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FROM THE EDITOR

As we go to press, a major journalistic and scientific topic is the Kyoto, Japan conference on international agreements to control greenhouse gas emissions. The media blitz includes feature stories, articles and editorials (including letters to editors) in newspapers, newsmagazines and science journals. For many weeks the public has had the opportunity to be educated about at least two aspects of the greenhouse problem: the scientific and the economic. The only aspect of the greenhouse phenomenon that elicits no disagreement is the increase in atmospheric carbon dioxide over the past four decades. Most people seem to agree that this increase is chiefly due to industrial activity. What is debated, particularly in widely circulated newspapers such as the *Wall Street Journal*, is the role of industrial emissions in the carbon dioxide increase (this is relatively uncontroversial), and whether carbon dioxide is responsible for warming, or even if warming is taking place. Some of the skeptics about global warming are well-known scientists, such as S. Fred Singer, who has just published the book *Hot Air, Cold Science: Global Warming's Unfinished Debate.*

Few doubts about the cause-and-effect relation exist among those who run the general circulation models, and who study the major climate changes and carbon dioxide inferences recorded in the geologic record. Skeptics point out the uncertainties in modeling the effects of clouds, the complexities of aerosol-photon interactions, and external factors such as solar activity that affect global temperature. It is hard to tell sometimes if skeptics have agendas other than scientific objectivity. Here is where socioeconomics becomes important. Atmospheric carbon dioxide is closely linked with industrial activity, which is closely linked with the economic health of countries. In particular, countries on a steep economic rise are understandably concerned about potential limits of their industrial growth. It is rare in history that the scientific method, with its inherent uncertainties and probabilistic conclusions, has been displayed to public observation and governmental decision. A decision would, of course, be easy if it were guaranteed not to affect nations' economies, and such assurance itself carries a level of uncertainty. If only life and science were not so uncertain!

Which brings us to cosmogenic and thermo-nucleogenic isotopes . . . in particular tritium and radiocarbon. Our favorite isotopes have played important roles in calibrating models of carbon sequestration in soils and oceans. Numerous articles published in this journal have not only provided baseline data for radiocarbon and tritium as global radioactive tracer experiments, but also demonstrated the direct application of those data to natural attenuation of greenhouse carbon dioxide. The original collectors of the data may not have anticipated its now recognized value to society. A development or product often turns out to have applications or uses not originally intended or imagined. In this case, the application has global reach. It is our intent for this journal to continue to publish articles that present baseline data as well as ones that interpret data. Stay tuned.

Austin Long

[RADIOCARBON, VOL. 39, NO. 2, 1997, P. 121–137]

DISTRIBUTION OF SITES AND RADIOCARBON DATES IN THE SIERRA NEVADA: IMPLICATIONS FOR PALEOECOLOGICAL PROSPECTING

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ABSTRACT. The number of paleoecological records for the Sierra Nevada of California has increased substantially since the compilation of Adam (1985). We examine here the geographical and temporal distribution of records within the range in order to identify areas for which "gaps" exist in our paleoecological knowledge. Seventy-two sites with paleoecological information are identified; these sites are dated with 234 radiocarbon dates. Sites occur primarily between *ca.* 36°N and 38°30′N latitudes, and from *ca.* 1000 m to over 3000 m elevation on both sides of the Sierran crest, although more sites have been analyzed on the west side of the crest than the east side. In general, packrat *(Neotoma)* midden series are located at the lowest elevations, meadow and marsh cores originate from mid-elevations, and lake sediments have been analyzed from the highest elevations. Significant gaps in our knowledge occur for much of the east side of the crest, for both sides of the range above modern treeline, and for time periods older than the latest Pleistocene.

INTRODUCTION

Analysis of pollen and plant macrofossils from sedimentary deposits has become an essential tool for the paleoecologist. Beginning in the mid-20th century, the number of sites from eastern North America increased rapidly and they presently number in the hundreds. A similar increase for western North America did not begin until after 1970 (Baker 1983; Barnosky, Anderson and Bartlein 1987), due, in part, to a perceived lack of suitable sites. An increase in the number of researchers examining sediments from high-elevation lakes and meadows, as well as the development of packrat *(Neotoma)* midden analysis from lower elevations (Betancourt, Van Devender and Martin 1990) has revolutionized our understanding of vegetation change within the more arid regions of western North America.

California is one region in western North America that witnessed little paleoecological research until recently. Adam (1985), which listed and annotated both published and unpublished studies for several regions of the state, was important in identifying "gaps" in our paleoecological knowledge, allowing investigators to provide research bridges between sites and to increase our understanding of paleoenvironments of the past. Here we concentrate on the Sierra Nevada range of California, summarizing and analyzing the recent explosion of information for that region. Our purpose is to identify the location and types of sites that have been most productive paleoecologically, as a logical step in paleoecological "prospecting", to identify possible locations for additional study.

DESCRIPTIVE BACKGROUND

The Sierra Nevada

The Sierra Nevada range, oriented with its major axis northwest to southeast, is located almost entirely within eastern California. The range extends almost 575 km from near Mt. Lassen in the north to Walker Pass in the south, with widths varying from *ca.* 100–125 km. The gentle slopes of 2–6% on the west side contrast with slopes of almost 26% on the east side near Owens Valley (Storer and Usinger 1963).

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The climate of the Sierra Nevada is Mediterranean, with hot, arid summers and cool, humid winters (Mitchell 1976; Major 1988). Topographic relief and range orientation affects the distribution of temperature and precipitation. Air masses moving from west to east lose moisture as they are forced over the high elevations of the range, causing large precipitation differences between the west and east sides. For a given elevation, precipitation averages nearly twice as much on the west side as on the east (Major 1988).

The Sierra Nevada is today a significant biogeographic boundary, separating the vegetation of the Great Basin from that of the more diverse cismontane Californian Province. Anderson (1990) summarizes the vegetation of the central Sierra Nevada. On the west side a blue oak (*Quercus douglassi*) and gray pine (*Pinus sabiniana*) woodland occurs above a grass-dominated prairie zone (to *ca.* 700–915 m elevation). The chaparral association, including buckbrush (*Ceanothus* spp.), manzanita (*Arctostaphylos* spp.), mountain mahogany (*Cercocarpus* spp.) and chamise (*Adenostema fasciculatum*), occurs between *ca.* 915 and 1225 m. The Sierra montane forest (*ca.* 1200–2200 m) is dominated by ponderosa pine (*Pinus ponderosa*), incense cedar (*Calocedrus decurrens*), black oak (*Q. kelloggii*), sugar pine (*P. lambertiana*), and white fir (*Abies concolor*). Common trees in the upper montane forest (to *ca.* 2200–2750 m) include lodgepole pine (*P. contorta* var. *murrayana*), red fir (*A. magnifica*), sugar pine, western white pine (*P. monticola*), and Sierra juniper (*Juniperus occidentalis* ssp. *australis*). The subalpine forest (to *ca.* 2570–3200 m) consists of lodgepole pine with mountain hemlock (*Tsuga mertensiana*), western white pine and whitebark pine (*P. albicaulis*), with Sierra juniper on exposed locations. On the east side of the crest, limber pine (*P. flexilis*) replaces whitebark pine. The alpine zone is dominated by herbs and subshrubs.

On the east side of the crest, below the subalpine and upper montane zones described above, a Jeffrey pine (*Pinus jeffreyi*) woodland is found, often grading at lower elevation into a western juniper (*Juniperus occidentalis* ssp. *occidentalis*) and pinyon pine (*P. monophylla*) assemblage with sagebrush (*Artemisia tridentata*). Shadscale (*Atriplex confertifolia*), greasewood (*Sarcobatus vermicullatus*), and joint-fir (*Ephedra* spp.) are found in valley bottoms.

Compilation of the Database

The database for this study consists of a compilation of locations ("sites") where paleoecological significance could be demonstrated. A "site" was considered to have paleoecological significance if 1) chronological control was present, with a minimum of one ^{14}C date, and 2) some indication of sedimentological change (pollen or plant macrofossils, inorganic sediments) was apparent. Most sites include locations where comprehensive studies of pollen and/or plant macrofossil stratigraphies were conducted. Rarely, some sites include only dated stratigraphic profiles.

Sites (with the associated ^{14}C dates) used in this analysis were compiled from various sources. The published literature on Sierra Nevada paleoecology was perused, yielding data on individual ^{14}C dates. Only those records analyzed specifically for paleoecological information were included in this study; sites designated primarily as archaeological were excluded. Unpublished data were integrated from various sources. Much of the data from unpublished sites was readily available and was analyzed by one or more of the authors of this paper.

Results and Discussion

Sites compiled for this study are located primarily within the central and southern portions of the Sierra Nevada (Fig. 1). Paleoecological studies have been conducted on both sides of the Sierran crest, as well as from one site on the crest itself. Sedimentary deposits analyzed include lakes, meadows, marshes, packrat middens and, in one case, an archaeological excavation.

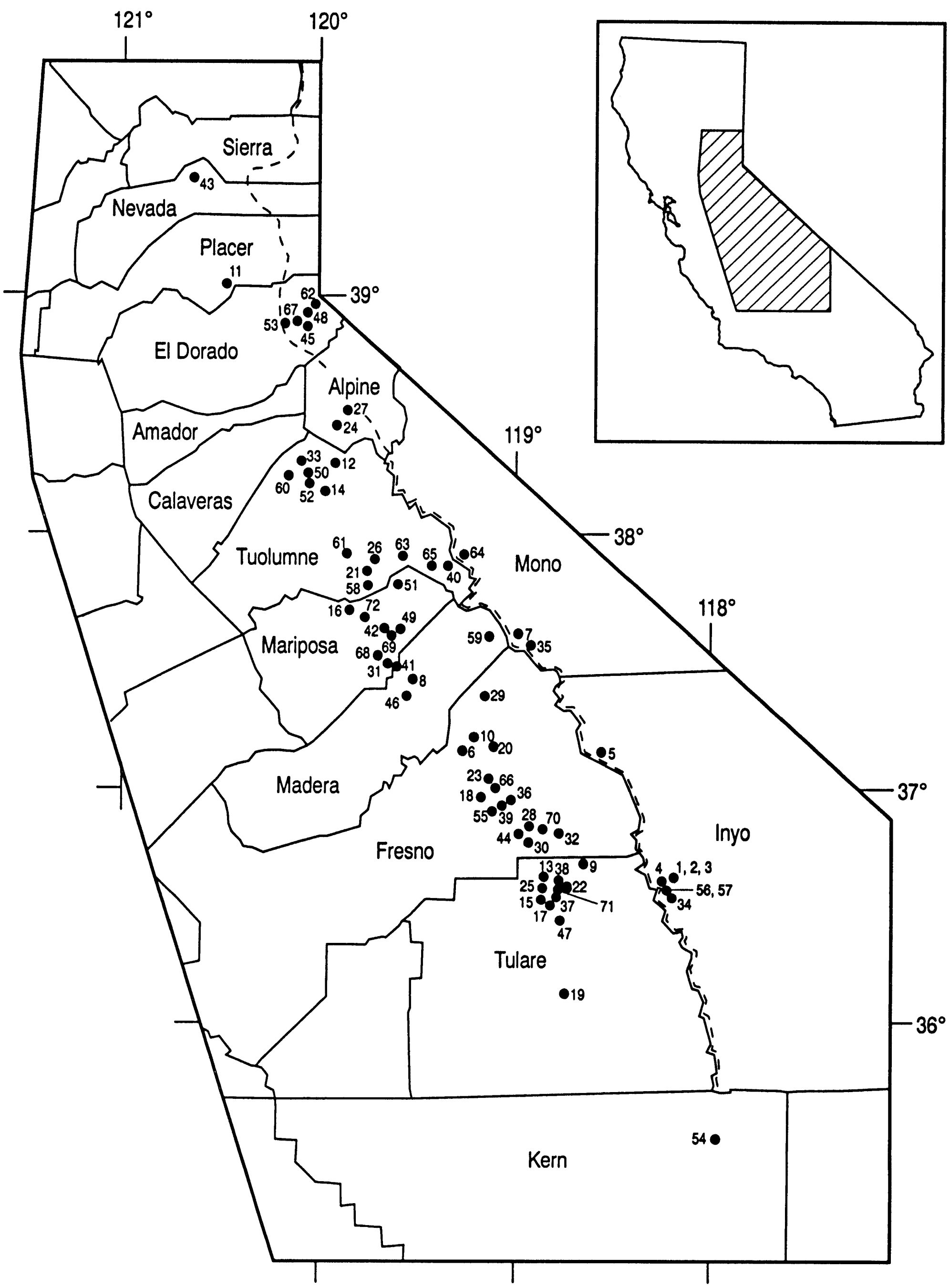

Fig. 1. Location of paleoecological sites within the Sierra Nevada. Numbers are keyed to Appendix. --- = the Sierra crest, separating the east from the west sides.

Data were compiled from 72 sites (Appendix), undoubtedly making the Sierra Nevada one of the most heavily studied regions in western North America. A total of 234 ^{14}C dates for the 72 sites have been obtained. The number of dates per record ranges from 1 (25 sites) to 12 (1 site) (Fig. 2).

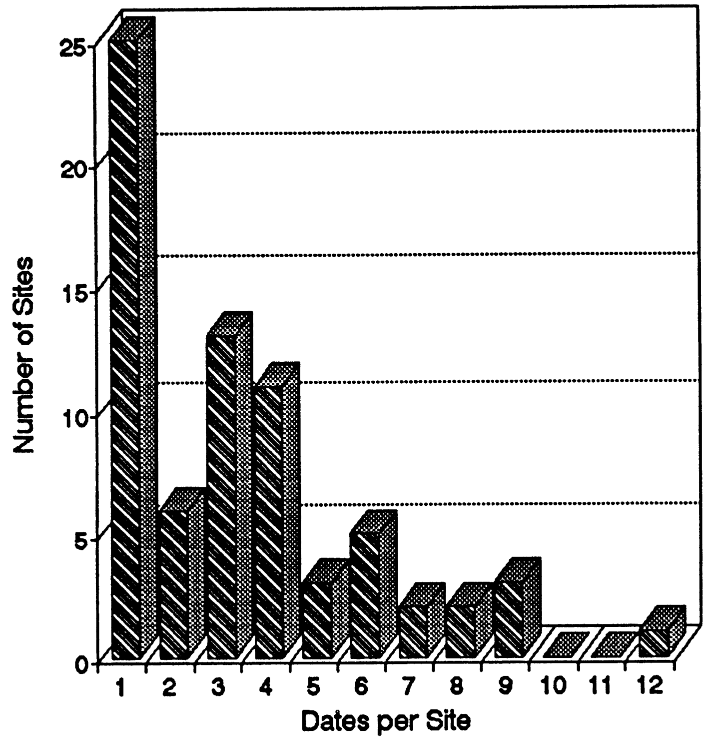

Fig. 2. Distribution of the number of sites with a given number of dates

Location of Sites

Most of the lands in the central Sierra Nevada are administered by the federal government or other governmental agencies (SNEP Science Team 1996). The locations of many paleoecological sites were chosen in order to answer questions pertaining to management of forests under government stewardship. Forty studies were conducted on lands administered by the U.S. Forest Service, and an additional 28 studies within U.S. National Parks. Portions of the Sierra Nevada lie within *ca.* 20 California counties. However, the 72 locations enumerated here occur largely within 10 counties in the central and southern Sierra (Appendix), while two sites occur in the northern Sierra.

Published *vs.* Unpublished Records

Adam (1985) pointed out that records of many of the California sites were unpublished. Data reported here show that trend has been reversed (Appendix). Only 41% of the sites have not been published (we include here M.S. and Ph.D. theses in this category). The number of published ^{14}C dates exceeds unpublished (183 *vs.* 51).

Distribution by Sediment Type

Several sediment types are available for paleoecological study in the Sierra Nevada. Analysis of cores or sections from montane meadows comprise 51% (37) of the studies conducted to date (Table 1). Thirty-three percent (24) of studies are from lakes, followed by 7% each (5) for packrat middens and marshes. However, packrat midden studies include a larger average number of individual dates per study (6.2), compared to lake (3.1), meadow (3.1) and marsh (2.5) studies. This is because each midden must be individually ^{14}C-dated, while fewer dates are generally necessary to establish a stratigraphic chronology.

The majority of dates obtained from meadows are of bulk colluvial/alluvial sediments, though wood samples have been used extensively for establishing sediment chronologies (Table 1). For packrat middens, fecal pellets and amberat (crystallized rat urine, which cements most middens) have been the preferred materials for dating.

TABLE 1. Distribution of ^{14}C Dates by Sediment Type

Sediment type	No. of dates	Total dates	No. of sites
Marsh		**11**	**5**
Peat	9		
Wood	1		
Lake	1		
Meadow		**116**	**37**
Charcoal	9		
Peat	11		
Wood	24		
Colluvial; alluvial	72		
Midden		**31**	**5**
Fecal/amberat	27		
Plant material	4		
Lake		**75**	**24**
Archaeological	1	**1**	**1**
Total		**234**	**72**

Age Distribution

Figure 3 shows bar graphs of age distribution of ^{14}C dates and calibrated ages by 1000-yr intervals. Calibration of ^{14}C ages from the present to 19,262 BP was performed using the CALIB 3.0 program of Stuiver and Reimer (1993). From 19,262 to 27,120 BP, we linearly interpolated between equivalent ^{14}C and U-Th ages given by Bard *et al.* (1990). From 27,120 to 50,000 BP, we used the relationship suggested by Mazaud *et al.* (1991) and Thouveny, Creer and Williamson (1993).

A bimodal distribution of ages is apparent, centered around 1000–4000 BP and 10,000–12,000 BP. The number of dates older than *ca.* 12,000 BP declines toward zero, with the oldest date recorded at >45,000 BP (Kings Canyon midden series). All of the dates older than 20,000 BP are from packrat midden series, whereas the oldest date from a stratigraphic sequence is *ca.* 17,000 BP. Thus, Holocene events are well represented paleoecologically, while the Pleistocene of the Sierra is much less well known.

In their analysis of 1113 packrat midden dates, Webb and Betancourt (1990) noted a similar bimodal distribution of ^{14}C dates, with maximum number of dates in the time ranges of 0–3000 and *ca.* 10,000–12,000 ^{14}C yr ago. They compared their histogram distribution with a gamma probability distribution, which largely describes frequency distributions with an apparent exponential decay. An ideal gamma distribution shows a greater number of ^{14}C dates for the youngest portion of the time-scale, with an exponential decay (fewer dates) with increasing age. Webb and Betancourt's (1990) bimodal distribution was explained by a combination of researcher bias and decreased preservation potential with increasing age. Early in the development of midden analysis, middens with extralocal plant fossils were preferentially selected for analysis and dating. This created a large number of middens of latest Pleistocene age. Only later were Holocene-age middens collected and analyzed. Thus, the midden record represents two different populations—one Pleistocene and one Holocene (O. Davis, personal communication 1997).

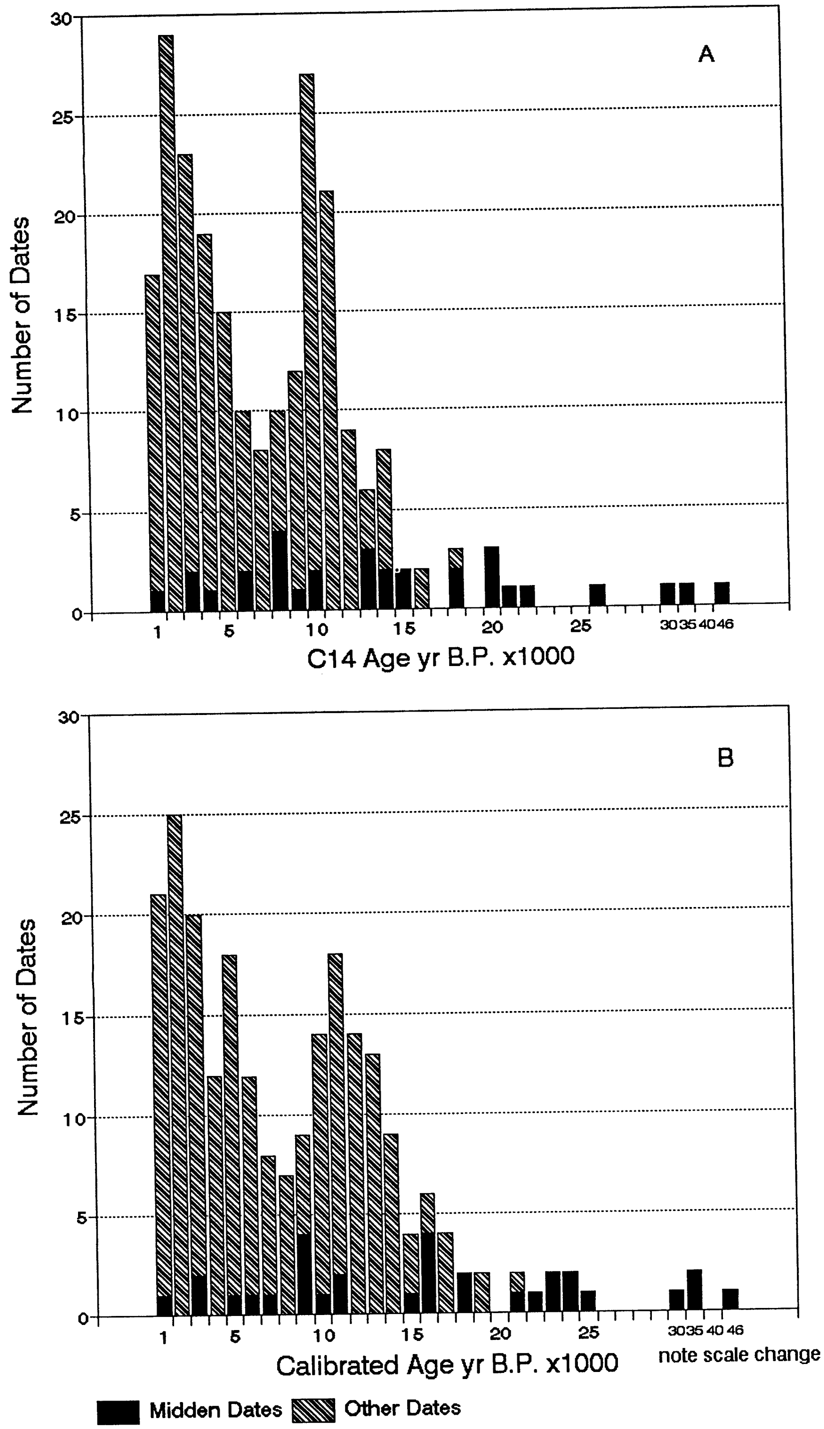

Fig. 3. Distribution of individual ^{14}C dates by 1000-yr intervals. A. Ages listed in ^{14}C yr BP; B. Ages listed in calendar years before present. Note scale change at the right of each diagram.

Graphically, the patterns identified in the Webb and Betancourt (1990) study and the present one (Fig. 3) are similar, but the explanations are different. Though fewer midden dates were collected in the present study than in Webb and Betancourt's study, temporal distribution of midden dates is approximately uniform through time (Fig. 3, black bars), minimizing the importance of collector bias or changing environmental conditions as explanations for the Sierran midden record. Stratigraphic dates account for most of the patterns seen in Figure 3. Because most of the dates come from continuous sections (Table 1), any level within the section could have been chosen for dating by the individual investigator. The peak in ^{14}C ages from *ca.* 9000 to 11,000 BP (Fig. 3A; somewhat smoothed out in the calibrated ages curve, Fig. 3B) results from dating of basal sediments. Thirty-seven percent (21) of the 57 records with basal dates occur within this 2000-yr interval (Fig. 4). Furthermore, 54% of basal dates occur between 8000 and 12,000 yr BP, suggesting that the majority of stratigraphic records in the Sierra extend back only to the early Holocene or latest Pleistocene.

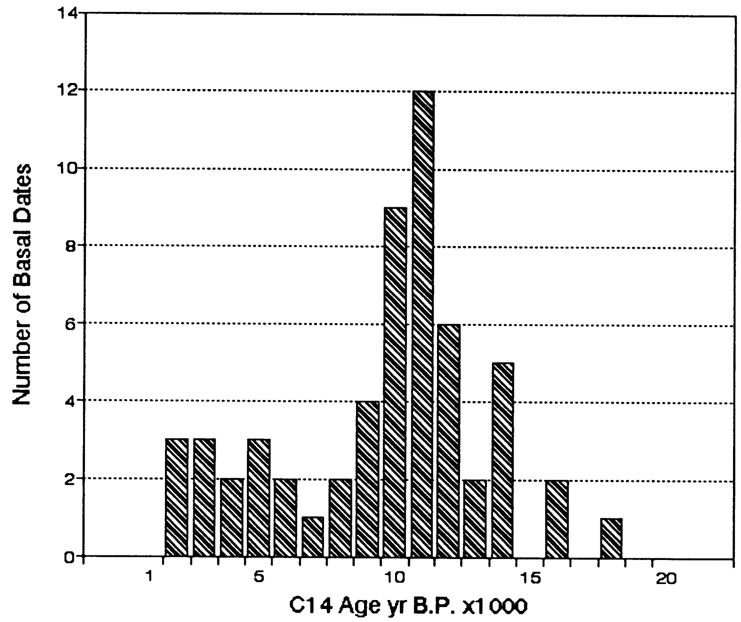

Fig. 4. Distribution of age of basal ^{14}C dates by 1000-yr intervals for stratigraphic records

The abundance of dates between 1000 and 4000 BP almost certainly correlates with an important paleoecological change in the sedimentary column. Using pollen and sedimentary changes, Anderson and Smith (1994) showed widespread, late Holocene changes, and suggested a probable connection with the onset of the Neoglacial interval (Burke and Birkeland 1983). An alternative explanation suggests the "pull of the recent", with a greater likelihood of preservation of younger records than older ones. This explanation cannot account for all of the distribution, since 56% of sites with one or more dates in the 1000 to 4000-yr range also have basal dates of *ca.* 8000 yr or older. The patterns exhibited in Figure 3 are clearly nonrandom.

Distribution of Sites by Elevation and Latitude

Figures 5 and 6 depict plots of location of sites and ages of ^{14}C samples (and by inference the location of sites in space and time) for both the east and west sides of the Sierran crest. Far fewer paleoecological sites with associated ^{14}C dates have been analyzed on the east side of the crest (17 sites and 53 ages) than on the west side (55 and 179).

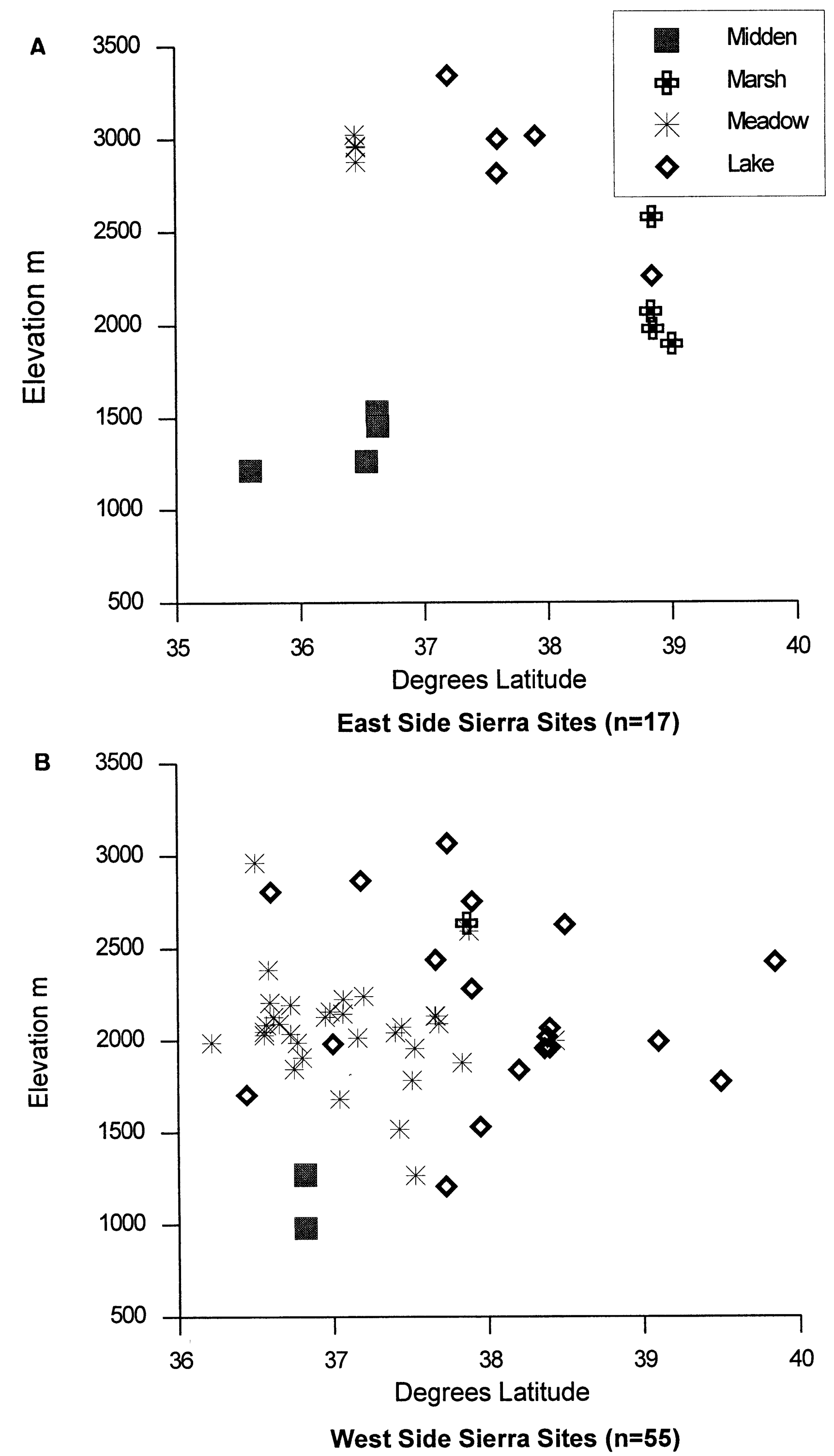

Fig. 5. Distribution of ^{14}C dates by elevation and latitude for the east side (A) and west side (B) of the Sierra crest. Sediment type is also indicated by symbols in legend.

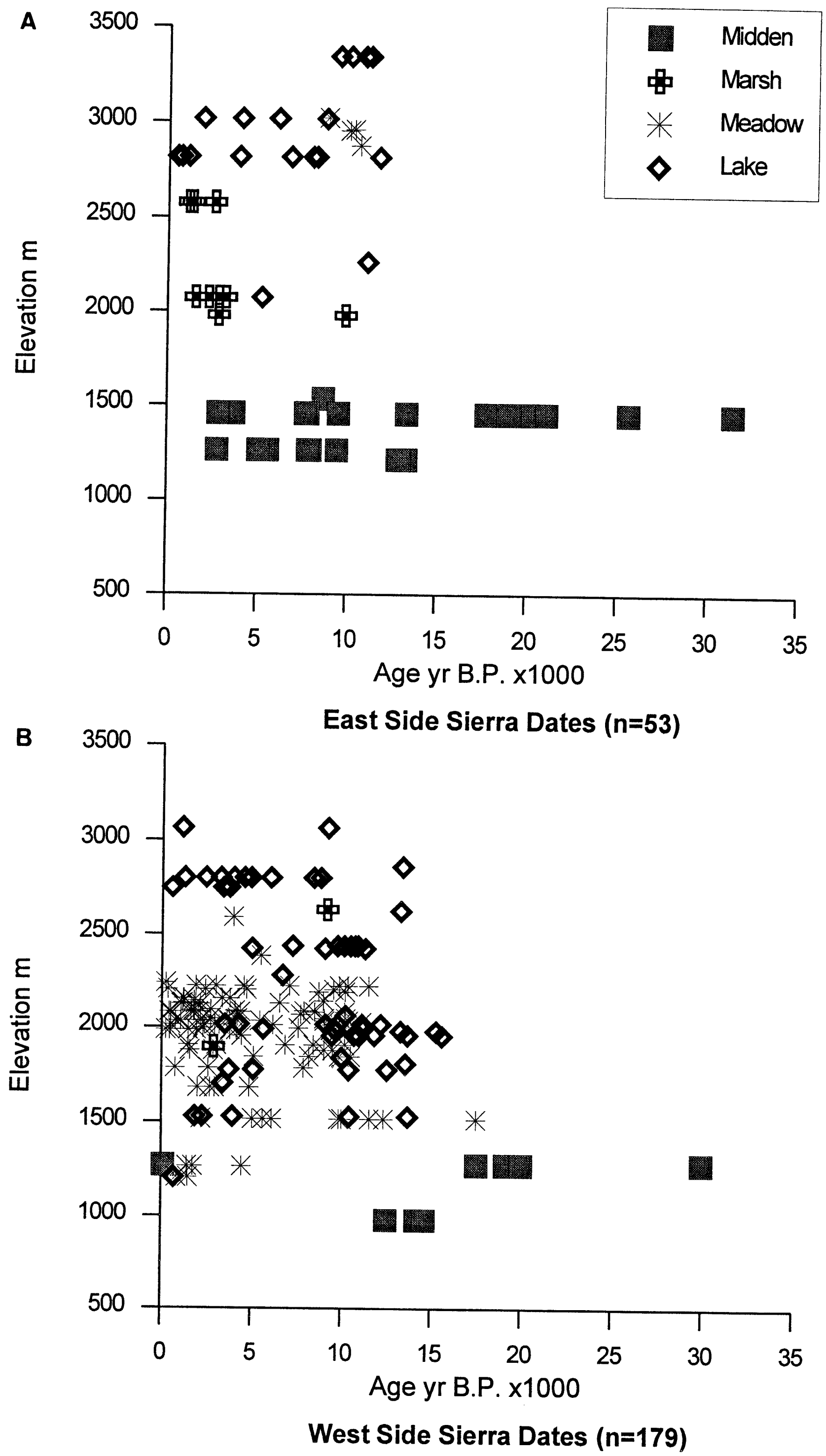

Fig. 6. Distribution of ^{14}C dates by elevation and age for the east side (A) and west side (B) of the Sierra crest. Sediment type is also indicated by symbols in the legend.

Several factors account for this. First, the east side of the Sierra lies in a rain shadow. For any given elevation, the greater aridity of the east side results in fewer sites with wet sediment accumulation. Second, the Sierra Nevada consists of a gently sloping west slope, and a much steeper east slope that is less areally extensive. Third, because of the steepness of the east side, glaciation was confined largely to high-elevation plateaus and to major drainages, and less so to interfluves. On the west side of the crest, however, the more gently sloping topography and greater ice accumulation enabled glacial activity to produce many basins (Huber 1987).

Sites East of the Crest

Seventeen sites record paleoecological changes east of the crest (Fig. 5). However, sites are not distributed uniformly with respect to elevation. Sites are segregated into packrat midden series below 1460 m elevation, and stratigraphic deposits above 1888 m elevation. For the latter, marsh deposits occur from *ca.* 1888 m (Taylor Marsh) to *ca.* 2580 m elevation (Ralston Ridge Bog). With two exceptions, analysis of lake and meadow deposits has been confined to locations above 2816 m elevation.

The latitudinal distribution of sites is not uniform either (Fig. 5). For the east side, the three packrat midden sites (all at lowest elevations) are located at the southern end of the study area. The high-elevation meadow sites are also located toward the south, while most high-elevation lake sites are found within the northcentral part of the study area. However, the mid-elevation records between *ca.* 1900 and 2600 m elevation occur only in the northern portion, near Lake Tahoe.

Sites West of the Crest

Fifty-five sites on the west side of the crest (Fig. 5) provide somewhat greater resolution of the paleoecology of the range than that provided on the east side. As on the east side, sites are segregated by elevation with respect to sediment type, but to a lesser degree. Packrat midden series are confined to the lowest elevations, below 1275 m. Primarily lake sites have been analyzed above 2740 m. At mid-elevations, both meadow and lakes have been investigated.

The latitudinal distribution of sites with respect to elevation on the west side of the Sierra reflects a different pattern than on the east. Western Sierra sites occur over a narrower range in latitude, primarily between *ca.* 36° and 38°30′ N (Fig. 5); three outliers, Siesta, McMurray and Bunker Lakes, occur north of 39° N. In the southern portion of the study area meadow sites predominate, especially at locations between 1500 m and 2220 m; lake sites are rare within this elevational range. However, lakes in general become increasingly more abundant toward the north. Consequently, more lakes than meadows have been analyzed toward the north (Fig. 5). Lake sites are primarily distributed around 38° N latitude, in and near Yosemite National Park. Exceptions to this include Emerald Lake (2804 m) and Oriole Lake (1697 m), both located in Sequoia National Park in the south.

Though limited latitudinally, lake sites have been analyzed from nearly the entire elevational range. Meadow sites, virtually all to the south of 38° N, are concentrated over a somewhat narrower range of elevations than the lakes. The lowest-elevation meadow sites analyzed on the west side (Wawona and Nichols Meadows) are found in the central portion of the study area. In general, the lowest elevation of stratigraphic paleoecological sites increases from north to south on the west side. This may reflect a decrease in effective precipitation from north to south for any given elevation (Major 1988), and the resulting potential for accumulation of wet sediment.

Identifying Gaps in Paleoecological Knowledge

The data are useful in identifying gaps in our knowledge of events in time and space for the Sierra Nevada. At present, many more gaps in the record exist for the east side than for the west side of the crest.

For the east side, the mid-Wisconsin period is known only from the Alabama Hills Two Goblin site, in the south (Fig. 6). No site older than *ca.* 11,500 BP is found above 1460 m elevation. Similarly, large gaps exist in the elevational ranges of *ca.* 1500–2000 m (4900–6600 ft) and *ca.* 2100–2600 m (6900–8500 ft). These elevations presently encompass the sagebrush and lodgepole-fir belts in the north, and the sagebrush and pinyon pine belts in the south. In addition, sites above modern treeline have not been analyzed. Low-, and additional high-, elevation sites need to be analyzed in the northern portion of the study area, while mid-elevations in the central and southern portions lack data.

On the west side, the mid-Wisconsin is known only from one low-elevation site in the south—two middens from Kings Canyon (1280 m; Fig. 6). Unlike the east side, five sites above 1500 m elevation stretch back to *ca.* 15,000–17,000 BP (Nichols Meadow, 1518 m; Swamp Lake Yosemite, 1554 m; Swamp Lake Batchelder, 1951 m; Lilypad Lake, 1980 m; and Lake Moran, 2020 m). While Nichols Meadow was apparently below the Tioga glacial limit (Alpha, Wahrhaftig and Huber 1987), the latter four sites come from glaciated terrain, and suggest early deglaciation at these elevations. Additional temporal gaps include most of the Holocene and late Pleistocene for locations below *ca.* 1500 m (4900 ft). These elevations today include the lower portion of the Sierra montane forest (including the ponderosa pine belt), the chaparral, blue oak–gray pine woodland and the valley prairie ecozones. Little information exists for *ca.* 1550–1750 m (5100–5700 ft) for the early Holocene, and *ca.* 2300–2700 (7550–8900 ft) elevation for the late Holocene. Vegetation occurring there today is part of the Sierra montane and upper montane forests, respectively. As with the east side, no sites above treeline have been analyzed. Latitudinally, information is limited north of *ca.* 38°30′N and south of 36°N latitudes.

Conclusion

David Adam's (1985) compilation of paleoecological sites within California provided palynologists working in western North America with a tool useful for planning future research. Adam identified significant holes in our knowledge of late Quaternary environments of California. One range in particular, the Sierra Nevada, has attracted several researchers. Though the Sierra still contains geographic and temporal gaps in our paleoenvironmental knowledge, the present compilation demonstrates that those gaps have narrowed significantly.

With respect to the latitudinal distribution of sites, our knowledge of the northern Sierra is less than that of the central or southern portions of the range. Northern Sierra vegetation has greater affinities to that of the Great Basin and the Cascade Range than does vegetation in the south. Additional study here could provide needed insight into the biogeographic connections between the more northerly regions.

Additional studies should be undertaken on the east side of the crest to partially fill gaps in our knowledge of elevational vegetation change. High-elevation studies are few in the north, and mid-elevation studies in the south are completely lacking. Though the steep escarpment there may preclude finding suitable sites, such a study in the south could illuminate the location of high-elevation conifers during the late Wisconsin in the Sierra. The midden series from the Alabama Hills (Koehler and Anderson 1995) is apparently from too low an elevation to record the occurrence of important Sierran trees during that time.

No study has been conducted at sites above modern treeline. Such an effort could illuminate potentially higher treelines during the early Holocene, when climatic conditions were at their warmest and driest (Anderson 1990, 1996). These new studies may also be important in evaluating use of the early Holocene as an analog for future greenhouse warming.

Though study of sediments from pluvial lakes (*e.g.,* Atwater *et al.* 1986; Litwin *et al.* 1997) reveals vegetation changes at the lowest elevations on both sides of the crest, efforts should be continued to identify additional packrat midden series. For instance, Cole (1983) documented the Wisconsin-age occurrence of important Sierra montane species, such as ponderosa pine, in modern chaparral, and suggested that giant sequoia *(Sequoiadendron giganteum)* may have grown nearby as much as 500 m below its modern distribution. Additional series further to the north are necessary to identify other Wisconsin-age refugia, and to complete the picture of the development of the Sierra montane forest in general.

Within the Sierra, many types of sediments are available to the paleoecologist, and the choice of sediment type depends largely upon elevation. In general, lakes are most abundant above the Sierra montane zone, though several important studies have been conducted from lower-elevation lakes (Fig. 5). Within the Sierra montane zone, where lakes are rare, meadow stratigraphies have been analyzed to a greater extent (Anderson and Smith 1994). At even lower elevations, sedimentary deposits with appropriate preservation potential are rare, and packrat midden studies predominate.

Each sediment type has advantages and disadvantages. Packrat middens often occur at the lower, more arid elevations, where other stratigraphic deposits are not found. However, individual middens represent discrete windows in space and time, and the midden series rarely represent continuous changes in vegetation. Meadow sediments provide a mid-elevation record, yet are subject to periodic desiccation. Drying events, along with periodic fires that burn the meadows, are potential causes of disconformities in the pollen stratigraphy. Lakes are abundant at high elevations, but only rarely occur below the late Wisconsin glacial limit. Using a combination of studies from each elevation allowed Anderson and Smith (1991) and Woolfenden (1996) to summarize the story of vegetation change for the Sierra.

Though many studies have appeared in the literature since 1985, more than 40% of the site reports remain unpublished. This is the mark of active research within a region. Further investigation within the range will fill additional gaps in the history of vegetation change, refining our understanding of the development of the rich vegetation assemblages that are characteristic of the Sierra Nevada. It will also undoubtedly provide the starting point for research unanticipated at present.

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APPENDIX: LOCATION OF PALEOECOLOGICAL SITES AND ^{14}C DATES WITHIN THE SIERRA NEVADA

	Site	County	Elevation feet	Elevation m	Sediment type	No. dates	References
1	Alabama Hills, Corsair	Inyo	5035	1535	Midden/fecal pellets	1	Koehler & Anderson 1995
2	Alabama Hills, Lubkin Cyn.	Inyo	4146	1264	Midden/fecal pellets	6	Koehler & Anderson 1995
3	Alabama Hills, Two Goblin	Inyo	4780	1457	Midden/fecal pellets	12	Koehler & Anderson 1995
4	Atchoo Meadow	Inyo	9700	2957	Peat	1	Mezger 1986, unpubl.
5	Baboon Lakes	Inyo	10,976	3346	Lake sediment	4	Hemphill & Clark 1996
6	Balsam Meadow	Fresno	6610	2015	Meadow sediment	6	Davis *et al.* 1985
7	Barrett Lake	Mono	9240	2816	Lake sediment	8	Anderson 1990
8	Beasore Meadow	Madera	6800	2073	Wood (fir)	1	Brandau & Nokes 1975; Wood 1975
9	Boggy Meadow	Tulare	7200	2195	Wood (softwood)	2	Brandau & Nokes 1975; Wood 1975
10	Boneyard Meadow	Fresno	7350	2240	Wood	2	DeGraaf, unpubl.
11	Bunker Lake	Placer	6540	1993	Lake sediment	3	Edlund 1994
12	Burgson Lake	Tuolumne	6430	1960	Lake sediment	3	Byrne, unpubl.
13	Cabin Creek Meadow	Tulare	6860	2091	Meadow sediment	1	Anderson, unpubl.
14	Catfish Lake	Tuolumne	6040	1841	Lake sediment	1	Byrne, unpubl.
15	Circle Meadow	Tulare	6840	2085	Meadow sediment	8	Anderson 1996; Anderson & Smith 1994; Anderson & Smith 1997
16	Crane Flat	Mariposa	6180	1884	Archaeol. midden	1	Adam 1967
17	Crescent Meadow	Tulare	6660	2030	Peat	1	Anderson, unpubl.
18	Dinkey Meadow	Fresno	5520	1682	Meadow sediment	4	Davis & Moratto 1988
19	Dogwood Meadow	Tulare	6520	1987	Meadow sediment	4	Anderson 1996; Anderson & Smith 1994; Anderson & Smith 1997
20	East Lake	Fresno	9395	2864	Lake sediment	1	Power, unpubl.
21	East Meadow, Aspen Valley	Tuolumne	6170	1881	Charcoal	4	Wood 1975
22	Emerald Lake	Tulare	9200	2804	Lake sediment	9	Whitehead, unpubl.
23	Exchequer Meadow	Fresno	7300	2225	Colluvium	7	Brandau & Noakes 1975; Davis & Moratto 1988; Wood 1975
24	Gabbott Megadow	Alpine	6550	1996	Colluvium	4	Mackey & Sullivan, unpubl.; Mackey & Sullivan 1991

Site	County	Elevation feet	Elevation m	Sediment type	No. dates	References
25 Halstead Meadow	Tulare	6980	2128	Meadow sediment	1	Anderson, unpubl.
26 Harden Lake	Tuolumne	7484	2281	Lake sediment	1	Batchelder, unpubl.
27 Highland Lake	Alpine	8614	2626	Lake sediment	1	Byrne, unpubl.
28 Hightop Meadow	Fresno	6260	1908	Meadow sediment	5	Anderson 1996; Anderson & Smith 1994; Anderson & Smith 1997
29 Hoffman Meadow	Fresno	6700	2042	Conifer cone	2	DeGraaf, unpubl.
30 Huckleberry Meadow	Fresno	6520	1987	Peat	6	Anderson & Smith 1997
31 J.B. Swale	Mariposa	5860	1786	Meadow sediment	3	Anderson, unpubl.; Anderson & Smith 1997
32 Kings Canyon	Fresno	4165	1269	Midden	9	Cole 1983
33 Lake Moran	Tuolumne	6620	2018	Lake sediment	6	Byrne 1988; Edlund 1991, unpubl.; Edlund & Byrne 1991
34 Last Chance Meadow	Inyo	9720	2963	Peat	1	Mezger 1986, unpubl.
35 Laurel Lakes (Lower)	Mono	9840	3000	Lake sediment	0	Pohl *et al.* 1996
36 Lily Pad Lake	Fresno	6500	1981	Lake sediment	3	Edlund 1992
37 Log Meadow	Tulare	6720	2048	Meadow sediment	4	Anderson 1994
38 Long Creek Meadow	Fresno	7080	2158	Wood (fir)	4	Brandau & Nokes 1975; Wood 1975
39 Long Meadow	Tulare	7240	2207	Meadow sediment	4	Anderson 1996; Anderson & Smith 1994; Anderson & Smith 1997
40 Lower Gaylor Lake	Tuolumne	10,060	3066	Lake sediment	2	Anderson, unpubl.
41 Mariposa Grove	Mariposa	6420	1957	Colluvium; alluvium	1	Anderson, unpubl.
42 McGurk Meadow	Mariposa	6860	2091	Meadow sediment	3	Anderson 1996; Anderson & Smith 1994
43 McMurray Lake	Nevada	5832	1778	Lake sediment	4	Edlund 1992
44 Meadow of Honor	Fresno	6060	1847	Meadow sediment	4	Anderson 1996; Anderson & Smith 1994
45 Meyers Grade Marsh	El Dorado	6800	2073	Peat	5	Dorland 1980, unpubl.; Dorland, Adam and Batchelder 1980
46 Nichols Meadow	Madera	4980	1518	Wood	9	Koehler and Anderson 1994; DeGraaf unpubl., Swetnam, unpubl.; Koehler 1993 unpubl.
47 Oriole Lake	Tulare	5600	1707	Lake sediment	1	M.B. Davis, unpubl.
48 Osgood Swamp	El Dorado	6495	1980	Peat	2	Adam 1967; Zauderer 1973 unpubl.
49 Ostrander Meadow	Mariposa	7000	2134	Meadow sediment	1	Anderson, unpubl.
50 Paradise Lake	Tuolumne	5940	1811	Lake sediment	1	Byrne, unpubl.
51 Polly Dome Lake	Mariposa	8640	2633	Marsh	1	Batch 1977, unpubl.
52 Pond 3	Tuolumne	6780	2067	Lake sediment	1	Byrne, unpubl.
53 Ralston Ridge Bog	El Dorado	8460	2579	Roots	3	Sercelj & Adam 1975
54 Robbers Roost	Kern	3985	1215	Midden	3	McCarten & Van Devender 1988
55 Ross Meadow	Fresno	6980	2128	Wood	2	DeGraaf, unpubl.
56 Round Valley Meadow	Inyo	9920	3024	Peat	1	Mezger 1986, unpubl.

Site	County	Elevation feet	Elevation m	Sediment type	No. dates	References
57 Second Chance Meadow	Inyo	9440	2877	Peat	1	Mezger 1986, unpubl.
58 Siesta Lake	Tuolumne	7950	2423	Lake sediment	3	Brunelle 1997, unpubl.
59 Starkweather Pond	Madera	8000	2438	Lake sediment	6	Anderson 1990
60 Swamp Lake (Batch-elder)	Tuolumne	6420	1957	Lake sediment	3	Batchelder 1980
61 Swamp Lake, Yosemite	Tuolumne	5018	1529	Lake sediment	5	Smith 1989, unpubl.; Smith & Anderson 1992
62 Taylor Marsh	El Dorado	6229	1899	Lake sediment	1	West, unpubl.
63 Ten Lakes #3	Tuolumne	9020	2749	Lake sediment	3	Anderson 1987, unpubl.
64 Tioga Pass Pond	Mono	9900	3018	Lake sediment	4	Anderson 1990; Anderson 1996; Anderson & Smith 1994
65 Tuolumne Meadows	Tuolumne	8500	2591	Charcoal	1	Wood 1975
66 Upper Cabin Meadow	Fresno	7040	2146	Wood	3	Brandau & Nokes 1975; Wood 1975
67 Upper Echo Lake	El Dorado	7420	2262	Lake sediment	1	Adam 1985
68 Wawona Meadow	Mariposa	4150	1265	Meadow sediment	3	Anderson, unpubl.; Anderson & Carpenter 1991
69 Well Meadow	Mariposa	7000	2134	Meadow sediment	1	Anderson, unpubl.
70 Weston Meadow	Tulare	6680	2036	Meadow sediment	7	Anderson 1996; Anderson & Smith 1994; Anderson & Smith 1997
71 Willow Root Meadow	Tulare	7820	2384	Meadow organics	1	Anderson, unpubl.
72 Woski Pond	Mariposa	3955	1205	Lake sediment	3	Anderson & Carpenter 1991

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RADIOCARBON RESERVOIR AGES IN THE GULF OF CALIFORNIA: ROLES OF UPWELLING AND FLOW FROM THE COLORADO RIVER

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ABSTRACT. We measured apparent radiocarbon ages of live-collected, pre-bomb mollusk shells from the northern and central Gulf of California to determine the source of the reservoir ages and the reservoir age correction offsets for calibrating ^{14}C dates of fossil samples. Reservoir ages average 860 yr in the northern Gulf and 725 yr in the central Gulf. The corresponding ΔR values (the deviation from typical worldwide values) are 540 yr and 395 yr, respectively, with variabilities (SD) of 90 and 110 yr. This variability significantly limits the precision of calibrated ^{14}C ages. The apparent ^{14}C age of Colorado River water (as measured in a freshwater mussel, collected in the 1890s, before diversion of river flow) is not sufficiently high (1420 yr) to account for the high reservoir ages in the Gulf. The lack of a relation between the stable isotope composition of Gulf mollusks and their reservoir ages is further evidence that the Colorado River does not make a significant contribution to Gulf reservoir ages. Upwelling of old, deep Pacific-derived water appears to be the cause of the large reservoir ages.

INTRODUCTION

Several factors contribute to the apparent radiocarbon age of inorganic carbon in marine waters (the marine ^{14}C reservoir age), which averages *ca.* 400 yr worldwide (Stuiver, Pearson and Braziunas 1986). In deep ocean waters, and in areas where such waters upwell, large reservoir ages occur because of the long residence time of carbon in the bicarbonate pool. So, in upwelling areas such as the California coast (Berger, Taylor and Libby 1966) or the Pacific coast of South America (Taylor and Berger 1967), reservoir ages are higher than average. In addition, continental waters may contribute hardwater effects (from the dissolution of limestone); their input into marine waters *via* either rivers (Little 1993) or groundwater (Heier-Nielsen *et al.* 1995) may increase ^{14}C reservoir ages. In Arctic areas, stratification of marine waters and ice cover reduces exchange with the atmosphere and thus results in higher reservoir ages (Mangerud and Gulliksen 1975).

Large ^{14}C reservoir ages were first recognized in the Gulf of California based on analyses of two pre-bomb shell samples from the central Gulf by Berger, Taylor and Libby (1966), who suggested that upwelling of old Pacific water into the Gulf was likely responsible. However, shells collected alive in 1962 from the northern end of the Gulf showed apparent ages of only 210 and 270 yr (Hubbs, Bien and Suess 1965: 70), significantly *lower* than typical marine reservoir ages. Berger, Taylor and Libby (1966) concluded that these analyses indicated the lack of upwelling in the northern Gulf. However, subsequent studies have shown that by 1962, a measurable amount of the excess ^{14}C produced by thermonuclear bomb tests had already entered the world oceans (Druffel 1987, 1997; Weidman and Jones 1993). The presence of bomb carbon is therefore a likely explanation for the low apparent ages of the two northern Gulf mollusk samples.

The Gulf of California is known to be an area of significant upwelling (Roden 1964). Winds blow largely from the north or northwest along the axis of the Gulf, pushing surface water out the entrance of the Gulf in the south and sucking in water from depth to compensate. The entrance of the Gulf is >2000 m deep (Fig. 1), which permits relatively old Pacific bottom waters to be brought into the

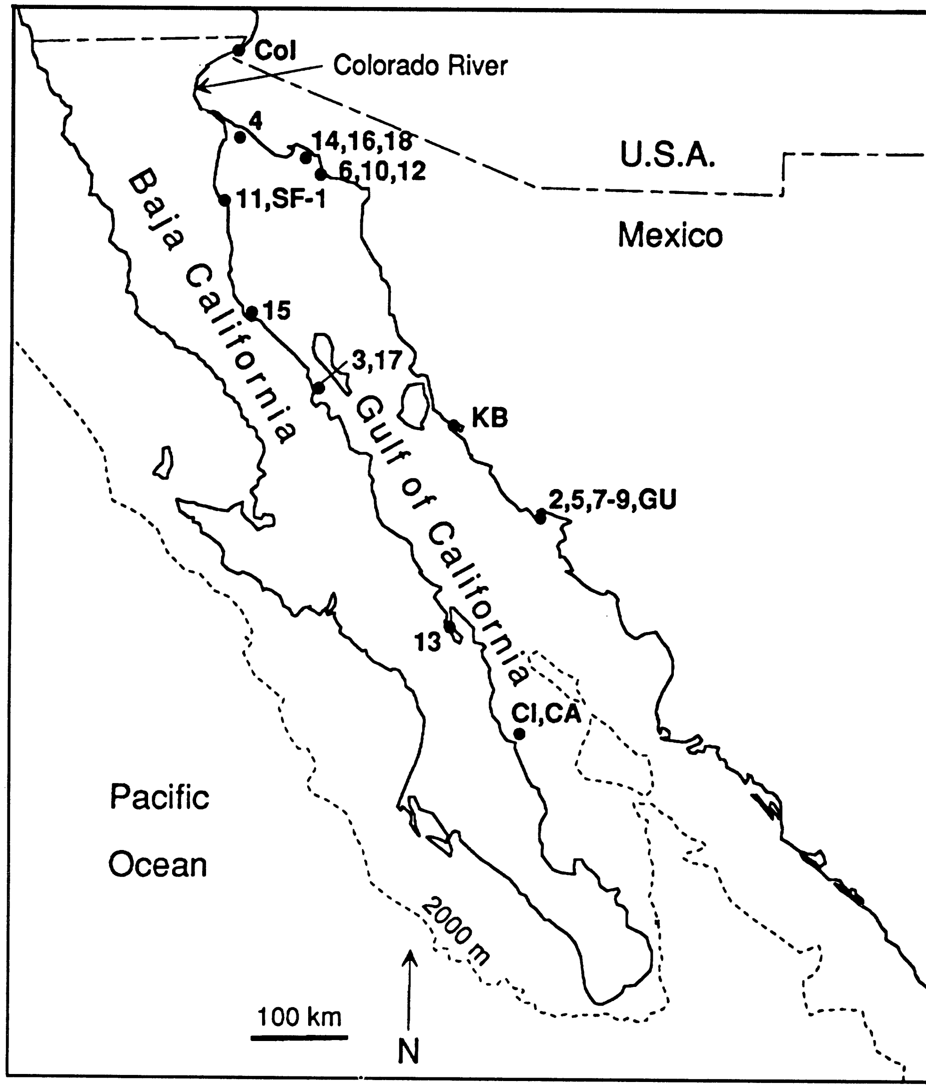

Fig. 1. Map of the Gulf of California and surrounding region, showing location of sample sites (Mod- numbers and letter abbreviations are listed in Table 1) and 2000 m isobath

Gulf. In the northern Gulf, the large tidal range (up to 10 m; Thompson 1968) favors mixing of surface waters. Overturn of surface waters (down to 100 m) may occur during the winter (Roden 1964).

The Colorado River no longer flows into the Gulf, except during unusual flood events. All the water is now diverted for human use before it reaches the sea. Substantial diversion of Colorado River water to the Imperial Valley, California, began in 1901 and was followed in 1905 by the accidental diversion of the entire flow of the river into the Salton Sea, which continued until 1907. Upstream dams and diversions were subsequently built to control and divert the river's flow. The completion of Hoover Dam in 1935 and subsequent irrigation projects in the Imperial Valley significantly decreased the river's flow at the Mexican border. Mexican agriculture utilizes the entire 1.5 million acre-feet (= 1.85×10^9 m^3) per year (10% of the river's estimated virgin flow) allocated to it under international treaty. (See Fradkin (1984) for the history of the river's modification and use.)

In the present study, we analyzed apparent ^{14}C ages in pre-bomb live-collected clams from the northern and central regions of the Gulf of California (Fig. 1) in order to assess ^{14}C reservoir ages within the Gulf and their spatial and temporal variation. To evaluate the possible influence of Colorado River flow on the reservoir ages of Gulf waters, we also analyzed the stable isotope composition of these shells and determined the apparent ^{14}C age and stable isotope composition of Colorado River water bicarbonate (before extensive diversion of the river) through analysis of a sample of late 19th-century freshwater mussel shell from the river. If flow from the Colorado River were a significant influence on reservoir ages, then a correlation between reservoir ages and both $\delta^{18}O$ and $\delta^{13}C$ values would be expected, since the river water is quite depleted in both ^{18}O and ^{13}C compared to marine water (Keith, Anderson and Eichler 1964).

Materials and Methods

Specimens of articulated bivalve shells from the Gulf of California and the Colorado River were obtained from the U.S. National Museum of Natural History (Washington, D.C.), the California Academy of Sciences (San Francisco), the Los Angeles County Museum, and the San Diego Museum of Natural History. In addition, we used published ^{14}C data for five shell samples (Berger, Taylor and Libby 1966; Flessa, Cutler and Meldahl 1993; Ingram and Southon 1997). In all, ^{14}C ages of 8 specimens from the northern Gulf and 12 specimens from the central Gulf were obtained (Fig. 1).

Our specimen Mod-3 is noteworthy for historical and literary reasons. This specimen of *Chione californiensis* is from the Ricketts collection, now housed in the National Museum of Natural History. It is undoubtedly one of the specimens mentioned by John Steinbeck in his description of his and Ricketts's work in Angeles Bay (Bahía de los Ángeles) on April 1, 1940: "We … then took the skiff to the sand flats on the northern side of the bay. It was hard, compact mud sand with a long shallow beach, and it was heavy and difficult to dig into. We took there a number of *Chione* and *Tivela* clams and one poor half-dead amphioxus" (Steinbeck 1986: 262).

Radiocarbon and stable isotope analyses were carried out on shell pieces cut in a wedge from the growth edge of the shells using a Dremel motorized tool with a 1-inch (2.5 cm) diameter circular saw blade. Cuts *ca.* 1 cm deep were made to ensure that an average value, rather than a seasonally biased one, was obtained. Radiocarbon analyses were carried out by accelerator mass spectrometry (AMS) at the NSF-Arizona AMS Facility at the University of Arizona, Tucson. Stable isotope analyses were carried out in the laboratory of Dr. K. C. Lohmann at the University of Michigan, Ann Arbor.

Radiocarbon Reservoir Ages in the Gulf

Apparent ^{14}C ages of the Gulf mollusk samples are presented in Table 1. Radiocarbon reservoir ages (R; Table 1) were calculated as the difference between the measured ^{14}C age and the ^{14}C age of atmospheric CO_2 contemporary with each of the samples (Stuiver and Braziunas 1993). For both the northern and central Gulf, a wide range of reservoir ages was obtained (230 to 960 yr).

One specimen (sample Mod-14), collected in 1956, has an anomalously low reservoir age. One possible explanation is that some bomb ^{14}C reached the sample. Annual records of ^{14}C in corals at Fanning Island in the Pacific (4°N, 159°W) show that bomb carbon was first detected in 1958 (Druffel

TABLE 1. Radiocarbon Ages of Live-Collected Mollusk Shells from the Gulf of California and their Reservoir Ages (R)

Sample no.	Location	Year of collection	Species*	Museum no.†	Lab code	^{14}C age (yr BP)	Atm. ^{14}C (yr BP)‡	R (yr)	ΔR (yr)§
Northern Gulf samples									
Mod-4	Mouth of Colorado R.	1884	*Chione fl.*	NMNH36869	AA-14992	1080 ± 50	120	960	600
Mod-6	Puerto Peñasco	1940	*Protothaca*	NMNH538887	AA-14994	1110 ± 85	160	950	640
Mod-10	Puerto Peñasco	1930s	*Chione cal.*	SDSNH27677	AA-14998	875 ± 50	150	725	405
Mod-11	San Felipe	1934	*Chione gib.*	CASIZ102517	AA-17482	1090 ± 55	145	945	620
Mod-12	Punta Peñasco	1934	*Protothaca*	CASIZ102515	AA-17483	1005 ± 70	145	860	535
Mod-14#	Cholla Bay	1956	*Chione gni.*	CASIZ102516	AA-17485A	475 ± 55	200	275	−5
Mod-16#	Cholla Bay	1956	*Chione gni.*	CASIZ102516	AA-17485B	430 ± 50	200	230	−50
Mod-18**	Cholla Bay	1949	*Chione cal.*	LACM49-356	?	850 ± 65	200	650	370
Mod-15	Bahía S. L. Gonzago	1921	*Chione cal.*	CASIZ092335	AA-17486	1055 ± 55	115	940	595
Central Gulf samples									
Mod-2	Guaymas	*ca.* 1884	*Chione cal.*	NMNH23592	AA-14990	930 ± 50	120	810	450
Mod-3	Bahía de los Ángeles	1940	*Chione cal.*	NMNH538274	AA-14991	985 ± 50	160	825	515
Mod-5	Guaymas	1859	*Chione fl.*	NMNH714226	AA-14993	635 ± 50	125	510	145
Mod-7	Pajaro I.	1940	*Protothaca*	NMNH538351	AA-14995	910 ± 50	160	750	440
Mod-8††	Guaymas	1930	*Chione cal.*	SDSNH27745	AA-14996	680 ± 50	145	535	210
Mod-9††	Guaymas	1930	*Chione cal.*	SDSNH27745	AA-14997	810 ± 50	145	665	340
Mod-13	Santa Inez Bay	1936	*Chione kel.*	CASIZ055762	AA-17484	795 ± 55	160	635	325
Mod-17	Bahía de los Ángeles	1921	*Chione cal.*	CASIZ092331	AA-17744	895 ± 40	115	780	435
(KB)‡‡	Kino Bay	1935	*Tivela br.*	?	UCLA914	990 ± 50	160	830	520
(CI)‡‡	Carmen I.	1911	*Strombus gr.*	?	UCLA917	1000 ± 50	80	920	540
(CA)§§	Carmen I.	1940	*Ostrea*	A-3646	CAMS18499	910 ± 60	160	750	435
(GU)§§	Miramar Bch., Guaymas	1940	*Macoma*	B-839	CAMS18489	860 ± 50	160	700	385

**Chione cal.* = *Chione californiensis*; *Chione fl.* = *Chione fluctifraga*; *Chione gib.* = *Chione gibbolusa*; *Chione gni.* = *Chione gnidia*; *Chione kel.* = *Chione kelletti*; *Protothaca* = *Protothaca grata*; *Strombus gr.* = *Strombus granulatus*; *Tivela br.* = *Tivela bryonensis*.

†CASIZ = California Academy of Sciences, Invertebrate Zoology (San Francisco); LACM = Los Angeles County Museum (Los Angeles); NMNH = National Museum of Natural History (Washington, D.C.); SDSNH = San Diego Natural History Museum.

‡Mean decadal values from Stuiver and Becker (1993).

§Deviation of ^{14}C age from model reservoir age of Stuiver and Braziunas (1993).

#Mod-14 and Mod-16 samples were taken from the same shell; Mod-14 is from the margin of the shell, whereas Mod-16 is from near the umbo of the shell.

**From Flessa, Cutler and Meldahl (1993).

††Mod-8 and Mod-9 represent different individuals from the same sample collection.

‡‡From Berger, Taylor and Libby (1966); isotopic fractionation correction recalculated.

§§From Ingram and Southon (1997).

1987). However, some spatial variation in the timing of the bomb spike may be expected (*cf.* the record for Uva Island; Druffel 1987). A second sample of the shell (Mod-16), from earlier growth near the umbo, was also analyzed. This older portion of the shell should have been laid down at least a year or two earlier, when the influence of bomb carbon is even less likely. The similarly low reservoir age obtained for this sample suggests that bomb ^{14}C is not a likely explanation. Possibly this specimen lived at a time when unusual storm activity resulted in enhanced mixing of atmospheric carbon into the northern coastal Gulf waters. Because of uncertainties regarding the unusual value of this specimen, it is left out of further consideration of reservoir ages. However, it does raise the possibility that extreme but short-lived conditions may occur in the Gulf.

For the northern Gulf, reservoir ages were found to average 860 ± 125 yr, whereas for the central Gulf, ages were younger on average (725 ± 135 yr) (Table 2) and this difference is statistically significant ($p = 0.04$, $t = 2.31$, 2-tailed test with 17 d.f.). Part of the variability within each region is attributable to analytical error. To obtain the net variability, the variance (σ^2) of the analytical error was subtracted from the total variance of R. This net variance was then converted to standard deviation units by taking the square root of the variance. The net variability (SD) of the reservoir ages for both the northern and central Gulf samples was found to be 110 yr. No temporal trends in the reservoir ages are apparent (Fig. 2). In particular, there is no apparent difference between samples collected prior to construction of the Hoover Dam (in the 1930s) and those collected subsequently. Neither do there seem to be consistent local patterns of deviation of reservoir ages: a wide range of reservoir ages occurs in multiple samples of various ages from both Puerto Peñasco (and nearby Cholla Bay) in the northern Gulf as well as for the Guaymas area in the central Gulf (Table 1).

TABLE 2. Gulf of California Radiocarbon Reservoir Ages (R) and Their Variability

Region	*N*	R (yr)	SD of R (yr)	net SD of R (yr)*	ΔR (yr)	SD of ΔR (yr)	net SD of ΔR (yr)*
Northern Gulf†	7	861	125	109	538	108	89
Central Gulf	12	726	122	111	395	122	111

*After subtraction of variation attributable to analytical error (see text for procedure). Mean analytical errors (1σ) are 61 yr for the northern Gulf samples and 50 yr for the central Gulf samples.

†Shell from 1956 (Mod-14 and -16) not included in analysis.

Marine reservoir ages may vary over time because they are affected not only by contemporary atmospheric ^{14}C levels but also by the integrated history of atmospheric ^{14}C levels. For this reason, ΔR values, representing the offset between a local marine reservoir age and the average worldwide reservoir age (based on models of exchange with atmospheric carbon; Stuiver, Pearson and Braziunas 1986), are usually used for calibrating marine ^{14}C dates. Thus a ΔR value of 0, for example, would characterize a sample that has a reservoir age typical for worldwide oceans. Except for the problematic 1956 shell discussed above, all Gulf samples show large, positive ΔR values. For the northern Gulf, these average 540 yr (SD = 110 yr); for the southern Gulf, they average 395 yr (SD = 120 yr) (Table 2). Gulf of California samples thus show consistently higher ^{14}C reservoir ages, relative to the world oceans; and, on average, the northern Gulf samples show a reservoir age 150 yr older than central Gulf samples. After removal of variation due to the average analytical error, the standard deviation is 90 yr for the northern Gulf and 110 yr for the central Gulf. Central Gulf samples thus show slightly higher variability of ΔR values, despite having smaller reservoir ages.

We also determined the ^{14}C reservoir age of northern Gulf waters before the period represented by museum collections, by analysis of charcoal and shell from a midden in San Felipe, Baja California

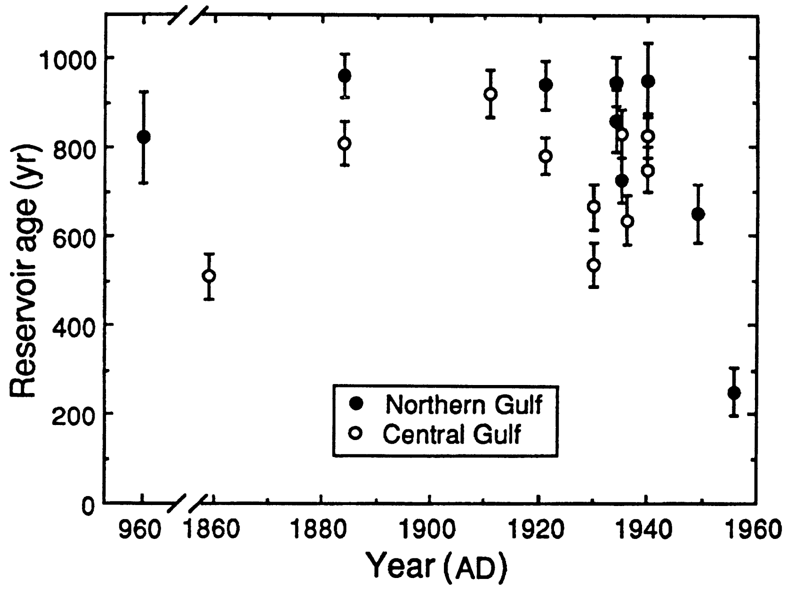

Fig. 2. Radiocarbon reservoir ages (R) of mollusk samples from the northern and central Gulf of California, in relation to their year of collection. The AD 960 sample represents fossil material from a midden (see text). Error bars are ±1σ.

(100 m SW of the lighthouse; SF-1, Fig. 1). Because the charcoal samples represent atmospheric ^{14}C levels at the time of growth of the wood and the interstratified shells generally are contemporary with the charcoal (but see below), the offset between marine and atmospheric ^{14}C values can be determined from ^{14}C analysis of the materials. This approach was used by Little (1993) to analyze variation in late Holocene marine reservoir ^{14}C ages around the New England region of the United States. Along the Baja California coast, there are few trees or shrubs. However, there is an abundant supply of driftwood, brought down by the Colorado River when it still flowed into the Gulf. Such driftwood may be the source of the charcoal found in the midden at San Felipe, located only a few hundred meters from the shore. Because some of the driftwood may have had a significant age at the time it was collected for firewood, we analyzed three charcoal samples from the midden to check for age variation. Results (Table 3) indicate that one of the three samples is significantly older than the others, but the two youngest ones are of analytically identical age (1075 ± 50 and 1065 ± 50 BP). We accept this age as representing the age of the midden and therefore also the ^{14}C activity of the atmo-

TABLE 3. Other Radiocarbon Dates

Sample no.	Material	Site	Lab code	^{14}C age (yr BP)
Mo-Col	Freshwater mussel*	Colorado River, at U.S.-Mexican border	AA-19662	1420 ± 80
SF-1	Shell (*Protothaca grata*)	San Felipe midden	AA-17766	1885 ± 90
SF-1	Charcoal	San Felipe midden	AA-17768	1220 ± 50
SF-1	Charcoal	San Felipe midden	AA-17769	1075 ± 50
SF-1	Charcoal	San Felipe midden	AA-17770	1065 ± 50

**Anodonta dejecta*; NMNH130171; collected March, 1894.

sphere contemporary with the shells in the midden. Comparison of this charcoal ^{14}C age to that of a shell sample from the midden (1885 ± 90 BP) indicates a reservoir age (R) of 815 ± 100 yr. This is well within the range of values determined in late 19th and early-to-middle 20th century samples from museum collections (Fig. 2) and suggests that more recent conditions in the Gulf are representative of conditions in the more distant past. Calibration of the two charcoal ^{14}C dates gives an age of AD 960 for the midden.

Causes of Large Radiocarbon Reservoir Ages in the Gulf

We consider here two possible sources of old carbon contributing to the large ^{14}C reservoir ages in the Gulf of California: input from the Colorado River flowing into the northern end of the Gulf and upwelling of deep Pacific water drawn up into the Gulf from the south.

In order to assess the possible contribution of old bicarbonate carbon from the Colorado River, we carried out ^{14}C analysis on shell carbonate of a freshwater mussel sample collected from the lower reaches of the river in the 1890s, before flow conditions of the river were altered. The apparent ^{14}C age of this sample is 1420 BP (Table 3). In relation to atmospheric ^{14}C levels at that time (apparent age of 104 BP; Stuiver and Becker 1993), this sample shows a ^{14}C deficiency equivalent to 1315 yr. This is the result of the dissolution of limestone or the input of old groundwater along the river's course.

Using a simple mass balance approach, we can consider what proportion of river water of this apparent age would have to be mixed with Pacific surface waters in order to obtain the observed average reservoir ages of 860 and 725 yr for the northern and central Gulf areas, respectively. For this purpose, the situation in AD 1880 is calculated, because this is around the time for which a Colorado River ^{14}C datum is available. Radiocarbon activity values (A) were calculated from the model marine ^{14}C age for that time (480 yr; Stuiver and Braziunas 1993) and the ΔR values for the northern and central Gulf (Table 2) and for Eastern Pacific surface waters around Mexico (ΔR = 185 yr; Stuiver, Pearson and Braziunas 1986). The A values are 0.881 and 0.897 for the northern and central Gulf respectively, 0.921 for Pacific waters, and 0.838 for Colorado River water. Calculations yield an estimate of 48% for the proportion of bicarbonate carbon derived from the Colorado River for the northern Gulf and 29% for the central Gulf under this scenario. However, because bicarbonate concentrations in river water are low compared to the ocean, an even higher proportion of river water to Pacific water would be required to produce the estimated carbon proportions. In the 1950s, Colorado River water contained only 2.9 ppm bicarbonate (Roden 1964) or about an order of magnitude less than typical ocean water. Hence a mixture of river and ocean water in which 48 to 29% of the bicarbonate was of river origin would have to be largely fresh water. In fact, both the northern and central Gulf regions are slightly hypersaline (35–36‰; Roden 1964). Thus, water from the Colorado River cannot be the predominant source of the observed ^{14}C reservoir ages in the Gulf.

As a further test of the possible influence of the Colorado River on reservoir ages in the Gulf, we analyzed the stable isotope composition ($^{18}O/^{16}O$ and $^{13}C/^{12}C$) of the ^{14}C-dated mollusk shells. Generally, river waters show $\delta^{18}O$ values depleted in ^{18}O relative to marine waters, except where evaporative enrichment has occurred during the course of flow to the sea. River $\delta^{13}C$ values also tend to be depleted in ^{13}C, due to input of carbon from decomposition of terrestrial plant material. For conditions in the lower Colorado River prior to diversion, we turn to analysis of the 1894 freshwater mussel sample. Isotopic analysis gives a $\delta^{18}O$ value of −8.16‰ and a $\delta^{13}C$ value of −8.32‰. For comparison, a *Chione* shell collected alive from Vega Island in the northern Gulf in 1993 (when there was no flow from the Colorado River and thus representing a pure marine signal) gave $\delta^{18}O$ =

−2.29‰ and $\delta^{13}C$ = +0.07‰. If marine reservoir ages were significantly influenced by Colorado River flow, then it would be expected that higher reservoir ages would be associated with more negative $\delta^{18}O$ and $\delta^{13}C$ values. Results of isotopic analyses of our pre-bomb bivalve sample set are presented in relation to the ^{14}C reservoir ages of the specimens in Fig. 3. For both oxygen and carbon isotopes, no trend of isotope ratios in relation to reservoir ages is seen for either the northern or central Gulf samples. Also, mean stable isotope values are similar for both the northern and central Gulf, whereas one would expect more negative $\delta^{13}C$ and $\delta^{18}O$ values in the northern Gulf if Colorado River flow had a significant influence. Thus, the stable isotope results support the ^{14}C results in pointing to an insignificant influence of Colorado River flow on ^{14}C reservoir ages in the Gulf.

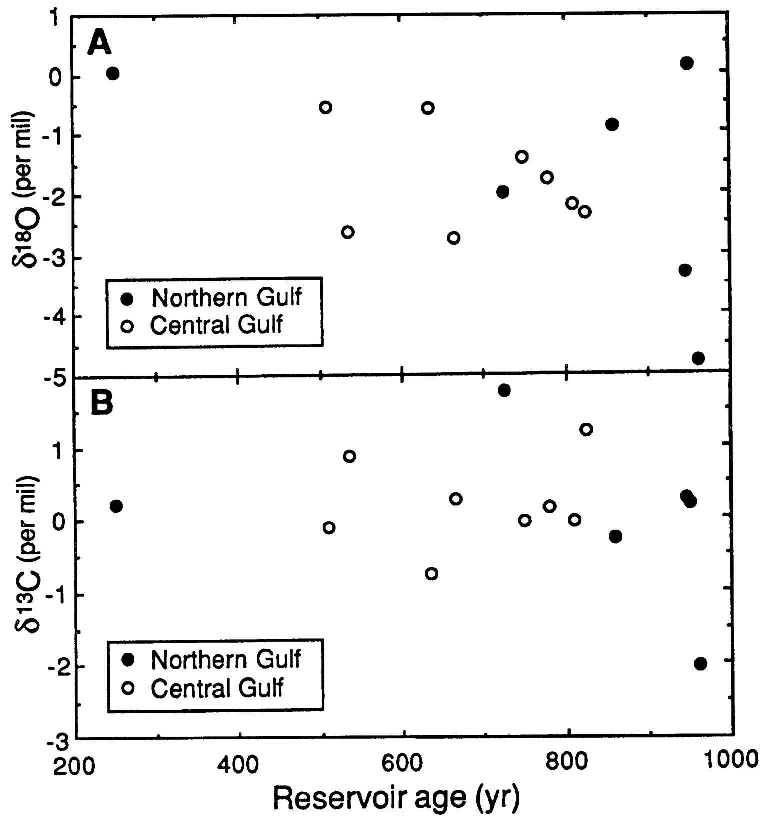

Fig. 3. Stable isotope composition of Gulf mollusks in relation to their radiocarbon reservoir ages. A. Oxygen isotope composition; B. Carbon isotope composition.

If the Colorado River has little or no effect on ^{14}C ages, then we infer that upwelling must be the predominant cause of the high reservoir ages observed in the Gulf. Water in the Pacific Ocean has an apparent age of >2000 yr at depths of 2000 m or more (Bien, Rakestraw and Suess 1963). The much smaller reservoir ages observed in the Gulf thus represent mixing of such old upwelling waters with surface waters that have been exchanging with atmospheric CO_2. The ^{14}C results indicate that the effects of upwelling are more predominant in the northern Gulf than in the central Gulf. This could be the result of greater upwelling in the north. However, the larger tides in the north, resulting in greater mixing of surface waters with older deep water, could also be a factor.

Discussion

The analyses presented above provide factors (ΔR values) that can be used for correction of ^{14}C ages of fossil samples from the northern and central regions of the Gulf of California. It should be noted, however, that the standard deviations of these reservoir age corrections are rather large (90 to 120 yr; Table 2). This variability in reservoir ages limits the precision of age determination of marine samples in the area by ^{14}C analysis. Consideration of the additional error due to variability of the ΔR values is provided for in the widely used ^{14}C calibration program CALIB 3.0 (Stuiver and Reimer 1993).

In only a few areas of the world oceans are there sufficient numbers of analyses of modern pre-bomb samples to reliably quantify the variability of ΔR values. In southern Norway, variation of apparent ^{14}C ages of 11 samples (collected between 1898 and 1923) was found to be essentially the same as analytical error, thus indicating no detectable variation in reservoir ages (Mangerud and Gulliksen 1975). However, for the coastal waters of Denmark (excluding samples from fjords), analysis of 14 samples of mollusks (collected between 1885 and 1916) shows a variation (SD) in ΔR values of 80 yr (Heier-Nielsen *et al.* 1995). After subtraction of the average analytical error (62 yr), a net residual variation of 51 yr for ΔR remains. Along the California coast (Bouey and Basgall 1991; data from Berger, Taylor and Libby 1966 and Robinson and Thompson 1981, compiled and analyzed by Stuiver, Pearson and Braziunas 1986), 14 samples (1878–1949) show a mean ΔR value of 355 ± 193 yr; after removal of the average analytical error (57 yr), the net variability of the reservoir ages is 185 yr. Analyses of 14 samples of northern and southern California coastal mollusk samples by Ingram and Southon (1997) show a similar mean ΔR value (391 yr) but a slightly larger net variability (252 yr). Large temporal variations in ^{14}C reservoir ages have also been documented for the California coast, based on ^{14}C analysis of pteropod shells in varved sediments (Southon and Baumgartner 1996). Thus, the contribution of uncertainties in ΔR to the overall error of calibrated marine ^{14}C dates ranges from negligible in some situations (southern Norway) to other situations, such as the Gulf of California and the coast of California, in which the variability of ΔR is considerably greater than the analytical error of the dated sample. Areas having high ^{14}C reservoir ages due to upwelling may also be expected to have higher variation in reservoir ages due to spatial and/or temporal variability in upwelling.

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EVIDENCE FOR LATE POLYNESIAN COLONIZATION OF NEW ZEALAND: UNIVERSITY OF WAIKATO RADIOCARBON MEASUREMENTS

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ABSTRACT. We present radiocarbon determinations for 271 New Zealand archaeological samples measured at the University of Waikato Radiocarbon Dating Laboratory between 1975 and 1995. A discard protocol is applied to the series and the list culled to winnow the acceptable dates from those that may incorporate error. None of the 221 acceptable ^{14}C determinations older than 600 BP (in the case of terrestrial samples) or 930 BP (in the case of marine and estuarine shell) extends beyond cal AD 1250. This conclusion supports the short chronology model of New Zealand prehistory presented by Anderson (1991).

INTRODUCTION

Radiocarbon dating the New Zealand prehistoric sequence has provided archaeologists and ^{14}C specialists alike with considerable challenge. The principal reason is the brevity of the prehistoric period. Until recently, it had been widely accepted that the first Polynesian colonizers made landfall on the last major landmass to be settled by humans *ca.* 1000 yr ago (Davidson 1984). Due to this brevity, ^{14}C dating at routine levels of precision (Δ^{14}C $\sigma = \pm 5$–7‰) has made it difficult to differentiate statistically between successive cultural strata with confidence (McFadgen 1982a). Recent developments in attainable precision have improved this situation, with precision of ±2.5‰ in Δ^{14}C now available in the University of Waikato Radiocarbon Laboratory. Despite this improvement, inherent wiggles in the calibration curve may spread converted ages, increasing uncertainty further.

There are two principal archaeological questions to which ^{14}C analyses have been applied in New Zealand, aside from the building of regional chronologies: the date of first colonization and the onset of *paa* (fort) building. Three general models have been proposed for the date of initial human colonization.

- Davidson (1981; 1984) described the view of the majority of New Zealand archaeologists of the time when she outlined the orthodox model, with colonization beginning *ca.* AD 800.
- Sutton (1987) presented a model influenced by Kirch's (1986) reanalysis of the prehistoric sequence of East Polynesia, suggesting that the dates for colonization of New Zealand may have to be revisited and could be much earlier than hitherto anticipated. The interpretation was based upon a number of natural sites containing dated charcoal lenses, possibly related to anthropogenic deforestation. Sutton stated that human colonization may have occurred between AD 0 and 500 (Sutton 1987). Chester (1986), Sutton (1987) and Elliot *et al.* (1995) have utilized palynological and paleoenvironmental indicators such as this to argue for early human presence, represented by possible anthropogenic modification of a virgin land.
- Anderson (1991) took an alternative approach by examining ^{14}C determinations from sites already excavated. He analyzed ^{14}C determinations that predated 600 BP (in the case of moa bone and charcoal) and 930 BP (in the case of marine and estuarine shell) and pruned those that did not fit a set of acceptability criteria (Anderson 1991). Anderson's (1991) conclusion was that the acceptable ^{14}C determinations yielded evidence in support of a short prehistory, probably no more than 700–800 yr in duration, with colonization by *ca.* AD 1100.

Similar research using the available corpus of ^{14}C data has suggested not only a late colonization date, but also a later date for the onset of *paa* building (Schmidt 1993, 1996; McFadgen, Knox and Cole 1994). Reanalysis of the critical Kaharoa Tephra has shown that its deposition in northern New

Zealand occurred between cal AD 1300 and 1390 (Lowe *et al.*, in press). No unequivocal cultural remains have been found beneath this layer of tephra. The earliest sustained periods of human deforestation occurred around, or soon after, the time of this eruption (Newnham *et al.*, in press).

Recent accelerator mass spectrometry (AMS) dates on rat bone gelatin presented by Holdaway (1996) show bone from natural cave sites ranging in age from ~400 BC to ~1200 AD. Because rats are a human commensal, such dates imply an earlier human presence than that indicated by the late settlement proponents. Anderson (1996), however, has dated rat bone gelatin samples from the Shag River Mouth site (Anderson, Smith and Higham 1996) that yield an age range at odds with one derived from more acceptable dating materials, suggesting the problem may be related to the material itself. Further investigations of the accuracy of rat bone for dating are currently underway (Beavan and Sparks, in press). Until more is known about the relative acceptability of this sample type, it would be wise to remain cautious about accepting these dates as reliable.

Anderson (1991) concentrated principally upon ^{14}C determinations from the Rafter Radiocarbon Laboratory at the Institute of Geological and Nuclear Sciences Ltd (IGNS) in Lower Hutt, New Zealand in his reanalysis of the ^{14}C record. In the Appendix to this paper, we present a list of ^{14}C determinations from New Zealand's other ^{14}C laboratory, at the University of Waikato in Hamilton, which began producing ^{14}C measurements in 1975. Over 300 ^{14}C determinations have been made from New Zealand archaeological sites from 1975 to 1995. The presentation of a date list is a useful exercise in its own right: many ^{14}C dates remain unpublished, still others are published in obscure reports and manuscripts. In addition, the publication of date lists enables the testing of previous models using updated data sets and encourages their use (*cf.* Spriggs 1996). Our intention in this paper, apart from presenting this list, is to consider how the results impact the differing colonization models for New Zealand. In order to do so, we first evaluate the measurements in terms of their accuracy for dating the New Zealand sequence by applying a discard protocol to them.

Trotter (1968), McFadgen (1982a), Law (1984), Anderson (1989), Anderson and McGovern-Wilson (1990), Caughley (1988), Anderson (1991) and McFadgen, Knox and Cole (1994) have cautioned against dating wood or wood charcoal derived from unknown, or long-lived tree species. All charcoal identifications are therefore included in the list. (McFadgen, Knox and Cole (1994) have provided a summary of New Zealand wood species and their estimated life span.) We have also included the identifications of marine and estuarine shell species that have been dated. Significant comments from submitters are given where applicable. Publications that contain the determinations listed, or discuss them in greater detail, are provided where possible. The ^{14}C determinations originate from a wide range of prehistoric sites and we present them by region, from north to south (Figs. 1, 2). We also provide the New Zealand Archaeological Association's (NZAA) new site record number in parentheses after the site name where known (Smith 1994). Only ^{14}C analyses from submitters who have given their permission are included in this paper, except where the determinations have been published. In total, 41 determinations were withheld from this list at the request of submitters. (These were mostly samples dated recently and in preparation for publications.)

Sutton (1994: 247) has suggested that one of the shortcomings of the "short prehistory" model is the disproportionately large number of ^{14}C determinations that come from sites in the South Island and central North Island, to the exclusion of sites north of the Hauraki Gulf, and in Northland. This list is dominated by ^{14}C determinations that come from northern sites (Fig. 1) (70% of the determinations are from North Island sites) and therefore should constitute an important test of Anderson's (1991) assumption that human arrival affected all areas at a similar time in prehistory (Sutton 1994).

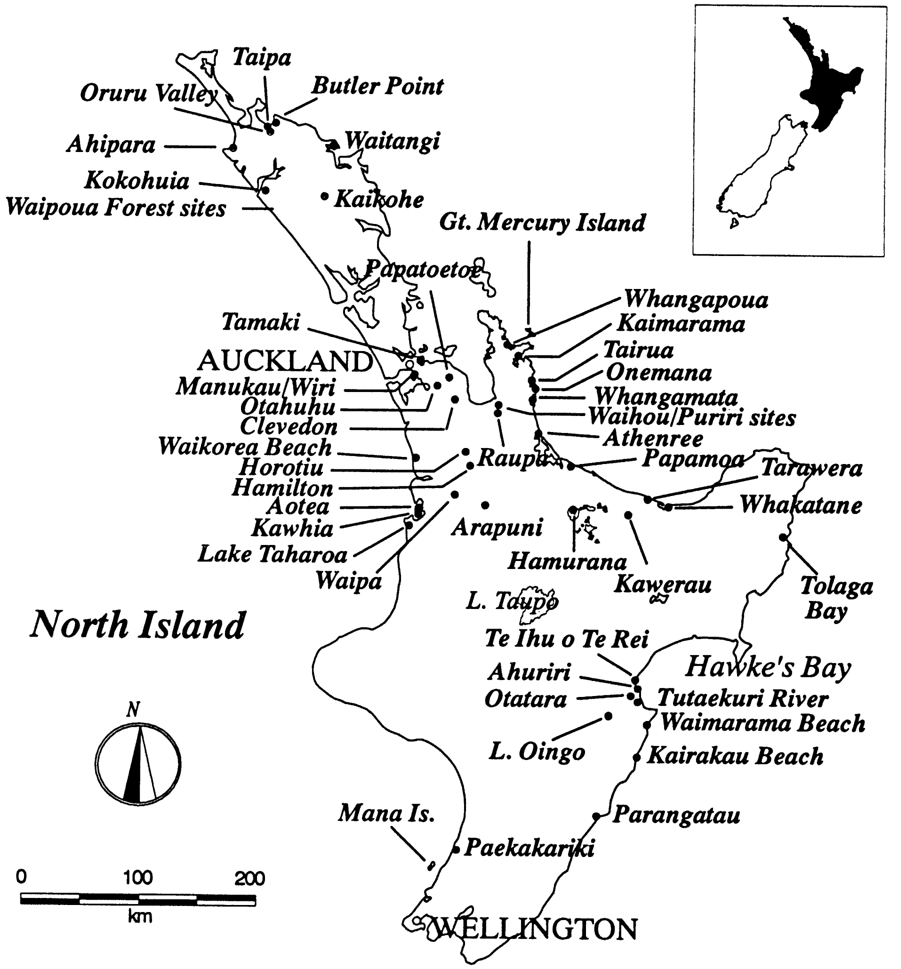

Fig. 1. North Island archaeological sites mentioned in the text and date list

Methods

The Waikato Laboratory measures ^{14}C activity by the liquid scintillation counting (LSC) method (Hogg, Lowe and Hendy 1987). We measure β decay activity in six LKB-Wallac Oy 1220 Quantulus™ spectrometers equipped with 0.35, 3.0 and 10.0 ml synthetic silica vials in lead and aluminum holders (Hogg 1992). For New Zealand archaeological samples we use 3.0 ml vials (2.7 g benzene), achieving a routine precision of ±40–50 ^{14}C yr (Δ^{14}C σ = 5–6‰). We use 10.0 ml vials (7.5 g benzene) for our high-precision (Δ^{14}C σ = 2–3‰) ^{14}C calibration program. All ages are reported as conventional ^{14}C ages BP, based on the Libby half-life and calculated according to the recommendations outlined by Stuiver and Polach (1977). Conventional ^{14}C ages BP are reported with reference to the net corrected activity of the modern reference standard HOxII (SRM-4990C, NIST HOxII). We use ANU sucrose as a routine secondary laboratory standard (Polach 1976; Currie and Polach 1980). The standard error for each ^{14}C determination represents one standard deviation (1σ). A laboratory error multiplier (K) of 1.22 has been included to increase standard errors measured since 1990, after Stuiver and Pearson (1993). ^{14}C determinations are corrected for isotopic fractionation, normalized with respect to VPDB (Coplen 1994).

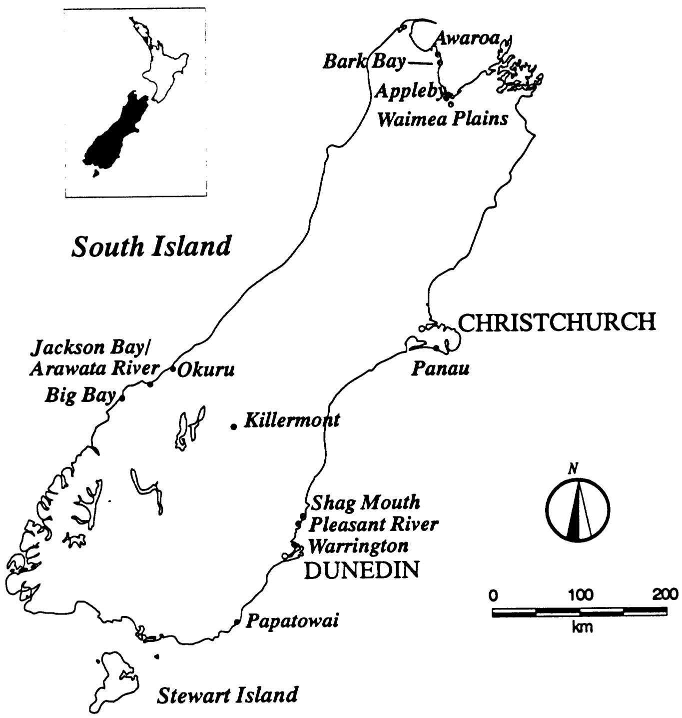

Fig. 2. South Island archaeological sites mentioned in the text and date list

Rationale for Discard Protocols

The application of a discard protocol is critical for examining the accuracy of multiple ^{14}C determinations from different archaeological sites. The brevity of the New Zealand prehistoric sequence requires a careful approach to sample selection and provenience, and a rigorous approach to the analysis of the corpus of available determinations. Spriggs (1989, 1996), Anderson (1991), Spriggs and Anderson (1993) and Schmidt (1993, 1996) have presented protocols for the discard of New Zealand and Polynesian archaeological ^{14}C determinations on the basis of sample reliability and archaeological integrity. Similarly, Kuzmin and Tankersley (1996) have ranked ^{14}C dates in terms of sample type and stratigraphic integrity in their analysis of the date of colonization of Siberia. We have developed a discard protocol for accepting or rejecting assays listed in the Appendix to examine their accuracy in dating archaeological events, and to consider how the earliest acceptable determinations challenge the various colonization hypotheses.

Archaeological Sample Protocols

The archaeological discard protocol is as follows:

1. Charcoal samples from species that are unidentified and may possess a high inbuilt age (McFadgen 1982a) and therefore do not date the archaeological event accurately, are rejected.

Wk-94 from Great Mercury Island and the series of dates from Hamurana, Rotorua (Wk-1218 to 1222, inclusive) are rejected as unidentified. The Aotea and Kawhia dates Wk-31 and -32 are unidentified and rejected. Wk-1899 was identified, but its exact sample constituents are unknown so it is rejected. The same applies to Wk-1389 and 1390 from Jackson Bay. Wk-1088 is of unidentified charcoal although it is listed as dominated by twigs; nevertheless, as Anderson (1991: 780) has shown, twigs and branchwood that originate from long-lived species may still incorporate inbuilt age. This date is therefore rejected. Wk-2737 from Arapuni is composed of unidentified charcoal.

2. Charcoal samples that are identified but belong to species of trees that may possess a high inbuilt age and therefore do not date the archaeological event accurately, are rejected.

Wk-1907, -1910 and -1912 from Raoul Island are all rejected because they are dominated by *Metrosideros kermadecensis*, a long-lived tree. Wk-968 from Whangapoua comes from maire branchwood (*Nestigis* sp.). According to McFadgen, Knox and Cole (1994), although this is classified as a medium-span species (100–300 yr), it can survive for much longer. The Hamilton samples Wk-2703, -2704 and -2736 are dominated by long-lived species and are rejected.

3. Dates obtained from materials that have been shown to produce erroneous ^{14}C *ages, such as riverine shells, are rejected.*

All dates of *Amphibola crenata* (mudsnail) from the list are rejected. These have been shown to yield erroneous ^{14}C dates (Law 1984; Anderson 1989, 1991; Higham 1993; Higham and Hogg 1995; Hogg, Higham and Dahm, in press). Wk-2367, -2633 and -2507 are of *Amphibola crenata*.

Wk-2738 from Arapuni is composed of freshwater *Hyridella menziesii* shell from a Waipa River bank site. That the shell overlies alluvial deposits dated at *ca.* 1850 BP or younger indicates that the date returned is stratigraphically inverted and clearly too old. Freshwater shells such as these may incorporate an unknown reservoir age. It is also possible that the sample may originate from natural shell material redeposited at the site to form a living floor or terrace.

4. Single dates from dispersed charcoal or sediments excavated from agricultural soils, are rejected. These dates may possess error due to inbuilt age (McFadgen 1982a) or fail to relate sample to event.

Wk-1754 is rejected. This sample of sediment comes from a drainage ditch and provides a minimum age for the feature. It may have incorporated carbon of unknown inbuilt age. Wk-2702 is dominated by a selection of short-lived species, but two water-rolled "pebbles" of totara are indicative of inherent provenience problems, according to Dr. R. Wallace, who identified the samples. The sample originates from a borrow pit feature, the remnant of pits excavated in prehistory for extracting coarse grit and pebbles used to modify soils (McFadgen 1980). The accuracy of dates on samples from features such as this is questionable. The charcoal may derive from earlier burnoff of vegetation and ground cover. Wk-2705 and -2706 are similarly unreliable and rejected.

5. Dates that are 300 yr or greater adrift in a series from an identical stratigraphic horizon that is otherwise statistically indistinguishable at 1 σ*, are rejected. In these instances, especially in the case of charcoal, there is the possibility that inbuilt age may have made the determination artificially old.*

6. Samples that may have been contaminated post-depositionally or inadequately pretreated, are rejected.

7. Samples from areas with equivocal cultural context or in which redeposition may have occurred, are rejected.

Wk-1754 falls into this category as well as into category 4. Wk-1911 from Raoul Island dates a paleosol, whereas Wk-1907 is from a "disturbed context". Wk-1143 also dates deforestation, which may not be human-related. Layers 3 and 4 of the Pleasant River Area D series have been mixed in places, and material from a later occupation dated at *ca.* 400 BP has become incorporated with material from an earlier *ca.* 600 BP occupation. All of the results from Area D, except for those determinations of layer 4 moa eggshell, whose context was secure, are therefore rejected for this analysis (Allingham, personal communication).

8. Marine and estuarine shell dates that originate from areas where there may be a high risk of oceanic upwelling or old carbon dissolution, are rejected.

9. Dates that are based upon mixtures of different sample types, such as charcoal and bone or mixtures of shell of different species, are rejected. (N.B.: No bone samples from New Zealand archaeological sites were dated at the Waikato Laboratory between 1975 and 1995.)

Wk-1151, -1168, -2306, -2307 fall into this category and are rejected.

10. Determinations of shell of unknown species are rejected. In this category, there is the possibility that shell of unreliable species such as Amphibola crenata *may have become incorporated in the sample.*

Wk-2273, -2274, -2872, -2873, -2874, -2875 and -3048 were unidentified shell and are rejected.

Radiocarbon Protocols

The preceding protocols were devised from an archaeological perspective; thus, they take no account of the analytical and statistical variables involved in a ^{14}C determination. Clearly, a protocol for the rejection or acceptance of a ^{14}C date must embrace these parameters in addition to archaeological variables, since the utility of any ^{14}C measurement is dependent upon its archaeological context, sample composition and the rigor of the laboratory analysis and measurement. Understandably, the task of combining these variables into a single discard protocol is complex, particularly as the release of a ^{14}C determination by a laboratory implies the acceptability of that ^{14}C measurement. We suggest that additional discard variables, related to Quality Assurance programs, be associated with "chronometric hygiene" analyses such as this, particularly when multiple laboratory date lists are being examined. We offer three possibilities here by way of example.

1. A laboratory error multiplier (K) must be incorporated into the standard error for any ^{14}C date to account for variation in reproducibility in routine sample dating (Stuiver and Pearson 1993).

2. The laboratory must demonstrate its accuracy by reference to the library of international standards prepared by the International Atomic Energy Agency (IAEA) Intercomparison and the Third International Radiocarbon Intercalibration (TIRI) (Gulliksen and Scott 1995).

The exceptions are in instances where the submitted values for a particular standard are so spread that the consensus value loses meaning as a reflection of the "true" age of the sample (*cf.* IAEA C4 standard, Rozanski *et al.* 1992; Hogg *et al.* 1995).

3. All ^{14}C dates must be ^{14}C ages BP *based upon the recommendations of Stuiver and Polach (1977) with correction for isotopic fractionation.*

Results

In the culled list are 221 ^{14}C results from New Zealand sites that we suggest are acceptable. We rejected 50 determinations in total; 25 of charcoal, 21 of marine, estuarine or freshwater shell and 4 wood, sediment or eggshell samples. Of the acceptable determinations, 159 are of marine or estuarine shell, 50 are charcoal and 12 are of other sample types, principally wood and moa eggshell.

We have collated those ^{14}C determinations of charcoal, wood and moa eggshell that extend beyond 600 BP, and marine and estuarine shell dates that extend beyond 930 BP (after Anderson (1991)) to examine the earliest possible colonization dates they imply. The resultant dates come from cultural deposits in sites in both islands that are considered early or Archaic phase occupations. We calibrated the shell dates using the marine curve of Stuiver and Braziunas (1993) with a local reservoir depletion, or ΔR, calculated at -25 ± 15 ^{14}C yr (Higham and Hogg 1995). We calibrated the charcoal and eggshell dates using the curves of Stuiver and Becker (1993), with a -27 ^{14}C year offset subtracted after McCormac *et al.* (in preparation) for Southern Hemispheric terrestrial samples.

The 22 shell determinations possess no calibrated age ranges that extend beyond AD 1250 (Fig. 3). None of the 9 pre-600 BP calibrated charcoal series range beyond AD 1250 either (Fig. 4). Among the eggshell determinations, there are also no determinations that approach the mid-13th century AD (Fig. 5).

All three sample types, then, show very close agreement in estimating the earliest calibrated age, which in no case challenges the 12th century. The earliest calibrated range across all sample types is very similar. This agreement is due principally to the application of the discard protocol and the rejection of measurements that are likely to be aberrant.

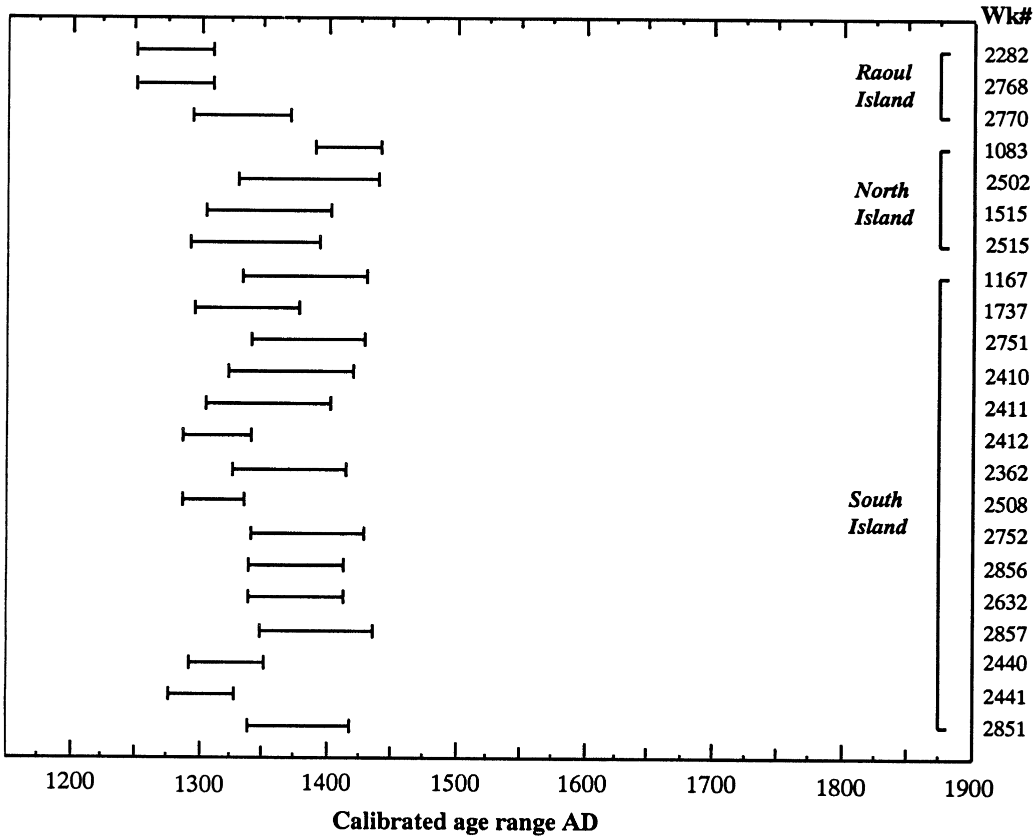

Fig. 3. Calibrated ^{14}C dates of shell from New Zealand archaeological sites that predate 930 BP. Determinations were calibrated after Stuiver and Braziunas (1993) with a ΔR of -25 ± 15 ^{14}C yr (Higham and Hogg 1995) using CALIB 3.0.3c (Stuiver and Reimer 1993).

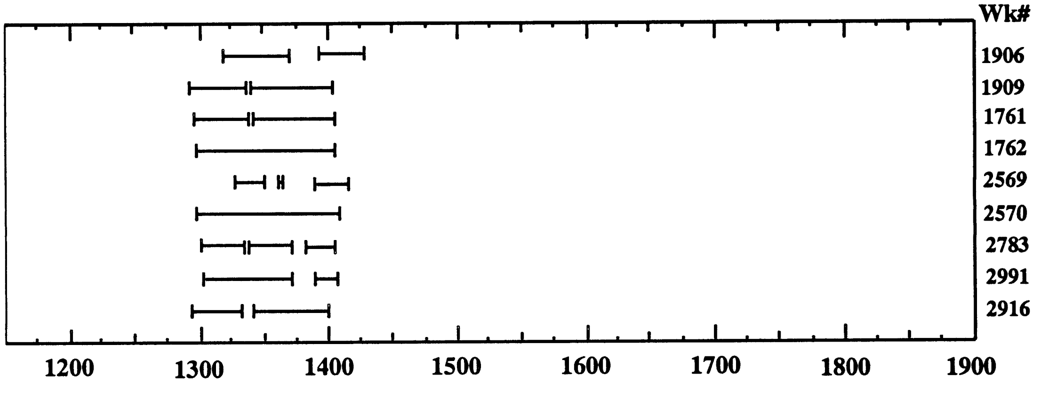

Fig. 4. Calibrated ^{14}C dates of charcoal from New Zealand archaeological sites that predate 600 BP. Determinations were calibrated using Stuiver and Becker (1993) with a −27 ^{14}C yr offset applied (McCormac *et al.*, in preparation). Wk-1906 and -1909 are dates from Raoul Island, the Kermadecs. The remainder are from sites in the South Island.

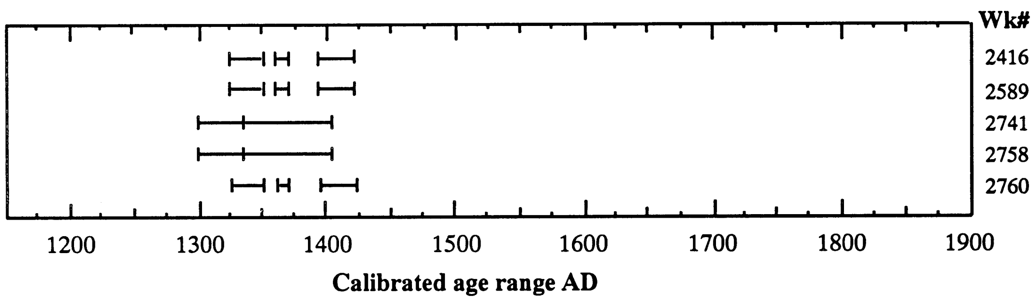

Fig. 5. Calibrated ^{14}C dates of moa eggshell from New Zealand archaeological sites that predate 600 BP. Determinations were calibrated as in Fig 4. All of the determinations are from sites in the South Island.

A feature of the calibrated data shown in Figures 3, 4 and 5 is the small number of acceptable North Island determinations that exceed the threshold for this analysis of colonization dates. In Anderson's (1991) analysis, ~35% of the available early ^{14}C determinations came from North Island sites, compared to ~65% from the South Island. In the Waikato list, only four North Island determinations of the shell series exceed 930 BP, and none of the charcoal and eggshell samples extend beyond 600 BP. Obviously, sampling considerations mean it would be unwise to overinterpret these data. In the shell series, for instance, the South Island series is dominated by determinations from the Shag River Mouth site. Nevertheless, the general tendency in both ^{14}C lists is for southern sites to yield a larger number of acceptable determinations beyond cal 600 BP. This may suggest that in the earliest phases of prehistory the South Island was the focus of population and settlement, although both were colonized at a similar time in prehistory.

Conclusion

Anderson (1991: 792) concluded that there are no sites in New Zealand dated to before the 12th century AD and that positing colonization about that time appeared to be "robust in the face of potential objections". In the Waikato series, no calibrated age ranges extend beyond *ca.* AD 1250. Our data therefore support the late settlement model, with human occupation beginning *ca.* 700 cal BP (*cf.* McFadgen, Knox and Cole 1994).

ACKNOWLEDGMENTS

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ARCHAEOLOGICAL DATES

RAOUL ISLAND[1]

Raoul Island series

(Submitted 1 October 1990, by L. Johnson, Department of Conservation, Auckland)

Woolshed Flat, Farm Terraces (K036/2)

Wk-1906. R.I.1 **600 ± 60**
Charcoal $\delta^{13}C = -25.7‰$

Comment: (L.J.) The date will provide a minimum possible age for prehistoric occupation.
N.B.: charcoal species identified as pohutukawa (*Metrosideros kermadecensis*), mahoe (*Melicytus ramiflorus*), kawakawa (*Macropiper excelsum*), karo (*Pittosporum crassifolium*), *Coprosma* sp., hutu (*Corarra lucida* var. *lanceolata*).

Wk-1907. R.I.2 **Modern**
Charcoal $\delta^{13}C = -24.9‰$

Comment: (L.J.) To provide a date for prehistoric settlement on the terraces.
N.B.: charcoal identified as pohutukawa (*Metrosideros kermadecensis*). Obtained from a "disturbed context".

Wk-1908. R.I.3 **580 ± 50**
Charcoal $\delta^{13}C = -25.1‰$

Comment: (L.J.) The date should provide a minimum possible age for construction of the archaeological feature.

[1]Raoul Island, the largest of the Kermadec group, is *ca.* 1000 km from New Zealand (29–31.5°S, 178–179°W). The prehistory of the Kermadecs is closely linked to New Zealand, however, through the discovery of obsidian from Mayor Island (Bay of Plenty) in cultural deposits on Raoul (Anderson and McFadgen 1990). This suggests that having found New Zealand, Polynesians succeeded in returning at least halfway back to island Polynesia.

N.B.: charcoal species identified as pohutukawa (*Metrosideros kermadecensis*), kawakawa (*Macropiper excelsum*), karo (*Pittosporum crassifolium*), mahoe (*Melicytus ramiflorus* and *Myrsine kermadecensis*).

Coral Bay (K036/4)

Wk-1909. R.I.4 **660 ± 50**
Charcoal $\delta^{13}C = -25.4‰$

Comment: (L.J.) The age of the settlement at Coral Bay.
N.B.: charcoal identified as mahoe (*Melicytus ramiflorus* and *Myrsine kermadecensis*) and pohutukawa (*Metrosideros kermadecensis*).

Low Flat (K036/1)

Wk-1910. R.I.5 **800 ± 40**
Charcoal $\delta^{13}C = -25.5‰$

Comment: (L.J.) Will provide a date for the occupation of the upper cultural layer at Low Flat.
N.B.: charcoal is pohutukawa (*Metrosideros kermadecensis*), all other species unidentified.

Wk-1911. R.I.6 **Modern**
Wood $\delta^{13}C = -24.5‰$

Comment: (L.J.) This ^{14}C date should mark the terminal point in the development of the paleosol.
N.B.: wood sample composed of candlenut (*Aleurites mollucana*).

Wk-1912. R.I.7 **1070 ± 40**
Charcoal $\delta^{13}C = -25.3‰$

Comment: (L.J.) Age of occupation of the lower cultural horizon.
N.B.: charcoal is 93% pohutukawa (*Metrosideros kermadecensis*), 7% karo (*Pittosporum crassifolium*). Sample comes from a lower cultural horizon earth oven in association with obsidian blades, adze roughouts and midden remains.

Wk-2282. U.C.H.2 R.A.O **1100 ± 45**
Shell (*Patella kermadecensis*) $\delta^{13}C = +0.8‰$

Comment: (L.J.): Sample should provide a minimum age for the occupation of the upper cultural horizon.
N.B.: see Johnson (1991, 1995).

Low Flat (K036/1)

(Submitted 1 December 1992 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato, Hamilton).

Wk-2768. Low Flat upper layer **1100 ± 45**
Shell (*Patella kermadecensis*) $\delta^{13}C = +1.3‰$

Wk-2769. Low Flat upper layer **1050 ± 45**
Shell (*Patella kermadecensis*) $\delta^{13}C = +1.3‰$

Wk-2770. Low Flat lower layer **1040 ± 45**
Shell (*Patella kermadecensis*) $\delta^{13}C = +1.3‰$

N.B.: see Johnson (1995), Higham and Johnson (in press).

NORTHLAND

Mangonui (O04/116)

(Submitted 27 January 1989 by L. Johnson, Department of Conservation, Auckland)

Wk-1373. C.L.10 Level 5 **610 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -2.1‰$

Comment: (L.J.) The sample should date the latest phase of occupation of the site and offer the upper parameter for occupation of the site as a whole.

Wk-1374. C.L.2 Level 9 **570 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -2.0‰$

Comment: (L.J.) as above. *N.B.*: see Johnson (1992).

Butler Point, Mangonui series (O04/56)

(Submitted 15 May 1992 by A. Slocombe/J. Maingay, Department of Conservation, Whangarei)

Wk-2384. O04/56 147 Area B base of pebble layer **Modern**
Charcoal $\delta^{13}C = -28.4‰$

Comment: (A.S.) Date of occupancy of *paa* is not known. Dating of different material excavated there could indicate when this took place and whether successive occupations of the site occurred.

N.B.: sample of charcoal identified as seven fragments of *Kunzea/Leptospermum* and three of broadleaf twigs (*Griselinia littoralis*).

Wk-2500. O04/56 54 **540 ± 60**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.6‰$

Comment: (A.S.) as for Wk-2384. Sample comes from Area F under defensive bank layer 3 post-hole.

Wk-2563. O04/56 65 **720 ± 60**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.6‰$

Comment: (J.M.) The shell appears to have been deposited prior to construction of the major earthworks of the *paa*. It could provide a date for an earlier undefended occupation level. Sample is composed of shell fill in a posthole in layer 3.

Wk-2922. O04/56 33 (layer 2) **500 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.6‰$

Comment: (A.S.) This sample could date a period of occupation of the *paa* site.

Wk-2923. O04/56 66 (layer 4) **700 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Comment: (A.S.) This sample could date a period of occupation of the *paa* site.

Wk-2924. O04/56 (A) L6 (layer 2) **700 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Comment: (A.S.) This sample could date a period of occupation of this coastal camp site.

N.B.: Wk-2922, -2923 and -2924 submitted 10 May 1993 by A. Slocombe, Department of Conservation, Whangarei.

Wk-3318. O04/56 4 Area D trench 3, top of layer 2 **670 ± 60**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Comment: (S.B.) Probably will reflect the final occupation of the *paa* as a traditional fortification.

Wk-3933. O04/56/1995/1 Area D, fill of feature under layer 3 **640 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.1‰$

Comment: (S.B.) Dates the dismantling of a large structure (house or platform).

Wk-3934. O04/56/1995/2 Area F, fill of feature in layer 3 **530 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.8‰$

Comment: (S.B.) Dates the dismantling of a large structure (house or platform) inside fortification.

Wk-3935. O04/56/1995/3 Area F, fill of feature in top of layer 4 **570 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.2‰$

Comment: (S.B.) Dates the end of the occupation of a structure inside the defenses of a site.

Wk-3936. O04/56/1995/4 Area D, terrace A, layer 2 **580 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.8‰$

Comment: (S.B.) Dates the construction of a shell-paved terrace outside defended area of site.

N.B.: Wk-3933 to -3935 submitted 28 June 1994 by S. Bulmer, Department of Conservation, Auckland. Wk-3318 submitted 28 June 1994 by S. Bulmer, Department of Conservation, Auckland. Wk-2384 submitted 2 March 1992 by A. Slocombe, Department of Conservation, Whangarei. (See Bulmer and Maingay, in preparation.)

Taipa, Doubtless Bay (O04/580)

(Submitted 18 May 1990 by L. Johnson, Department of Conservation, Auckland)

Wk-1753. M.S.4(6) **700 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.6‰$

Comment: (L.J.) The relationship between the midden from which this sample was taken and the wetland drainage system that we wish to date is that the two should be contemporary. However, I cannot be certain about this. Apart from the drainage system itself, the midden that occurred in the swamp was the only other feature that provided dateable material.

Wk-1754. D.S.1 **840 ± 55**
Sediment $\delta^{13}C = -27.6‰$

Comment: (L.J.) This sample should provide a minimum possible age for construction of the wetland drainage system. It appeared from the excavated profile that the fill from which the sample was taken was deposited toward the end of the use of the system or shortly after the point at which the system became redundant.

Oruru Valley (O04/253 and O04/260)

(Submitted by Y. Marshall, Anthropology Department, University of Auckland)

Wk-976. O04/253 **830 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +2.2‰$

Comment: (Y.M.) To date undefended storage complex in the Oruru Valley.

Wk-977. O04/260 T.P.I **770 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +2.1‰$

Comment: (Y.M.) as above.

Wk-978. O04/260b **660 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +2.2‰$

Comment: (Y.M.) To date storage complex in the Oruru Valley.

Reef Point, Ahipara (N05/301)

(Submitted 7 June 1991 by L. Johnson, Department of Conservation, Auckland)

Wk-2100. N05/301.1. **400 ± 50**
Wood $\delta^{13}C = -26.1‰$

N.B.: twigs identified as pohutukawa (*Metrosideros excelsa*), *Cassinia retorta*, ngaio (*Myoporum laetum*), mapou (*Myrsine australis*), matai (*Prumnopitys taxifolia*). All shrubs selected.

Ahipara 2 (N05/302)

(Submitted 15 April 1992 by A. Slocombe, Department of Conservation, Whangarei)

Wk-2501. Sample 1 (layer 2) **630 ± 60**
Shell (*Turbo smaragda*) $\delta^{13}C = +3.0‰$

Comment: (A.S.) This could date a more recent period of occupation at this coastal camp site.

Wk-2502. Sample F36B (layer 4) **950 ± 60**
Shell (*Turbo smaragda*) $\delta^{13}C = +3.0‰$

Comment: (A.S.) This sample could date one of the earliest periods of occupation at this coastal camp site.

Waitangi (P05/611)

(Submitted 9 December 1992 by A. Slocombe, Department of Conservation, Whangarei)

Wk-2773. Sample 1 (layer 4) **620 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.7‰$

Comment: (A.S.) This sample could provide a date for an early period of settlement at this site.

Kokohuia (O06/317)

(Submitted 7 August 1987 by M. Taylor, Department of Conservation, Waipoua Forest, Dargaville)

Wk-1086. Koko-10 **880 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +1.6‰$

Comment: (M.T.) Date of base of midden excavated at Kokohuia, Omapere.

Kokohuia (O06/317)

(Submitted 9 June 1992 by J. Maingay, Department of Conservation, Whangarei)

Wk-2564. O06/317 40 (layer 2) **790 ± 60**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.6‰$

Comment: (J.M.) A previous sample, Wk-1086, taken by M. Taylor from a slope northwest of excavation dated to 880 ± 50 BP. This sample is to determine whether the areas of the site are contemporaneous.

Kaikohe (P06/82)

(Submitted 4 June 1995 by A. Slocombe, Department of Conservation, Whangarei)

Wk-3919. P06/82/1 **220 ± 50**
Wood $\delta^{13}C = -24.8‰$

Comment: (A.S.) This sample will date a period of occupation of the area possibly associated with *paa* sites located nearby and may also determine whether or not PO6/82/1 and PO6/82/2 are contemporaneous.
N.B.: the wood was identified as hinau kernels (*Elaeocarpus dentatus*).

Wk-3920. P06/82/2 **220 ± 40**
Wood $\delta^{13}C = -24.8‰$

Comment: (A.S.) By association, this sample could date the deposition of the artifacts and may also determine whether or not PO6/82/1 and PO6/82/2 are contemporaneous.
N.B.: the wood was identified as hinau kernels (*Elaeocarpus dentatus*). See Slocombe (1996).

Waipoua Forest series

(Submitted 7 August 1987 by M. Taylor, Department of Conservation, Waipoua Forest, Dargaville)

Wk-1083. O06/290 1 **930 ± 45**
Shell (*Turbo smaragda*) $\delta^{13}C = +3.7‰$

Comment: (M.T.) Dates of deposition of midden at Motuhuru, archaeological site O06/290. Predates forest clearance.

Wk-1084. O06/171 67 **570 ± 105**
Charcoal $\delta^{13}C = -21.3‰$

Comment: (M.T.) Date of occupation of pit site O06/171.
N.B.: charcoal species identified as *Myrsine* sp., rangiora (*Brachyglottis repanda*), akeake (*Dodonaea viscosa*), makamaka (*Ackama rosifolia*), *Coprosma* sp., *Olearia* sp.

Wk-1085. O06/249 132 **460 ± 50**
Charcoal $\delta^{13}C = -26.4‰$

Comment: (M.T.) Date of occupation of house site O06/249, Waipoua Forest.

N.B.: charcoal consisted of the following: twig species—rewarewa (*Knightia excelsa*), hinau (*Elaeocarpus dentatus*), matai (*Prumnopitys taxifolia*), puriri (*Vitex lucens*), kohekohe (*Dysoxylum spectabile*), tarairi (*Beilschmeidia tarairi*), akeake (*Dodonaea viscosa*), mahoe (*Melicytus ramiflorus*); short-lived species—rangiora (*Brachyglottis repanda*), pate (*Scheffliera digitata*), fivefinger (*Pseudopanax arboreus*), makamaka (*Ackama rosifolia*), *Pittosporum* sp., *Coprosma* sp., *Olearia* sp.

Wk-1087. O06/170 **360 ± 50**
Charcoal $\delta^{13}C = -22.3‰$

Comment: (M.T.) Date of occupation of pit site O06/170, Waipoua Forest.

N.B.: charcoal consisted of mainly short-lived species; makamaka (*Ackama rosifolia*), rata vine (*Metrosideros robusta*), rangiora (*Brachyglottis repanda*), putaputaweta (*Carpodetus serratus*), also some ponga (*Cyathea dealbata*).

Wk-1088. O06/170-12 **480 ± 45**
Charcoal $\delta^{13}C = -25.8‰$

Comment: (M.T.) Date of occupation of pit site O06/170.

N.B.: charcoal was unidentified shrub species, all twig wood.

AUCKLAND

Theatre Lane, Auckland City (R11/1559)

(Submitted by S. Best, Department of Anthropology, Auckland University)

Wk-1142. R11/1559-C14/1 **850 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.6‰$

Comment: (S.B.) The first date associated with Maori occupation in central Auckland and its relationship to forest clearance in the area.

Wk-1143. R11/1559-C14/2 **750 ± 50**
Wood $\delta^{13}C = -25.3‰$

Comment: (S.B.) Dates of deforestation in the Waihorotiu Stream watershed, and whether this occurred within the period of human occupation.

N.B.: wood was described as "leaf litter". See Best (1992).

Newmarket site (R11/1694)

(Submitted 24 April 1991 by D. Wilson, Department of Anthropology, University of Auckland)

Wk-2051. **Modern**
Charcoal $\delta^{13}C = -24.8‰$

Comment: (D.W.) A ^{14}C date (charcoal) excavated at site R11/1694 Auckland from prehistoric earth oven.

N.B.: charcoal identified as *Coprosma* sp. and twigs—kohekohe (*Dysoxylum spectabile*).

Cryers Road, Tamaki (R11/1519)

(Submitted 20 October 1987 by C. Fredericksen and E. Visser, New Zealand Historic Places Trust, Private Bag, Auckland)

Wk-1126. LN1 — **300 ± 50**
Charcoal — $\delta^{13}C = -24.8‰$

Comment: (C.F./E.V.) Dates important in establishing the phases of activity on the terrace site, able to correlate it with ^{14}C dates from terrace and R11/1519; activities associated with occupants of Green Mount, East Tamaki.

N.B.: charcoal identified as *Hebe* sp., fern, ngaio (*Myoporum laetum*), kapuka (broadleaf) (*Griselinia littoralis*), tawa (*Beilschmeidia tawa*), lancewood (horoeka) (*Pseudopanax crassifolius*), *Nestigis* sp., matai (*Prumnopitys taxifolia*).

Wk-1127. LN3 — **750 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.4‰$

Comment: (C.F./E.V.) Dates are important in establishing the length of prehistoric Maori activity in East Tamaki and the Auckland region generally.

Wk-1128. LN4 — **700 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +0.7‰$

Comment: (C.F./E.V.) as above.

Wk-1129. LN5 — **670 ± 40**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +0.7‰$

Comment: (C.F./E.V.) as above.

Wk-1130. LN6 — **590 ± 40**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.0‰$

Comment: (C.F./E.V.) as above.

Wk-1131. LN7 — **510 ± 40**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.0‰$

Comment: (C.F./E.V.) as above.

Wk-1132. LN8 — **680 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +0.5‰$

Comment: (C.F./E.V.) as above.

Wk-1133. LN9 — **690 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.2‰$

Comment: (C.F./E.V.) Dates will give archaeologists a time period in which this particular site was utilized. Dates can be compared to others in the Auckland area. Sample taken from a low-level (in terms of archaeological stratigraphy) fire scoop. This means that this could give us the earliest date for the site.

Wk 1134. LN10 — **520 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = -1.3‰$

Comment: (C.F./E.V.) Sample will date the latter phase of activity on the terrace (FA41) and, combined with samples LN1 and LN9, will define the time period during which the terrace was utilized.

N.B.: see Fredericksen and Visser (1989, 1991).

Westfield site, George Bourke Drive, Tamaki (R11/898)

(Submitted by B. Sewell, Department of Conservation, Auckland)

Wk-1720. 268 **630 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.4‰$

Wk-1721. 269 **540 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.5‰$

Wk-2030. **340 ± 45**
Charcoal $\delta^{13}C = -30.1‰$

N.B.: charcoal identified as mamaku (*Cyathea medullaris*).

Te Apunga o Tainui, Panama Road, Tamaki (R11/10)

(Submitted by B. Sewell, Department of Conservation, Auckland)

Wk-1722. 270 **680 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.7‰$

Tamaki River series (R11/1506)

(Submitted 4 December 1990 by R. Foster, Department of Conservation, Auckland)

Wk-1940. ACI/R/506 F65 **730 ± 35**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.3‰$

Comment: (R.F.) Dates occupation of *paa* site R11/1506.

Wk-1941. ACI/R/506 F33 **720 ± 35**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.4‰$

Comment: (R.F.) as above.

Wk-1942. ACI/R/82 **670 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.2‰$

Comment: (R.F.) as above.

Wk-1943. ACI/R/383 **750 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.9‰$

Comment: (R.F.) as above.

Wk-1944. ACI/R/420 **680 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.1‰$

Comment: (R.F.) as above.

Wk-1945. ACI/R/421 **690 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.5‰$

Comment: (R.F.) as above.

Tamaki (R11/1201)

(Submitted 4 December 1990 by B. Sewell, Department of Conservation, Auckland)

Wk-1946. 120/-2/90 **690 ± 35**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = 0.0‰$

Tamaki (R11/1591)

(Submitted 21 January 1993 by D. Veart, Department of Conservation, Auckland)

Wk-2810. Sample 1 **720 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.3‰$

Wk-2811. Sample 24 **690 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.2‰$

N.B.: see Bulmer (1994) for discussion and list of ^{14}C determinations from Tamaki.

Crater Hill, Waiokauri Creek, Papatoetoe (R11/602)

(Submitted 19 March 1991 by R. Foster, Department of Conservation, Auckland)

Wk-2023. **320 ± 45**
Charcoal $\delta^{13}C = -27.4‰$

N.B.: charcoal identified as 95% *Hebe* twigs.

Wk-2024. **330 ± 45**
Charcoal $\delta^{13}C = -25.8‰$

N.B.: charcoal identified as 90% *Hebe* twigs and 10% *Pseudopanax* sp. twigs.

Otahuhu *paa* (R11/13)

(Submitted 25 February 1991 by B. Sewell, Department of Conservation, Auckland)

Wk-2013. **600 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.2‰$

Manukau sites (R11/1800 and R11/229)

(Submitted 23 June 1994 by R. Foster, Department of Conservation, Auckland)

Wk-3313. R11/1800/P13 **630 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = 0.0‰$

Comment: (R.F.) Date for site R11/1800.

Wk-3314. R11/1800/P21 **540 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Comment: (R.F.) as above.

Wk-3315. R11/229/BP1 **490 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.2‰$

Comment: (R.F.) Check on traditional date for site R11/229.

Wk-3316. R11/229/EL1 **750 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.4‰$

Comment: (R.F.) Earliest occupation of R11/229.

Wk-3317. R11/229/GM1 **520 ± 40**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.2‰$

Comment: (R.F.) Check on traditional date for site R11/229.

Clevedon (S11/108)

(Submitted 21 November 1992 by A.Young, Department of Anthropology, University of Auckland)

Wk-2756. Sample 5 layer 3, sq 3–4 **320 ± 50**
Charcoal $\delta^{13}C = -25.6‰$

Comment: (A.Y.) Sample will date site to investigate association with neighboring *paa*.
N.B.: charcoal identified as mahoe (*Melicytus ramiflorus*), *Olearia* sp., *Pittosporum* sp. (*eugenioides?*), *Coprosma* sp., fivefinger (whauwhaupaku) (*Pseudopanax arboreus*), mangrove (*Avicennia resinifera*) and lancewood (horoeka) (*Pseudopanax crassifolius*).

Wk-2757. Sample 9 layer 2, sq 5 **360 ± 50**
Charcoal $\delta^{13}C = -26.1‰$

Comment: (A.Y.) To help date site in order to ascertain association with neighboring *paa*.
N.B.: charcoal identified as *Olearia* sp., *Coprosma* sp., manuka (*Leptospermum scoparium*), pohutukawa (*Metrosideros excelsa*)/kanuka (*Kunzea ericoides*), tarairi (*Beilschmeidia tarairi*).

WAIKATO

Waikorea Beach (R14/256)

(Submitted 10 September 1990, by N. Ritchie, Department of Conservation, Hamilton)

Wk-1899. W1 **560 ± 40**
Charcoal $\delta^{13}C = -25.7‰$

N.B.: charcoal was identified; no notes attached on sample constituents.

Horotiu (S14/16)

(Submitted August 1984 by B.G. McFadgen, New Zealand Historic Places Trust, Wellington)

Wk-502. Sample 1 **150 ± 50**
Charcoal $\delta^{13}C = -26.0‰$

Comment: (B.G.McF.) Sample will give a minimum date for "plaggen" soil on Taupo Pumice river terrace at Horotiu.
N.B.: charcoal identified as *Coprosma*/*Pittosporum* sp. (codominant) and *Leptospermum* sp. (subdominant).

Wk-503. Sample 2 **670 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = 1.9‰$

Comment: (B.G.McF.) as above. *N.B.*: see McFadgen (1982b).

Hamilton borrow pit sites

(Submitted 15 September 1992 by D. J. Lowe, University of Waikato, Hamilton)

Wk-2702. S14/164 Horotiu Road 1 **1100 ± 80**
Charcoal $\delta^{13}C = -26.9‰$

Comment: (D.J.L.) Attempt to date Maori modification of soils.

N.B.: charcoal identified as small vine sp. (*Metrosideros* sp.), 9 pieces; mangemange (*Lygodium articulatum*), 1 pc; conifer twig, 1 pc; shrub sp. (*Pseudopanax* sp.?), 6 pc; bark fragments, 2 pc; fern leaf midribs, 2 pc; ribbonwood (*Hoheria* sp.), 1 pc; unidentified shrub species, 1 pc; titoki (*Alectryon excelsus*), 1 pc; tawa (*Beilschmiedia tawa*), 3 pc; totara (*Podocarpus totara*), 3 pc. Species 1–8 were bagged separately for dating. Two of the totara pieces were in the form of water-rolled pebbles, which implies that the whole sample may have inherent provenience problems.

Wk-2703. S14/164 Horotiu Road 2 **900 ± 70**
Charcoal $\delta^{13}C = -24.9‰$

Comment: (D.J.L.) As above.
N.B.: charcoal identified as totara (*Podocarpus totara*), 4 pieces and matai (*Prumnopitys taxifolia*), 3 pc.

Wk-2704. S14/164 Horotiu Road 3 **800 ± 50**
Charcoal $\delta^{13}C = -25.1‰$

Comment: (D.J.L.) As above.
N.B.: charcoal identified as rimu (*Dacrydium cupressinum*), 2 pieces; totara (*Podocarpus totara*), 3 pc; kahikatea (*Dacrycarpus dacrydioides*), 8 pc.

Wk-2705. S14/204 Kay Road 1 **310 ± 150**
Charcoal $\delta^{13}C = -27.4‰$

Comment: (D.J.L.) As above.
N.B.: tawa twigs (*Beilschmeidia tawa*), 6 pieces; tawa, 10 pc.

Wk-2706. S15/378 Old School Road, Waipa **940 ± 100**
Charcoal $\delta^{13}C = -26.4‰$

Comment: (D.J.L.) As above.
N.B.: charcoal identified as tawa twigs (*Beilschmeidia tawa*), 6 pieces; bark fragments, 3 pc; rewarewa (?) (*Knightia excelsa*), 2 pc.

Kawhia

(Submitted March 1978 by C. F. Pain, Geography Department, University of Papua New Guinea, Port Moresby)

Wk-31. CFP 1 **660 ± 120**
Charcoal $\delta^{13}C = -25.0‰$

Comment: (C.P.) Date indicates 1) minimum age for the dune building phase prior to development of the Parangi soils, 2) time of Maori occupation in the area.
N.B.: $\delta^{13}C$ value estimated.

Lake Taharoa

(Submitted March 1978 by C. F. Pain, Geography Department, University of Papua New Guinea, Port Moresby)

Wk-33. CFP 3 **380 ± 110**
Charcoal *$\delta^{13}C$ = −25.0‰*

Comment: (C.P.) Date indicates 1) minimum age for the dune building phase prior to development of the Parangi soils, 2) time of Maori occupation in the area.
N.B.: $\delta^{13}C$ value estimated. See Pain (1979).

Arapuni (T15/223)

(Submitted 29 October 1992 by D. J. Lowe, University of Waikato, Hamilton)

Wk-2736. A1 **940 ± 100**
Charcoal *$\delta^{13}C$ = −26.4‰*

N.B.: charcoal identified as matai (*Prumnopitys taxifolia*), 10 pieces; kaikomako (*Pennantia corymbosa*), 1 pc; shrub sp., 3 pc.

Wk-2737. A2 **1220 ± 50**
Charcoal *$\delta^{13}C$ = −26.0‰*

Comment: (D.J.L.) Attempt to date Maori modification of soils. Sample A2 may relate to pre-Maori geomorphic event.
N.B.: sample was unidentified wood.

Wk-2738. A3 **5190 ± 60**
Shell (*Hyridella menziesii*) *$\delta^{13}C$ = −4.7‰*

Comment: (D.J.L.) Attempt to date Maori modification of soils indirectly, sample dates occupation at Arapuni site. Shells occur in topsoil directly overlying volcanogenic alluvium (Hopuhopu Sand Member of Taupo Pumice Alluvium) that was deposited after eruption of Taupo Tephra, 1850 BP. Dates on charcoal in this alluvium nearby confirm timing of deposition (Wk-2974–2976; D. J. Lowe, personal communication 1993). Thickness of shells is unusual, but not unknown (B. Hayward, personal communication 1993).
N.B.: shells were identified as freshwater *Hyridella menziesii* by B. Hayward, Auckland Museum.

COROMANDEL PENINSULA/THAMES VALLEY

Te Maketu, North Coralie Bay, Great Mercury Island

(Submitted 10 December 1976 by S. Edson, Waikato Art Museum, Hamilton)

Wk-94. **410 ± 130**
Charcoal *$\delta^{13}C$ = −25.0‰*

Comment: (S.E.) Sample derived from a large oven area associated with an extensive working floor, some 200–300 m^2 of which has been seriously affected by erosion and wandering stock. Site appears to be spatially substantial but probably occupied only once.
N.B.: charcoal was not identified; $\delta^{13}C$ value estimated.

Whangapoua Forest series

(Submitted 17 February 1987 by L. Furey, New Zealand Forest Service, P.O. Box 39, Auckland)

Wk-968. T11/644 Area 1 **940 ± 45**
Wood $\delta^{13}C = -28.5‰$

Comment: (L.F.) Dating of prehistoric Maori occupation of inland terrace structure at Whangapoua, Coromandel.
N.B.: wood identified as maire branchwood (*Nestigis* sp.).

Wk-969. T11/636 **780 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.8‰$

Wk-970. T11/643-4 **840 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +3.1‰$

Comment: (L.F.) To date open settlement occupation at Whangapoua, Coromandel.

Wk-971. T11/679-22 Area B **850 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +2.4‰$

Comment: (L.F.) To date use of site.

Wk-972. T11/661 **790 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +2.4‰$

Wk-973. T11/644, trench 2, 4.5 **720 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +2.1‰$

Comment: (L.F.) To date open settlement (Maori) at Whangapoua, Coromandel.

Wk-974. T11/635 **840 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.9‰$

Wk-975. T11/648-18 G40 spit 9 **770 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +2.1‰$

Comment: (L.F.) To date open settlement occupation at Whangapoua.

Kaimarama *paa*, Whitianga

(Submitted 1988 by H. Larsen, Ferry Landing, RD. 1, Whitianga)

Wk-1151. **640 ± 45**
Shell (*Paphies subtriangulatum*/*Austrovenus*/gastropods) $\delta^{13}C = +1.0‰$

Comment: (H.L.) Determination of occupancy date of site.

Paku, Tairua (T11/308)

(Submitted 6 December 1993 by C. Barr, Department of Conservation, Hamilton)

Wk-3100. Paku Sample 1 **710 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.8‰$

Comment: (C.B.) Date will provide information regarding the occupation of midden site.

Tairua (T11/805)

(Submitted 17 September 1994 by C. Barr, Department of Conservation, Hamilton)

Wk-3385. Sample 18 **820 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.3‰$

Wk-3386. Sample 15 **760 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +1.2‰$

Tairua (T11/300)

(Submitted 30 June 1995 by C. Barr, Department of Conservation, Hamilton)

Wk-3952. T11/300/1 **660 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +1.0‰$

Wk-3953. T11/300/2 **680 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = -1.2‰$

Whitipirorua, Onemana (T12/16)

(Submitted 13 May 1988 by L. Furey, Department of Conservation, Auckland)

Wk-1169. Square 4, layer 2 **870 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Wk-1515. Square 8, layer 5 **990 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +0.9‰$

N.B.: see Furey (1991). Wk-1515 submitted on 17 August 1989.

Whangamata (T12/654)

(Submitted by S. Short, Department of Anthropology, University of Auckland)

Wk-1153. Sample 1 **670 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.3‰$

Comment: (S.S.) Dating of second phase of occupation on terrace 1 at T12/654, an open settlement site at Whangamata.

Wk-1154. Sample 2 **700 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.8‰$

Comment: (S.S.) Dating of initial occupation on Terrace 1 at T12/654, an open settlement at Whangamata.

Wk-1156. T12/654 sample 6 **730 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +2.0‰$

Comment: (S.S.) To date initial occupation of terrace 3 at T12/654, an open settlement site at Whangamata.

Wk-1157. T12/654 sample 11 **580 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.4‰$

Comment: (S.S.) Dating of occupation at two adjacent terraces (5 and 6) at T12/654, an open settlement site at Whangamata.

Puriri series

(Submitted 10 August 1992 by S. Bedford and H. Allen, Department of Anthropology, University of Auckland)

Wk-2640. T12/882 Midden F Sample 1 **Modern**
Charcoal $\delta^{13}C = -27.2‰$

Comment: (S.B.) Only way of dating a now destroyed midden.
N.B.: wood identified as bark (2 species), manuka (*Leptospermum scoparium*), mapou (*Myrsine australis*), *Hebe* sp.

Wk-2641. T12/340 Area D2 Sample 2 **Modern**
Charcoal $\delta^{13}C = -25.3‰$

N.B.: wood identified as manuka (*Leptospermum scoparium*), 10 pieces; fivefinger (*Pseudopanax arboreus*), 1 pc; *Hebe* sp., 5pc; mahoe (*Melicytus ramiflorus*), 1 pc; *Coprosma* sp., 1 pc; *Olearia* sp, 1 pc; tawheowheo (*Quintinia serrata*), 2 pc.

Wk-2642. T12/885 Sq H Sample 3 **Modern**
Charcoal $\delta^{13}C = -25.6‰$

N.B.: wood identified as manuka (*Leptospermum scoparium*), 8 pieces; Akeake (*Dodonaea viscosa*), 6 pc; *Pittosporum* sp., 1 pc; *Hebe* sp., 1 pc; rangiora (*Brachyglottis repanda*), 1 pc.

Wk-2643. T12/882 Midden F Sample 4 **590 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +0.8‰$

N.B.: same provenience as sample Wk-2640.

Wk-2644. T12/340 Area D2 Sample 5 **610 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.6‰$

N.B.: same provenience as sample Wk-2641.

Wk-2645. T12/885 Sq H Sample 6 **610 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.5‰$

N.B.: same provenience as sample Wk-2642.

Wk-2646. T12/883 Sq H Sample 7 **550 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.5‰$

Comment: (S.B.) This site is an historic Maori site which dates to *ca.* 1860. However, dead shell may have been brought into the area to build up the site, rather than for consumption, hence the interest in the date of the shell.
N.B.: see Bedford and Allen (1993).

Hurumoimoi *paa*, Kopu (T12/347)

(Submitted 25 March 1993 by T. Doelman and H. Allen, Department of Anthropology, University of Auckland)

Wk-2852. S1375 layer 5 **380 ± 50**
Charcoal $\delta^{13}C = -26.0‰$

Comment: (T.D./H.A.) The charcoal sample may mark the initial exploration and settlement of the area. It may show land clearance and time of occupation.

N.B.: charcoal was identified as manuka (*Leptospermum scoparium*), 7 pieces; *Hebe* sp., 12 pc; *Pittosporum* sp., 4 pc; fivefinger (*Pseudopanax arboreus*), 5 pc; unidentified shrub species, 2 pc.

Wk-2853. B1809 layer 3 **Modern**
Charcoal $\delta^{13}C = -26.0‰$

Comment: (T.D./H.A.) The charcoal sample marks a single event within a prehistoric occupation. It will date a hangi [earth oven—*T.H.*] found during excavation and may give a time depth for the *paa*.

N.B.: charcoal was identified as *Olearia* sp., 9 pieces; *Hoheria* sp. (ribbonwood/lacebark), 3 pc; mangrove (*Avicennia resinifera*), 5 pc; akeake (*Dodonaea viscosa*), 1 pc; manuka (*Leptospermum scoparium*), 5 pc; unidentified shrub species, 1 pc.

N.B.: see Doelman (1995).

Wk-2854. B1809 layer 3 shell **670 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = -0.8‰$

Comment: (T.D./H.A.) as for Wk-2853.

Waihou River series

(Submitted 15 April 1993 by H. Allen, Department of Anthropology, University of Auckland)

Wk-2872. Orurukumatua *paa* T12/569 Sample 1/2 **690 ± 50**
Shell (Marine species) $\delta^{13}C = +1.1‰$

Comment: (H.A.) Will aid in reconstruction of settlement along the Waihou River.

Wk-2873. Whetukura *paa* T12/345 Sample 2/2 layer 2 **770 ± 50**
Shell (Marine species) $\delta^{13}C = +0.6‰$

Comment: (H.A.) Comparison with nearby site of Oruarangi *paa*. Sample marks expansion of site to much larger defended settlement.

Wk-2874. Whetukura *paa* T12/345 Sample 2/2 layer 5 **710 ± 50**
Shell (Marine species) $\delta^{13}C = -1.0‰$

Comment: (H.A.) Comparison with nearby site of Oruarangi *paa*. Sample marks initial occupation of what was to become one of the largest *paa* sites in the region.

Wk-2875. Turua *paa* T12/789 **550 ± 50**
Shell (Marine species) $\delta^{13}C = +0.7‰$

Comment: (H.A.) Comparison with other *paa* constructed in area. Should date first defense of site.

Whetukura *paa* (T12/345)

(Submitted 14 June 1993 by H. Allen, Department of Anthropology, University of Auckland)

Wk-2949. Whetukura *paa* T12/345 Sample 1/1 layer 4 **210 ± 90**
Charcoal $\delta^{13}C = -27.3‰$

Comment: (H.A.) Will aid in reconstruction of settlement along the Waihou River.
N.B.: charcoal identified as mapou (*Myrsine australis*), putaputaweta (*Carpodetus serratus*), mahoe (*Melicytus ramiflorus*), lancewood (horoeka) (*Pseudopanax crassifolius*), ramarama (*Lophomyrtus bullata*), *Dracophyllum* sp., manuka (*Leptospermum scoparium*), unidentified shrub and bark.

Wk-2950. Whetukura *paa* T12/345 Sample 2/1 layer 2 **350 ± 50**
Charcoal $\delta^{13}C = -26.0‰$

Comment: (H.A.) Comparison with nearby site of Oruarangi *paa*. Samples marks expansion of site to much larger defended settlement.
N.B.: charcoal identified as akeake (*Dodonaea viscosa*), *Hebe* sp., manuka (*Leptospermum scoparium*), fivefinger (*Pseudopanax arboreus*) (whauwhaupaku), lancewood (horoeka) (*Pseudopanax crassifolius*), ramarama (*Lophomyrtus bullata*), *Olearia* sp., unidentified shrub.

Wk-2951. Whetukura *paa* T12/345 Sample 2/3 layer 5 **320 ± 90**
Charcoal $\delta^{13}C = -25.4‰$

Comment: (H.A.) Comparison with nearby site of Oruarangi *paa*. Sample marks initial occupation of what was to become one of the largest *paa* sites in the region.
N.B.: charcoal identified as fivefinger (*Pseudopanax arboreus*) (whauwhaupaku), *Pittosporum* sp., *Dracophyllum* sp., unidentified shrub.

Pukehue *paa* (T12/299)

(Submitted 22 September 1993 by H. Allen, Department of Anthropology, University of Auckland)

Wk-3038. Area A, layer 2 **Modern**
Charcoal $\delta^{13}C = -25.0‰$

Comment: (H.A.) Dates the occupation of the foothills in a general comparison to the low-lying swamp *paa*. A settlement movement may be defined.
N.B.: charcoal identified as manuka (*Leptospermum scoparium*), *Hebe* sp., fivefinger (*Pseudopanax arboreus*) (whauwhaupaku), *Dracophyllum* sp. See Allen *et al.* (1994).

Raupa, Ohinemuri River, Paeroa (T13/13)

(Submitted 22 March 1991 by N. Prickett, Auckland Institute and Museum, Auckland)

Wk-2039. **510 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = 0.0‰$

Wk-2040. **620 ± 50**
Shell (*Paphies/Austrovenus*) $\delta^{13}C = +0.7‰$

Wk-2041. **Modern**
Charcoal $\delta^{13}C = -27.9‰$

N.B.: charcoal was identified *Coprosma* sp., 8 identifications. See Prickett (1992).

BAY OF PLENTY

Tauwhare 2, Whakatane (W15/35)

(Submitted 7 June 1990, by K. Jones, Department of Conservation, Wellington)

Wk-1765. Tauwhare 2 — **670 ± 45**
Shell (*Paphies australis*) — $\delta^{13}C = +1.3‰$

Comment: (K.J.) Date gives maximum age for principal surviving defensive earthworks of a major *paa* in the Whakatane area.
N.B.: see Bowers and Jones (1991).

Papamoa

(Submitted 28 September 1992 by D. Kahotea, Te Ongaonga Rd, RD1, Tauranga)

Wk-2713. Sample 2 — **800 ± 50**
Shell (*Paphies australis*) — $\delta^{13}C = +0.8‰$

Comment: (D.K.) Important for cultural layer date.

Wk-2714. Sample 2 lens B — **540 ± 50**
Shell (*Paphies australis*) — $\delta^{13}C = +1.3‰$

Comment: (D.K.) as above.

Wk-2715. Area 2 knoll — **490 ± 50**
Shell (*Paphies australis*) — $\delta^{13}C = +1.2‰$

Comment: (D.K.) as above.

Wk-2716. A-sample in wall — **830 ± 60**
Shell (*Paphies australis*) — $\delta^{13}C = +1.3‰$

Comment: (D.K.) as above.

Wk-2717. R14, T2 S1 — **650 ± 50**
Shell (*Paphies australis*) — $\delta^{13}C = +1.5‰$

Comment: (D.K.) as above.

Royal Palm Beach, Papamoa (U14/1717)

(Submitted 31 January 1995 by R. McGovern-Wilson, SouthernArc, P.O. Box 9004, Dunedin)

Wk-3623. RPB/1 Area 2 — **690 ± 50**
Shell (*Paphies subtriangulatum*) — $\delta^{13}C = +2.2‰$

Comment: (R.McG.-W.) The midden from which this sample derived is a concentrated area within a large (*ca*. 400 m^2) midden scatter, and is one of a number of dates submitted to detail the period of coastal activity in the vicinity of Papamoa.

Wk-3630. RPB/2 Area A midden 5 — **760 ± 50**
Shell (*Paphies subtriangulatum*) — $\delta^{13}C = +1.8‰$

Comment: (R.McG.-W.) These date a large midden scatter and appear to date to a significantly earlier period of Papamoa than previously recorded.

Wk-3631. RPB/3 Area A midden 13 **820 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.0‰$

Comment: (R.McG.-W.) as above.

Wk-3632. RPB/4 Area A midden 15 layer 3 **760 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.4‰$

Comment: (R.McG.-W.) as above.

Wk-3633. RPB/5 Area B midden 3 **730 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.7‰$

Comment: (R.McG.-W.) as above.

Wk-3634. RPB/6 Area E **810 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.8‰$

Comment: (R.McG.-W.) as above.

Wk-3635. RPB/7 Area G midden 2 **690 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.8‰$

Comment: (R.McG.-W.) as above.

Papamoa (U14/2841)

(Submitted 25 October 1995 by C. Fredericksen, P.O. Box 91206, Auckland)

Wk-4189. ^{14}C 1 **800 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.3‰$

Comment: (C.F.) Dates first use of the terrace. Eastern Bay of Plenty culture history.

Wk-4190. ^{14}C 3 **730 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.2‰$

Comment: (C.F.) Date of infilling of "bin pit". Eastern Bay of Plenty culture history.

Wk-4191. ^{14}C 4 **840 ± 50**
Shell (*Struthiolaria papulosa*) $\delta^{13}C = +1.1‰$

Comment: (C.F.) Dates final stage of terrace use. Eastern Bay of Plenty culture history.

Wk-4192. ^{14}C 5 **760 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.3‰$

Comment: (C.F.) as above.

Tupitika *paa*, Whakatane (W15/9)

(Submitted 2 June 1995 by R. McGovern-Wilson, SouthernArc, P.O. Box 9004, Dunedin)

Wk-3750. TP/1 **710 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +1.6‰$

Comment: (R.McG.-W.) The *rua* [subterranean storage pit—*T.H.*] from which these samples derive was being used for dumping midden in. The dates will provide an indication of when the *paa* was being occupied.

Wk-3754. TP/2 **660 ± 50**
Shell (*Paphies australis*) $\delta^{13}C = +1.1‰$

Comment: (R.McG.-W.) as above.

Athenree (U13/46)

(Submitted 2 June 1995 by R. McGovern-Wilson, SouthernArc, P.O. Box 9004, Dunedin)

Wk-3751. WA/1 **660 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.1‰$

Comment: (R.McG.-W.) The features from which these samples derive are from an early phase of the *paa* development and will date, or approximate, when the *paa* was built.

Wk-3755. WA/2 **720 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.3‰$

Comment: (R.McG.-W.) as above.
N.B.: See Phillips and Allen (1996) for further dating and discussion.

Robbie's Midden, Tarawera River, East of Rangitaiki Plains (V15/1209)

(Submitted 2 June 1995 by R. McGovern-Wilson, SouthernArc, P.O. Box 9004, Dunedin)

Wk-3752. MP/1 **600 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.5‰$

Comment: (R.McG.-W.) It is predicted that this site may be from the early prehistoric period and will mark early settlement on the Rangitaiki Plains.

Uretara Island, Ohiwa Harbour (W15/363)

(Submitted 2 June 1995 by R. McGovern-Wilson, SouthernArc, P.O. Box 9004, Dunedin)

Wk-3753. MP/2 **600 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.5‰$

Comment: (R.McG.-W.) There are many shell middens around the Ohiwa Harbour—this may be one of the earlier ones; it is sitting near the surface of a Taupo ash fall.

Kawerau sites

(Submitted 21 April 1990, by I. T. Lawlor, Taiapa Road, Waimauku)

Wk-1740. 171#1 (Site V16/211) **460 ± 55**
Charcoal $\delta^{13}C = -29.0‰$

Comment: (I.T.L.) Age estimate of occupation of site V16/211, Kawerau, Bay of Plenty.
N.B.: charcoal identified as mahoe (*Melicytus* sp., *ramiflorus* or *lanceolatus*).

Wk-1741. 774 (adjacent to site V16/243) **400 ± 55**
Charcoal $\delta^{13}C = -27.8‰$

Comment: (I.T.L.) Age estimate for valley gardening adjacent to site V16/243, Kawerau, Bay of Plenty.
N.B.: wood identified as *Hebe* sp.

Wk-1742. 1070 (Site V16/220) **360 ± 55**
Charcoal $\delta^{13}C = -26.4‰$

Comment: (I.T.L.) Age estimate for occupation of site V16/220. Comparative date for adjacent shell midden age estimate.
N.B.: wood identified as *Hebe* sp. and manuka (*Leptospermum scoparium*).

Wk-1743. 1278 (Site V16/220) **520 ± 80**
Charcoal $\delta^{13}C = -26.4‰$

Comment: (I.T.L.) Age estimate of occupation of site V16/220. Comparative date for adjacent shell midden and hangi age estimates.
N.B.: wood is 95% tree fern trunk (ponga, *Cyathea dealbata*) and tanekaha or toatoa (*Phyllocladus*) sp.

Wk-1744. 1514 (Site V16/219) **370 ± 55**
Charcoal $\delta^{13}C = -25.5‰$

Comment: (I.T.L.) Age estimate of occupation of site V16/219. Postdates use of large kumara storage pit.
N.B.: charcoal is kanuka (*Kunzia ericoides*).

Wk-1745. 1572 (Site V16/219) **350 ± 55**
Charcoal $\delta^{13}C = -29.0‰$

Comment: (I.T.L.) Age estimate of occupation of site V16/219. Use of large kumara storage pit.
N.B.: wood is ponga (*Cyathea dealbata*).

Hamurana, Lake Rotorua (U15/35)

(Submitted 13 May 1988 by D. Kahotea, Department of Social Anthropology, University of Waikato)

Wk-1218. **Modern**
Charcoal $\delta^{13}C = -27.4‰$

Wk-1219. **230 ± 125**
Charcoal $\delta^{13}C = -26.6‰$

Wk-1220. **280 ± 50**
Charcoal $\delta^{13}C = -26.5‰$

Wk-1221. **Modern**
Charcoal $\delta^{13}C = -32.5‰$

Wk-1222. **Modern**
Charcoal $\delta^{13}C = -27.1‰$

N.B.: all dates on unidentified charcoal.

HAWKES BAY/EAST COAST

Tolaga Bay (Z17/211)

(Submitted December 1987 by K. Jones, Department of Conservation, Wellington)

Wk-1147. Z17/211 TGB 4 **350 ± 125**
Charcoal $\delta^{13}C = -25.2‰$

Comment: (K.J.) A maximum age for defensive ditch and bank of *paa* Z17/211, Tolaga Bay, New Zealand.

N.B.: Wood is *Hebe* and *Coprosma* sp. twigs and fern stems.

Wk-1148. TGB 10 **370 ± 70**
Charcoal $\delta^{13}C = -24.0‰$

Comment: (K.J.) Minimum age for *paa* fortification on East Coast, New Zealand.

N.B.: wood is *Pseudopanax* sp., tawa (*Beilschmeidia tawa*), *Hedycarya* sp., *Coprosma* twigs, fern stems, rangiora (*Brachyglottis repanda*). See Jones (1990).

Hawkes Bay series

(Submitted 11 December 1990 by M. Allen, Department of Anthropology, University of California at Los Angeles)

Heipipi *paa* (V20/9–14)

Wk-1956. Unit 1A **730 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = -0.1‰$

Comment: (M.A.) Date is for a shell midden directly associated with a traditionally important and early *paa* in Hawkes Bay.

Wk-1957. Unit 2 **680 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 0.4‰$

Comment: (M.A.) as above.

Wk-1958. Unit 4 **700 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = -0.2‰$

Comment: (M.A.) as above.

Wk-3048. **880 ± 50**
Shell (unknown) $\delta^{13}C = 0.8‰$

N.B.: Wk-3048 submitted 28 October 1993 by E. Pishief, 3 Hulcarere Road, Gisborne.

Matanginui *paa*, Waimarama Beach (V22/95)

Wk-1959. Unit 1 **500 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.3‰$

Comment: (M.A.) Date is for occupation of a traditionally important *paa* at Waimarama, Hawkes Bay.

Wk-1960. Unit 2 **520 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.9‰$

Comment: (M.A.) as above.

Wk-1961. Unit 3 **480 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.9‰$

Comment: (M.A.) as above.

Motukumara *paa*, Lake Oingo (V21/45)

Wk-1962. Unit 1, postholes 2-4 **220 ± 50**
Charcoal $\delta^{13}C = -25.8‰$

Comment: (M.A.) Dating midden layer with much charcoal associated with three postholes full of charcoal. The charcoal does not directly date the posts as it comprises many species. Provides a minimum age for fill and midden used to build up major defense on an inland freshwater *paa*.

N.B.: charcoal species identified as bark, sevenfinger, ribbonwood (*Hoheria* sp.), *Hebe* sp., *Coprosma* sp., mahoe (*Melicytus ramiflorus*), ngaio (*Myoporum laetum*), fivefinger (*Pseudopanax arboreus*), and other shrubs.

Wk-1963. Hangi feature 1 **Modern**
Charcoal $\delta^{13}C = -25.4‰$

Comment: (M.A.) Hangi sits on terrace and midden fill—postdates terrace construction on a strongly defended *paa* on a small freshwater lake in inland Hawkes Bay.

N.B.: charcoal identified as lancewood twigs (*Pseudopanax crassifolius*), sevenfinger, karaka twig (*Corynocarpus laevigatus*). Date from a hangi on rim of terraced *paa*.

Wk-1964. **Modern**
Charcoal $\delta^{13}C = -24.0‰$

Comment: (M.A.) Date for burning off of bracken fern prior to *paa* construction on inland freshwater lake in Hawkes Bay.

N.B.: charcoal identified as 80% bracken fern, sevenfinger, pate (*Scheffliera digitata*).

Manawarakau *paa*, Kairakau beach (V22/267 and V22/268)

Wk-1965. Unit 1 layer C **560 ± 50**
Shell (*Lunella smaragda*) $\delta^{13}C = +1.9‰$

Comment: (M.A.) Bottom layer of shell midden on slope below terrace of important coastal *paa* in Hawkes Bay.

Wk-1966. Unit 2 **590 ± 40**
Shell (*Lunella smaragda*) $\delta^{13}C = +2.1‰$

Comment: (M.A.) Shell midden postdates a defensive terrace on an important coastal *paa* in Hawkes Bay.

Wk-1967. Unit 3 **680 ± 40**
Shell (*Lunella smaragda*) $\delta^{13}C = +2.1‰$

Comment: (M.A.) Midden below likely house terrace on important coastal *paa* of Hawkes Bay.

Poto *paa*, Ahuriri (V21/9)

Wk-2130. Unit 1, 0-10 cm **660 ± 55**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.1‰$

Comment: (M.A.) Minimum age for defensive bank on headland *paa* above inner harbor of Hawke's Bay.

Wk-2131. Unit 1, layer D **790 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.9‰$

Comment: (M.A.) as above.

Koutouroa *paa*, Wharerangi district, Ahuriri (V21/26)

Wk-2132. No. 80 Unit 1 **750 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = 0.9‰$

Comment: (M.A.) Date for shell midden on *paa* site along former inner harbor of Hawke's Bay.

Wk-2133. No. 81 Unit 2 **840 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.6‰$

Comment: (M.A.) as above.

Wk-2134. No. 82 Unit 3 **710 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.1‰$

Comment: (M.A.) as above.

Te Mingi *paa*, Tutaekuri River (V21/49)

Wk-2135. Unit 1, No 3 **710 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +0.1‰$

Comment: (M.A.) Date for midden high on slope of large *paa* on the Tutaekuri river, Hawke's Bay.

Mangawharau *paa*, Waimarama Beach (W22/152)

Wk-2136. Unit 1, No 58 **640 ± 50**
Shell (*Haliotis* sp.) $\delta^{13}C = +1.3‰$

Comment: (M.A.) Midden on *paa* site at Waimarama beach, Hawke's Bay.

Wk-2137. Unit 2, No 59 **710 ± 50**
Shell (*Haliotis* sp.) $\delta^{13}C = +1.6‰$

Comment: (M.A.) Paua cache just outside of defensive bank at *paa* at Waimarama beach.

Wk-2138. Unit 3, No 61 **570 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.7‰$

Comment: (M.A.) Midden on *paa* site at Waimarama beach, Hawke's Bay.

Otatara *paa*, Taradale (V21/41)

(Submitted 29 October 1991 by P. Bain and E. Pishief, Department of Conservation, Napier)

Wk-2273. Sample 1 **810 ± 45**
Shell (unknown) $\delta^{13}C = +0.2‰$

Comment: (P.B.) Otatara *paa* Historic Reserve is described by Eileen Fox as the largest and most impressive of the many *paa* in Hawkes Bay. It is over 40 ha in size. It has a detailed traditional and archaeological history. It used to be two *paa*, a higher one called Hikurangi and a lower one called Otatara that has largely been quarried away. Traditionally, this site is known as the *paa* from which

Taraia gained the foothold that enabled *Ngati Kahungunu* to become the dominant *iwi* in Hawke's Bay.

Wk-2274. Sample 2 **750 ± 45**
Shell (unknown) $\delta^{13}C = -0.1‰$

Comment: (P.B.) as above.

Te Ihu O Te Rei (V21/28)

(Submitted 21 August 1991 by P. Bain, Department of Conservation, Gisborne)

Wk-2306. Sample 1 **660 ± 45**
Shell (mixture including *Venerupis largillierti*) $\delta^{13}C = -0.4‰$

Comment: (P.B.) Site uncovered during bulldozing work. Site traditionally important to *Ngati Kahungunu*. Located on one of a number of islands in *Te Whanganui a Orutu* lagoon.

Wk-2307. Sample 2 **720 ± 45**
Shell (*Paphies australis* and *Venerupis largillierti*) $\delta^{13}C = -0.2‰$

Comment: (P.B.) as above.

Parangatau (V23/21)

(Submitted 12 June 1992 by P. Bain, Department of Conservation, Gisborne)

Wk-2515. Midden V23/21 Square D (layer 6) **1040 ± 60**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = -0.4‰$

Comment: (P.B.) Parangatau area is extremely significant in traditional stories. Archaic artifacts collected in 1940s from the area.

WELLINGTON

Mana Island (R26/141)

(Submitted 13 June 1990 by L. M. Horwood, Wanganui Regional Museum, Wanganui)

Wk-1755. 141/6 **820 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.21‰$

Comment: (M.H.) Initial human occupation at northern end of site R26/141, Mana Island, New Zealand.

Paekakariki (R26/255)

(Submitted 8 June 1990 by B. G. McFadgen, Department of Conservation, Wellington)

Wk-1756. Paek M1 **680 ± 35**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.2‰$

Comment: (B.G.McF.) Provides maximum age for "Taupo dune" and close date for shell midden.

Wk-1757. Paek M2 **610 ± 70**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.4‰$

Comment: (B.G.McF.) Provides a minimum date for the formation of a foredune containing beds of lapilli-sized Taupo Pumice and a close date for a Maori occupation.

N.B.: see McFadgen (in press).

NELSON/MARLBOROUGH

Awaroa Inlet (N26/18)

(Submitted 17 August 1990 by I. Barber, Department of Anthropology, University of Otago)

Wk-1827. — **430 ± 60**
Charcoal — $\delta^{13}C = -28.4‰$

N.B.: charcoal identified as mahoe (*Melicytus ramiflorus*), fivefinger (*Pseudopanax arboreus*), kamahi (*Weinmannia* sp.), *Olearia* sp., rata (*Metrosideros* sp.) and beech (*Notofagus* sp.) fragments.

Wk-2094. — **460 ± 50**
Charcoal — $\delta^{13}C = -26.8‰$

N.B.: charcoal identified as mahoe (*Melicytus ramiflorus*), mapou (*Myrsine australis*), *Coprosma* sp., akeake (*Dodonaea viscosa*), kanuka (*Kunzia ericoides*), *Dracophylum* sp., *Olearia* sp., *Pittosporum* sp., bark of unidentified species. Submitted by I. Barber, 5 June 1991.

Wk-2869. Spit 3 — **800 ± 40**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.4‰$

Wk-2870. Spit 3 — **770 ± 40**
Shell (*Paphies subtriangulatum*) — $\delta^{13}C = +1.4‰$

N.B.: Wk-2869 and -2870 submitted by T. Higham, Radiocarbon Dating Laboratory, University of Waikato.

Sawpit Point, Awaroa Inlet (N26/214)

(Submitted 6 December 1994 by I. Barber, Department of Anthropology, University of Otago)

Wk-3099. C14-15/SPA 122D — **800 ± 50**
Shell (*Paphies australis*) — $\delta^{13}C = +1.7‰$

Bark Bay (N26/16)

(Submitted 2 April 1993 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato)

Wk-2863. Bark Bay 3A Sample 1 — **840 ± 45**
Shell (*Paphies australis*) — $\delta^{13}C = +2.0‰$

Wk-2866. Bark Bay 3A Sample 2 — **800 ± 50**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.0‰$

Wk-2867. Bark Bay 11/13 Sample 3 — **770 ± 40**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +1.2‰$

Wk-2868. Bark Bay 11/13 Sample 4 — **820 ± 45**
Shell (*Paphies subtriangulatum*) — $\delta^{13}C = +1.9‰$

Appleby (N27/118)

(Submitted 1 November 1991 by I. Barber, Department of Anthropology, University of Otago)

Wk-2278. **770 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.2‰$

Comment: (I.B.) Clarification of chronology of settlement and associated horticulture on the Waimea plain (*i.e.*, pre-European settlement).

Waimea Plains (N27/122)

(Submitted 5 September 1990 by B. G. McFadgen, Department of Conservation, Wellington)

Wk-1776. **360 ± 50**
Charcoal $\delta^{13}C = -26.1‰$

N.B.: wood identified as charcoal from matai bark (*Prumnopitys taxifolia*).

WESTLAND

Okuru series

(Submitted 2 April 1991 by R. Hooker, Department of Conservation, Hokitika)

Wk-2043. F37/8 Okuru 1 **830 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.3‰$

Wk-2044. F37/8 Okuru 2 **790 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.3‰$

Wk-2045. F37/7 Okuru 3 **920 ± 40**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.2‰$

Wk-2046. F37/19 Okuru 4 **870 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.3‰$

Wk-2047. F37/17 Okuru 5 **810 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = 1.2‰$

N.B.: see Hooker (1986).

Arawata River Mouth (E37/5)

(Submitted 9 February 1989 by R. Hooker, Department of Conservation, Hokitika)

Wk-1388. E37/5 A south side Arawata River Mouth **850 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.6‰$

Comment: (R.H.) Dates Maori occupation at mouth of Arawata River.

Jackson Bay (E37/4)

(Submitted 9 February 1989 by R. Hooker, Department of Conservation, Hokitika)

Wk-1389. E37/4A Sea front **650 ± 45**
Charcoal $\delta^{13}C = -28.4‰$

Comment: (R.H.) Dates Maori occupation at Jackson Bay, South Westland. Sample is wooden stake from similar context.

Seacombe Creek, Jackson Bay (E37/14)

(Submitted 9 February 1989 by R. Hooker, Department of Conservation, Hokitika)

Wk-1390. E37/14A North side of creek **410 ± 50**
Charcoal $\delta^{13}C = -29.0‰$

Comment: (R.H.) Dates Maori occupation of Jackson Bay site E37/14, beside Seacombe Creek. *N.B.*: no species given with charcoal identification in submission forms for Wk-1388 to 1390 inclusive, but charcoal was identified by R. Wallace.

Big Bay (D39/7)

(Submitted in 1989 by R. Hooker, Department of Conservation, Hokitika)

Wk-1167. D39/7/5 **960 ± 45**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.7‰$

Comment: (R.H.) Date of Maori settlement at Big Bay.

Wk-1168. D39/7/6 **900 ± 45**
Shell (*Paphies* and *Turbo smaragda*) $\delta^{13}C = +2.4‰$

Comment: (R.H.) Date of Maori occupation at Big Bay.

CANTERBURY

Panau, Banks Peninsula (N36/72)

(Submitted 15 June 1992 by C. Jacomb, Canterbury Museum, Christchurch)

Wk-2566. Pan/1 (layer 2a) **Modern**
Charcoal $\delta^{13}C = -27.0‰$

N.B.: saltmarsh ribbonwood (*Plagianthus divaricatus*), 6 pieces; *Coprosma* sp., 3 pc; fivefinger (*Pseudopanax arboreus*), 6 pc; akeake (*Dodonaea viscosa*), 2 pc; mapou (*Myrsine australis*), 4 pc; *Dracophyllum* sp., 2 pc.

Wk-2567. Pan/2 (layer 2c) **380 ± 55**
Charcoal $\delta^{13}C = -25.3‰$

N.B.: saltmarsh ribbonwood (*Plagianthus divaricatus*), 8 pieces; *Coprosma* sp., 2 pc; *Pseudopanax* sp., 2 pc; *Hebe* sp., 2 pc; *Pittosporum* sp., 2 pc; *Melicytus ramiflorus,* 3 pc; akeake (*Dodonaea viscosa*), 2 pc; *Myrsine australis,* 3 pc.

Wk-2569. Pan/4 (layer 2c) **600 ± 45**
Charcoal $\delta^{13}C = -24.7‰$

N.B.: saltmarsh ribbonwood (*Plagianthus divaricatus*), 4 pieces; akeake (*Dodonaea viscosa*), 4 pc; matagouri (*Discaria toumatou*), 1 pc; *Olearia* sp., 7 pc.

Wk-2570. Pan/5 (layer 2b) **640 ± 50**
Charcoal $\delta^{13}C = -24.5‰$

N.B.: saltmarsh ribbonwood (*Plagianthus divaricatus*), 5 pieces; *Coprosma* sp., 5 pc; *Pseudopanax* sp., 2 pc; akeake (*Dodonaea viscosa*), 3 pc; mapou (*Myrsine australis*), 2 pc.

Wk-2571. Pan/6 (layer 2c) — **Modern**
Charcoal — $\delta^{13}C = -26.2‰$

N.B.: saltmarsh ribbonwood (*Plagianthus divaricatus*), 20 pieces; *Coprosma* sp., 2 pc; akeake (*Dodonaea viscosa*), 2 pc. See Jacomb (1995).

Killermont (H39/19)

(Submitted 1990–1993 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato)

Wk-2783. KLM 6 — **640 ± 35**
Charcoal — $\delta^{13}C = -25.3‰$

Wk-2991. KLM 62 — **630 ± 40**
Charcoal — $\delta^{13}C = -24.8‰$

Wk-2916. KLM 45 — **660 ± 45**
Charcoal — $\delta^{13}C = -25.5‰$

N.B.: all Killermont charcoal identified as *Olearia* sp., *Hebe* sp., *Archeria traversii*, *Coprosma* sp., *Pittosporum* sp., mapou (*Myrsine australis*), matagouri (*Discaria toumatou*) and one other unknown shrub species.

Otago/Southland

Pleasant River (J43/1)

(Submitted 1990–1993 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato)

Wk-2507. Area 1 layer 2 B1 F5 — **1180 ± 45**
Shell (*Amphibola crenata*) — $\delta^{13}C = +1.2‰$

Wk-2741. Area D layer 4 — **650 ± 45**
Moa eggshell — $\delta^{13}C = -12.1‰$

Wk-2753. Area 1 B1 — **910 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +0.4‰$

Wk-2758. Area D layer 4 — **650 ± 45**
Moa eggshell — $\delta^{13}C = -14.0‰$

Wk-2759. Area D layer 4 — **590 ± 40**
Moa eggshell — $\delta^{13}C = -14.2‰$

Wk-2760. Area D layer 4 — **600 ± 45**
Moa eggshell — $\delta^{13}C = -13.9‰$

Wk-2761. Area D layer 4 — **1120 ± 45**
Shell (*Austrovenus stutchburyi*) — $\delta^{13}C = +0.8‰$

Wk-2762. Area D layer 4 — **1110 ± 45**
Shell (*Paphies subtriangulatum*) — $\delta^{13}C = +1.9‰$

Wk-2763. Area D layer 3 **920 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.2‰$

Wk-2764. Area D layer 3 **790 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.7‰$

Wk-2765. Area D layer 3 **600 ± 45**
Moa eggshell $\delta^{13}C = -12.2‰$

Wk-2771. Area D layer 3 **740 ± 45**
Shell (*Cookia sulcata*) $\delta^{13}C = +1.3‰$

Wk-2772. Area D layer 4 **780 ± 45**
Shell (*Paphies australis*) $\delta^{13}C = +1.7‰$

Wk-2789. PRD-7 Area D layer 4 **550 ± 90**
Charcoal $\delta^{13}C = -26.3‰$

N.B.: charcoal identified as matagouri (*Discaria toumatou*), 13 pieces; *Pittosporum* sp., 4 pc; *Muehlenbeckia* sp., 6 pc; *Coprosma* sp., 1 pc; shrub sp., 1 pc.

Wk-2790. PRD-14 Area D layer 3 **700 ± 90**
Charcoal $\delta^{13}C = -27.9‰$

N.B.: charcoal identified as *Muehlenbeckia* sp., 10 pieces; *Coprosma* sp., 4 pc; matagouri (*Discaria toumatou*), 6 pc; saltmarsh ribbonwood (*Plagianthus divaricatus*), 5 pc; *Olearia* sp., 3 pc.

Wk-2851. Area 1 layer 2 B1 F5 **970 ± 35**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.4‰$

N.B.: see Higham 1993.

Pleasant River (J43/1)

(Submitted 14 December 1994, by I. W. G Smith, Department of Anthropology, University of Otago)

Wk-3508. PLR-1100 **880 ± 40**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.4‰$

Comment: (I.S.) Dates horizon overlying moa butchery.

Wk-3509. PLR-1101 **760 ± 40**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.0‰$

Comment: (I.S.) Dates horizon overlying evidence of moa hunting.

Wk-3510. PLR-1102 **720 ± 40**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +0.5‰$

Comment: (I.S.) Dates evidence of primary moa butchery.

Shag River Mouth (J43/2)

(Submitted 1990–1993 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato)

Wk-2362. L4 G8 **1010 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.3‰$

Wk-2367. L4 G8 **1160 ± 50**
Shell (*Amphibola crenata*) *$\delta^{13}C$ = +1.3‰*

Wk-2410. L4 F7 **1020 ± 50**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.5‰*

Wk-2411. L4 F7 **990 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +0.8‰*

Wk-2412. L4 F7 **980 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.2‰*

Wk-2416. L5 E5 **600 ± 50**
Moa eggshell *$\delta^{13}C$ = −15.2‰*

Wk-2417. L6 F2/E2 **560 ± 45**
Moa eggshell *$\delta^{13}C$ = −15.0‰*

Wk-2440. L4 J5 **1050 ± 50**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +0.7‰*

Wk-2441. L4 J5 **1070 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.0‰*

Wk-2508. L4 H8 **1060 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = −0.7‰*

Wk-2589. L5 E5 **600 ± 50**
Moa eggshell *$\delta^{13}C$ = −15.2‰*

Wk-2604. L8 I3/I4 **570 ± 45**
Moa eggshell *$\delta^{13}C$ = −11.4‰*

Wk-2632. L4 J5 **980 ± 40**
Shell (*Paphies australis*) *$\delta^{13}C$ = +1.4‰*

Wk-2633. L4 J5 **1070 ± 80**
Shell (*Amphibola crenata*) *$\delta^{13}C$ = +0.7‰*

Wk-2751. L4 F7 **960 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.0‰*

Wk-2752. L4 J5 **960 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.0‰*

Wk-2856. L4 J5 **980 ± 40**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.0‰*

Wk-2857. L4 J5 **950 ± 45**
Shell (*Austrovenus stutchburyi*) *$\delta^{13}C$ = +1.0‰*

N.B.: see Higham (1993); Anderson, Smith and Higham (1996).

Warrington (I44/177)

(Submitted by B. J. Allingham, Seacliff, R.D.1, Warrington)

Wk-1737. W5 **1040 ± 50**
Shell (*Paphies subtriangulatum*) $\delta^{13}C = +1.2‰$

Comment: (B.J.A.) Dates base of lowest cultural layer at Warrington site I44/177.

Wk-1738. **870 ± 50**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.2‰$

Comment: (B.J.A.) Sample dates period of moa decline in the Blueskin Bay area of the Otago coast. The sample should also date the upper Maori cultural layer of site I44/177.

Wk-1739. **840 ± 45**
Shell (*Austrovenus stutchburyi*) $\delta^{13}C = +1.2‰$

Comment: (B.J.A.) Sample dates an early period of occupation at site I44/177.

Wk-2744. W9 **590 ± 45**
Moa eggshell $\delta^{13}C = -14.7‰$

N.B.: Wk-2744 submitted in 1992 by T. Higham, Radiocarbon Dating Laboratory, University of Waikato.

Papatowai (G47/50)

(Submitted 25 June 1990, by I. W. G. Smith, Department of Anthropology, University of Otago)

Wk-1761. THK/1 **650 ± 45**
Charcoal $\delta^{13}C = -25.9‰$

N.B.: wood identified as twig from following species; manuka (*Leptospermum scoparium*), ribbonwood (*Hoheria* sp.), fivefinger (*Pseudopanax arboreus*), horopito (pepper tree) (*Pseudowintera colorata*), beech (*Nothofagus* sp.), *Coprosma* sp., *Pittosporum* sp., *Archeria traversii.*

Wk-1762. THK/9 **640 ± 45**
Charcoal $\delta^{13}C = -25.4‰$

N.B.: wood identified as manuka (*Leptospermum scoparium*), raukawa (*Pseudopanax edgerleyi*), mapou (*Myrsine australis*), ribbonwood (*Hoheria* sp.), *Dracophyllum* sp. See Anderson and Smith (1992).

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LEAST-SQUARES FITTING A SMOOTH CURVE TO RADIOCARBON CALIBRATION DATA

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ABSTRACT. We Fourier transformed and filtered calibration curve data to compensate for the averaging effect of radiocarbon-dating sets of adjacent tree rings. A Wiener Filter was also applied to minimize the effects of the counting errors of the dates on the resulting calibration curve and to produce a least-squares curve through the data. The method is illustrated using a short ^{14}C-dated tree-ring sequence from New Zealand to produce a calibration curve at yearly intervals for New Zealand matai (*Prumnopitys taxifolia*). The resulting curve has a nominal standard error of 10 ± 3 yr, which is *ca.* half the average standard error of the original raw data.

INTRODUCTION

We previously showed (McFadgen, Knox and Cole 1994) that conversion of radiocarbon dates to calendar dates using currently accepted methods results in an artificial spreading and clumping of the calendar dates. The spreading and clumping, referred to as calibration stochastic distortion (CSD), is brought about by the interaction of the standard errors of the dates with the change in slope of the calibration curve. The distortion increases both the overall spread of dates and the possibility of date reversals. We suggested that the CSD effect could be overcome by deconvolving counting statistics from the ^{14}C dates to obtain the true distribution of ^{14}C dates, and then mapping the deconvolved set through the calibration curve onto the calendar axis in the usual way. The efficacy of the whole procedure depends on minimizing those changes of slope of the calibration curve caused by counting statistics.

There are calibration curves for terrestrial samples and for marine samples (Stuiver and Reimer 1993). Marine calibration data are derived from terrestrial data (Stuiver and Braziunas 1993) and are not considered further here. Terrestrial calibration curves are based on ^{14}C dates of tree-ring dated wood (*e.g.*, Stuiver and Pearson 1993; Pearson and Stuiver 1993; Stuiver and Becker 1993). Each dated sample comprises a group of adjacent rings, and the dates have statistical errors associated with them that introduce spurious wiggles into the calibration curves and contribute to changes in the slopes of the curves.

Terrestrial calibration data span some 8000 yr and are derived from measurements of several tree-ring chronologies. The longest chronologies are from the Northern Hemisphere. Southern Hemisphere chronologies include a ^{14}C-dated tree-ring sequence from New Zealand spanning the period from AD 1335 to 1745 (Sparks *et al.* 1995).

In addition to their use in calibration, smoothed, accurate and precise versions of these curves are a prerequisite for comparison of the Northern and Southern Hemisphere data to test the assumption that ^{14}C variations in the Southern Hemisphere match those of the Northern Hemisphere. They are also necessary to shed light on the relevant geophysical processes that produce the major changes in slope of the calibration curve.

We here describe a method of deriving a smoothed, more accurate and precise calibration curve by removing the spurious wiggles introduced by counting errors inherent in ^{14}C measurements of tree rings, and by compensating for the averaging effect brought about by dating sets comprised of a number of adjacent tree rings. Our analysis uses the short ^{14}C-dated tree-ring sequence from New Zealand in order to establish the method. The longer published Northern Hemisphere sequences will be considered in a subsequent paper.

Finally, the method described here has wider application than just to ^{14}C calibration curves. It is generally applicable to producing least-squares smoothed curves through any regularly spaced set of discrete data points with known error estimates.

METHODS

The raw ^{14}C calibration data set of ^{14}C *vs.* tree-ring age is Fourier transformed from the time to the frequency domain, where we design and apply filters to the transformed data, based on 1) the standard deviation of the measured tree rings, and 2) the fact that each sample measured contained wood spanning ten rings. We transform back to the time domain to obtain a smoothed calibration curve with substantially reduced errors attributable to counting statistics, and with some compensation for the averaging effect of using wood spanning ten adjacent tree rings in each measurement.

We develop the method using ^{14}C dates of tree rings for New Zealand matai (*Prumnopitys taxifolia*) measured at the Rafter Radiocarbon Laboratory, New Zealand Institute of Geological and Nuclear Sciences (Sparks *et al.* 1995: Table 2). Before Fourier transforming the data set, we remove the ideal (straight line) ^{14}C age *vs.* tree-ring age. The difference between raw data points and corresponding points on the ideal line is the detrended data listed in Table 1, columns 4 and 8. The end points of the data set differ from the ideal by only 1–2 yr. Since ^{14}C dates are normally reported to the nearest year, we use 1 yr (y) as our unit of time, and correspondingly 1 cycle per year (y^{-1}) as the unit of frequency.

Table 1 contains 42 points at 10-yr intervals, extending over 420 annual tree rings. Computer programs in the field of Fourier analysis often require the number of data points to be a power of 2, so we extend our data period to 512 yr by padding it with an approximately equal number of zeros at the beginning and end.

We use the discrete Fourier transform (*e.g.,* Press *et al.* 1994: §12.1)

$$T_n \equiv \sum_{k=0}^{N-1} \tau_k e^{2\pi i k \frac{n}{N}} \tag{1}$$

and its inverse

$$\tau_k = \frac{1}{N} \sum_{n=0}^{N-1} T_n e^{-2\pi i k \frac{n}{N}} , \tag{2}$$

where $i = \sqrt{-1}$, $N = 512$, n and k are integers in the range 0 to N–1 inclusive, and τ_k takes the data values given in Table 1 or else is zero. n/N is the frequency in the chosen units (y^{-1}).

To check how zero padding and choice of N affect accuracy, the set of τ_k was Fourier transformed, and immediately inverse Fourier transformed to recover the set of τ_k (including the zeros between and outside the values of τ_k given in Table 1). The recovered values agree with the original values to better than 0.003 yr, confirming the padding and the choice of N = 512 as adequate for calculating to the nearest year.

TABLE 1. ^{14}C age and calendar age of tree-ring dated wood of New Zealand matai (*Prumnopitys taxifolia*) from Sparks *et al.* (1995: Table 2). Detrended data = 1950 – ^{14}C age – calendar age. k = the index number of the data point in the extended data set after zero padding.

Calendar age (AD) T_k	Conventional ^{14}C age (yr BP)	k	Detrended data τ_k(yr)	Calendar age (AD) T_k	Conventional ^{14}C age (yr BP)	k	Detrended data τ_k(yr)
1335	617 ± 22	50	−2	1545	324 ± 14	260	81
1345	635 ± 19	60	−30	1555	322 ± 18	270	73
1355	639 ± 20	70	−44	1565	307 ± 22	280	78
1365	683 ± 20	80	−98	1575	377 ± 25	290	−2
1375	637 ± 22	90	−62	1585	385 ± 26	300	−20
1385	618 ± 17	100	−53	1595	396 ± 21	310	−41
1395	593 ± 19	110	−38	1605	361 ± 12	320	−16
1405	599 ± 19	120	−54	1615	367 ± 17	330	−32
1415	530 ± 20	130	5	1625	360 ± 21	340	−35
1425	471 ± 21	140	54	1635	286 ± 18	350	29
1435	484 ± 21	150	31	1645	288 ± 20	360	17
1445	422 ± 21	160	83	1655	290 ± 16	370	5
1455	453 ± 17	170	42	1665	220 ± 20	380	65
1465	450 ± 19	180	35	1675	163 ± 22	390	112
1475	420 ± 22	190	55	1685	163 ± 20	400	102
1485	417 ± 17	200	48	1695	182 ± 23	410	73
1495	380 ± 23	210	75	1705	167 ± 21	420	78
1505	380 ± 21	220	65	1715	157 ± 17	430	78
1515	372 ± 15	230	63	1725	167 ± 20	440	58
1525	334 ± 21	240	91	1735	176 ± 21	450	39
1535	323 ± 15	250	92	1745	206 ± 17	460	−1

In the actual calibration procedure, taking successive sets of D(=10) tree rings at a time to supply the carbon for dating is mathematically equivalent to taking a running mean over D yr of the true calibration curve, and then sampling the running mean once every D yr. Because the width of rings varies from year to year, the mean over D yr is not well defined, so we simply assume the ring widths within any D yr set to be constant. This assumption must introduce some error into the correction for averaging, but as the correction itself, given below, is found to make a difference of somewhat less than 1 yr, the overall error introduced should not be significant.

For constant ring width, then, the running mean in the time domain amounts to convolving a response function, of amplitude 1/D y^{-1}, constant from −D/2 to D/2 y and zero elsewhere, with the true calibration curve (Press *et al.* 1994: §13.1). In the frequency domain this is equivalent to multiplying together the Fourier transforms of the response function and the calibration curve (Press *et al.* 1994: §12.0). The Fourier transform of the response function can be shown to be

$$R_n = \frac{\sin\left(\pi D \frac{n}{N}\right)}{\pi D \frac{n}{N}} \tag{3}$$

(Press *et al.* 1994: §12.0, 12.1); thus, to correct for the running mean in the time domain by deconvolving it from the true calibration curve, the frequency domain representation of the data set must be divided by R_n.

A possible problem arises with the above deconvolving procedure due to R_n becoming zero for n/N = 1/D; *i.e.,* we would be dividing the Fourier component at frequency $1/D(=0.1)y^{-1}$ (and higher harmonics) by zero. We avoid this problem, however, because we filter out by multiplying by zero all Fourier components at frequencies $\geq 0.5/Dy^{-1}$, in order to remove the discrete character of the raw data set (*i.e.,* finite values at intervals of D yr and zero values every year in between). In general, to remove the discreteness a specifically designed filter would be required, but it will be seen below that with the data we are using here, the discreteness is removed incidentally by a further filter that is required in order to reduce variation due to counting statistics. This further filter multiplies by zero all Fourier components at frequencies greater than a cut-off value which, in this case, is considerably less than $0.5/Dy^{-1}$.

Variation due to counting statistics amounts to adding a component of noise to the quantity being measured. A filter that minimizes such added noise, in the sense that when applied to the noisy data it produces a least-squares curve passing through the data, is the Wiener filter (Press *et al.* 1994: §13.3). If T_n and Y_n are, respectively, the Fourier transforms of the noisy data and of the noise alone, the Wiener filter is

$$\Phi_n = 1 - \frac{|Y_n|^2}{|T_n|^2}\,, \tag{4}$$

where $|Y_n|^2$ and $|T_n|^2$ can be shown to be power spectra (Press *et al.* 1994: §13.4). The expression for calculating T_n has already been given; for the noise alone it is

$$Y_n = \sum_{k=0}^{N-1} \upsilon_k e^{2\pi i k \frac{n}{N}}\,, \tag{5}$$

where each υ_k noise is obtained as a number of years selected randomly according to a normal distribution having a standard deviation equal to that given for the corresponding k in Table 1.

A difficulty arises because only one randomly chosen value of υ_k is used at each value of k. Different runs of randomly chosen values were in general found to give a very irregular power spectrum $|Y_n|^2$ (Press *et al.* 1994: §13.4), varying appreciably from one run to the next. However, an average of 500 runs of $|Y_n|^2$ was found to produce an acceptably constant and smooth set of values, denoted here by $\langle |Y_n|^2 \rangle$.

The same difficulty must appear in the power spectrum $|T_n|^2$ because each τ_k is measured only once and only one set of data is available, but overcoming the difficulty requires a more elaborate procedure than that given above for $|Y_n|^2$. To make a first estimate of a least-squares smoothed curve through the data points τ_k, take the inverse Fourier transform of T_n multiplied by the filter

$$\Phi'_n = 1 - \frac{\langle |Y_n|^2 \rangle}{|T_n|^2}\,, \tag{6}$$

i.e., take the least-squares curve as

$$\theta'_k = \frac{D}{N} \sum_{n=0}^{N-1} \Phi'_n T_n e^{-2\pi i k \frac{n}{N}}\,, \tag{7}$$

where the need for the normalizing factor D will be discussed later. Now, as in deriving Y_n above, for each value of k in Table 1 add to θ'_k a number (of years) selected randomly according to a normal distribution having a standard deviation equal to that given for the corresponding k, and represented as τ'_k. The Fourier transform of a set of τ'_k is

$$T'_n = \sum_{k=0}^{N-1} \tau'_k e^{2\pi i k \frac{n}{N}} , \tag{8}$$

and we may average as many runs of $|T'_n|^2$ as necessary to obtain an acceptably constant and smooth spectrum. As with $|Y_n|^2$, an average of 500 runs was found to be sufficient, and we represent the average as $\langle |T'_n|^2 \rangle$.

The above procedure finally allows us to give our best estimate of the Wiener filter as

$$\langle \Phi'_n \rangle = 1 - \frac{\langle |Y_n|^2 \rangle}{\langle |T'_n|^2 \rangle} , \tag{9}$$

and the least-squares smoothed curve through the data points τ_k, also corrected for the running mean over D tree rings, as

$$\theta_k = \frac{D}{N} \sum_{n=0}^{N-1} \frac{\langle \Phi'_n \rangle}{R_n} T_n e^{-2\pi i k \frac{n}{N}} . \tag{10}$$

The normalizing factor D is required because the power in the spectrum $|T_n|^2$ derives only from the finite data values τ_k separated by D yr with zero values assumed for all years in between, whereas the finite values of θ_k are for *every* year in the range of interest. $\langle \Phi'_n \rangle$ is listed in Table 2.

TABLE 2. Wiener Filter ($\langle \Phi'_n \rangle$) *vs.* Frequency ($(n/N)y^{-1}$)

n	Frequency: $(n/N)y^{-1}$	$\langle \Phi'_n \rangle$
0	0	1
1	0.001953125	0.973
2	0.003906250	0.987
3	0.005859375	0.952
4	0.007812500	0.969
5	0.009765625	0.819
6	0.011718750	0.378
7	0.013671875	0.059
8	0	0
.	.	and zero for all higher frequencies

The ideal ^{14}C *vs.* tree-ring curve, initially subtracted to produce the data in the fourth and eighth columns of Table 1, is now added to θ_k to yield the smoothed, error-reduced and running mean corrected ^{14}C *vs.* tree-ring calibration. This calibration is listed in the Appendix and plotted as a graph in Figure 1.

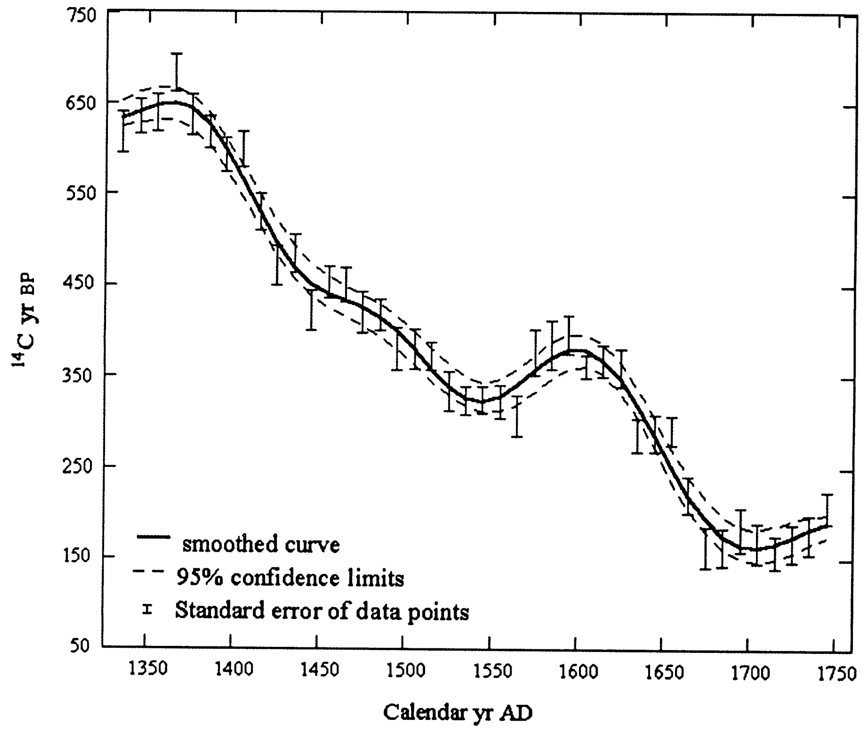

Fig. 1. Least-squares smoothed calibration curve for New Zealand matai (*Prumnopitys taxifolia*) corrected for a running mean over 10 tree rings compared with ±1 standard error range at each of the measured 42 data points. Mean nominal standard error of the curve is 10 ± 3 yr.

Statistical tests and standard deviation of curve

We now test to see if the deviation between 10-yr averages of the above calibration curve and the data is Gaussian. A χ^2 test (Snedecor and Cochran 1967: 84) of the differences between the 42 raw data points in Table 1 (= ^{14}C ages) and a mean over 10 yr centered on the corresponding points of the smoothed calibration curve (column 2, Appendix), using the corresponding standard deviations listed in Table 1, yields $\chi^2 = 5.0$ (df = 5), which is not significant at the 0.95 level ($\chi^2_{0.95,\,df=5} = 11.1$). This indicates that the set of data points constitutes a Gaussian distribution about the averaged calibration curve with the appropriate standard deviations, as it should.

We determine the likely error in the calibration curve itself by constructing from it a set of simulated raw data and then recovering a curve from these data by the procedure described in this paper. Repeating this 500 times allows us to obtain 95% confidence limits and 68% confidence limits. In a Gaussian distribution these confidence limits would correspond respectively to ±2 and ±1 standard deviations, but here this correspondence is only nominal, as there is no guarantee that errors in the estimation of the calibration curve have a Gaussian distribution. The distribution of the data points about the averaged calibration curve, however, is still Gaussian.

In implementing the procedures described in the preceding paragraph we took a normal distribution centered at each point of the 10-yr running mean of the calibration curve corresponding to a value of τ_k in Table 1, and with the corresponding standard deviation of the measured date. A raw data set is simulated by randomly selecting one value from each of these normal distributions, and this simulated data set is processed as described to give a simulated calibration curve. Inspection of the 500 simulated points for each τ_k allowed an estimate of the 95% confidence limits for the calibration curve that are plotted as the dashed lines in Figure 1.

The 68% confidence limits were derived in the same way and averaged to yield an effective overall nominal standard deviation of 10 ± 3 yr. This standard deviation is approximately half the average standard deviation of each raw data point, indicating that the curve has been smoothed in a running fashion over *ca.* 4 consecutive data points.

Comment on the Use of Fourier Analysis

The method presented here, of estimating the true ^{14}C calibration curve from discrete measured data regularly spaced in calendar time, assumes that the ^{14}C age is a continuous, single-valued function of calendar age. It further assumes that after subtracting out the ideal straight line representing equality of ^{14}C and calendar ages, the amplitude of the curve representing deviation from the ideal is everywhere finite. From inspection of the calibration data and consideration of the physics involved, we consider that both assumptions are valid.

Under the above two assumptions, any finite length of curve may be as closely approximated as desired by a weighted sum of sinusoids, *i.e.*, the Fourier sum. Once expressed in this form, the well-developed techniques of Fourier analysis readily allow the weights, and therefore the curve, to be derived from the data while eliminating much of the variation due to counting (or any other known) statistics. Furthermore, distortions of the curve by known processes, such as averaging the ^{14}C age over a number of tree rings, may be corrected by the technique of deconvolving.

Other techniques are available for deriving a continuous curve from the calibration data, but have disadvantages. For example, simple cubic splines create a continuous line through the data points, but in so doing cannot eliminate any of the statistical variation: many of the smaller wiggles in the curve are merely artifacts due to counting statistics. Straight lines joining the data points suffer the same disadvantage, while also introducing artificial discontinuities of slope at the data points.

Running means can eliminate some statistical noise, but in general do not do so in an optimal fashion related to the signal-to-noise ratio in the data. Also, running means require additional criteria for deciding the type of mean, and how many data points the mean is to be taken over.

The method described here can be considered a particular case of least-squares fitting a regression, the Fourier sum, to the data. Least-squares fitting other regressions to the data are potentially capable of equalling or surpassing the performance of the present method, but since we do not know all the physical processes responsible for the deviations of the calibration curve away from the straight line ideal, we cannot choose the correct mathematical form for the regression. We should therefore use a general-purpose function, such as a Fourier sum, which is capable of approximating as closely as desired any mathematical function satisfying the assumptions made earlier concerning the calibration curve. Finally, Fourier analysis has the advantage of being a mathematically well-developed, and widely used and understood technique.

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Appendix

Least-squares smoothed calibration curve at yearly intervals for New Zealand matai (*Prumnopitys taxifolia*) corrected for a running mean over 10 tree rings. Mean nominal standard error of the curve is 10 ± 3 yr.

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1330	629	1321
1331	630	1320
1332	630	1320
1333	631	1319
1334	631	1319
1335	632	1318
1336	633	1317
1337	633	1317
1338	634	1316
1339	635	1315
1340	635	1315
1341	636	1314
1342	637	1313
1343	638	1312
1344	639	1311

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1345	639	1311
1346	640	1310
1347	641	1309
1348	642	1308
1349	643	1307
1350	643	1307
1351	644	1306
1352	645	1305
1353	646	1304
1354	646	1304
1355	647	1303
1356	647	1303
1357	648	1302
1358	648	1302
1359	649	1301

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1360	649	1301
1361	649	1301
1362	650	1300
1363	650	1300
1364	650	1300
1365	650	1300
1366	649	1301
1367	649	1301
1368	649	1301
1369	648	1302
1370	648	1302
1371	647	1303
1372	647	1303
1373	646	1304
1374	645	1305
1375	644	1306
1376	643	1307
1377	641	1309
1378	640	1310
1379	638	1312
1380	637	1313
1381	635	1315
1382	633	1317
1383	631	1319
1384	629	1321
1385	627	1323
1386	625	1325
1387	623	1327
1388	620	1330
1389	618	1332
1390	615	1335
1391	612	1338
1392	609	1341
1393	606	1344
1394	603	1347
1395	600	1350
1396	597	1353
1397	594	1356
1398	591	1359
1399	587	1363
1400	584	1366
1401	580	1370
1402	577	1373
1403	573	1377
1404	570	1380
1405	566	1384
1406	563	1387
1407	559	1391
1408	555	1395

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1409	552	1398
1410	548	1402
1411	544	1406
1412	541	1409
1413	537	1413
1414	533	1417
1415	530	1420
1416	526	1424
1417	523	1427
1418	519	1431
1419	516	1434
1420	512	1438
1421	509	1441
1422	505	1445
1423	502	1448
1424	499	1451
1425	496	1454
1426	493	1457
1427	490	1460
1428	487	1463
1429	484	1466
1430	481	1469
1431	479	1471
1432	476	1474
1433	474	1476
1434	471	1479
1435	469	1481
1436	467	1483
1437	464	1486
1438	462	1488
1439	460	1490
1440	458	1492
1441	457	1493
1442	455	1495
1443	453	1497
1444	452	1498
1445	450	1500
1446	449	1501
1447	447	1503
1448	446	1504
1449	445	1505
1450	444	1506
1451	443	1507
1452	442	1508
1453	441	1509
1454	440	1510
1455	439	1511
1456	438	1512
1457	437	1513

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1458	436	1514
1459	436	1514
1460	435	1515
1461	434	1516
1462	434	1516
1463	433	1517
1464	432	1518
1465	432	1518
1466	431	1519
1467	431	1519
1468	430	1520
1469	429	1521
1470	429	1521
1471	428	1522
1472	427	1523
1473	427	1523
1474	426	1524
1475	425	1525
1476	424	1526
1477	423	1527
1478	422	1528
1479	422	1528
1480	421	1529
1481	420	1530
1482	418	1532
1483	417	1533
1484	416	1534
1485	415	1535
1486	414	1536
1487	412	1538
1488	411	1539
1489	409	1541
1490	408	1542
1491	406	1544
1492	405	1545
1493	403	1547
1494	401	1549
1495	400	1550
1496	398	1552
1497	396	1554
1498	394	1556
1499	392	1558
1500	390	1560
1501	388	1562
1502	386	1564
1503	384	1566
1504	382	1568
1505	380	1570
1506	378	1572

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1507	375	1575
1508	373	1577
1509	371	1579
1510	369	1581
1511	367	1583
1512	365	1585
1513	362	1588
1514	360	1590
1515	358	1592
1516	356	1594
1517	354	1596
1518	352	1598
1519	350	1600
1520	348	1602
1521	346	1604
1522	344	1606
1523	342	1608
1524	340	1610
1525	339	1611
1526	337	1613
1527	335	1615
1528	334	1616
1529	332	1618
1530	331	1619
1531	330	1620
1532	329	1621
1533	328	1622
1534	326	1624
1535	326	1624
1536	325	1625
1537	324	1626
1538	323	1627
1539	323	1627
1540	322	1628
1541	322	1628
1542	322	1628
1543	321	1629
1544	321	1629
1545	321	1629
1546	322	1628
1547	322	1628
1548	322	1628
1549	322	1628
1550	323	1627
1551	324	1626
1552	324	1626
1553	325	1625
1554	326	1624
1555	327	1623

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1556	328	1622
1557	329	1621
1558	330	1620
1559	331	1619
1560	332	1618
1561	334	1616
1562	335	1615
1563	337	1613
1564	338	1612
1565	340	1610
1566	341	1609
1567	343	1607
1568	344	1606
1569	346	1604
1570	348	1602
1571	349	1601
1572	351	1599
1573	353	1597
1574	354	1596
1575	356	1594
1576	358	1592
1577	359	1591
1578	361	1589
1579	362	1588
1580	364	1586
1581	365	1585
1582	367	1583
1583	368	1582
1584	370	1580
1585	371	1579
1586	372	1578
1587	373	1577
1588	374	1576
1589	375	1575
1590	376	1574
1591	377	1573
1592	378	1572
1593	379	1571
1594	379	1571
1595	380	1570
1596	380	1570
1597	381	1569
1598	381	1569
1599	381	1569
1600	381	1569
1601	381	1569
1602	381	1569
1603	381	1569
1604	380	1570

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1605	380	1570
1606	379	1571
1607	378	1572
1608	378	1572
1609	377	1573
1610	376	1574
1611	374	1576
1612	373	1577
1613	372	1578
1614	370	1580
1615	369	1581
1616	367	1583
1617	365	1585
1618	364	1586
1619	362	1588
1620	360	1590
1621	357	1593
1622	355	1595
1623	353	1597
1624	350	1600
1625	348	1602
1626	345	1605
1627	343	1607
1628	340	1610
1629	337	1613
1630	334	1616
1631	331	1619
1632	328	1622
1633	325	1625
1634	322	1628
1635	319	1631
1636	316	1634
1637	313	1637
1638	310	1640
1639	306	1644
1640	303	1647
1641	300	1650
1642	296	1654
1643	293	1657
1644	289	1661
1645	286	1664
1646	282	1668
1647	279	1671
1648	275	1675
1649	272	1678
1650	269	1681
1651	265	1685
1652	262	1688
1653	258	1692

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1654	255	1695
1655	252	1698
1656	248	1702
1657	245	1705
1658	242	1708
1659	238	1712
1660	235	1715
1661	232	1718
1662	229	1721
1663	226	1724
1664	223	1727
1665	220	1730
1666	217	1733
1667	214	1736
1668	211	1739
1669	208	1742
1670	206	1744
1671	203	1747
1672	200	1750
1673	198	1752
1674	196	1754
1675	193	1757
1676	191	1759
1677	189	1761
1678	187	1763
1679	185	1765
1680	183	1767
1681	181	1769
1682	179	1771
1683	178	1772
1684	176	1774
1685	174	1776
1686	173	1777
1687	172	1778
1688	170	1780
1689	169	1781
1690	168	1782
1691	167	1783
1692	166	1784
1693	165	1785
1694	165	1785
1695	164	1786
1696	163	1787
1697	163	1787
1698	163	1787
1699	162	1788
1700	162	1788
1701	162	1788
1702	162	1788

Tree-ring date (AD)	^{14}C age (yr BP)	^{14}C age (AD)
1703	162	1788
1704	162	1788
1705	162	1788
1706	162	1788
1707	162	1788
1708	162	1788
1709	163	1787
1710	163	1787
1711	163	1787
1712	164	1786
1713	164	1786
1714	165	1785
1715	166	1784
1716	166	1784
1717	167	1783
1718	168	1782
1719	168	1782
1720	169	1781
1721	170	1780
1722	171	1779
1723	172	1778
1724	172	1778
1725	173	1777
1726	174	1776
1727	175	1775
1728	176	1774
1729	177	1773
1730	178	1772
1731	178	1772
1732	179	1771
1733	180	1770
1734	181	1769
1735	182	1768
1736	183	1767
1737	183	1767
1738	184	1766
1739	185	1765
1740	185	1765
1741	186	1764
1742	187	1763
1743	187	1763
1744	188	1762
1745	188	1762
1746	189	1761
1747	189	1761
1748	190	1760
1749	190	1760
1750	190	1760

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TWENTY YEARS OF ATMOSPHERIC $^{14}CO_2$ OBSERVATIONS AT SCHAUINSLAND STATION, GERMANY

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ABSTRACT. We present and discuss quasi-continuous long-term $^{14}CO_2$ observations from the continental background station Schauinsland (48°N, 8°E, 1205 m asl, Black Forest, southern Germany). The observed steady decline of atmospheric $^{14}CO_2$ from 1977 to 1996 can be described by a single exponential function with an e-folding time of (16.3 ± 0.2) yr. Summer means (May to August) in atmospheric $^{14}CO_2$ at Schauinsland compare within $\Delta^{14}C = \pm 4‰$ with measurements made on individual rings from a tree grown in the near vicinity of the Schauinsland site. Both data sets are slightly depleted by up to 5‰ if compared to maritime background measurements of atmospheric $^{14}CO_2$ made at Izaña, Tenerife. This is due to the influence of fossil fuel CO_2 emissions over the European continent as well as generally in mid latitudes of the Northern Hemisphere. $\delta^{13}C$ analyses from the Schauinsland samples show mean seasonal variations with an amplitude of ±0.4‰, caused by atmosphere-biosphere exchange, and a mean decrease from 1977 to 1996 of $\delta^{13}C = -0.017‰\ yr^{-1}$. This trend is mainly due to an increasing quantity of fossil fuel CO_2 in the atmosphere, depleted in $^{13}C/^{12}C$ ratio, and compares well to trends measured at other stations in mid-to-high northern latitudes.

INTRODUCTION

During atmospheric nuclear weapon testing in the 1950s and early 1960s, large amounts of radiocarbon were generated in the atmosphere. This artificial ^{14}C input caused a global increase of the $^{14}C/^{12}C$ ratio in atmospheric CO_2 by a factor of almost two in 1963 (see Fig. 1), leading to a substantial disequilibrium of ^{14}C between atmosphere, biosphere and surface ocean water. In the last 20 years, this atmospheric ^{14}C perturbation has been used extensively to investigate CO_2 cycling between the atmosphere and the rapidly exchanging ocean and biosphere reservoirs (*e.g.*, Stuiver 1980; Druffel and Suess 1983; Goudriaan 1992). More recent quantitative attempts to budget bomb ^{14}C in the global carbon system, however, led to evidence of a serious imbalance (Hesshaimer, Heimann and Levin 1994) that has still not been resolved. Nevertheless, constraints on exchange rates provided by bomb ^{14}C are largely strengthened with the length of the observational record of bomb ^{14}C decline in the atmosphere.

We here present our extended data set of atmospheric $^{14}CO_2$ observations from continental Europe for three main purposes. First, we want to make this record available to serve as an input function for global carbon cycle modeling. Second, for investigations of anthropogenic perturbations such as regional contamination by ^{14}C-free fossil fuel CO_2 emissions or by releases of $^{14}CO_2$ by nuclear power plants, the Schauinsland station can serve as an ideal reference, at least for Central Europe. Third, our record may be applied in dating young (post-bomb) organic materials where the exact time-dependent $^{14}CO_2$ level is needed as a reference.

^{14}C data of individual samples from the two Central European sites—Vermunt, Austrian Alps (47°N, 10°E, 1800 m asl) and Schauinsland, Black Forest, Germany (48°N, 8°E, 1205 m asl)—have already been published and provided in tabulated form through 1983 by Levin *et al.* (1985), together with some earlier Heidelberg $^{14}CO_2$ data from a number of other sites, also in the Southern Hemisphere (see also Fig. 1). The extended data set from Schauinsland station was discussed in detail by Levin, Graul and Trivett (1995) and the individual data were made available through the Carbon Dioxide Information Analysis Center (DIAC) (Levin *et al.* 1994). Here we will provide, in tabulated

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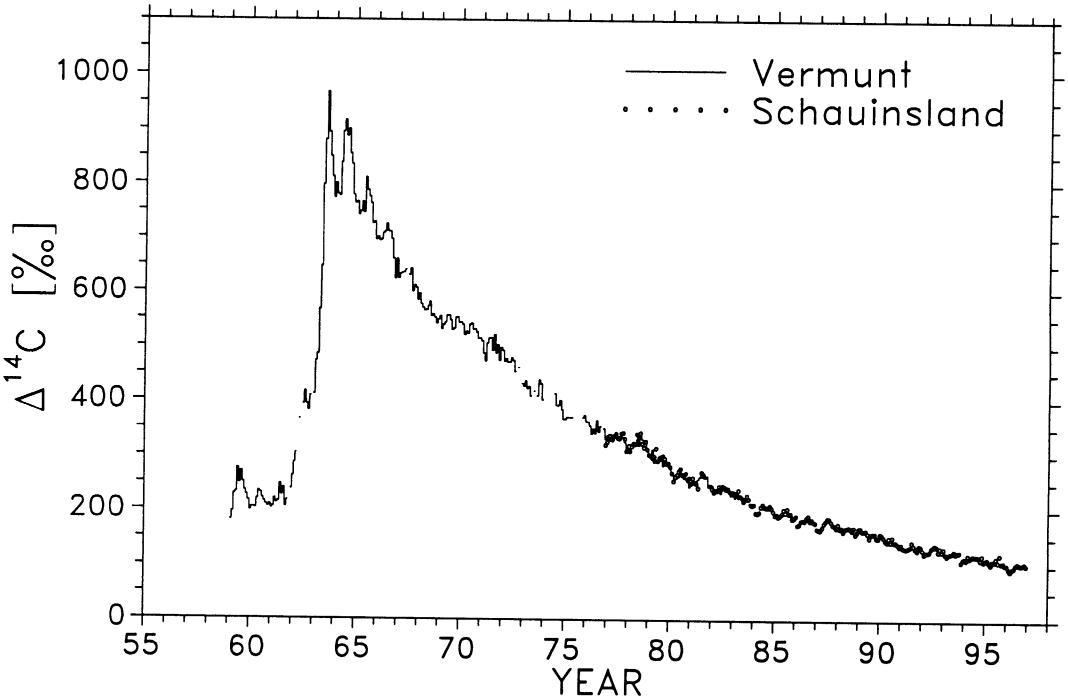

Fig. 1. Long-term observations of $\Delta^{14}C$ in atmospheric CO_2 in the Northern Hemisphere (Levin *et al.* 1985 with extended data from Table 1). The Vermunt record overlaps with Schauinsland data from 1977 to 1983. Shortly after the atmospheric test ban treaty in 1962, the $^{14}CO_2$ level in the Northern Hemisphere was twice as high as the natural equilibrium value. $\Delta^{14}C$ decreases thereafter due to equilibration with the world oceans and the terrestrial biosphere.

form (Table 1, Appendix), the Schauinsland data from 1983 onwards extended until the end of 1996 (monthly mean values as shown in Figs. 1 and 2 will be made available via FTP). In addition, as a service for dating purposes we present summer means together with ^{14}C data from wood samples of a tree grown in the immediate vicinity of the Schauinsland site (Table 2, Appendix).

Sampling Site

The regional GAW (Global Atmosphere Watch of the World Meteorological Organisation) station Schauinsland (48°N, 8°E) is located close to the top of Schauinsland Mountain in the Black Forest, southern Germany, at an elevation of 1205 m asl. The observatory is run by the Federal Environmental Agency (UBA), Berlin. At a height of more than 1000 m above the Upper Rhine Valley, the station is usually above the ground-level inversion layer of the valley, but during daytime and particularly in the summer months contamination from Rhine Valley pollutant sources may regularly occur. Surrounding the station are pastures and forest areas. The station itself is set up in a remote building with electrical heating only. Occasional local contamination is possible only from local traffic of the station personnel. As was shown from continuous CO_2 measurements performed at the Schauinsland site by UBA (Levin, Graul and Trivett 1995), during moderate and strong winds the station samples air representative of mean atmospheric conditions over Western Europe at this elevation of *ca.* 1000 m asl.

Measurement Techniques

All air samples were collected from a ventilated intake stack at an elevation of *ca.* 7 m above local ground. CO_2 samples integrated over two weeks from *ca.* 15–20 m^3 of air were continuously collected by dynamic quantitative absorption in carbonate-free sodium hydroxide solution as described in detail by Levin, Münnich and Weiss (1980). ^{13}C analyses of the CO_2 were performed by mass spectrometry, ^{14}C analyses by high-precision proportional counting of the purified CO_2 sample (Schoch *et al.* 1980; Kromer and Münnich 1992). $\delta^{13}C$ values are given relative to the VPDB standard (Hut 1987); the overall precision of a single analysis is typically ±0.15‰. Conventionally $\delta^{13}C$-corrected $\Delta^{14}C$ data are given relative to NBS oxalic acid activity corrected for decay (Stuiver and Polach 1977); the precision of a single $\Delta^{14}C$ measurement is typically ±(3–5)‰. Tree-ring samples were pretreated following the procedure outlined by Kromer and Becker (1993), which is Soxhlet extraction followed by the A-A-A sequence.

Results and Discussion

Long-Term Trend of $\Delta^{14}CO_2$ in Central Europe

Since the nuclear test ban treaty in 1962, 35 years of atmospheric $^{14}CO_2$ observations, typical of well-mixed air over Central Europe, are now available (Fig. 1). They complement data sets by other groups performed at northern hemispheric background sites (Nydal and Lövseth 1996) as well as in polluted areas (Kuc 1989). $^{14}CO_2$ in the Northern Hemisphere was dominated in the early sixties by large seasonal variations that are caused by seasonal input of bomb ^{14}C-rich air from the stratosphere into the northern hemispheric troposphere (Hesshaimer and Levin, submitted). The subsequent bomb ^{14}C decline observed after 1963 mainly reflects the $^{14}CO_2$ exchange fluxes with the ocean and the biosphere, which are governed by the internal circulation dynamics within these two reservoirs. But anthropogenic CO_2 emissions also contribute to the observed $^{14}CO_2$ decline, whereas ^{14}C emissions from the nuclear industry slightly counteract (by <1.5‰ per year) these effects (Hesshaimer, Heimann and Levin 1994). Figure 1 shows the combined data sets from Vermunt and Schauinsland. As discussed earlier, during the period of overlapping samples (1977–1983), results from both stations agree very well within measurement accuracy (Levin *et al.* 1985).

$\Delta^{14}CO_2$ at Schauinsland Station

The complete record of monthly mean $\Delta^{14}CO_2$ data from the Schauinsland site is displayed in Figure 2. The $^{14}C/^{12}C$ ratio shows a steady and approximately exponential decrease from 1977 until today with a time constant of $\tau = (16.3 \pm 0.2)$ yr. Overlying this trend is a seasonality with minimum values occurring during the winter months. ^{14}C analyses of individual tree rings (*Picea abies*) from 1974 to 1985, collected in the near vicinity of the Schauinsland station, are also displayed in Figure 2. The tree-ring ^{14}C data closely match the summer values of the air samples averaged over the months May to August. Both data sets closely follow the upper envelope of the continuous atmospheric record, and are assumed to be representative for the respective growing seasons in Western and Central Europe.

The ^{14}C background level in mid latitudes of the Northern Hemisphere can be derived from observations at the GAW station Izaña, Tenerife (28°N, 16°W, 2376 m asl) and from the High Alpine Research Station Jungfraujoch in the Swiss Alps (47°N, 8°E, 3454 m asl). At these sites, quasi-continuous $^{14}CO_2$ samples have been measured beginning in 1984 and 1986, respectively (Levin *et al.* 1992, and unpublished Heidelberg data). In the period of 1986 to 1995 the Schauinsland $^{14}CO_2$ level during the summer months (May–August) is on average lower by $\Delta^{14}C = (1.8 \pm 0.8)$‰ if compared

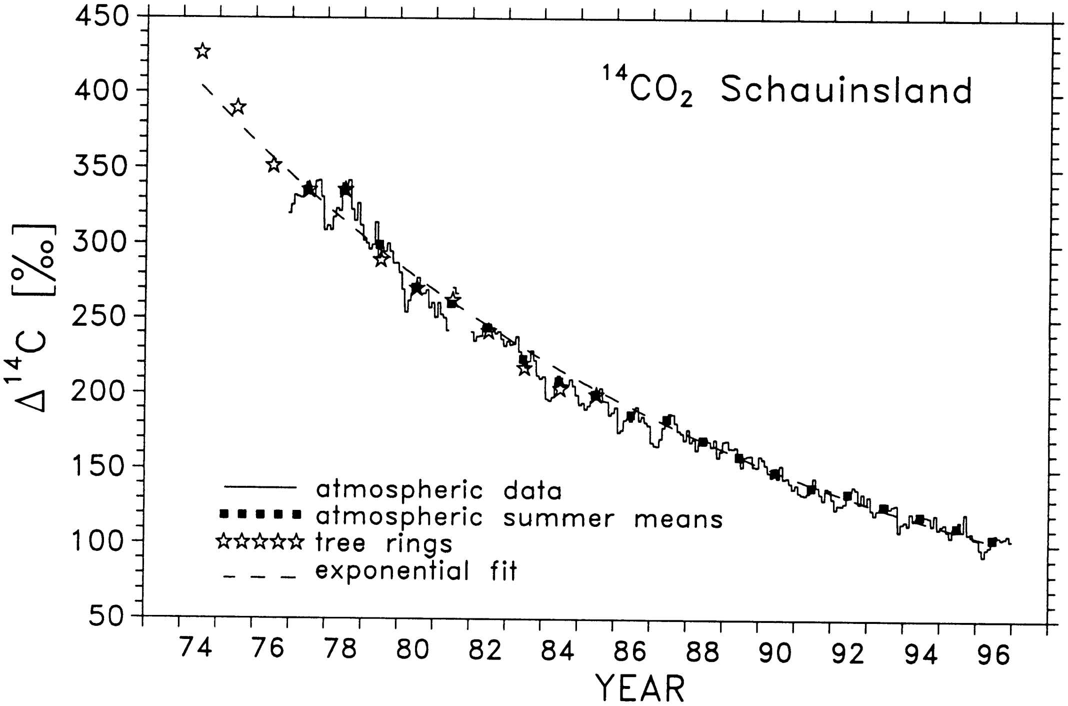

Fig. 2. Monthly mean $\Delta^{14}C$ in atmospheric CO_2 at Schauinsland (histogram) compared to values from individual rings of a tree grown close to the Schauinsland site. For overlapping years, the tree ring and summer mean (May–August) atmospheric values agree within ±4‰. -- = an exponential fit through the combined summer mean and tree ring values described by the function $\Delta^{14}C$ (t) = 417 • exp(−t/16.0); t = years after 1974.

to Jungfraujoch, and by $\Delta^{14}C$ = (4.3 ± 0.6)‰ if compared to Izaña. The difference between the two continental sites and Izaña is partly caused by the general continental pileup of fossil fuel CO_2 in Central Europe. However, due to fast atmospheric mixing in the west wind belt, mid northern latitudes (contributing >80% of global CO_2 emissions from fossil fuels (Rotty 1983)) may be generally influenced by fossil fuel CO_2 even over the Atlantic ocean.

As described previously (Levin, Graul and Trivett 1995), the regular seasonal variations after 1982, when all atmospheric tests stopped, have been attributed to seasonally varying contributions of fossil fuel CO_2 at the Schauinsland site. After extension of our observational $^{14}CO_2$ network to maritime clean-air stations, however, significant seasonal variations were observed at all northern hemispheric sites with *ca.* 5–8‰ higher $\Delta^{14}C$ values in late summer compared to early spring (Levin *et al.* 1992 and unpublished Heidelberg data). We are therefore confident that only about half of the seasonal amplitude observed at Schauinsland is caused by regional fossil fuel CO_2 contamination. The remaining part can be traced back to stratosphere-troposphere exchange ($\Delta^{14}C$ = 1–2‰), as well as to atmosphere-biosphere exchange through isotopic fractionation and disequilibrium effects (Hesshaimer 1997).

$\delta^{13}CO_2$ at Schauinsland Station

As a by-product of the $^{14}CO_2$ analyses of our large-volume CO_2 samples, the stable isotope ratio $^{13}C/^{12}C$ in CO_2 was obtained at Schauinsland during the period of 1977 to 1996 (Fig. 3). A large seasonal cycle with a mean amplitude of $\delta^{13}C$ = ±0.4‰ is observed, closely anti-correlated with atmo-

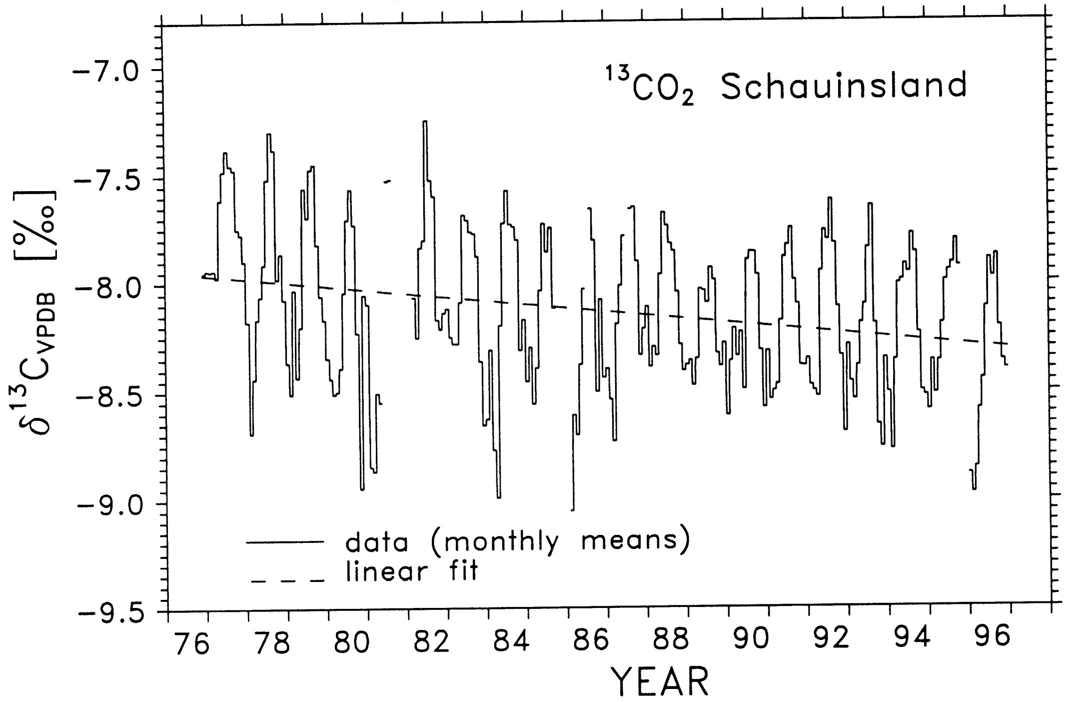

Fig. 3. Monthly mean values of $\delta^{13}C$ in atmospheric CO_2 at the Schauinsland site; -- a linear fit through the monthly data showing a mean decreasing trend of 0.017‰ yr^{-1}.

spheric CO_2 concentration (Levin, Graul and Trivett 1995). The mean $\delta^{13}C$ decreases from 1977 to 1996 by 0.017‰ yr^{-1}, comparable to trends observed at maritime background stations (Keeling *et al.* 1995). One may question the reliability of atmospheric $^{13}CO_2$ data derived from these samples as they may be partly fractionated during purification over charcoal. Therefore, we compared $\delta^{13}C$ results obtained by the chemical absorption method used here with those from samples specifically collected in glass flasks for stable isotopic analysis. CO_2 from whole air samples (*ca.* 100 ml of air) was trapped cryogenically (Finnigan, Bremen, MT-Box) and measured online with our MAT 252 mass spectrometer. These samples showed a systematic shift of +0.2‰ (after correction for N_2O) compared to the data presented here, which may partly be due to the different sampling and analysis techniques, and also to smaller regional source CO_2 contamination of the flask samples that were selectively collected during high wind speed situations. This contamination may arise from anthropogenic as well as from local biospheric CO_2 emissions, both depleted in $\delta^{13}C$. From the comparison of $\Delta^{14}C$ and $\delta^{13}C$ records, it is worth mentioning that both the seasonal amplitude of $^{14}CO_2$ and the seasonal amplitude of $^{13}CO_2$ vary from year to year. Particularly small seasonal $\delta^{13}C$ variations are observed in the years 1988 to 1990 when we also found only very small wintertime ^{14}C depletions (see Fig. 2). These years are characterized by relatively less severe winters associated with frequent maritime air mass flow in Western and Central Europe.

Conclusion

Atmospheric $^{14}CO_2$ in continental Europe shows an exponential decline with an e-folding time of *ca.* 16 yr, very similar to what is observed globally. During the growing season, May to August, the influence from continental fossil fuel CO_2 sources at Schauinsland, *ca.* 1000 m asl, causes a $\Delta^{14}C$

depletion on the order of ≤5‰. During winter, this depletion is about twice as large. Schauinsland observations can therefore serve well as a reference for regional atmospheric $^{14}CO_2$ studies and also for dating of modern organic material or groundwater in Central Europe. If corrected for the small anthropogenic effect, our Schauinsland record can be used as an input function for global carbon cycle modeling studies.

Acknowledgments

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Appendix: Data from Schauinsland Station and Tree-Ring Samples

TABLE 1. $\Delta^{14}C$ in atmospheric CO_2 at Schauinsland, Germany (48°N, 8°E, 1205 m asl). * = $\delta^{13}C$ values fractionated during sampling.

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-8662	Sch-156	11/06/84 – 26/06/84	216 ± 3	−7.76
Hd-5789	Sch-157	25/06/84 – 09/07/84	208 ± 4	−7.53
Hd-8774	Sch-158	09/07/84 – 23/07/84	206 ± 2	−7.55
Hd-8776	Sch-159	23/07/84 – 06/08/84	211 ± 4	−7.65
Hd-8790	Sch-160	06/08/84 – 20/08/84	203 ± 4	−7.76
Hd-8909	Sch-161	20/08/84 – 03/09/84	209 ± 3	−6.52*
Hd-8857	Sch-162	07/09/84 – 24/09/84	209 ± 4	−7.80
Hd-8936	Sch-163	24/09/84 – 04/10/84	198 ± 13	−7.59
Hd-8937	Sch-164	04/10/84 – 15/10/84	206 ± 4	−7.79
Hd-8946	Sch-165	15/10/84 – 30/10/84	216 ± 4	−7.86
Hd-9008	Sch-166	30/10/84 – 13/11/84	205 ± 2	−8.10*
Hd-9014	Sch-167	13/11/84 – 26/11/84	207 ± 2	−8.31
Hd-9015	Sch-168	26/11/84 – 10/12/84	203 ± 2	−8.33*
Hd-9111	Sch-169	10/12/84 – 21/12/84	206 ± 4	−7.92
Hd-9112	Sch-170	21/12/84 – 14/01/85	190 ± 4	−8.43
Hd-9122	Sch-171	14/01/85 – 28/01/85	194 ± 4	−8.52
Hd-9162	Sch-172	28/01/85 – 11/02/85	199 ± 4	−8.27
Hd-9364	Sch-173	11/02/85 – 25/02/85	192 ± 3	−8.29
Hd-9365	Sch-174	25/02/85 – 06/03/85	190 ± 5	−8.40
Hd-9366	Sch-175	06/03/85 – 18/03/85	184 ± 4	−8.70
Hd-9367	Sch-176	18/03/85 – 02/04/85	195 ± 4	−8.49
Hd-9368	Sch-177	02/04/85 – 15/04/85	198 ± 4	−8.22
Hd-9387	Sch-178	15/04/85 – 29/04/85	186 ± 4	−8.55
Hd-9528	Sch-179	29/04/85 – 13/05/85	194 ± 4	−8.32
Hd-9529	Sch-180	13/05/85 – 28/05/85	196 ± 4	−7.88
Hd-9530	Sch-181	28/05/85 – 10/06/85	200 ± 4	−7.72
Hd-9531	Sch-182	10/06/85 – 24/06/85	203 ± 4	−7.58
Hd-9648	Sch-183	24/06/85 – 08/07/85	205 ± 4	−8.05
Hd-9649	Sch-184	08/07/85 – 22/07/85	191 ± 4	−7.86
Hd-9650	Sch-185	22/07/85 – 05/08/85	199 ± 4	−7.71
Hd-9651	Sch-186	05/08/85 – 19/08/85	208 ± 4	−7.62
Hd-9829	Sch-187	19/08/85 – 02/09/85	202 ± 4	−7.90
Hd-9828	Sch-188	02/09/85 – 16/09/85	193 ± 4	−8.14
Hd-9830	Sch-189	16/09/85 – 30/09/85	197 ± 4	−8.33*
Hd-9858	Sch-190	30/09/85 – 14/10/85	204 ± 4	−8.45*
Hd-9974	Sch-191	14/10/85 – 28/10/85	187 ± 4	−8.70*
Hd-9975	Sch-192	28/10/85 – 18/11/85	195 ± 4	−8.14*

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-9976	Sch-193	18/11/85 – 02/12/85	174 ± 4	−9.48*
Hd-9977	Sch-194	02/12/85 – 16/12/85	188 ± 4	−9.04*
Hd-9997	Sch-195	16/12/85 – 13/01/86	189 ± 4	−5.97*
Hd-10123	Sch-196	13/01/86 – 27/01/86	192 ± 4	−9.66*
Hd-10124	Sch-197	27/01/86 – 03/02/86	195 ± 4	−10.32*
Hd-10125	Sch-198	03/02/86 – 17/02/86	163 ± 4	−9.58*
Hd-10126	Sch-199	17/02/86 – 03/03/86	184 ± 4	−9.05
Hd-10181	Sch-200	03/03/86 – 17/03/86	161 ± 4	−8.96
Hd-10182	Sch-201	17/03/86 – 01/04/86	189 ± 4	−8.20
Hd-10183	Sch-202	01/04/86 – 14/04/86	174 ± 4	−9.02
Hd-10222	Sch-203	14/04/86 – 28/04/86	191 ± 4	−8.50
Hd-10398	Sch-204	28/04/86 – 12/05/86	182 ± 4	−8.26
Hd-10399	Sch-205	12/05/86 – 26/05/86	186 ± 5	−8.47
Hd-10400	Sch-206	26/05/86 – 09/06/86	182 ± 2	−8.89*
Hd-10401	Sch-207	09/06/86 – 23/06/86	180 ± 5	−8.03
Hd-10406	Sch-208	23/06/86 – 07/07/86	186 ± 5	−8.21*
Hd-10490	Sch-209	07/07/86 – 21/07/86	186 ± 2	−7.83*
Hd-10491	Sch-210	21/07/86 – 04/08/86	192 ± 2	−7.75*
Hd-10494	Sch-211	04/08/86 – 18/08/86	193 ± 4	−7.66
Hd-10562	Sch-212	18/08/86 – 02/09/86	190 ± 2	−8.72*
Hd-10563	Sch-213	02/09/86 – 15/09/86	184 ± 4	−7.77
Hd-10564	Sch-214	15/09/86 – 29/09/86	180 ± 4	−7.84
Hd-10583	Sch-215	29/09/86 – 13/10/86	182 ± 3	−8.62*
Hd-10661	Sch-216	13/10/86 – 27/10/86	188 ± 3	−8.50
Hd-10662	Sch-217	27/10/86 – 10/11/86	185 ± 2	−8.61*
Hd-10673	Sch-218	10/11/86 – 24/11/86	180 ± 3	−8.64*
Hd-10710	Sch-219	24/11/86 – 08/12/86	179 ± 3	−8.08
Hd-10711	Sch-220	08/12/86 – 22/12/86	178 ± 2	−8.64*
Hd-10724	Sch-221	22/12/86 – 02/01/87	181 ± 3	−8.71
Hd-10801	Sch-222	02/01/87 – 19/01/87	161 ± 2	−8.98*
Hd-10802	Sch-223	19/01/87 – 02/02/87	176 ± 3	−8.36
Hd-10813	Sch-224	02/02/87 – 16/02/87	173 ± 3	−8.27
Hd-10868	Sch-225	16/02/87 – 02/03/87	157 ± 2	−8.85
Hd-10869	Sch-226	02/03/87 – 16/03/87	167 ± 3	−9.31
Hd-10875	Sch-227	16/03/87 – 30/03/87	164 ± 4	−8.18
Hd-10876	Sch-228	30/03/87 – 13/04/87	172 ± 4	−8.38
Hd-11028	Sch-229	13/04/87 – 27/04/87	169 ± 3	−8.03
Hd-11029	Sch-230	27/04/87 – 11/05/87	172 ± 2	−8.18
Hd-11032	Sch-231	11/05/87 – 25/05/87	180 ± 2	−7.98
Hd-11033	Sch-232	25/05/87 – 09/06/87	182 ± 3	−7.83
Hd-11037	Sch-233	09/06/87 – 22/06/87	180 ± 3	−7.76
Hd-11253	Sch-234	22/06/87 – 13/07/87	186 ± 4	−7.92*
Hd-11254	Sch-235	13/07/87 – 03/08/87	188 ± 4	−7.90*
Hd-11255	Sch-236	03/08/87 – 17/08/87	189 ± 4	−7.59
Hd-11256	Sch-237	17/08/87 – 03/09/87	184 ± 4	−7.73
Hd-11258	Sch-238	03/09/87 – 14/09/87	183 ± 4	−7.56
Hd-11259	Sch-239	14/09/87 – 28/09/87	180 ± 4	−7.68
Hd-11369	Sch-240	28/09/87 – 12/10/87	174 ± 5	−7.81

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-11370	Sch-241	12/10/87 – 26/10/87	178 ± 4	−7.84
Hd-11371	Sch-242	26/10/87 – 09/11/87	173 ± 4	−8.25
Hd-11372	Sch-243	09/11/87 – 23/11/87	180 ± 4	−8.26
Hd-11438	Sch-244	23/11/87 – 07/12/87	164 ± 4	−8.56
Hd-11439	Sch-245	07/12/87 – 21/12/87	168 ± 4	−8.21
Hd-11442	Sch-246	21/12/87 – 04/01/88	175 ± 3	−8.01
Hd-11539	Sch-248	18/01/88 – 01/02/88	177 ± 4	−8.14
Hd-11540	Sch-249	01/02/88 – 15/02/88	168 ± 4	−8.29
Hd-11549	Sch-250	15/02/88 – 29/02/88	168 ± 4	−8.49
Hd-11620	Sch-252	14/03/88 – 28/03/88	174 ± 4	−8.25
Hd-11621	Sch-253	28/03/88 – 11/04/88	156 ± 3	−8.47
Hd-11630	Sch-254	11/04/88 – 25/04/88	167 ± 3	−8.32
Hd-11701	Sch-255	25/04/88 – 09/05/88	165 ± 4	−8.13
Hd-11702	Sch-256	09/05/88 – 24/05/88	168 ± 5	−7.91
Hd-11703	Sch-257	24/05/88 – 06/06/88	174 ± 4	−7.89
Hd-11767	Sch-258	10/06/88 – 20/06/88	174 ± 4	−7.51
Hd-11867	Sch-259	20/06/88 – 04/07/88	163 ± 4	−7.73
Hd-11868	Sch-260	04/07/88 – 18/07/88	172 ± 4	−7.75
Hd-11879	Sch-261	18/07/88 – 01/08/88	171 ± 4	−7.73
Hd-11880	Sch-262	01/08/88 – 15/08/88	167 ± 4	−7.77
Hd-12010	Sch-263	15/08/88 – 29/08/88	171 ± 3	−7.88
Hd-12013	Sch-264	29/08/88 – 12/09/88	165 ± 5	−7.81
Hd-12020	Sch-265	12/09/88 – 26/09/88	163 ± 5	−7.85
Hd-12021	Sch-266	26/09/88 – 10/10/88	171 ± 4	−8.00
Hd-12101	Sch-267	10/10/88 – 24/10/88	173 ± 4	−7.94
Hd-12102	Sch-268	24/10/88 – 07/11/88	163 ± 4	−8.29
Hd-12162	Sch-269	07/11/88 – 21/11/88	158 ± 4	−8.26
Hd-12128	Sch-270	21/11/88 – 05/12/88	155 ± 3	−8.32
Hd-12131	Sch-271	05/12/88 – 19/12/88	160 ± 5	−8.52
Hd-12132	Sch-272	19/12/88 – 02/01/89	167 ± 5	−8.31
Hd-12277	Sch-273	02/01/89 – 16/01/89	167 ± 5	−8.50
Hd-12278	Sch-274	16/01/89 – 30/01/89	171 ± 4	−8.27
Hd-12283	Sch-275	30/01/89 – 13/02/89	165 ± 4	−8.34
Hd-12284	Sch-276	13/02/89 – 27/02/89	173 ± 4	−8.33
Hd-12525	Sch-277	27/02/89 – 13/03/89	170 ± 5	−8.75
Hd-12638	Sch-278	13/03/89 – 28/03/89	159 ± 3	−8.29
Hd-12648	Sch-279	28/03/89 – 10/04/89	165 ± 4	−8.28
Hd-12654	Sch-280	10/04/89 – 24/04/89	164 ± 4	−8.39
Hd-12661	Sch-281	24/04/89 – 08/05/89	162 ± 5	−8.37
Hd-12978	Sch-282	08/05/89 – 22/05/89	168 ± 5	−7.89
Hd-12979	Sch-283	22/05/89 – 05/06/89	162 ± 3	−7.98
Hd-13019	Sch-284	05/06/89 – 19/06/89	163 ± 3	−8.09
Hd-13027	Sch-285	19/06/89 – 03/07/89	155 ± 5	−8.00
Hd-12844	Sch-286	03/07/89 – 17/07/89	154 ± 3	−8.18
Hd-12845	Sch-287	17/07/89 – 31/07/89	149 ± 4	−8.03
Hd-12910	Sch-288	31/07/89 – 14/08/89	161 ± 3	−8.01
Hd-12911	Sch-289	14/08/89 – 28/08/89	157 ± 5	−7.90
Hd-12913	Sch-290	28/08/89 – 11/09/89	154 ± 4	−7.80

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-12914	Sch-291	12/09/89 – 25/09/89	162 ± 4	–7.99
Hd-12929	Sch-292	25/09/89 – 09/10/89	162 ± 3	–8.35
Hd-12930	Sch-293	09/10/89 – 23/10/89	159 ± 3	–8.23
Hd-13040	Sch-294	23/10/89 – 06/11/89	157 ± 3	–8.46
Hd-12993	Sch-295	06/11/89 – 20/11/89	152 ± 3	–8.39
Hd-12994	Sch-296	20/11/89 – 04/12/89	150 ± 3	–8.34
Hd-13076	Sch-297	04/12/89 – 18/12/89	149 ± 3	–8.36
Hd-13077	Sch-298	18/12/89 – 02/01/90	155 ± 3	–8.18
Hd-13085	Sch-299	02/01/90 – 15/01/90	159 ± 3	–8.93
Hd-13182	Sch-300	15/01/90 – 29/01/90	161 ± 5	–8.39
Hd-13183	Sch-301	29/01/90 – 12/02/90	150 ± 4	–8.44
Hd-13213	Sch-302	12/02/90 – 26/02/90	162 ± 2	–8.35
Hd-13214	Sch-303	26/02/90 – 12/03/90	162 ± 2	–8.08
Hd-13194	Sch-304	12/03/90 – 26/03/90	150 ± 4	–8.09
Hd-13215	Sch-305	26/03/90 – 09/04/90	144 ± 3	–8.79
Hd-13256	Sch-306	09/04/90 – 23/04/90	151 ± 4	–8.20
Hd-13257	Sch-307	23/04/90 – 07/05/90	148 ± 4	–8.10
Hd-13345	Sch-308	07/05/90 – 21/05/90	142 ± 4	–8.09
Hd-13264	Sch-309	21/05/90 – 05/06/90	148 ± 4	–8.49
Hd-13265	Sch-310	05/06/90 – 25/06/90	154 ± 3	–8.15*
Hd-13392	Sch-311	25/06/90 – 16/07/90	146 ± 3	–8.50*
Hd-13418	Sch-312	16/07/90 – 30/07/90	143 ± 5	–7.89
Hd-13444	Sch-313	30/07/90 – 06/08/90	145 ± 5	–7.97
Hd-13407	Sch-314	13/08/90 – 28/08/90	157 ± 4	–7.80
Hd-13408	Sch-315	28/08/90 – 10/09/90	148 ± 3	–7.96
Hd-13445	Sch-316	10/09/90 – 24/09/90	139 ± 6	–7.81
Hd-13612	Sch-317	24/09/90 – 08/10/90	149 ± 5	–7.84
Hd-13622	Sch-318	08/10/90 – 22/10/90	142 ± 6	–7.87
Hd-13634	Sch-319	22/10/90 – 05/11/90	145 ± 5	–8.21
Hd-13635	Sch-320	05/11/90 – 19/11/90	146 ± 4	–8.20
Hd-13647	Sch-321	19/11/90 – 03/12/90	134 ± 5	–8.49
Hd-13582	Sch-322	03/12/90 – 17/12/90	138 ± 5	–8.62
Hd-13709	Sch-323	17/12/90 – 31/12/90	137 ± 5	–8.58
Hd-13680	Sch-324	31/12/90 – 14/01/91	142 ± 5	–8.08
Hd-13685	Sch-325	14/01/91 – 28/01/91	139 ± 3	–8.48
Hd-13731	Sch-326	28/01/91 – 11/02/91	138 ± 3	–8.57
Hd-13808	Sch-327	11/02/91 – 25/02/91	134 ± 4	–8.56
Hd-13809	Sch-328	25/02/91 – 11/03/91	130 ± 5	–8.36
Hd-13845	Sch-329	11/03/91 – 25/03/91	137 ± 5	–8.49
Hd-13846	Sch-330	25/03/91 – 08/04/91	132 ± 5	–8.73
Hd-13872	Sch-331	08/04/91 – 22/04/91	135 ± 6	–8.42
Hd-13987	Sch-332	22/04/91 – 06/05/91	131 ± 4	–8.32
Hd-13988	Sch-333	06/05/91 – 21/05/91	132 ± 5	–8.25
Hd-13999	Sch-334	21/05/91 – 03/06/91	140 ± 5	–8.01
Hd-14005	Sch-335	03/06/91 – 17/06/91	130 ± 3	–8.00
Hd-14012	Sch-336	17/06/91 – 01/07/91	141 ± 5	–7.75
Hd-14070	Sch-337	01/07/91 – 17/07/91	146 ± 5	–7.81
Hd-14115	Sch-338	17/07/91 – 29/07/91	145 ± 4	–7.88

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-14102	Sch-339	29/07/91 – 12/08/91	134 ± 3	–7.76
Hd-14183	Sch-340	12/08/91 – 26/08/91	142 ± 4	–7.76
Hd-14217	Sch-341	26/08/91 – 09/09/91	140 ± 6	–7.72
Hd-14260	Sch-342	09/09/91 – 23/09/91	128 ± 4	–8.06
Hd-14227	Sch-343	23/09/91 – 07/10/91	138 ± 3	–8.17
Hd-14202	Sch-344	07/10/91 – 21/10/91	124 ± 6	–8.15
Hd-14239	Sch-345	21/10/91 – 04/11/91	133 ± 6	–8.00
Hd-14378	Sch-346	04/11/91 – 18/11/91	144 ± 4	–8.44
Hd-14381	Sch-347	18/11/91 – 02/12/91	133 ± 5	–8.42
Hd-14388	Sch-348	02/12/91 – 16/12/91	141 ± 4	–8.33
Hd-14441	Sch-349	16/12/91 – 30/12/91	134 ± 3	–8.46
Hd-14504	Sch-350	30/12/91 – 13/01/92	134 ± 4	–8.17
Hd-14505	Sch-351	13/01/92 – 27/01/92	130 ± 4	–8.45
Hd-14467	Sch-352	27/01/92 – 10/02/92	125 ± 5	–8.54
Hd-14728	Sch-353	10/02/92 – 24/02/92	123 ± 4	–8.45
Hd-14729	Sch-354	24/02/92 – 09/03/92	124 ± 4	–8.42
Hd-14578	Sch-355	09/03/92 – 23/03/92	127 ± 5	–8.40
Hd-14607	Sch-356	23/03/92 – 06/04/92	129 ± 4	–8.73
Hd-14858	Sch-357	06/04/92 – 21/04/92	131 ± 4	–8.48
Hd-14859	Sch-358	21/04/92 – 04/05/92	118 ± 4	–8.48
Hd-14869	Sch-359	04/05/92 – 18/05/92	124 ± 4	–7.98
Hd-14870	Sch-360	18/05/92 – 01/06/92	134 ± 5	–7.79
Hd-14875	Sch-361	01/06/92 – 15/06/92	136 ± 5	–7.75
Hd-14876	Sch-362	15/06/92 – 29/06/92	133 ± 4	–7.77
Hd-15100	Sch-363	29/06/92 – 13/07/92	132 ± 5	–7.83
Hd-15056	Sch-364	13/07/92 – 27/07/92	141 ± 4	–7.81
Hd-15150	Sch-365	27/07/92 – 10/08/92	134 ± 5	–7.74
Hd-15202	Sch-366	10/08/92 – 24/08/92	141 ± 3	–7.56
Hd-15153	Sch-367	24/08/92 – 07/09/92	142 ± 3	–7.59
Hd-15170	Sch-369	21/09/92 – 05/10/92	134 ± 5	–7.98
Hd-15204	Sch-370	05/10/92 – 19/10/92	123 ± 4	–8.29
Hd-15232	Sch-371	19/10/92 – 02/11/92	131 ± 3	–7.97
Hd-15155	Sch-372	02/11/92 – 16/11/92	135 ± 3	–8.38
Hd-15176	Sch-373	16/11/92 – 30/11/92	134 ± 5	–8.32
Hd-15211	Sch-374	30/11/92 – 14/12/92	134 ± 4	–8.65
Hd-15212	Sch-375	14/12/92 – 28/12/92	122 ± 3	–8.79
Hd-15229	Sch-376	28/12/92 – 11/01/93	125 ± 3	–8.46
Hd-15238	Sch-377	11/01/93 – 25/01/93	142 ± 6	–8.17
Hd-15245	Sch-378	25/01/93 – 08/02/93	124 ± 3	–8.27
Hd-15588	Sch-379	08/02/93 – 22/02/93	127 ± 4	–8.44
Hd-15589	Sch-380	22/02/93 – 08/03/93	116 ± 3	–8.70
Hd-15622	Sch-381	08/03/93 – 22/03/93	120 ± 5	–8.48
Hd-15635	Sch-382	22/03/93 – 05/04/93	124 ± 4	–8.50
Hd-15641	Sch-383	05/04/93 – 19/04/93	122 ± 5	–8.41
Hd-15648	Sch-384	19/04/93 – 03/05/93	125 ± 4	–8.31
Hd-15991	Sch-385	03/05/93 – 17/05/93	115 ± 3	–8.17
Hd-15992	Sch-386	17/05/93 – 01/06/93	134 ± 5	–8.19
Hd-16123	Sch-387	01/06/93 – 14/06/93	116 ± 4	–8.22

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-16124	Sch-388	14/06/93 – 28/06/93	134 ± 5	–8.03
Hd-16131	Sch-389	28/06/93 – 12/07/93	125 ± 3	–7.93
Hd-16132	Sch-390	12/07/93 – 26/07/93	131 ± 3	–7.83
Hd-16158	Sch-391	26/07/93 – 09/08/93	130 ± 5	–7.72
Hd-16157	Sch-392	09/08/93 – 23/08/93	125 ± 6	–7.48
Hd-16165	Sch-393	23/08/93 – 06/09/93	119 ± 4	–7.86
Hd-16168	Sch-394	06/09/93 – 20/09/93	130 ± 4	–8.40
Hd-16136	Sch-395	20/09/93 – 04/10/93	125 ± 3	–8.09
Hd-16150	Sch-396	04/10/93 – 18/10/93	133 ± 4	–8.54
Hd-16169	Sch-397	18/10/93 – 02/11/93	121 ± 4	–8.92
Hd-16143	Sch-398	02/11/93 – 15/11/93	107 ± 4	–8.62
Hd-16151	Sch-399	15/11/93 – 29/11/93	109 ± 5	–8.93
Hd-16144	Sch-400	29/11/93 – 15/12/93	119 ± 4	–8.31
Hd-16381	Sch-401	15/12/93 – 27/12/93	109 ± 3	–8.38
Hd-16396	Sch-402	27/12/93 – 10/01/94	114 ± 4	–8.40
Hd-16397	Sch-403	10/01/94 – 24/01/94	117 ± 4	–8.44
Hd-16404	Sch-404	24/01/94 – 07/02/94	116 ± 4	–8.76
Hd-16685	Sch-405	07/02/94 – 21/02/94	109 ± 4	–8.97
Hd-16760	Sch-406	21/02/94 – 07/03/94	119 ± 5	–8.42
Hd-16676	Sch-407	07/03/94 – 21/03/94	125 ± 4	–8.34
Hd-16765	Sch-408	21/03/94 – 06/04/94	118 ± 4	–8.35
Hd-16677	Sch-409	06/04/94 – 18/04/94	112 ± 5	–8.73
Hd-16678	Sch-410	18/04/94 – 02/05/94	120 ± 4	–7.18
Hd-16601	Sch-411	02/05/94 – 16/05/94	120 ± 5	–8.08
Hd-16766	Sch-412	16/05/94 – 30/05/94	117 ± 5	–8.00
Hd-16684	Sch-413	30/05/94 – 13/06/94	120 ± 4	–7.87
Hd-16672	Sch-414	13/06/94 – 27/06/94	120 ± 4	–7.93
Hd-16736	Sch-415	27/06/94 – 11/07/94	123 ± 5	–8.06
Hd-16840	Sch-416	11/07/94 – 25/07/94	117 ± 3	–7.91
Hd-16775	Sch-417	25/07/94 – 08/08/94	120 ± 5	–7.90
Hd-16776	Sch-418	08/08/94 – 22/08/94	118 ± 5	–7.81
Hd-16785	Sch-419	22/08/94 – 05/09/94	121 ± 5	–7.65
Hd-16970	Sch-421	19/09/94 – 04/10/94	118 ± 5	–7.95
Hd-16969	Sch-422	04/10/94 – 17/10/94	112 ± 4	–8.34
Hd-16985	Sch-423	17/10/94 – 31/10/94	113 ± 5	–8.19
Hd-17006	Sch-424	31/10/94 – 14/11/94	122 ± 4	–8.62
Hd-16984	Sch-425	14/11/94 – 28/11/94	120 ± 4	–8.41
Hd-17094	Sch-426	28/11/94 – 12/12/94	116 ± 3	–8.37
Hd-17106	Sch-427	12/12/94 – 27/12/94	108 ± 4	–8.49
Hd-17107	Sch-428	27/12/94 – 09/01/95	108 ± 4	–8.99
Hd-17118	Sch-429	09/01/95 – 23/01/95	116 ± 5	–8.50
Hd-17119	Sch-430	23/01/95 – 06/02/95	114 ± 5	–8.34
Hd-17087	Sch-431	06/02/95 – 20/02/95	114 ± 3	–8.30
Hd-17175	Sch-432	20/02/95 – 06/03/95	115 ± 5	–8.48
Hd-17176	Sch-433	06/06/95 – 20/03/95	116 ± 4	–8.43
Hd-17336	Sch-434	20/03/95 – 03/04/95	107 ± 5	–8.53
Hd-17356	Sch-435	03/04/95 – 18/04/95	114 ± 4	–8.30
Hd-17360	Sch-436	18/04/95 – 02/05/95	95 ± 4	–8.41

TABLE 1. (Continued)

Lab code	Sample no.	Sampling period (dd/mm/yy–dd/mm/yy)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
Hd-17370	Sch-437	02/05/95 – 15/05/95	114 ± 5	–8.21
Hd-17562	Sch-438	15/05/95 – 29/05/95	112 ± 4	–8.18
Hd-17553	Sch-439	29/05/95 – 12/06/95	106 ± 5	–8.06
Hd-17547	Sch-440	12/06/95 – 26/06/95	112 ± 4	–7.99
Hd-17652	Sch-441	26/06/95 – 10/07/95	118 ± 4	–7.86
Hd-17842	Sch-442	10/07/95 – 24/07/95	116 ± 4	–7.99
Hd-17843	Sch-443	24/07/95 – 07/08/95	114 ± 5	–7.99
Hd-17850	Sch-444	07/08/95 – 21/08/95	103 ± 5	–7.88
Hd-17831	Sch-445	21/08/95 – 04/09/95	115 ± 5	–7.92
Hd-17851	Sch-446	04/09/95 – 18/09/95	125 ± 5	–7.77
Hd-17818	Sch-447	18/09/95 – 02/10/95	119 ± 4	–7.82
Hd-17976	Sch-448	02/10/95 – 16/10/95	107 ± 4	–7.51
Hd-17947	Sch-449	16/10/95 – 30/10/95	107 ± 5	–8.36
Hd-18158	Sch-450	30/10/95 – 20/11/95	110 ± 5	–7.81*
Hd-18175	Sch-451	20/11/95 – 11/12/95	106 ± 4	–9.40*
Hd-18192	Sch-452	11/12/95 – 27/12/95	103 ± 4	–8.69*
Hd-18118	Sch-453	27/12/95 – 22/01/96	108 ± 4	–9.53*
Hd-18170	Sch-454	22/01/96 – 05/02/96	97 ± 5	–8.89
Hd-18105	Sch-455	05/02/96 – 19/02/96	97 ± 5	–9.07
Hd-18333	Sch-456	19/02/96 – 04/03/96	99 ± 4	–8.88
Hd-18346	Sch-457	04/03/96 – 18/03/96	88 ± 4	–9.09
Hd-18326	Sch-458	18/03/96 – 01/04/96	97 ± 3	–8.61
Hd-18327	Sch-459	01/04/96 – 15/04/96	94 ± 4	–8.82
Hd-18329	Sch-460	15/04/96 – 29/04/96	102 ± 4	–8.35
Hd-18321	Sch-461	29/04/96 – 13/05/96	95 ± 4	–8.55
Hd-18507	Sch-462	13/05/96 – 28/05/96	103 ± 3	–8.45
Hd-18506	Sch-463	28/05/96 – 10/06/96	100 ± 3	–8.07
Hd-18485	Sch-464	10/06/96 – 25/06/96	106 ± 3	–8.14
Hd-18486	Sch-465	25/06/96 – 08/07/96	109 ± 3	–8.15
Hd-18516	Sch-466	08/07/96 – 22/07/96	107 ± 3	–7.76
Hd-18669	Sch-467	31/07/96 – 19/08/96	100 ± 3	–8.03
Hd-18655	Sch-468	19/08/96 – 02/09/96	114 ± 4	–7.91
Hd-18685	Sch-469	02/09/96 – 16/09/96	105 ± 3	–7.80
Hd-18675	Sch-470	16/09/96 – 30/09/96	103 ± 3	–7.94
Hd-18692	Sch-471	30/09/96 – 14/10/96	103 ± 3	–8.32
Hd-18769	Sch-472	14/10/96 – 28/10/96	106 ± 3	–8.10
Hd-18779	Sch-473	28/10/96 – 11/11/96	109 ± 3	–8.20
Hd-18764	Sch-474	11/11/96 – 25/11/96	108 ± 3	–8.51
Hd-18809	Sch-475	25/11/96 – 09/12/96	101 ± 6	–8.29
Hd-19003	Sch-476	09/12/96 – 23/12/96	105 ± 3	–8.45
Hd-18994	Sch-477	23/12/96 – 13/01/96	99 ± 3	–8.76

TABLE 2. $\Delta^{14}C$ in individual tree rings (*Picea abies*) grown in the near vicinity of Schauinsland. Summer means (May–August) from atmospheric samples are also reported for comparison.

	Tree rings			Atmosphere
Year	Lab code	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)
1974	Hd-10088	427 ± 3	−25.75	
1975	Hd-10087	390 ± 3	−26.02	
1976	Hd-10074	352 ± 3	−25.43	
1977	Hd-10075	336 ± 3	−24.42	335.3 ± 3.4
1978	Hd-10076	336 ± 3	−24.37	334.9 ± 7.9
1979	Hd-10077	290 ± 3	−25.76	299.4 ± 8.8
1980	Hd-10052	271 ± 3	−25.71	271.1 ± 4.6
1981	Hd-10051	263 ± 3	−26.40	260.0 ± 12.8
1982	Hd-10049	242 ± 3	−25.76	244.1 ± 1.7
1983	Hd-10045	218 ± 2	−24.52	223.4 ± 3.9
1984	Hd-10040	204 ± 2	−24.99	208.7 ± 2.2
1985	Hd-10039	200 ± 3	−25.65	199.8 ± 3.7
1986				186.4 ± 3.7
1987				183.4 ± 3.8
1988				169.4 ± 0.8
1989				158.7 ± 4.5
1990				148.6 ± 3.7
1991				138.4 ± 3.8
1992				134.4 ± 4.2
1993				125.9 ± 1.6
1994				119.5 ± 0.6
1995				111.9 ± 2.5
1996				104.3 ± 3.0

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BOOK REVIEW

C. E. Buck, W. G. Cavanagh and C. D. Litton. *Bayesian Approach to Interpreting Archaeological Data.* Chichester, England, J. Wiley and Son, 1996: 382 p. ISBN 0-4719619-7-3.

Bayesian Approach to Interpreting Archaeological Data is intended for undergraduate and postgraduate students of archaeology and for professional archaeologists and members of related disciplines. The authors explain the basic rationale of the Bayesian approach in archaeological investigation, highlight its advantages and illustrate the range of archaeological problems that lend themselves to a Bayesian approach. The volume is one of the Wiley "Statistics in Practice" series, which covers statistical concepts, methods and worked case studies.

The book is divided into two main sections. Chapters 1–8 cover the principles underlying the Bayesian approach and practice, including the Bayesian approach to statistical archaeology, modeling in archaeology, quantifying uncertainty using probability concepts, statistical modeling with some material on distributions, Bayesian inference and finally implementation issues (which I think could easily be skipped by the archaeological reader; Bayesian methods very often tend to be computationally intensive and this chapter explores some of the technical difficulties). The examples include provenancing and seriation, tree-ring and radiocarbon dating and spatial analysis. The next four chapters provide a series of detailed case studies, one to a chapter: "Interpretation of Radiocarbon Results", "Spatial Analysis", "Sourcing and Provenancing" and "Application to other Dating Methods". Each chapter is made up of a number of archaeological case studies, which are presented in a consistent manner, with a clear discussion of the archaeological context of the problem, followed by discussion of the statistical model, data, prior, likelihood, posterior and then conclusions. It is perhaps not obvious exactly what the gains are from having completed a Bayesian analysis, nor is the effort involved in eliciting and quantifying prior information demonstrated.

The book is very thorough, but a reader hoping for some simple recipes to apply would be disappointed, because they may not exist. There is no intention that the archaeologist should now be able to perform the analysis unaided. Currently, Bayesian analysis requires a specialist statistical knowledge, but the book explains the ingredients and some of the terminology that a collaborating statistician will use. The authors state clearly at the end of the text that each problem must be tackled afresh, although following the same general principles. The book is liberally scattered with many examples and case studies that should offer the archaeologist both familiarity and enhanced understanding.

The final chapter, entitled "The Way Forward", lists some requirements on both the archaeological and statistical communities and makes a plea for proper resourcing of statistical analysis following major archaeological explorations.

The book provides interesting material for the more numerate archaeologist (but at postgraduate or professional level). Bayesian analysis is becoming more and more popular and this book will encourage that interest. The problem of implementing the approach still remains; principles are necessary but the practice is still not at the stage of "off-the-shelf" analysis.

Marian Scott
Department of Statistics
University of Glasgow

[RADIOCARBON, VOL. 39, NO. 2, 1997, P. 221]

LETTER TO THE EDITOR

17 September 1997

Dear Editor,

Professor R. E. Taylor, in his review for *RADIOCARBON* of my book *Relic, Icon or Hoax? Carbon Dating the Turin Shroud* (Taylor 1997) noted that I had incorrectly used the word "invent" and its derivatives in connection with the origins of accelerator mass spectrometry (AMS). A more accurate description of the development of AMS is to be found in the papers that I co-authored (Gove, Litherland and Purser 1987) and authored (Gove 1992) prior to publication of my book. Who actually "invented" AMS is not clear. Certainly, strong contenders are L. W. Alvarez and R. Cornog (Alvarez and Cornog 1939) and K. H. Purser (Purser 1977). The contributions made by Purser, A. E. Litherland and me to the development of AMS were recognized by Pergamon Press in 1980 when the Board of Editors of the *International Journal of Applied Radiation and Isotopes* (*JARI*) voted to give us the first *JARI* award. I should note that neither of my two colleagues with whom I was involved in the development of AMS, Professor Litherland nor Dr. Purser, saw a copy of my book before publication. If they had, this unintended contretemps would not have occurred.

Yours sincerely,

H. E. Gove
Professor Emeritus of Physics
The University of Rochester
Rochester, New York 14627 USA

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[RADIOCARBON, VOL. 39, NO. 2, 1997, P. 223]

RADIOCARBON UPDATES

General Index of Louvain Dates Published

Ivan Jadin informs us that the ^{14}C laboratory at Louvain, headed by Etienne Gilot, closed in September 1997. M. Gilot has just issued a general index of Lv- dates spanning the lab's 40 years of operation, as described in the following announcement:

> *Index Général des Dates Lv- (Laboratoire du Carbone 14 de Louvain/Louvain-la-Neuve)*
>
> After 40 years of activity, the ^{14}C Dating Laboratory of the Catholic University of Louvain is closing its doors. And as always in such a case, access to the archived information will soon become difficult, then altogether impractical. Most of the dates have indeed been published. The first, up to 1973, were primarily published in the journal *RADIOCARBON*. Afterwards the others were presented mostly in articles, often interdisciplinary, devoted specifically to studied sites. Still others remain unpublished. How can Ariadne's thread be found amidst this dispersion?
>
> To alleviate this difficulty, we have gathered in one index volume all the ^{14}C dates obtained at the Louvain/Louvain-la-Neuve (Lv) laboratory. The framework of such a work of course precludes detail; it imposes simplifications that are sometimes treacherous. The intention is to provide researchers with minimal information enough to permit them to pursue their investigations. [from E. Gilot's Introduction; translated from the French]

Cost of the 224-page volume is 500 BEF plus postage. For further information about the volume, please contact Ivan Jadin, Secretary, FNRS Contact Group "Prehistory", Rue Vautier 29, B-1000 Brussels, Belgium (tel. +32 2 627 4386; fax +32 2 646 4433; e-mail Ivan.Jadin@kbinirsnb.be).

Workshop on Global Paleoenvironmental Data

The Second Workshop on Global Paleoenvironmental Data will take place 9–12 February 1998 in Boulder, Colorado, USA. The conference organizers list these workshop goals:

> Evaluate the spectrum of PAGES science activities and tasks from the perspective of well-coordinated data management and full and open sharing of scientific data. Data management encompasses the technical details of how PAGES data sets are processed, documented, archived and distributed, whereas data sharing focuses on the ease of timely availability and usefulness both of data required to actually carry out the scientific research and data generated as a result of the scientific research. A challenge within the PAGES science activities and tasks is to ensure end-to-end data management and data access while maintaining the emphasis on basic scientific research questions. The systematic evaluation of the PAGES activities and tasks will provide a mechanism to identify common problems and to develop crosscutting solutions to overcome potential roadblocks. The resulting workshop report will describe how needed data management and access can be unobtrusively integrated into the PAGES science activities and tasks, and present an implementation plan for the next five years.

Among the crosscutting issues alluded to will be improved chronologies and correlations for these different projects.

For information, contact Robin Webb or Dave Anderson: tel. +1 303 497-6160; fax +1 303 497-6513; Internet danderson@ngdc.noaa.gov, rwebb@ngdc.noaa.gov.

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NOTICE TO READERS AND CONTRIBUTORS

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

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

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

For	*Date*
Vol. 39, No. 3, 1997	January 1, 1998
Vol. 40, No. 1, 1998	May 1, 1998
Vol. 40, No. 2, 1998	September 1, 1998

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

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

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

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

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CONTENTS