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RADIOCARBON DATING MARINE SHELL IN SAMOA – A REVIEW

Fiona Petchey* and David J. Addison†

ABSTRACT

This paper presents a discussion of marine reservoir research in Samoa. Two new ΔR results of known-age, pre-1950 shells from Tutuila Island, American Samoa, are given, and extant ΔR values obtained from both archaeological (Cleghorn and Shapiro 2000; Kirch 1993) and known-age, pre-AD 1950 shellfish (Phelan 1999) are evaluated. We suggest that a ΔR value of 25 ± 28 ^{14}C yrs is currently the most suitable for the Samoan Islands. This analysis highlights that careful selection of samples is required when undertaking ΔR research.

INTRODUCTION

A plant or animal that obtains carbon from a marine source (or reservoir) yields what is termed an 'apparent age'. The surface ocean (down to around 200 m depth) has an apparent ^{14}C age that is, on average, 400 years older than the terrestrial (atmospheric) reservoir. This is known as the marine reservoir effect and is caused both by a delay in the ^{14}C exchanged between the atmosphere and ocean, and by the mixing of surface waters with upwelled, ^{14}C-depleted deep ocean water (Stuiver *et al.* 1986: 982). This reservoir effect is automatically corrected for when a marine shell conventional radiocarbon age (CRA)[1] is calibrated using the modelled marine ^{14}C calibration curve (e.g., Marine04: Hughen *et al.* 2004). This calibration curve represents a global average of the surface ocean ^{14}C as it changes over time. Local and regional deviation from this global average, however, complicates the calibration of marine samples. To account for this deviation a local correction factor, or ΔR–the difference between the modelled ^{14}C age of surface water and the actual ^{14}C age of surface water at that locality–needs to be determined. This can be calculated from contemporaneous terrestrial/marine samples, or from marine samples collected prior to AD 1950, whose age of death is known precisely (i.e., annually banded corals, shells and/or otoliths of surface dwelling fish) (e.g., Kalish 1993; Dye 1994; Guilderson *et al.* 2004; Petchey *et al.* 2004).

Data collected over the last decade (see Reimer and Reimer 2007) suggest that ΔR values from pre-AD 1950 marine proxies in the Pacific region vary significantly both geographically and over time. However, the limited number of available ΔR values and a lack of guidelines governing the selection of appropriate ΔR values for each island, have been continuing problems for the accurate calibration of dates on marine shell and other animals that subsisted on marine resources. The few available calculated ΔR values obtained from archaeological terrestrial/shell pairs seem to support both geographical variation (Petchey *et al.* 2005) and chronological change (Ingram 1998; Deo *et al.* 2004; Culleton *et al.* 2006), but in general the difficulty of locating undisputed near-contemporaneous paired samples has resulted in scepticism over many ΔR values obtained in this way.

In this paper, we attempt to address this problem for the Samoan Archipelago (see Figure 1), and present two new ΔR results for Tutuila, American Samoa[2] obtained from known- age, pre-AD 1950 shells. These results are compared to published ΔR values from this region based on known-age samples (Phelan 1999) and extant ΔR values calculated from archaeological charcoal/shell samples (Kirch 1993; Cleghorn and Shapiro 2000) (Tables 1 and 2).

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1 A conventional radiocarbon age is obtained from a radiocarbon measurement following the conventions set out by Stuiver & Polach (1977). A CRA must be calibrated to determine a calendar age. By convention, the symbol BP means 'conventional radiocarbon years before AD 1950', whereas the symbols cal BP or BC/AD are used to express calibrated radiocarbon ages.

2 The Samoan Archipelago spans some 300 km. 'Upolu, Savai'i and several smaller islands make up the Independent State of Samoa. When discussing these islands as a group we have used the geographic reference 'western Samoa'. The Territory of American Samoa is composed of the Manu'a Group (Ofu, Olosega and Ta'u), Tutuila and several smaller islands. For these we have used the term 'eastern Samoa'.

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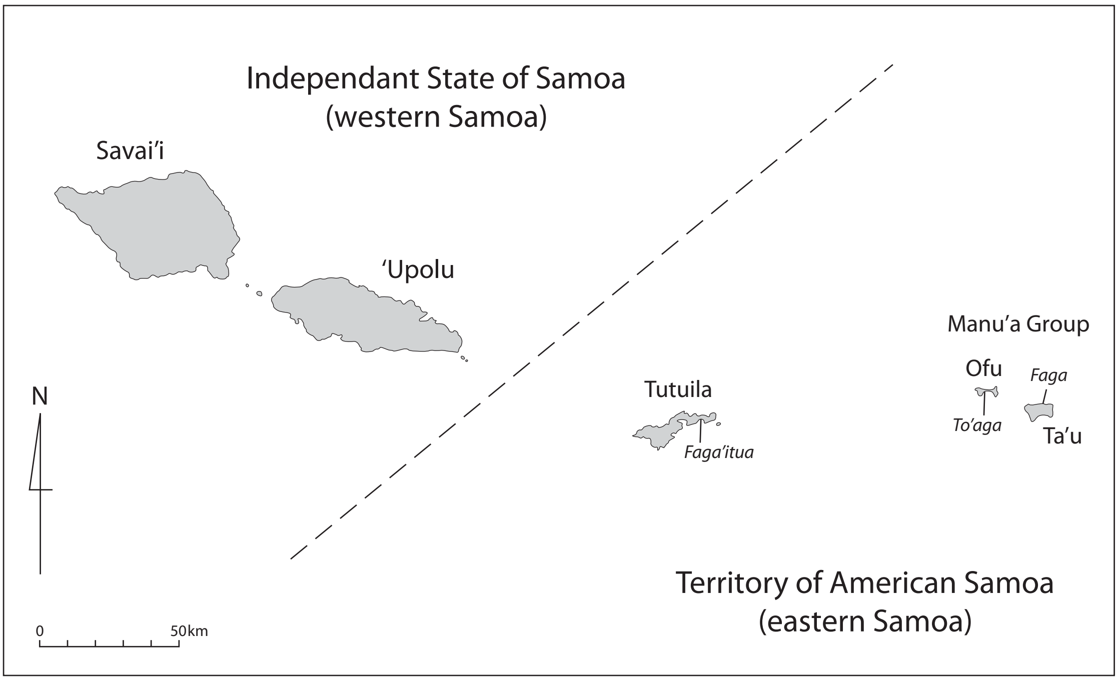

Figure 1: Map showing the Samoan Archipelago and places mentioned in the text.

BACKGROUND: PREVIOUS SAMOAN ΔR RESEARCH

In order to calibrate shell radiocarbon ages obtained during excavations at To'aga, on Ofu Island in eastern Samoa, Kirch (1993: 87) calculated a ΔR correction factor that was a weighted average of empirically determined ΔR values from the mid-Pacific islands of Eniwetok, Hawai'i, Tahiti and Mo'orea (Society Group). This value (ΔR = +100 ± 24 ^{14}C yrs) was far from ideal due to the wide geographical spread of the values used, but it produced consistent calibrated ^{14}C results for charcoal and shell from the same excavation level of the site (see Table 2 for sample details).

Phelan (1999) would later use the To'aga shell/charcoal pair to calculate a ΔR value of -230 ^{14}C yrs for the site.[3] However, this value was at odds with three ΔR values Phelan obtained from known-age, pre-AD 1950 shells from 'Upolu, western Samoa, which resulted in a weighted mean of +57 ± 23 ^{14}C yrs (see Table 1). Phelan (1999: 100) suggested this discrepancy indicated either: a difference in the surface ocean ^{14}C activity between western and eastern Samoa; that there had been a change in the regional oceanic processes over time; or a problem of association between the two archaeological determinations from To'aga.

Also recognizing the need for a Samoa-specific ΔR value, Cleghorn and Shapiro (2000: 31, 83, 84) selected a terrestrial/marine pair from Fagā Village, Ta'u Island, eastern Samoa to calculate a regional ΔR value (see Table 2 for sample details). They concluded that when calibrated the charcoal was only 25 years older than the shell, which suggested to them that no, or minimal ΔR correction factor was needed in eastern Samoa.

Despite a recommendation by Kirch (1993), Cleghorn and Shapiro (2000) and Phelan (1999) that the Samoan ΔR needed further investigation, there has been no attempt to address this problem within the Samoan Archipelago until now.

METHODOLOGY

Samples selected for ΔR research must conform to a number of strict prerequisites:

1 The marine sample must have been collected live, or the date of death independently validated. For pre-AD 1950, known-age shells this can best be demonstrated by the presence of museum documentation, the fleshy remains of an animal, or valves in articulation with intact ligaments. For archaeological shell samples, the shell should be the remains of food (as opposed to the remains of some industry or part of a natural beach deposit).

2 The geographic location where the samples were collected must be known.

3 The marine sample must be identified to genus level, and the dietary and habitat preferences of that genus must closely represent that of the reservoir you are investigating (e.g., open ocean, estuarine, etc.).

4 For historic proxies, the date of collection must be known and be before AD 1950 (i.e., prior to detonation

3 Calculated using the calibration curves IntCal98 (Stuiver et al. 1998) and Marine98 (Stuiver, Reimer and Braziunas 1998).

Table 1. *Radiocarbon ages and ΔR results for known age, pre-AD 1950 shells from Samoa.**

Location	Lab. No.	Family, Genus, Species †, ‡	$\delta^{13}C$ ¶ ‰	Year Collected	CRA (Rs(t)) + error	Marine modeled age (Rg(t))	ΔR (yr) Rs(t) – Rg (t) §
Faga'itua, Tutuila Island	Wk-19682	Cardiidae: *Fragum fragum* (SF)	2.981	1933	460 ± 19	456 ± 23	4 ± 19
Pago Pago, Tutuila Island	Wk-19683	Veneridae: *Antigona reticulata* (SF)	2.568	1865	500 ± 20	480 ± 23	20 ± 20
'Upolu (?)	Wk-6383	Turbinidae: *Turbo petholatus* (H)	2.0	1882	550 ± 40	474 ± 23	76 ± 40
	Wk-6384	Strombidae: *Strombus pacificus* (H)	2.1		500 ± 40		26 ± 40
	Wk-6385	Strombidae: *Strombus lentiginosus* (H)	3.2		560 ± 40		86 ± 40

* The Tutuila samples are first published here, the 'Upolu samples are from Phelan (1999) and provenance is uncertain.

† Diet preferences (in brackets): SF = suspension-feeder; H = herbivore.

‡ Venerids may live for more than 40 years (Beesley et al. 1998: 356) and Cardiidae generally less than 10 years (Beukema 1989). Because mollusc shells are built up over their entire life the margins of the shell will be younger than the hinge. In the case of Wk-19683 we have sampled no more than 5 'circuli'. Therefore, when calculating the marine modelled age for these shells we have assumed that the carbon was fixed into the shells close to the year of collection for Wk-19682 and Wk-19683 where outer rings were sampled.[4] The limited data available for reef gastropods suggests that most live >5 years and some may reach 20 years of age (Frank 1969: 247). Because whole shells were dated in the case of Wk-6383, Wk-6384 and Wk-6385 we have used an average of the Marine04 data (Hughen et al. 2004) points over a 10 year period prior to the collection date. Where necessary we have interpolated between the 5-year increments in the Marine04 ages.

¶ $\delta^{13}C$ reported relative to the VPDB standard with a precision of 0.2‰.

§ The uncertainty in the radiocarbon age is used for the ΔR uncertainty since the marine model error is now included in Marine04 (pers. comm. P. Reimer Jan 2007). No Suess correction has been applied to these calculations due to uncertain effect of anthropogenic ^{14}C in the southwest Pacific (Druffel and Griffin 1993).

Table 2. *Radiocarbon data for paired charcoal/shell samples from archaeological sites in Samoa.*

Lab. No.	Location	Material	$\delta^{13}C$ ‰	^{14}C CRA ± error (BP)	Marine modelled age (Rg(t))*	ΔR (yr) Rs(t) – Rg (t)
Fagā Village (AS-11–1), Feature Complex B, Ta'u Island, Manu'a Group (Cleghorn and Shapiro 2000).						
Beta-109584	TU12, layer V, 96 cmbs (SCS RC No.99)	Charcoal unidentified	-29.0	700 ± 50	1116 ± 28	-75 ± 55
Beta-132436	(SCSRC No. 155)	Archidae sp. (SF)†	3.4	1040 ± 50	–	
To'aga, Ofu Island, Manu'a Group (Kirch 1993).						
Beta-35603	Unit 28, Transect 9	Charcoal unidentified	-28.4	2600 ± 170	2926 ± 173	-155 ± 190
Beta 35604	Unit 28, Transect 9	*Tridacna maxima* (SF)†	1.7	2770 ± 80	–	

* An estimate of the atmospheric calibration curve error (INTCAL04: Reimer *et al.* 2004)[5] over the 1σ span of the radiocarbon age was used to derive the calculated marine modelled age (Rg(t)), whereby, atmospheric age $\sigma = \sqrt{(\sigma^{14}C\ age^2 + \text{average of calibration curve error}^2)}$.

† Diet preferences (in brackets): SF = suspension-feeder (Beesley et al. 1998: 333).

4 Circuli are concentric ridges formed on the surface of bivalve shells by the periodic addition of material to the edge of the shell. They become crowded together at the annuli (Almeida and Sheehan 1997) and should not be confused with annuli. Growth rings (or annuli) on the surface of bivalve shells represent periods of growth cessation, which are often interpreted as yearly rings associated with changing season. However, they can be caused by a variety of environmental and biological causes and their annual relationship is less certain in locations without seasonal extremes (Jones 1989).

5 For ^{14}C purposes the boundary between the Southern and Northern Hemispheres atmosphere is considered to lie along the thermal equator or the Inter-Tropical Convergence Zone (ITCZ) during the respective growing seasons (McCormac *et al.* 2004: 1088). Because Samoa lies at the limit of the South Pacific Convergence Zone which merges with the ITCZ to the west we have opted to use the Northern Hemisphere calibration curve (INTCAL04: Reimer *et al.* 2004) for the terrestrial calibrations, though this is likely to fluctuate seasonally and over time.

of thermonuclear devices). For archaeological ΔR research, the paired charcoal sample is used to verify the collection date of the shell, therefore the charcoal must be short-lived (e.g., twig from a short lived species or nutshell, both of which have <10 yrs inbuilt age[6]).

The ΔR for a specific location '(s)' can be calculated from known-age shells, collected prior to atmospheric bomb testing using the formula: $Rs(t) - Rg(t) = \Delta R(s)$, where ($\Delta R(s)$) is the difference between the global average ($Rg(t)$) and the actual ^{14}C activity of the surface ocean at a particular location ($Rs(t)$) at that time. When calculating ΔR using charcoal and shell ^{14}C results from archaeological sites the standard approach is to convert the 1σ age range of the terrestrial ^{14}C value to a model marine ^{14}C age ($Rg(t)$) using the relevant calibration curve data (e.g., Marine04: Hughen *et al.* 2004)(see Ulm 2002 for methodology). This value is then subtracted from the paired marine shell CRA ($Rs(t)$) and the ΔR standard error is calculated by the formula: $\Delta R\sigma = \sqrt{(\sigma Rg(t)^2 + \sigma Rs(t)^2)}$.

Even when samples are carefully selected according the prerequisites listed above, there are a number of uncertainties in the accuracy of any ΔR calculation due to the postulated time of carbon uptake before collection, the influence of diet, habitat and short-term fluctuations in the water masses. When calculating the amount of uncertainty added to the ΔR value introduced by the non-uniform ^{14}C content of the shellfish, the standard approach has been to calculate the scatter σ in the unweighted mean (i.e., the empirical standard deviation = $\sigma/\sqrt{n}$) and compare this to the weighted mean, taking the larger of the two as the ΔR uncertainty (±) following the recommendations of Stuiver *et al.* (1986: 982). Reimer and Reimer (2006) recently advocated the use of the standard deviation (σ) as a more accurate assessment of ΔR variability. This does not, however, take into account the uncertainty associated with each result. Instead, we have opted to follow the methodology recommended by Bondevik and Gulliksen in Mangerud *et al.* (2006: 3241) where the Chi squared (χ^2) test is used to test the internal variability in a group of ΔR values. If the $\chi^2/(n\text{-}1)$ is >1 the group has additional variability beyond measurement uncertainties, and the additional variance (σ_{ext}) and uncertainty are calculated and applied to the ΔR (Table 3). When $\chi^2/(n\text{-}1)$ is ≤1 the weighted mean is used (see Mangerud *et al.* 2006: 3241–2 for explanation).

We obtained two known-age pre-AD 1950 shells from the Australian Museum (Table 1). The sample from Faga'itua (Museum acquisition number = AM:C061233; *Cardiidae: Fragum fragum*) was obtained by Ted Dranger who was stationed in the Pacific between 1925 and 1935 (Schwengel 1957). John Brazier collected the shell sample from Pago Pago (AM:C015564; Veneridae: *Antigona reticulata*) during the South Seas Expedition in 1865 (Iredale 1931). All samples had the remains of hinge ligaments indicating either live, or near live collection. Both Cardiidae sp. and Veneridae sp. are suspension-feeding shellfish (Beesley *et al.* 1998: 328, 356). Suspension feeders generally consume suspended phytoplankton and dissolved inorganic carbon from seawater and, therefore, should reflect the surface ocean reservoir conditions (Tanaka *et al.* 1986).

From each of these shells we removed a 5 mm cross-section perpendicular to the edge of the shell across multiple increments of growth to avoid intra-shell variations in ^{14}C (Culleton *et al.* 2006, Petchey in prep) and provide an average value over a maximum period of five years (i.e., one increment in the Marine04 dataset).

RESULTS

Pre-AD 1950, Known-age Shells

The results of ΔR calculations for the pre-AD 1950, known age shells are shown in Table 1. The weighted mean of the two Tutuila ΔR values is 12 ± 14 ^{14}C years with no additional uncertainty in the ΔR (Table 3). Recalculation of the previous values obtained by Phelan (1999) using the current calibration dataset (Marine04: Hughen *et al.* 2004) results in a weighted mean for 'Upolu of 63 ± 23 ^{14}C years– again with no additional uncertainty.

When pooled, the weighted mean for all the pre-AD 1950, known-age Samoan shells is 25 ± 12 ^{14}C years, but $\chi^2/(n\text{-}1)$ is 1.31 indicating non-uniform ^{14}C content. An additional uncertainly has therefore been added to the ΔR mean value to give 25 ± 28 ^{14}C years (Table 3).

Archaeological Shell/Charcoal Pairs

ΔR values obtained from archaeological terrestrial and marine samples from the sites of To'aga and Fagā Village have been recalculated using the Marine04 (Hughen *et al.* 2004) and IntCal04 (Reimer *et al.* 2004) calibration datasets (see Table 2). Despite the large standard errors associated with the archaeological ΔR values and apparent consistency between the two results ($\chi^2/(n\text{-}1) = 0.16$), when compared to the pre-AD 1950, known- age shells, additional variability beyond measurement uncertainty is indicated ($\chi^2/(n\text{-}1) = 1.54$) (Table 3).

DISCUSSION

The ΔR value from To'aga, originally calculated by Phelan (1999) as -230 ^{14}C yrs is very different to the new value calculated in Table 2 (ΔR=-155 ± 190 yrs). Phelan (1999: 100) followed the methodology for calculating ΔR as laid out by Stuiver and Braziunas (1993: 153, Figure 15B), whereby the charcoal ^{14}C age was converted to a model marine ^{14}C

6 Inbuilt age refers to either the growth age of the tree where older wood from the center of the trunk is dated, or the storage age where a period of time has elapsed from the death of the tree to its use by people (McFadgen 1982). Inbuilt age may result in errors of hundreds of years unless only short-lived species, twigs, or seeds are selected for dating (Allen and Wallace 2007).

Table 3. *ΔR Statistics*

Description	No.	Dietary preference	ΔR pooled + error (E)	$X^2/(n-1)$	ΔR with external variance*
Tutuila, eastern Samoa	2	Suspension feeders	12 ± 14	0.34	No variance
ʻUpolu, western Samoa	3	Herbivores	63 ± 23	0.65	No variance
All pre-1950, known age Samoan shells	5	–	25 ± 12	1.31	25 ± 28†
Archaeological and pre-1950, known age shells	7	–	20 ± 12	1.54	29 ± 81†

* The additional variance (σ_{ext}) is obtained by subtracting the ^{14}C measurement variance from the total population variance and obtaining the square root, e.g. $\sigma_{ext} = \sqrt{(\sigma^2_{pop} - \sigma^2_{meas})}$.

† The uncertainty given includes the additional variance and is calculated by $\sqrt{(E^2_{\Delta R pooled} + \sigma^2_{ext})}$.

age by extrapolation through the graphed, but highly condensed, 1993 atmospheric and marine calibration datasets. The use of Stuiver and Braziunas' (1993) Figure 15B resulted in a margin of error that is not immediately apparent from the original ΔR value. The recalculated ΔR for To'aga has a very large standard error due to the imprecision of the original CRAs. Consequently, when the standard error is taken into account, the new ΔR value for To'aga is similar to the pre-AD 1950 historic shell values given above and not anomalous as Phelan suggested. This highlights the necessary caution when dealing with ^{14}C data with large standard errors. However, there is evidence of variation between the three data sets (eastern Samoa (this paper), western Samoa (Phelan 1999) and the archaeological samples (Cleghorn and Shapiro 2000; Kirch 1993), which could be caused by a number of factors.

Change over Time

One possibility is change in ^{14}C over time in response to changes in ocean circulation and climatic conditions. This has been documented in banded coral records (Druffel and Griffin 1999; Guilderson *et al.* 1998) and from archaeological ΔR studies (Deo *et al.* 2004; Ingram 1998; Reimer *et al.* 2002). It is possible that the variation seen in the data presented here may reflect a change over the last 3000 years, but the three known-age, pre-AD 1950 samples from ʻUpolu collected during the same period (1882) show greater variance ($\chi^2/(n\text{-}1) = 0.65$) than the two samples from Tutuila collected 68 years apart ($\chi^2/(n\text{-}1) = 0.34$). We think that there are a number of problems with the available data that are more instrumental in causing the variation seen, as discussed below.

Marine Shell

The ^{14}C content of shellfish is tied closely to the peculiarities of habitat and diet (Tanaka *et al.* 1986; Hogg *et al.* 1998). It has been well documented that herbivores and deposit feeders can give anomalous ΔR values due to the intake of detrital matter, especially in areas with limestone geology (Dye 1994; Spennemann and Head 1998; Petchey *et al.* 2004, Petchey in press). Phelan considered this to be of minimal concern for the three pre-AD 1950, known-age herbivorous shellfish used in his study because the geology of ʻUpolu and the Samoan Archipelago is entirely volcanic in origin, and the only geological carbonates available are Holocene (<10,000 year old) beach sands (Keating 1992). However, it is by no means certain that the ^{14}C content of herbivorous shellfish will stand up to the scrutiny of ΔR analysis, and the digestion of Holocene beach sands by herbivorous species may account for the variability seen here.

Geographical and Oceanic Variation

The ΔR variation seen between eastern and western Samoan pre-AD 1950, known-age shells could also represent geographic variability (and possibly also the archaeological ΔR values from the Manu'a Group which are separated from Tutuila by 150 km). Significant ΔR variation has been noted over short distances in the Bismarck Archipelago (Petchey *et al.* 2004), which are attributed to upwelling associated with current reversals. ΔR variation within incrementally sampled marine shells has also been noted in areas of upwelling and varying riverine input (e.g., along the Californian coastline (Culleton *et al.* 2006) and the Galapagos Islands (Druffel 1987)). However, Samoa is encircled by the South Pacific Gyre. This circulatory system creates relatively stable surface water conditions at the centre (Rougerie and Wauty 1993) and reliable published ΔR values from the South Pacific region tend to be fairly uniform (Petchey in press), but there are currently too few ^{14}C values to effectively evaluate the true extent or cause of ΔR variability in the Oceania region. The possibility of large-scale eddies, similar to that suggested for variable ΔR conditions in the Hawaiian Islands (Petchey in press), may also be a concern.

Stratigraphic Problems and Limitations of the ΔR Calculation Technique.

In the case of archaeological pairs, the samples used in the ΔR equation must belong to near-penecontemporaneous events (Stuiver & Braziunas 1993) (though see Petchey *et al.* 2005 and Jones *et al.* (2007) for an alternative approach to calculating ΔR value that does not require the dated events to be tightly constrained). This ΔR requirement is a common hindrance when using archaeological shell/charcoal pairs from the Pacific where the stratigraphy is often complex and sites used over many centuries. Moreover, the statistical methodology of Bondevik and Gulliksen used here to compare the Samoan ΔR values needs to be evaluated further using archaeological pairs from other localities.

Charcoal Inbuilt Age

Explicit in the notion that the samples must be near contemporaneous is that the target event and the age determined by the charcoal sample (or Rg(t)), must have no offset in age (c.f., a robust determination [Mook and Waterbolk 1985]). The notion of inbuilt age in charcoals is a well-recognised ^{14}C problem (e.g., Anderson and Clark 1999; Kirch 1993: 87), however, Pacific archaeologists rarely identify their charcoal because of the lack of suitable Pacific wood reference collections, and rarely incorporate any inbuilt age into the subsequent chronological interpretations. A recent study of radiocarbon determinations from the Cook Islands by Allen and Wallace (2007) has demonstrated that uncalibrated, identified charcoal species[7] can give radiocarbon results that are on average 64 ^{14}C yrs older than short-lived nutshell samples, with the more disturbing prospect that some unidentified samples could be 300 or 400 years too old. Neither the charcoal sample from To'aga nor the sample from Fagā were identified to the species level. If we assume the possibility of an average 64 years of inbuilt age in these samples the ΔR would be closer to that of the pre-AD 1950, known-age samples.

CONCLUSION

We currently recommend the use of a ΔR value for Samoa of 25 ± 28 ^{14}C years derived from five known-age, pre-AD 1950 marine shells. Additional research into archaeological shell/charcoal pairs from Samoan sites is needed before any firm conclusions about change over time in ΔR can be made. Suspension-feeding shell samples from 'Upolu are currently being analysed in order to test whether geographical variation or shell dietary preferences are the likely cause of minor ΔR variation between eastern and western Samoan Islands.

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7 Although Allen and Wallace 2007, specifically selected small diameter material for ^{14}C dating, some of the charcoal species used could potentially have significant inbuilt age.

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