50′ 40″ E). Coll Aug 1985 and subm June 1986 by P Bonenfant, Free Univ Brussels, Belgium. Results used to date protohistoric pit.

IRPA-785. Hastedon 5 **1750 ± 100**
$\delta^{13}C = -24‰$
Charcoal. Diluted; 39.5% sample.

IRPA-784. Hastedon 6 **2195 ± 40**
$\delta^{13}C = -24‰$
Charcoal.

2300 ± 60

IRPA-802. Kooigem $*\delta^{13}C = -24‰$

Charcoal from funerary deposit in trench of cult site at Kortrijk, W Vlaanderen (50° 50′ N, 3° 19′ E). Coll 1985 by E Glabeke and subm 1987 by J Termote, Vereninging voor Oudheidkundige Bodemonderzoek in W Vlaanderen. Based on typological study, date should be La Tène Ib or La Tène Ic-II period.

Oudenburg series

Samples from well in Roksem, W Vlaanderen (51° 10′ 35″ N, 3° 1′ 15″ E). Coll Nov 1986 by J de Meulemeester (de Meulemeester & Dewilde, 1987) and subm March 1987 by G de Boe, Natl Service Excavation, Belgium. Results used to date archaeol site of Oudenburg. Middle Age period expected.

1370 ± 50

IRPA-809. Well 1 $\delta^{13}C = -26.4‰$

Wood.

1030 ± 20

IRPA-810. Well 2 $\delta^{13}C = -26.4‰$

Wood.

4990 ± 90

IRPA-861. En 83/50 $\delta^{13}C = -25.3‰$

Charcoal from prehistoric level of Mark Castrum (Callebaut, 1984) in Ename, O Vlaanderen. Coll Oct 1983 and subm Nov 1987 by D Callebaut, Natl Service Excavations, Belgium. Expected age: Late Neolithic. Diluted; 64.51% sample.

Hamipré series

Charcoal from oven in Iron Age "tombelle" at Hamipré, Luxembourg (49° 50′ N, 5° 30′ 45″ E). Coll 1983 and subm 1987 by A Cahen-Delhaye, Natl Service Excavations, Belgium. Date from same site, Hv-12992: 360 ± 65.

2330 ± 60

IRPA-814. 83Ha32 $\delta^{13}C = -24.5‰$

Result agrees with other date.

1220 ± 50

IRPA-815. 83Ha37 $\delta^{13}C = -24.4‰$

Date is too young.

Ursel series

Samples from excavations of Ursel at Knesselare, O Vlaanderen. Coll 1987 by J Bourgeois and J Vanmoerkerke and subm 1988 by J Nenquin, Univ Gent, Belgium.

IRPA-818. S54 **3620 ± 60**
$\delta^{13}C = -25.7‰$
Charcoal from Bronze Age tumulus.

IRPA-819.A S26 **2490 ± 55**
$\delta^{13}C = -24.8‰$
Charcoal from Bronze Age tumulus; SW section.

IRPA-819.B S26 **2500 ± 60**
$\delta^{13}C = -25.1‰$
Charcoal from Bronze Age tumulus; S section.

IRPA-820. Tomb 7 **1980 ± 60**
$\delta^{13}C = -25.8‰$
Charcoal from Iron Age. No NaOH pretreatment. Diluted; 63.8% sample.

IRPA-821. Tomb 8 **1990 ± 50**
$\delta^{13}C = -25.5‰$
Charcoal from Iron Age.

IRPA-822. Tomb 12 **2070 ± 50**
$*\delta^{13}C = -25‰$
Charcoal from Iron Age.

IRPA-823. Tomb 23 **1990 ± 50**
$\delta^{13}C = -25.7‰$
Charcoal from Iron Age.

General Comment (JN): dates agree with archaeol expectation.

Donk series

The following results complete series (R, 1987, v 29, no. 2, p 205) of samples from multicomponent site in Donk, Limburg (50° 57′ 24″ N, 5° 07′ 56″ E). Coll Oct 1986 and subm Dec 1986 by L van Impe, Natl Service Excavations, Belgium.

IRPA-795. 86/DO/1319 **1360 ± 50**
$\delta^{13}C = -27‰$
Wood used to protect river bank.

IRPA-796. 86/DO/1318 **1290 ± 50**
$\delta^{13}C = -25.9‰$
Wood from pile-planking.

IRPA-797. 86/DO/1317 **1380 ± 50**
$*\delta^{13}C = -25‰$
Wood from pile-planking.

IRPA-798. 86/DO/1321 **1010 ± 50**
$\delta^{13}C = -28.2‰$
Wood from branch.

IRPA-799. 86/DO/1323 **1180 ± 50**
$\delta^{13}C = -28.3‰$
Wood from branch.

IRPA-800. 86/DO/1276 **1180 ± 50**
$\delta^{13}C = -28.1‰$
Wood from branch.

IRPA-801. 86/DO/1320 **1330 ± 50**
$\delta^{13}C = -28.5‰$
Wood from branch.

IRPA-879. Abdÿ 't Park **305 ± 60**
$\delta^{13}C = -25.9‰$
Straw in plaster from Abdij of Park at Heverlee, Brabant (50° 52′ N, 4° 45′ E). Coll and subm 1988 by R M Lemaire, Univ Leuven, Belgium.

Balearic Islands

Taula del Torralba series

Samples from Menorca, Spain (39° 35′ N, 2° 44′ E). Coll April 1987 and subm July 1987 by W Waldren, Deya Archaeol Mus and Research Centre, Deya Mallorca, Spain.

IRPA-781. Sample 3 **2020 ± 70**
$*\delta^{13}C = -24‰$
Charcoal.

IRPA-782. Sample 4 **2400 ± 60**
$*\delta^{13}C = -24‰$
Charcoal.

IRPA-813. SFO YS T1 **2830 ± 100**
$*\delta^{13}C = -25‰$
Charcoal from red earth on bedrock at Ferrandel-Oleza, Mallorca, Spain (39° 34′ N, 2° 44′ E). Coll April 1987 and subm July 1987 by W Waldren.

Mallorca series

Lime burials from Mallorca, Spain (39° 94′ N, 2° 44′ E). Coll and subm 1985–1986 by W Waldren. CO_2 extraction follows method described in van Strydonck, Dupas and Dauchot-Dehon (1986). See Tables 1 and 2.

TABLE 1
Mallorca radiocarbon dates

Ref	IRPA no.	Fraction (%)	Date	Isotopic fractionation (%)
ABSM-QL	−676	100	2330 ± 60	−15.7
≠7		50	2550 ± 60	−14.2
		25	2330 ± 60	−13.88
ABSM-QL	−695	100	2040 ± 60	−12.28
CE(23)		52	2620 ± 60	−11.55
		24	2050 ± 60	−10.57
		12	1960 ± 100	−10.44
SFO-YS	−710	98	1790 ± 60	−17.71
		53	1965 ± 60	−15.92
		16	1560 ± 60	−14.49
ABSM	−762	100	22.460 ± 400	−1.38
Pretalyot c		49	23.731 ± 460	0.69
		19	18.300 ± 240	4.14
SFO-YS	−778	100	1990 ± 60	−11.58
T1		50	1520 ± 60	−17.6
		30	1490 ± 60	−16.32
		17	1520 ± 60	−17.49
ABSM-QL	−789	100	2280 ± 60	−16.48
≠12		21	2350 ± 60	−13.69
ABSM-QL	−790	100	2430 ± 60	−18.79
NR4		50	2570 ± 60	−18.02
		14	2360 ± 60	−17.85

ART SAMPLES

Belgium

510 ± 50

IRPA-786. DI 86/3483 2L/35 *$*\delta^{13}C = -20‰$*

Bones from tomb in S'Niklaas church at Gent, O Vlaanderen (51° 3′ N, 4° 47′ E). Subm June 1986 by J de Boeck, IRPA. Result used to date textile found in same tomb.

Tancrémont series

Statue of Christ on crucifix in Tancrémont chapel at Pepinster, Liège (50° 32′ N, 5° 50′ E). Subm by M Serck, IRPA.

570 ± 50

IRPA-787. DI 84/2955 2L/47 A *$*\delta^{13}C = -24‰$*

Wood (*Quercus*) from cross.

1160 ± 50

IRPA-788. DI84/2955 2L/47 B *$*\delta^{13}C = -24‰$*

Wood (*Tilia*) from Christ. *Comment:* date of cross is younger than that of Christ.

TABLE 2
Mallorca radiocarbon dates

Ref	IRPA no.	Fraction (%)	Date	Isotopic fractionation (%)
ABSM-QL ≠9	−750	20	2100 ± 60	−17.83
		20	2150 ± 60	−17.84
		18	2610 ± 60	−17.85
		18	2520 ± 60	−18.61
ABSM-QL ≠10	−751	21	2500 ± 60	−12.14
		19	3660 ± 70	−11.31
		19	4190 ± 70	−10.79
		20	4620 ± 80	−10.79
		21	5270 ± 80	−9.68
ABSM-QL ≠8	−752	20	2090 ± 60	−14.84
		21	2540 ± 60	−14.5
		18	2390 ± 60	−14.58
		20	2310 ± 70	−15.03
		21	2440 ± 60	−14.76
ABSM-QL ≠13	−803	19.3	2270 ± 60	−14.13
		19.45	2560 ± 60	−14.37
		19.67	2320 ± 60	−14.18
		20.08	2250 ± 60	−14.54
		21.49	2430 ± 60	−14.86
ABSM-NOP 2	−804	19.33	2590 ± 60	−18.28
		19.04	2700 ± 60	−19.27
		19.40	2900 ± 60	−20.34
		19.09	2930 ± 60	−20.96
		23.13	3070 ± 60	−21.21
	−806	18.59	2290 ± 60	−24.07
		19.19	2640 ± 60	−17.04
		17.82	2980 ± 60	−16.82
		18.43	2760 ± 60	−16.78
		26.14	2700 ± 60	−16.54
ABSM-NOP 3	−808	19.45	1970 ± 60	−22.39
		19.82	2250 ± 60	−23.07
		20.84	2270 ± 60	−24.57
		19.15	2350 ± 60	−24.15
		20.73	2250 ± 60	−24.83
ABSM-QL 6	−811	19	2460 ± 60	−14.27
		20	2530 ± 60	−14.15
		20	2650 ± 60	−14.7
		20	2620 ± 60	−14.92
		21	2530 ± 60	−15.37

General Comment (MVS): Samples show recarbonation of lime. Fossil carbonate was found only in a few samples. For comprehensive discussion, see van Strydonck and Waldren (1987).

IRPA-794. DI86/3574 2L/35 **370 ± 40**
$\delta^{13}C = -26.1‰$

Blue (indigo) cloth from "De zeven vrije kunsten" tapestry in Gruuthuse Mus Brugge, W Vlaanderen (51° 19′ N, 3° 9′ E). Subm Nov 1986 by J Vynckier, IRPA. Diluted; 79.28% sample. Expected age: 17th century AD.

IRPA-853. DI87/3813 2L/7 **170 ± 50**
$\delta^{13}C = -23.3‰$

Wooden Japanese mask; style of Nara period, 8th century AD.

Peru

Chancay series

Samples from Peru, Chancay period. Coll 1977 by J Purin and subm Jan 1986 by J de Boeck.

IRPA-620. AAM.65.13-6 **1240 ± 50**
$\delta^{13}C = -23.9‰$

Wood (bamboo).

IRPA-621. AAM.65.13-4 **1030 ± 60**
$\delta^{13}C = -24.4‰$

Wood (bamboo). Diluted; 71.15% sample.

IRPA-622. **670 ± 50**
$\delta^{13}C = -19.9‰$

Cloth (cotton).

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 201–210]

NOTES AND COMMENTS

CORRECTED CALIBRATION OF THE RADIOCARBON TIME SCALE, 3904–3203 CAL BC

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Since our publication of the high-precision calibration curve for the larger part of the 4th millennium BC (de Jong, Becker & Mook, 1986), we found that the dendrochronologic scale (cal BC) needs a correction of 26 years. Instead of using the zero-point of the Niederwill chronology (4039 BC) which was floating at the time, our dendrochronologic scale was erroneously based on the zero-point of the Hohenheim master chronology, which, in its 1986 stage, extended to 4065 BC.

By this correction of 26 years there is now good agreement with the calibration curve of Pearson *et al* (1986), as shown in Figure 1. The definitive calibration curve is shown in Figure 2. Table 1 contains the revised data.

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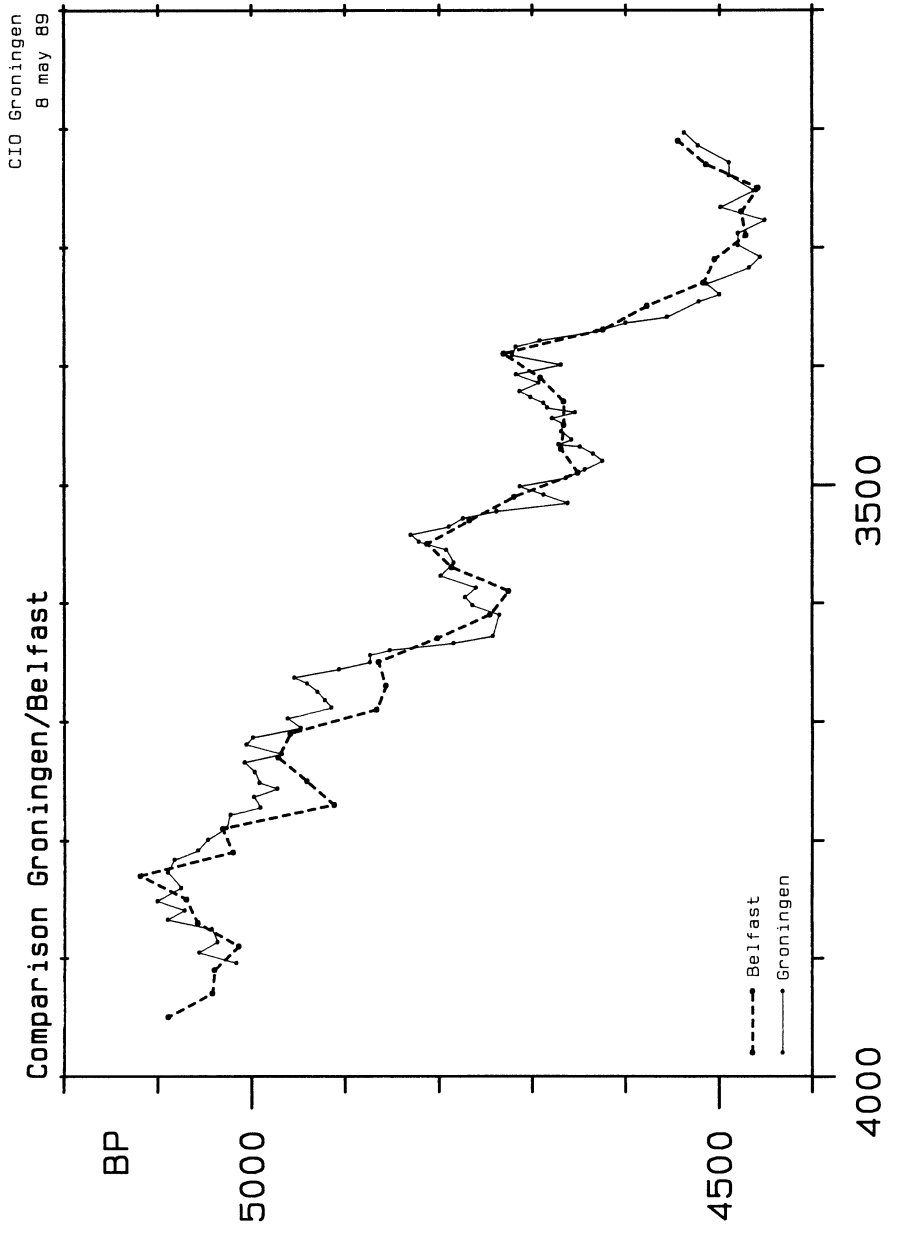

Fig 1. Comparison between the calibration data of Pearson *et al* (1986) and our present data

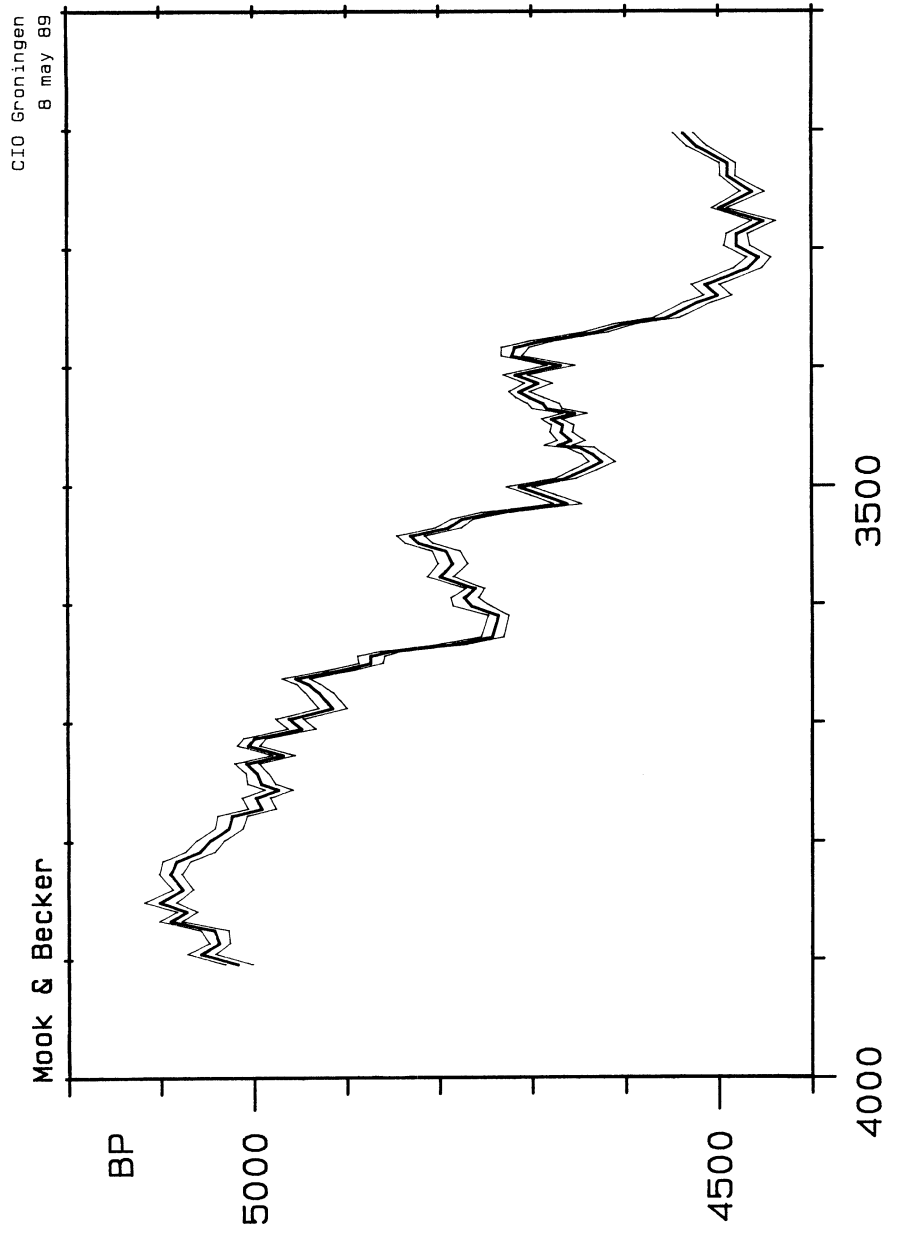

Fig 2. Calibration curve for one-year tree-ring samples from German Oak

TABLE 1

Results of ^{13}C(*vs* PDB) and ^{14}C analyses on tree rings from South German oak chronologies Donau 7, 3, 10 and 12. The absolute historical values are from the absolute master chronology (Becker & Kromer, 1986) and have been revised by 26 years as compared to de Jong *et al* (1986). The ^{14}C results are conventional ages (5568 yr half-life), corrected for ^{13}C.

GrN no.	Tree no.	Tree-ring no.	Dendro date BC	^{14}C age (BP)	$\delta^{13}C$ (‰)
9163	E1	136	3904	5017 ± 15	−26.18
9162	E1	145	3895	5057 ± 15	−25.90
9161	E1	154	3886	5037 ± 11	−26.01
9160	E1	165	3875	5043 ± 15	−25.42
9066	E1	173	3867	5090 ± 12	−25.51
9065	E1	181	3859	5072 ± 11	−25.54
9159	F1	189	3851	5101 ± 17	−24.50
9063	F1	200	3840	5076 ± 11	−25.17
9158	G1	213	3827	5090 ± 12	−26.16
9025	G1	224	3816	5083 ± 15	−25.21
9024	H1	232	3808	5058 ± 16	−25.05
9023	H1	241	3799	5047 ± 15	−25.46
9022	H1	251	3789	5027 ± 15	−25.36
9021	H1	262	3778	5023 ± 16	−25.54
9008	H1	268	3772	4991 ± 15	−25.55
9007	H1	277	3763	4998 ± 15	−25.30
9006	H1	284	3756	4973 ± 15	−25.37
9005	H1	289	3751	4992 ± 15	−24.93
9004	H1	298	3742	4997 ± 12	−25.06
9002	H1	306	3734	5008 ± 13	−24.30
9001	H1	313	3727	4968 ± 12	−24.65
8837	H1	321	3719	5006 ± 12	−24.40
8836	H1	327	3713	4999 ± 12	−24.54
8835	H1	335	3705	4948 ± 15	−25.37
8834	H1	343	3697	4962 ± 15	−24.53
8833	H1	352	3688	4915 ± 15	−24.79
8832	H1	358	3682	4922 ± 15	−24.73
8831	H1	365	3675	4930 ± 15	−24.68
8830	H1	372	3668	4941 ± 13	−24.53
8779	I1	377	3663	4955 ± 15	−24.54
8778	I1	384	3656	4907 ± 14	−24.82
8777	I1	390	3650	4874 ± 13	−24.90
8776	I1	396	3644	4874 ± 15	−24.59
8775	I1	400	3640	4853 ± 12	−25.09
8774	I1	406	3634	4785 ± 15	−24.84
8773	I1	412	3628	4743 ± 12	−25.26
8771	I1	430	3610	4736 ± 11	−25.27
8766	I1	438	3602	4765 ± 20	−25.27
8764	I1	445	3595	4773 ± 15	−24.81
8751	I1	453	3587	4761 ± 10	−24.37
8750	K1	463	3577	4799 ± 14	−24.49
8749	K1	474	3566	4785 ± 16	−24.69
8748	K1	485	3555	4793 ± 15	−24.68
8742	K1	492	3548	4822 ± 15	−24.76
8741	K1	498	3542	4831 ± 15	−24.65
8740	K1	505	3535	4790 ± 14	−25.06
8730	K1	512	3528	4775 ± 12	−24.90
8729	K1	518	3522	4739 ± 15	−24.60
8727	K1	525	3515	4662 ± 15	−24.43
8726	K1	532	3508	4688 ± 14	−25.31
8725	K1	539	3501	4714 ± 14	−25.21
8724	L1	546	3494	4664 ± 11	−25.02
8570	M1	553	3487	4644 ± 13	−25.54
8569	M1	560	3480	4625 ± 14	−24.71

TABLE 1 (continued)

GrN no.	Tree no.	Tree-ring no.	Dendro date BC	^{14}C age (BP)	$\delta^{13}C$ (‰)
8568	M1	566	3474	4635 ± 12	−25.03
8549	M1	572	3468	4649 ± 15	−26.12
8728	N1	574	3466	4672 ± 15	−23.99
8548	O1	578	3462	4658 ± 15	−25.66
8547	O1	585	3455	4669 ± 12	−25.69
8546	O1	591	3449	4667 ± 12	−25.58
8532	O1	596	3444	4679 ± 11	−25.09
8531	O1	601	3439	4654 ± 13	−24.60
8530	P1	605	3435	4684 ± 16	−25.33
8529	P1	609	3431	4688 ± 17	−24.95
8528	Q1	614	3426	4702 ± 15	−24.98
8527	Q1	619	3421	4714 ± 11	−25.13
8524	Q1	626	3414	4693 ± 15	−25.77
8523	Q1	633	3407	4718 ± 13	−25.35
8522	R1	641	3399	4669 ± 15	−25.46
8521	R1	649	3391	4722 ± 11	−25.26
8520	R1	656	3384	4718 ± 15	−25.63
8475	R1	661	3379	4692 ± 13	−25.44
8474	S1	669	3371	4631 ± 13	−25.46
8473	S1	676	3364	4600 ± 12	−25.27
8472	S1	687	3359	4556 ± 14	−24.84
8366	S1	694	3346	4522 ± 15	−24.79
8365	T1	700	3340	4500 ± 15	−24.20
8346	T1	709	3331	4514 ± 15	−24.43
8345	T1	723	3317	4468 ± 15	−24.05
8299	T1	732	3308	4456 ± 13	−24.81
8298	U1	742	3298	4480 ± 14	−24.98
8273	V1	752	3288	4480 ± 11	−24.53
8272	V1	763	3277	4451 ± 13	−25.37
8271	V1	774	3266	4499 ± 8	−24.57
8270	W1	788	3252	4463 ± 13	−24.67
8269	W1	801	3239	4490 ± 8	−24.41
8268	W1	812	3228	4490 ± 9	−25.28
8267	W1	826	3214	4523 ± 11	−25.03
8266	W1	837	3203	4538 ± 11	−25.28

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REPORT ON A MEETING HELD AT THE IAEA, VIENNA 20–21 FEBRUARY, 1989

Dear Colleague,

During the International Radiocarbon Conference in Dubrovnik in June 1988, several laboratories expressed the need for quality assurance. Furthermore, on several occasions ^{14}C laboratories have shown an interest in reference materials of known ^{14}C activity, apart from the recent activity of the NBS oxalic acid.

During a meeting which was attended by Lloyd A Currie, Wim Mook, Bob Otlet, Henry Polach and by R Gonfiantini and coworkers on behalf of the IAEA, the conclusion was reached that both wishes can only partly be combined. In particular, the IAEA declared that it is not equipped to undertake an operation which would involve a frequent distribution of samples of various activities, known to the IAEA, but unknown to the applicant, and to provide Quality Assurance in the legal sense.

The discussion, therefore, concentrated on the matter of reference materials. The IAEA declared itself prepared to act as the international body for storage and distribution of ^{14}C reference materials on equal basis as for stable isotopes, and as the coordination agency for this calibration program.

In principle, a first choice was made, after ample discussion, of carbonates and organic compounds of recent and (about) zero, and possibly intermediate activity. Provisional checks on the materials will be made shortly.

Determination of the true ^{14}C activities of the reference materials—with respect to NBS oxalic acid—will be a joint effort of the ^{14}C community, where especially laboratories with experience in high precision ($\leq 2‰$) and/or in low background are required to collaborate. The distribution of the materials (before 1990) as well as the evaluation by an open meeting of consultants (autumn 1990) will be organized by the IAEA.

By this announcement ^{14}C laboratories are requested to state their willingness for active cooperation by letter to:

Dr R Gonfiantini
Head Section Isotope Hydrology
International Atomic Energy Agency
P O Box 100
A-1400 VIENNA
Austria

Groningen, April 3, 1989

W G Mook

ISLANDS OF AFFLUENCE IN A SEA OF DESPAIR

I recently had the privilege of attending the Conference on Technology-Based Confidence Building: Energy & Environment, hosted by Los Alamos National Laboratory and The University of California, in Santa Fe, New Mexico, July 9–14, 1989.

Natural scientists, political scientists, social scientists and writers were some of the 165 participants from 13 countries: Australia, Austria, Canada, China, Costa Rica, Germany, Israel, Italy, Japan, UK, US, USSR and Yugoslavia.

The "leit motif" of the conference quickly came into focus and that was to save our planet, earth, through aggressive measures in science, industry, politics and international cooperation. In our rapidly degenerating global environment, international security (ecological, that is, not military) is at stake. We are in a world of transition, moving away from the era of Cold War weapons production towards the current mood of "Perestroika" and the smoothing of bilateral relations. However we now face a far more fearsome foe—irreversible environmental degradation. What we most urgently need to defeat the deadly dragon is "metanoia," said Thomas Malone, St Joseph College Scholar in Residence, or a change in our thinking.

Intensive discussions on such issues as the Greenhouse Effect, acid rain, CO_2 and methane levels, the ozone hole, deforestation, soil erosion, desiccation, alternative energy sources, chemical pollutants, population explosion and starvation led to recommendations from four specialized Workshops.

I. ENVIRONMENTAL CHALLENGES

Chair: Will Kellogg, National Center for Atmospheric Research

We must change our attitudes and perceptions; degradation of the earth is a present reality and remedial actions must be taken. The demand on natural resources by the population explosion must be carried to the highest levels of government, economics and academia. The world is in transition from military to environmental security.

The public does not share the sense of urgency felt within the sciences and must be educated. Scientists have a special responsibility to inform, reach consensus and to translate findings into political action.

Third-world nations are not concerned with global change—their priorities put survival first. Global insults to the earth are largely due to the actions of 25% of the world population that controls 75% of the wealth, energy and resources. Wealthy nations are obligated to cooperate and advise the poor.

It is not likely that the world will switch from fossil fuels, but we must move away from these by investing in research and development, which will buy us time from inevitable warming. Our long-term view should be towards solar energy conversion, other renewable energy sources and safe nuclear reactors. We must take a hard look at the impacts of global warming in the next century and broadcast our findings to the international com-

munity through a variety of governmental and non-governmental agencies.

II. FISSION ENERGY

Chair: Ron Augustson, Safeguards Assay Group, Los Alamos National Laboratory

Nuclear energy produces 17% of the world's electricity and is an acceptable energy option, given that we engage in a new generation of international projects towards nuclear reactor safety, nuclear waste disposal, safeguards (perhaps through the IAEA) and low-level radiation protection. Long-term energy alternatives should be sought, such as solar energy, fusion, conservation, cleaner fossil fuels, and a real commitment to the International Thermonuclear Experimental Reactor (ITER).

We must regain public confidence in nuclear energy through safe operation, communication and education. The re-establishment of nuclear energy should occur by the 21st century. Although there should be no single monetary source for these technologies, expenses should be transferred in general from the military. Sociologists and psychologists should play a role in this global transition.

III. CONSERVATION, FOSSIL FUELS AND RENEWABLES

Chair: Robert Schock, Energy Program, Lawrence Livermore National Laboratory

An International Center for Research on Energy and Environment should be established. Its scope should include energy conversion and end-use efficiency, technological development and transfer, policy formulation, database maintenance, resource extraction, economic development of less developed countries and collaborative projects on global limits to carbon emissions.

Dissemination of the results of this conference should be through the US National Academy of Sciences, the USSR Academy of Sciences as well as the legislative and executive branches of all national governments. A Bush-Gorbachev "Environmental Summit" should be convened.

IV. EMERGENCY RESPONSE TO ACCIDENTS

Chair: Ron Koopman, Lawrence Livermore National Laboratory

We must improve predictive capabilities for natural disasters, such as earthquakes, floods and tidal waves as well as for man-made disasters, such as radiation or chemical spills. An International Disaster Response Center should be established to coordinate programs for disaster response and the prevention and mitigation of accidents. The rarity of events make it difficult to maintain preparedness. Data bases should be maintained and pressure should be placed on the government to implement these measures.

Following the summaries of these dedicated scholars, organizer, Louis Rosen, of Los Alamos, closed the discussions on a note of optimism, liken-

ing the scholars and their recommendations to "islands of affluence in a sea of despair."

I felt compelled to share this enriching and hopeful experience with my colleagues and call upon you, as scientists and citizens, to do what you can for the survival of the earth.

Renee Kra
Managing Editor

The Mary Ingraham Bunting Institute of Radcliffe College

Science Scholars Fellowship Program 1990-91

Funded by the Office of Naval Research

As part of a $1.7 million grant, the Bunting Institute will fund a total of 45 women scientists from 1989 to 1995. This grant represents the third consecutive renewal of support from the Office of Naval Research, which began its support of the Institute in 1980. Since that time, we have hosted 32 post-doctoral women scientists and we will appoint seven new scholars for 1990-91.

Eligibility

Women scientists who are U.S. citizens or permanent residents are eligible for this program. Applicants must hold a Ph.D. degree by the date of appointment (July 1, 1990) in one of the following fields: astronomy, biochemistry, ecology, geology, physics, chemistry, engineering, computer science, mathematics, cognitive and neural science, and biological science.

Terms of Fellowship

$26,300 stipend plus research allowance for a one-year appointment, July 1, 1990-June 30, 1991. Private office space provided, along with access to Harvard/Radcliffe resources. Science Scholars are required to present a public lecture co-sponsored with the relevant Harvard University science department.

Residence Requirement

Science Scholars are required to be in residence in the Cambridge/Boston area for the entire term of appointment. We do not provide housing.

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If a laboratory affiliation is necessary to the proposed research project, applicants must establish an affiliation with a laboratory in the greater Boston area. It is *not* necessary to choose a laboratory at Harvard University.

Number of Fellowships Awarded for 1990-91

Seven.

Deadline

October 2, 1989 *(postmarked)*. Applicants will be notified of their status by March 1990.

For Application Materials contact:

Mary Ingraham Bunting Institute
Radcliffe College
34 Concord Avenue
Cambridge, MA 02138
(617) 495-8212

[RADIOCARBON, VOL 31, NO. 2, 1989, P 211–212]

REVIEW

Radiocarbon Dating Literature: The First 21 Years 1947–1968. Annotated Bibliography. Compiled by Dilette Polach. San Diego, California, 1988. Academic Press, Inc, 370 pages, $24.00

As one who appreciates heavy-duty reconnaissance, I can report that I am very impressed by this nearly-3000-entry summary of the first score years of ^{14}C dating. I can also save you time by recommending that you or your research library acquire this book forthwith.

Radiocarbon Dating Literature: The First 21 Years, 1947–1968 is a precisely explained presentation of numerous (nearly all known or possible English-language) articles and books on early ^{14}C discovery, research and results. By "precisely," I mean that author and compiler Polach's Preface is brief and blunt and that her single sentence or single paragraph annotations are very informative, often more so, as Forewarder Chappell also notes, than the original author's own abstracts. Frankly, these annotations are excellent.

The range of ^{14}C application has been immense, and there is a swell book-cover logo to emphasize this. In order to stuff us users into this diverse productivity, there are fourteen chapters. The first three are theory: Bibliographical, Theoretical, and Techniques and Instrumentation. The next four are topical: General Geology, Glacial Geology, Oceans and The Pleistocene. The next five are geographical: Africa, America, Asia, Europe and Oceania (this latter meaning especially Australia/New Guinea). Chapter 13 (only two pages) is a list of early conferences such as the early ^{14}C Conferences in Copenhagen and Andover in 1954. Chapter 14 is a long set of the Date Lists as were published by the many laboratories.

Ms Polach has also provided a seemingly complete Author Index (Broecker, Libby, Suess, and Rubin loom beaucoup numerous as you might guess), as well as a Subject Index that I thought was really helpful (at least as long as one doesn't take subject words like "Wisconsinan," "wood," "shell chronology," "sea-level," "stratigraphy," and "validity" too seriously), and a valuable Locational Index.

In the modern style of word processing, every title with its annotation is uniquely number-keyed for practically instant acquisition throughout the book from these Indices. (You might care to check out the ancestral—1946!—and wondrous 2.025, or even the single outlier 2.212 dating to 1940.) This clarity for users is no doubt a result of the author's profession as a librarian, from which she is now retired and serving as a Visiting Fellow at the Australian National University in Canberra. Her spouse, Henry, is the Director of ANU's ^{14}C lab, and this was clearly an important assistance and support over the ten years which Ms Polach has labored on her effort.

It is totally symptomatic of modern "World Science" and electronic communication that Ms Polach created this holistic, comprehensive research tool in Australia, that it was published by Academic Press internationally in London and in the United States in San Diego, and that it was actually printed in Scotland.

In using *Radiocarbon Dating Literature: The First 21 Years, 1947–1968, An Annotated Bibliography,* the main thing that must be held in mind, especially for those of us working on ^{14}C in more recent times, is that it goes only to 1968. There are many classics seemingly missing—until we remember this ending date of compilation.

And perhaps I might note, with warm humor, that actually the title itself has the characteristics of a ^{14}C date estimate. The "range" is given in the book title as 21 years, although in fact it is a 22-year period. Further, there are several citations (not counting the above 1940 outlier which we'll reject by Chauvenet's Criterion!) from 1946 (naturally!), and thus, the rendered period is actually a full 23 years. (Well; You know; Go for it!)

For the post-1968 ^{14}C world, however, there is good news. For this review, I recently spoke (probably via 18 microwave towers, 2 satellites, and numerous land lines, and ending with a radiotelephone out in her rose garden; everything but tin cans and string!) with Ms Polach, and she is already creating a sequel for the next dozen years: 1969–1980. Since the ^{14}C literature is on a fast-growth curve, rather than its subject's slow-decay curve, this sequel will have even more references for a much shorter period. The new effort will feature some organizational changes such as the addition of a chapter on Paleontology, the expansion of the Oceans material, and a separation of the Americas into North, Middle and South. Ms Polach intends it to be available for the next Radiocarbon Conference in Tucson in 1991. And in this connection, I really suggest that, if you have publications or references for her to consider, you might care to send her copies at P O Box 43, GARRAN, A C T 2605, Australia.

In summary (with $\pm 3\ \sigma$ confidence), I highly commend this book. For such a grand boon as ^{14}C dating, and from scrutinizing Ms Polach's book, you could learn a whole lot about whose shoulders we are standing on.

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[RADIOCARBON, VOL 31, NO. 2, 1989, P 213–227]

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AMS GEOSCIENTIST

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INTERNATIONAL WORKSHOP ON INTERCOMPARISON OF RADIOCARBON LABORATORIES

GLASGOW, 12–15 SEPTEMBER 1989

A workshop was held in Glasgow in September, 1989 on the topic of the InterComparison of Radiocarbon Laboratories. The meeting was hosted by the University of Glasgow, Scottish Universities Research and Reactor Centre and the NERC ^{14}C laboratory at East Kilbride. The scientific programme of the workshop covered previous and current intercomparison studies of radiocarbon laboratories, as well as future developments in this field.

The Proceedings will be published by *RADIOCARBON* as a Special Issue in Volume 32, No. 3, 1990. Participants should submit three double-spaced copies (with diskette, if available) of their manuscripts by November 15, 1989. Manuscripts received after this date will *not* be included in the Proceedings. Manuscripts should not exceed 10 printed pages.

Participants should submit manuscripts to:

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REVISED NOTICE TO READERS AND CONTRIBUTORS

Since its inception, the basic purpose of *RADIOCARBON* has been the publication of compilations of ^{14}C dates produced by various laboratories. These lists are extremely useful for the dissemination of basic ^{14}C information.

In recent years, *RADIOCARBON* has also been publishing technical and interpretative articles on all aspects of ^{14}C. We would like to encourage this type of publication on a regular basis. In addition, we will be publishing compilations of published *and unpublished* dates along with interpretative text for these dates on a regional basis. Authors who would like to compose such an article for his/her area of interest should contact the Managing Editor for information.

Other sections recently added to our regular issues include NOTES AND COMMENTS, LETTERS TO THE EDITOR and ANNOUNCEMENTS. Authors are invited to extend discussions or raise pertinent questions to the results of scientific investigations that have appeared on our pages. These sections include short, technical notes to relay information concerning innovative sample preparation procedures. Laboratories may also seek assistance in technical aspects of radiocarbon dating. Book reviews are also encouraged as are advertisements.

Manuscripts. Papers may now be submitted on both floppy diskettes and hard copy. When submitting a manuscript on a diskette, *always* include *two* hard copies, double-spaced, or wait until the final copy is prepared, after review, before sending the edited diskette. We will accept, in order of preference, WordPerfect, 5.0 or 4.2, Microsoft Word, WordStar or any major Macintosh or IBM word-processing software program. ASCII files, MS DOS and CPM formatted diskettes are also acceptable. The diskettes should be either 3½" (720K or 1.44 megabytes) or 5¼" (360K or 1.2 megabytes). Radiocarbon papers should follow the recommendations in *RADIOCARBON* Style Guide (R, 1984, v 26, p 152–158). Our deadline schedule for submitting manuscripts is:

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Half life of ^{14}C. In accordance with the decision of the Fifth Radiocarbon Dating Conference, Cambridge, 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, v 195, no. 4845, p 984, 1962), 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, 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 will now be reported as "cal BP" or "cal AD/BC" according to the consensus of the Twelfth International Radiocarbon Conference, Trondheim, Norway, 1985.

Meaning of $\delta^{14}C$. 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 8th Conference on Radiocarbon Dating, Wellington, New Zealand, 1972). The Ninth International Radiocarbon Conference, Los Angeles and San Diego, 1976, recommended that the reference standard, 0.95 times 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. For the present, therefore, we continue the editorial policy of using Δ notations for samples not corrected for age.

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