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Stability in the South Pacific surface marine ^{14}C reservoir over the last 750 years. Evidence from American Samoa, the southern Cook Islands and the Marquesas

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ABSTRACT

Although minor climatic and sea-level changes have been documented for the South Pacific during the late Holocene, our understanding of the consequent impact of these changes on the marine ^{14}C reservoir, and therefore the ^{14}C content of shellfish, is limited. Ultimately, this has implications for documenting the chronology of human movement and adaptation in this region. In this paper we compare marine reservoir (ΔR) data obtained from tightly controlled archaeological proveniences with known-age, pre-AD 1950 shells from the southern Cook Islands, American Samoa, and Marquesas Islands. Results indicate that there has been no significant change in the near-shore marine reservoir in these three locations over the last ca. 750 years. Furthermore, known-age, pre-AD 1950 shell samples provide more precise ΔR values for use in sample calibration than archaeological paired shell/charcoal samples. This is attributed in part to the limitations of assigning provenance and age to material from archaeological sites. On the basis of these results we conclude that the known-age, pre-AD 1950 shell derived ΔR values can be used to calibrate shell ^{14}C results from deposits of late Holocene age.

1. Introduction

Polynesia was one of the last places on the Earth to be permanently settled by humans. As a result it has a relatively short chronology compared with many other regions, with the duration of human occupation being less than 3200 years (Kirch, 2000). Moreover, human settlement in the central eastern archipelagos, along with Hawai'i, New Zealand, and Easter Island is probably less than 2000 years on current evidence. As elsewhere, archaeologists working in Polynesia are reliant on precise and accurate radiocarbon dates for resolving the timing and pattern of colonization, as well as sequences of cultural change and the chronology of environmental variability. In the past, archaeologists have relied heavily on ^{14}C determinations of wood charcoal, which may be problematic for a number of reasons. In some sites charcoal is rare or its association with the event of interest is uncertain (Anderson, 2001; Spriggs and Anderson, 1993). Radiocarbon results of wood charcoal samples may also be influenced by inbuilt age if they originate from long-lived species (Allen and Wallace, 2007), or by "storage age" if the species selected is resistant to weathering and decay, or if stored wood is burned (Schiffer, 1987). Unfortunately, wood charcoal can be difficult to identify, especially if the fragments are small, as is usually the case for AMS samples. In addition, suitable wood reference collections are not widely available to aid in identification. Where cultural sequences are short, the impact of this array of factors can lead to problematic interpretations, hence the significant controversies over the timing of colonization, settlement and many other cultural developments in the Pacific (e.g., Addison and Morrison, in press; Allen and Wallace, 2007; Anderson,1991; Anderson et al., 2000; Anderson and Clark, 1999; Anderson and Sinoto, 2002; Hunt and Lipo, 2006; Reith and Hunt, 2008; Spriggs and Anderson, 1993; Sutton, 1994).

Marine shell provides both a logical alternative to charcoal for radiocarbon dating and a useful complement when both are available. However, the accurate calibration of shell dates requires an understanding of the geographical variability in the surface ocean marine ^{14}C reservoir that is caused by variations in upwelling, ocean currents, and climate (Stuiver and Braziunas, 1993), as well as an understanding of the habitat and dietary preferences of different shellfish species (Dye, 1994; Hogg et al., 1998; Tanaka et al., 1986). A reservoir correction factor, commonly called a ΔR, is used to account for local marine ^{14}C variation. The

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marine ΔR is the difference between the global average modelled marine reservoir and the actual ^{14}C activity of the surface ocean at a particular location (Stuiver et al., 1986). ΔR can be calculated from paired terrestrial and marine ^{14}C samples excavated from archaeological sites (Deo et al., 2004; Ulm 2002), or from inshore/offshore isochrones such as tephra and foraminifera (Ascough et al., 2005; Sikes et al., 2000) providing the contemporaneity of the samples can be assured (Jones et al., 2007; Kennett et al., 2002). ΔR can also be calculated from known-age shells collected prior to atmospheric bomb testing (Reimer and Reimer, 2001; Southon et al., 2002), otoliths from surface dwelling fish (Higham and Hogg, 1995; Kalish, 1993), and annually banded coral species (Burr et al., 2006; Guilderson et al., 1998, 2004). Recent research into historic ΔR using shells collected post-AD 1865 within the South Pacific (Petchey et al., 2004, 2008a, 2008b; Petchey and Addison, 2008) has significantly improved our understanding of geographical variation in this region and has indicated that the most significant shifts in ΔR are found in locations where water depleted in ^{14}C is brought up to the surface (e.g., around the Chatham Islands) and areas where ancient ^{14}C is available from limestone (e.g., Tongatapu, Tonga and Mangaia, southern Cook Islands) (Fig. 1). Unfortunately, there have been few attempts to document how ΔR changes over time. Coral core data from the Marquesas Islands and southern Cook Islands suggest negligible change in the surface marine reservoir over the last 11,000 years (Bard, 1988; Paterne et al., 2004), while a shift of 330 years has been recorded from tephras and foraminifera ^{14}C dates collected just off the New Zealand coast dated to ca. 12,600 years ago (Sikes et al., 2000). Currently, there is no information for the period covered by human colonization and expansion in this region.

Changes in sea-level are well documented for the South Pacific region (Dickinson, 2001; Druffel and Griffin, 1993; Moriwaki et al., 2006; Pirazzoli and Montaggioni, 1988; Yonekura et al., 1988). Explanations for this sea-level flux include isostacy, climatic variability, and local tectonism, all of which could have had significant, but varied impact on humans. It is thought that initial human colonization in West Polynesia may have followed close on the heels of falling sea-levels after the mid-Holocene sea-level highstand ca. 3000–4000 years ago when new coastlines formed. It has also been argued that population expansion eastward into the

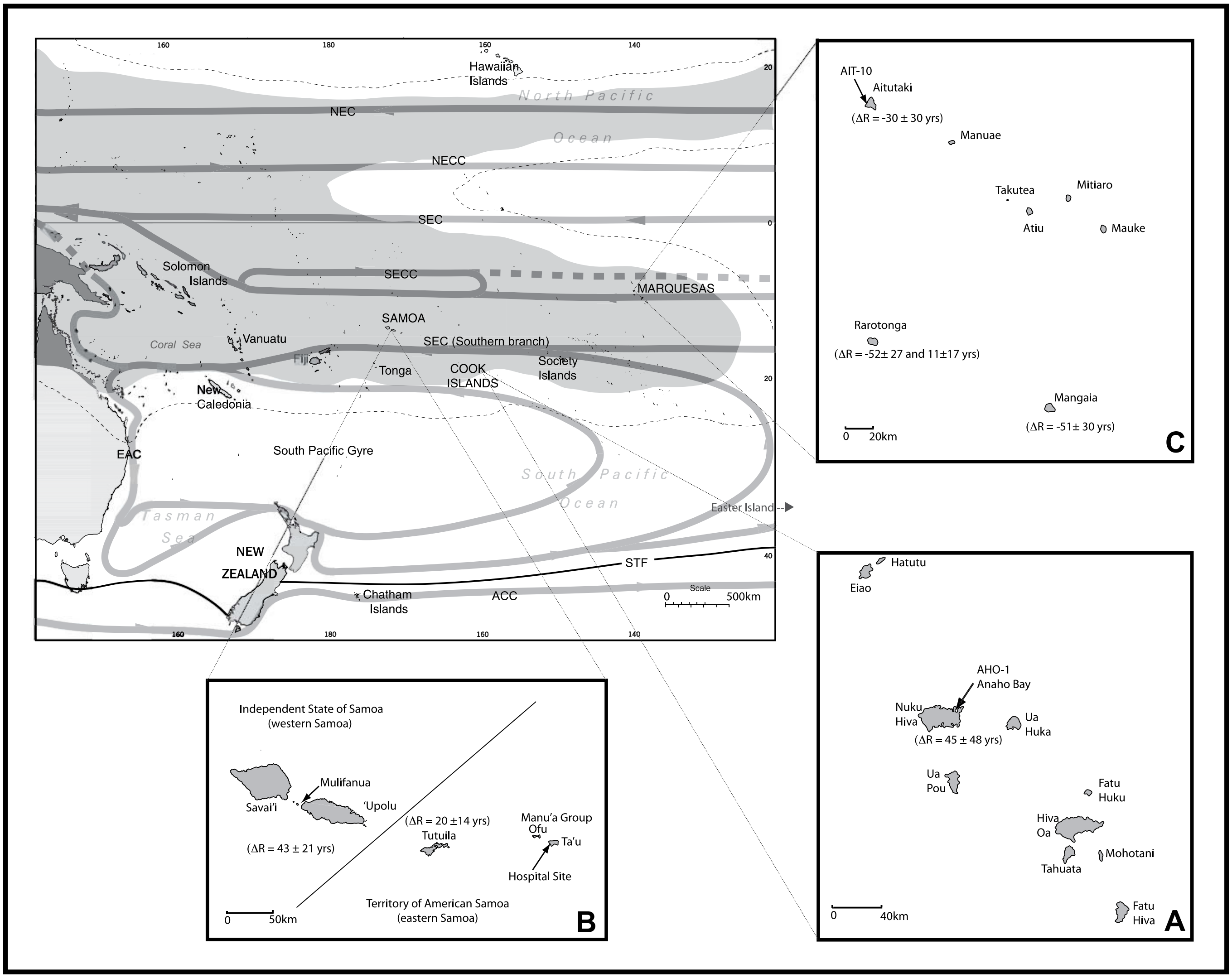

Fig. 1. The South Pacific Ocean showing the collection location of pre-AD 1950, known-age shell ΔR values and archaeological sites mentioned in text. Major oceanic currents within the South Pacific Ocean are based on Ganachaud et al. (2007:8, Fig. 4) and Tomczak and Godfrey (2001:111). Abbreviations: SEC, South Equatorial Current; SECC, South Equatorial Counter Current; NEC, North Equatorial Current; NECC, North Equatorial Counter Current; EAC, East Australian Current; STF, Subtropical Front; ACC, Antarctic Counter Current. The greyed area shows the approximate extent of the Inter-tropical and South Pacific Convergence Zones between 1968 and 1996, with maximum extent indicated by dotted line (after Linacre and Geerts, 1998). Inserts: (A) Marquesas Islands, (B) Samoan Archipelago, (C) southern Cook Islands.

southern Cook Islands, Marquesas and Society Islands, where cross-over dates range from AD 500 to AD 1400, may have been controlled by the persistence of the mid-Holocene hydro-isostatic highstand caused by increased crustal buoyancy within this region (Dickinson, 2001, 2003). Nunn and Britton (2001) have further argued for subtle climatically-induced sea-level fluctuations between AD 750 and AD 1800, but this interpretation has been challenged (Gehrels, 2001).

The potential influence of sea-level fluctuations, tectonism and climate variability on the more restricted estuarine and reef environments inhabited by many marine shellfish and corals is considerable. In some areas tidal inlets were turned into brackish lagoons with significant changes in local marine species (e.g., Tikopea (Kirch and Yen, 1982) and Tongatapu (Spennemann,1987)). In the most extreme cases archaeological sites have been completely submerged or buried by sediment since first occupied (e.g., the ca. 2700-year-old Samoan sites at Mulifanua and To'aga (Dickinson and Green, 1998; Kirch, 1993), and the ca. 1000-year-old site at Huahine, Society Islands (Anderson and Sinoto, 2002; Sinoto and McCoy, 1975)). Periods of marked cyclonic activity are also known, as for example on Aitutaki Island in the 14th century AD (Allen and Craig, in press), with obvious consequences for coastal resources. Increased precipitation associated with the warmer, wetter "Little Ice Age" conditions after AD 1550 (Allen, 2006; Cobb et al., 2003; Graham et al., 2007) may also have introduced large amounts of terrigenous sediment into lagoons, reducing their salinity and aiding the development of alluvial fans. Importantly, these are all factors that can significantly influence the ^{14}C content of marine shells (Hogg et al., 1998; Petchey et al., 2008a, 2008b; Southon et al., 2002). Moreover, the recorded global rise in sea-level over the past century, as evidenced by tide gauges (Dickinson, 2001:207) may have influenced the known-age, pre-AD 1950 shells currently used for ΔR control, making the application of these values to archaeological sites questionable.

Investigation of variation in the marine reservoir over time is, therefore, vital if marine shell is going to be used to establish chronological control over issues of island colonization and cultural change, or the evaluation of coastal geomorphology, environmental variability and climate change. Archaeological studies using contemporaneous marine/terrestrial samples (Ascough et al., 2005; Deo et al., 2004; Yoneda et al., 2001) have demonstrated the potential of longer-term ΔR evaluation. Unfortunately, although the few available South Pacific archaeological ΔR values appear to support some temporal variation (e.g., Cleghorn and Shapiro, 2000; Jones et al., 2007; Kirch, 1993; Phelan, 1999), the reliability of these values is currently hindered by problems of association and material suitability. Consequently, the difficulty of locating undisputed, near-contemporaneous paired samples has resulted in scepticism over many ΔR values obtained from archaeological material (Petchey and Addison, 2008).

In an attempt to correct this short-coming we have investigated ΔR variation over time by comparing ^{14}C results of known-age, pre-AD 1950 shells to radiocarbon determinations of marine and terrestrial samples collected from three archaeological sites: Ureia (AIT-10), Aitutaki Island, southern Cook Islands; Ta'u Hospital, Ta'u Island, American Samoa; and Teavau'ua (AHO-1), Anaho Bay, Nuku Hiva Island, Marquesas Islands (Fig. 1).

1.1. Teavau'ua (AHO-1), Anaho Bay, Nuku Hiva Island, Marquesas Islands

The Marquesas chain consists of ten main islands, of which Nuku Hiva is the largest (Fig. 1a). These islands lie at the eastern edge of the South Pacific Gyre, 1430 km from the Society Islands to the south-west (Fig. 1). Currently, the best documented early sites in the Marquesas Islands are Hane on Ua Huka and Hanamiai on Tahuata. The basal occupations from both these localities are thought to date to some time after AD 1000 (Anderson and Sinoto, 2002:251; Rolett, 1998:83–85). Anaho Valley, the locus of the samples reported herein, lies on the northern coast of Nuku Hiva, and the specific collection locality – Teavau'ua (AHO-1) – occupies several hundred square metres of the northern coastal flat (Allen, 2004). Three cultural layers have been identified. The oldest layer (Layer IV) dates to ca. AD 1289–1432 (2σ age range). Following a hiatus, re-occupation (Layer IIIb) and more intensified use of the area occurs in the period AD 1407–1797 (2σ age range). Activities associated with these two prehistoric layers included the production of pearl-shell fish-hooks and basalt adzes, as well as more general domestic activities. The third occupation layer (Layer IIIa) is historic in age and probably dates to the post-AD 1850 period based on its artefact content. The site thus covers much of the known Marquesan sequence outside of the initial settlement period. It also dates to after the period of significant sea-level fall, thought to have begun around AD 700 in this region (Dickinson, 2003; Pirazzoli and Montaggioni, 1988), but predates the warmer wetter conditions predicted by Cobb et al. (2003; see also Allen, 2006; Graham et al., 2007).

1.2. Ta'u Hospital, Ta'u Island, American Samoa

The Samoan Archipelago spans some 300 km (Fig. 1b). 'Upolu, Savai'i and several smaller islands make up the Independent State of Samoa, while the Territory of American Samoa is composed of the Manu'a Group (Ofu, Olosega and Ta'u), Tutuila and several smaller islands. Addison excavated two 1 × 1 m test units at the Ta'u Hospital site in May 2007. The two test units had similar stratigraphy (seven strata) with faunal remains (bone and shell food waste) throughout the layers. There was modern, historic, and traditional material in the upper strata (Layers 1–3). The middle strata (Layers 4–5) were dominated by coral-gravel paving ('ili'ili). This coral gravel petered out in Layer 6 and there was little cultural material in Layer 7. The cultural sequence at the site suggests initial, and probably occasional, use of a newly formed beach area for marine procurement activities. This was followed by intensification of activities and eventually by permanent habitation. Radiocarbon dates, cultural remains and geomorphological similarity to sites on Tutuila indicate occupation dating from ca. AD 1450 to the present (Addison, 2008). Sea-level changes around the Samoan Archipelago are complicated by the influence of volcanic loading, which has resulted in a complex history of subsidence and uplift, the chronology and spatial aspects of which are not fully documented or understood (Dickinson 2001:213–214). Tutuila specifically appears, however, to have undergone neither uplift nor subsidence (Dickinson, 1997). Sea-level and coastline stabilization following post-mid-Holocene drawdown does not occur on Tutuila until after ~AD 350 (Addison and Asaua, 2006). Addison (2008) has suggested that a similar coastline stabilization date may apply to Ta'u.

1.3. Ureia (AIT-10), Aitutaki, southern Cook Islands

Aitutaki is the northern-most island of the main southern Cook Island group (Fig. 1c). The island is composed of a remnant of the original volcanic cone (16 km^2) with several small coral detritus islands encircling a large lagoon (Stoddart, 1975). The Ureia (AIT-10) site lies on the mainland west coast on a coastal flat less than 0.5 km wide, with a steep cliff directly inland. The occupation layers here reflect varied domestic activities and, in the proto-historic period, use of the area as a burial ground. Originally excavated in the 1970s by Peter Bellwood, Allen conducted more extensive excavations (13 m^2) in 1987 and 1989. Her work verified three in-situ cultural units (identified by Allen as Zones C, E, and

G) separated by storm deposits (Zones B, D, F and H). Below Zone G Allen found cultural materials in a secondary context where fine lenses of sterile sand alternated with charcoal-stained sediments and artefacts. These sedimentary structures suggested fluvial deposition (Zones I and J1). A small remnant of the apparent source stratum for the cultural materials (designated Zone J2) was also identified. Recent research has added another 14 radiocarbon determinations to the original suite of 11 and led Allen and Wallace (2007) to place initial occupation at the site in the period AD 1225–1430 (1σ range), nearly 300 years later than previously thought. Overall, the Ureia sequence suggests an initial rapid build-up of sediments followed by slower sedimentation in the last few centuries. More recent analyses (Allen and Craig, in press; see also Allen, 1998) point to the 14th century AD as a period of significant coastal disruption by cyclonic activity with consequent impacts on marine organisms.

1.4. Extant ΔR data

A number of ΔR results of known age, pre-AD 1950 shells are now available from the South Pacific Gyre region for comparison with the archaeological shell/charcoal pairs reported here (see Petchey et al., 2008b) (Table 1 and Fig. 1). These “historical” values indicate that the regional offset (ΔR) from the modelled ^{14}C marine age has remained relatively constant over the 100 years prior to AD 1950 and that geographical variation is minor. Differences do exist, however, and the greatest variation has been attributed to localised upwelling around islands caused by the impact of large island chains (e.g., the Solomon Islands; cf. Hawai’i Island (Petchey, 2009)) disturbing the predominant surface water flow (i.e., the South Equatorial Current and the North Equatorial Current respectively) (Fig. 1), direct ingestion of old carbon by the live shellfish, the presence of a hardwater effect (Anderson et al., 2001; Spennemann and Head, 1998), or absorption of atmospheric CO_2 in lagoons and estuaries (Petchey et al., 2008b; Petchey and Clark, in press).

At the present time there is only one pre-AD 1950 ΔR value available from the Marquesas Islands for comparison with the archaeological material – a sample of coral from Anaho Bay that gives a ΔR of 45 ± 48 ^{14}C years (Burr et al., 2006). Four ΔR values have been reported from pre-AD 1950 shellfish from the southern Cook Islands. An anomalous ΔR of 219 ± 20 ^{14}C years for Wk-21062 from Mangaia Island was considered by Petchey et al. (2008b) to be caused by the uptake of ^{14}C from limestone bedrock. We have obtained an additional ^{14}C date of a herbivorous shellfish (*Cypraea tigris*) from Aitutaki (Wk-23148) for comparison. This sample was collected by C. Mills in 1925 and donated to the Auckland War Memorial Museum. No further information was available. With the anomalous Mangaia Island value excluded from the southern Cook Islands average, the four remaining values are statistically indistinguishable ($\chi^2_{3:0.05} = 5.86 < 7.81$) and give a regional southern Cook Islands ΔR of -18 ± 21 ^{14}C years. Six values have been reported from the Samoan Archipelago, including two samples from Tutuila. These are statistically indistinguishable ($\chi^2_{5:0.05} = 5.74 < 11.07$) and provide a ΔR weighted mean of 28 ± 26 ^{14}C years (Petchey and Addison, 2008) (see Table 1).

There have been a couple of attempts to calculate ΔR from archaeological samples from sites in the Samoan Archipelago (To’aga, on Ofu Island in eastern Samoa (Phelan, 1999), and Fagā Village, Ta’u Island (Cleghorn and Shapiro, 2000)). Unfortunately, in both cases the charcoal was unidentified. The calculated archaeological ΔR values are therefore of uncertain accuracy despite being broadly compatible with pre-AD 1950 ΔR results for the Samoan Archipelago obtained by Petchey and Addison (2008), Petchey et al. (2008b) and Phelan (1999). We are not aware of any extant archaeological shell/charcoal pairs from the southern Cook Islands or the Marquesas Islands.

2. Methodology

Regardless of whether archaeological shell/charcoal pairs or pre-AD 1950 shells are used for determining ΔR, the age of shellfish death must be known. For pre-AD 1950, known-age shells this can best be demonstrated by the presence of museum documentation in combination with the fleshy remains of an animal, or valves in articulation with intact ligaments. For archaeological shell samples the age is determined by dating short-lived charcoal from contemporaneous contexts (commonly referred to as shell/charcoal or marine/terrestrial pairs) (Stuiver and Braziunas, 1993). This strict ΔR requirement is a common hindrance when using archaeological shell/charcoal pairs from the Pacific. Unfortunately, few published archaeological pairs demonstrate irrefutable contemporaneity, in part because of potential inbuilt age when the charcoal is unidentified or because the identified charcoal has moderate inbuilt age (Allen and Wallace, 2007). For this reason we have used radiocarbon data obtained on nutshells (since they are typically mature within a year and thus have the least possible amount of inbuilt age), or charcoal where independent verification of limited inbuilt age is possible. Although a number of other potentially reliable

Table 1
Known-age, pre-AD 1950 ΔR results of marine shells from American Samoa, southern Cook Islands and Marquesas Islands (values from Petchey et al., 2008b except Wk-23148).

Island group	Specific location	Sample material[a]	ΔR (years)[b]	Regional average ΔR	Lab number[c]
Southern Cook Islands	Mangaia Island, reef	Conidae: *Conus* sp. (C)	219 ± 20	Excluded from regional average because of hardwater effect (see text)	Wk-21062
	Mangaia Island	Conidae: *Drupa ricinus* (C)	-51 ± 30	-18 ± 21 [$\chi^2_{3:0.05}=5.86<7.81$]	Wk-21983
	Rarotonga Island	Pteriidae: *Pinctada margaritifera* (FF)	11 ± 17		Wk-20340
	Rarotonga Island, 18 m depth	Coral: *Porites lutea*	-52 ± 27		CAMS-series
	Aitutaki	Cypraeidae: *Cypraea tigris* (O)	-30 ± 30		Wk-23148
Samoa	‘Upolu, Fagola	Cardiidae: *Fragum fragum* (FF)	31 ± 17	28 ± 26 [$\chi^2_{5:0.05}=5.74<11.07$]	Wk-20343
	‘Upolu ?	Turbinidae: *Turbo petholatus* (H)	79 ± 40		Wk-6383
	‘Upolu ?	Strombidae: *Strombus pacificus* (H)	29 ± 40		Wk-6384
	‘Upolu ?	Strombidae:*Strombus lentiginosus* (H)	89 ± 40		Wk-6385
	Tutuila Island, Fagaitua	Cardiidae: *Fragum fragum* (FF)	4 ± 19		Wk-19682
	Tutuila Island, Pago Pago	Veneridae: *Antigona reticulata* (FF)	20 ± 20		Wk-19683
Marquesas	Anaho Bay, Nuku Hiva	Coral: unknown species (av. 24 measurements)	45 ± 48	45 ± 48	AA-series

[a] Diet preferences (in brackets): FF, filter-feeder; C, carnivore; H, herbivore; O, omnivore.

[b] We have chosen not to apply any correction for fossil fuel input (Suess, 1955) to the ΔR values presented in this paper on the basis that the regional and global surface ocean act in parallel to atmospheric forcing (cf., Reimer et al., 2002).

[c] Lab prefixes: Wk, Waikato Radiocarbon Dating Laboratory; CAMS, Lawrence Livermore National Laboratories; AA, University of Arizona; OZI (see Table 2), Australian Nuclear Sciences and Technology Organisation.

charcoal dates may be available for these sites, they have not been included in the Δ*R* calculations presented here and are only used as a chronological cross-check (Fig. 2).

Anomalous results may also occur because of site disturbance or the incorporation of sub-fossil shell (Rick et al., 2005; Spriggs, 2001). Stratigraphic security is potentially the hardest parameter to control in Pacific archaeological sites because coastal locations have been favoured occupation areas for many centuries, and because in many cases these sites have relatively shallow but complex stratigraphies. To limit biases, we have used shells from known contexts in stratigraphic sequence with other dates. We have also used identifiable food shells and fish bone to supplement the less than ideal ^{14}C results from shell associated with tool production where shell blanks could have been stored for later use or existing tools retouched and reused.

The ^{14}C content of shellfish is also tied closely to the peculiarities of habitat and diet (Tanaka et al., 1986). Consequently, shells used for Δ*R* calculations must be identified to genus level and the dietary and habitat preferences of that genus must closely represent that of the reservoir under investigation (e.g., open ocean, estuarine, lagoon, etc.). We have selected both suspension-feeders and herbivores for this study. Suspension-feeders are generally considered to be the most reliable shellfish for radiocarbon dating archaeological deposits (Hogg et al., 1998; Petchey et al., 2004) because they mainly consume suspended phytoplankton and dissolved inorganic carbon (DIC) from seawater and therefore, should reflect the surface ocean reservoir conditions. Herbivores are considered less reliable for radiocarbon dating because of the possible ingestion of detrital matter especially in areas with limestone geology (Dye, 1994; Spennemann and Head, 1998). Because all locations under study here are volcanic islands, where the only geological carbonates available are Holocene beach sands (Chubb, 1930; Keating, 1992; Wood and Hay, 1970), any complications caused by dissolved bicarbonate or ingested limestone on the shellfish ^{14}C age should be minimal. Regardless of shellfish dietary habits, it is possible that carbon from sources other than ocean DIC could become incorporated in the shells. The analysis of oxygen and carbon stable isotopes in combination with Δ*R* data can be used to identify some of these detrimental environmental influences (Culleton et al., 2006; Petchey et al., 2008a). In particular, δ^{18}O is a highly sensitive indicator of change in water temperature and salinity, while the δ^{13}C value of marine shells is thought to predominantly reflect changes in water source and overall marine productivity (Keith et al., 1964; Kennett et al., 1997).

2.1. Sample selection

At Anaho Bay we restricted our selection of samples for Δ*R* analysis to material from the central coastal flat area where a well-stratified sequence was identified (test pits 5, 8, 9 and 11). Even though there are a large number of prior radiocarbon determinations from this site (Fig. 2), only a handful comply with the rigid requirements needed for determination of Δ*R*. We have selected only OZI-974 (unidentified nutshell), and Wk-20135 and Wk-20134 (*Cocos nucifera* ? endocarp) charcoal dates to compare with marine shell dates Wk-20133 (*Periglypta reticulata)* and Wk-13833 (*Pinctada* sp.) from Layer IV (Table 2). Worked pearl-shell (*Pinctada* sp.) was one of the more common artefacts at Teavau'ua and although material for this industry was most likely obtained from the nearby reef there is the remote possibility that it was imported from the Tuamotu Islands (see Suggs, 1961). It is for this reason that we have also obtained a date on a typical food shell – *Periglypta reticulata* (Wk-20133) – for comparison. We also calculated a Δ*R* value for Layer IIIb (Table 2). No nutshell dates are available from this layer, instead a sample of charcoal identified as *Thespesia populnea* provides a terrestrial baseline for Δ*R* calculation. Although *Thespesia populnea* could have lived for many decades (see Allen and Wallace, 2007:1170, Table 2) the potential impact of inbuilt age should be reduced because this species is considered to have been a Polynesian introduction to the islands (Fosberg, 1975). We stress, however, that is far from an ideal sample for Δ*R* analysis.

Only two samples suitable for Δ*R* analysis were obtained from the Ta'u Hospital site; a sample of *Cocos nucifera* endocarp (Wk-21993), and a sample of *Turbo crassus* shell (Wk-21994). Both come from Layer 5 (Table 2). A further three unidentified wood charcoal and two shell ^{14}C determinations are available for comparison (see Fig. 2).

Short-lived identified wood charcoal, charred nutshell samples and unidentified wood charcoal dates are available from AIT-10, Aitutaki (see Fig. 2). We have selected a sample of *Cocos nucifera* endocarp from Zone G (Wk-20568) and a sample of *Thespesia populnea* charcoal (see above for caveat) (Wk-18402) to compare with a sample of *Pinctada* sp. shell (Wk-20130) (Table 2). Allen and Steadman (1990:34) have concluded that pearl-shell would have been transported by people from the lagoon to AIT-10 because the reef flats in front of the site are too shallow to support this shell species. To avoid complications caused by lagoon specific ^{14}C variation (see Petchey et al., 2008b; Petchey and Clark, in press) we have also dated bone from *Holocentridae* (Wk-23091) – a small inshore fish found throughout the AIT-10 sequence (Allen, 2002) – to provide a check on this value. Although the Zone J material forms a tighter dating cluster than the Zone G material (see Fig. 2), Zone J is not an in-situ cultural layer and ^{14}C dates from here do not conform to the Δ*R* requirements. We have, therefore excluded these ^{14}C dates from the Δ*R* calculations.

Pretreated shell and charcoal samples were converted to graphite at the Waikato Radiocarbon AMS facility and compressed into a target for analysis at the National Isotope Centre, GNS Science, Wellington, or the KCCAMS accelerator mass spectrometry laboratory, University of California, Irvine. The Δ*R* for a specific location "(*s*)" is calculated using the formula: $R_s(t) - R_g(t) = \Delta R(s)$, where ($\Delta R(s)$) is the difference between the global average ($R_g(t)$) and the actual ^{14}C activity of the surface ocean at a particular location ($R_s(t)$) at that time. The Δ*R* standard error is calculated by the formula: $\Delta R\sigma = \sqrt{(\sigma^2_{Rg(t)} + \sigma^2_{Rs(t)})}$ (Stuiver et al., 1986). We have calculated the weighted mean ("regional average Δ*R*") for each island group (Table 1) following the methodology recommended by Bondevik and Gulliksen in Mangerud et al. (2006:3241), where the chi-square (χ^2) test is used to test the internal variability in a group of Δ*R* values. If the group has additional measurement variability (as indicated if $\chi^2/(n-1)$ is >1) an additional uncertainty is calculated and applied to the Δ*R* (see Bondevik and Gulliksen in Mangerud et al., 2006:3241–3242 for explanation).

To calculate Δ*R* from archaeological terrestrial/marine pairs, an estimate of the atmospheric calibration curve error over the 1σ span of the radiocarbon age was used to derive the calculated marine modelled age ($R_g(t)$), whereby atmospheric age $\sigma = \sqrt{(\sigma^{14}\text{C age}^2 + \text{average of calibration curve error}^2)}$ (Ulm, 2002). For ^{14}C purposes, the boundary between the atmosphere of the Southern and Northern Hemispheres is considered to lie along the thermal equator, commonly called the Inter-Tropical Convergence Zone (ITCZ) (McCormac et al., 2004:1088). Because the Samoan Archipelago and the Marquesas Islands lie within the South Pacific Convergence Zone, which merges with the ITCZ to the west (Fig. 1) we have opted to use the Northern Hemisphere calibration curve (IntCal04: Reimer et al., 2004) for the terrestrial calibrations. For the Cook Islands we have used the Southern Hemisphere terrestrial calibration curve (SHcal04: McCormac et al., 2004). Marine samples

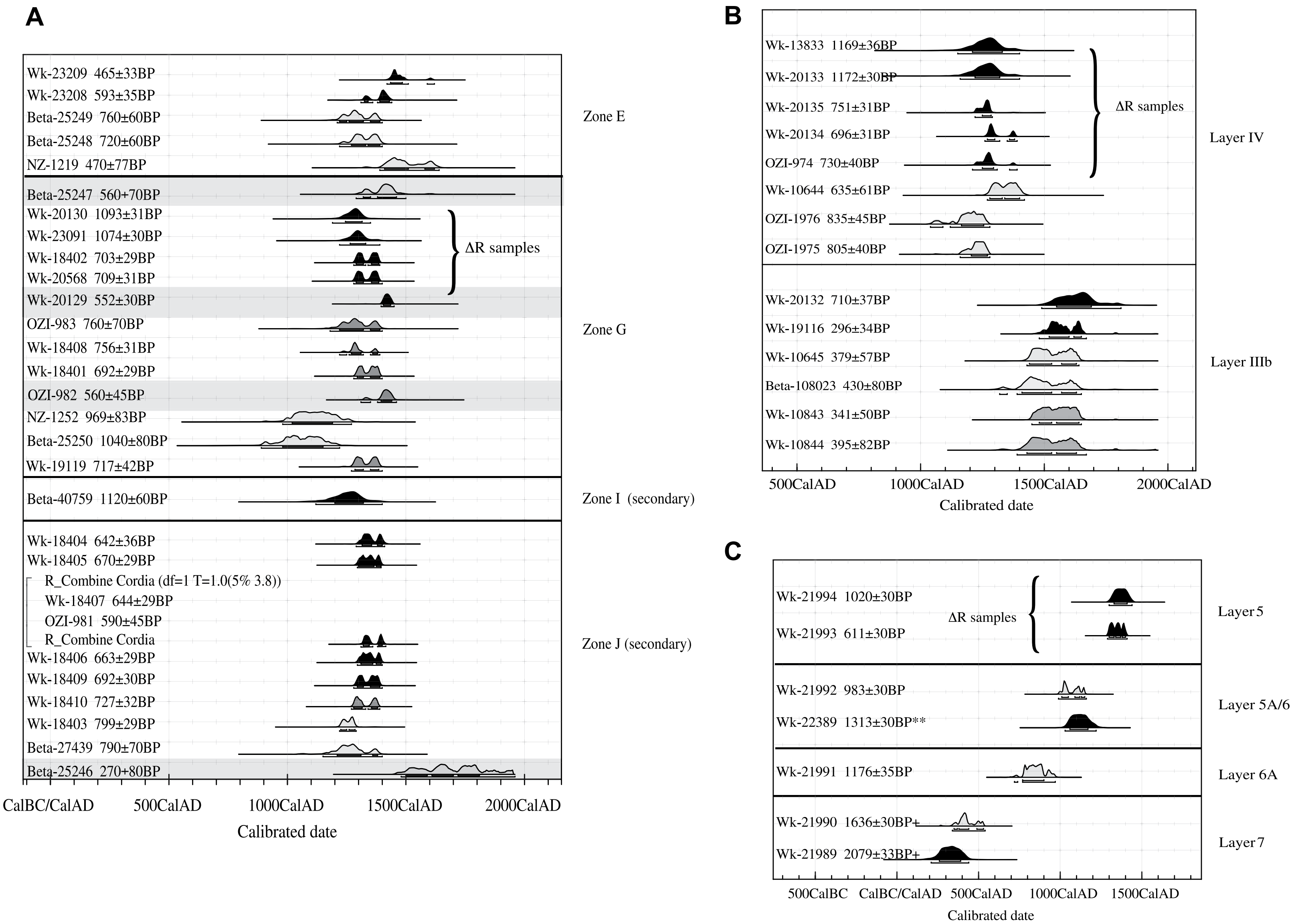

Fig. 2. Radiocarbon dates from: (A) Ureia (AIT-10), Aitutaki, southern Cook Islands (Allen and Wallace, 2007); (B) Teavau'ua (AHO-1), Anaho Bay, Marquesas Islands (Allen 2004); (C) Ta'u Hospital, Ta'u Island, American Samoa (Addison, 2008). Shell values are corrected using the average known-age, pre-AD 1950 Δ*R* value for each island group as shown in Table 1. Black probability distributions represents marine shell, short-lived nutshell or *Thespesia populnea* charcoal. Dark grey represents charcoal species with low to medium inbuilt age. Light grey represents charcoal from unidentified or broadleaf species.

#Minor variation in the radiocarbon results from these sites can be accounted for in most cases. At Urea, Beta-25246 from Zone J is clearly too young. The age of this sample is, however, consistent with that of Zone C and probably derived from a large posthole which originated in Zone C and extended down into Zone J. Also of note, Zones G and E were not always easy to separate because the intervening sterile sand layer was sometimes thin (Allen and Wallace, 2007:1167). To determine the true age of this layer we dated two nutshell samples from Zone E (Wk-23208; charred candlenut (*Aleurites molucanna*) and Wk-23209; charred unidentified nut) to confirm the age. On the basis of these results we have excluded Wk-20129 from the Zone G Δ*R* calculation and question the original Zone G designations of OZI-982 and Beta-25247. These samples of questionable provenance are highlighted in grey.

*Wk-18405 is from an intact remnant of the former Zone J cultural layer (Zone J2). This result indicates that the cultural materials in Zone J are quite close in age to those of Zone G and chronologically indistinguishable on the basis of radiocarbon determinations, but clearly older than those of Zone G on principles of superposition.

^OZ1-981 and Wk-18407 are from the same piece of nutshell split in half.

+Wk-21989 and Wk-21990 are from different test units, but conform to approximately the same depositional context. This is the most likely cause of the slight offset in calibrated age between these two ^{14}C results.

Table 2
Radiocarbon data for paired charcoal/marine shell samples from archaeological sites in American Samoa, the southern Cook Islands and the Marquesas Islands.

Lab no.	Location	Material[a]	δ^{13}C‰ (±0.2)[b]	δ^{18}O‰ (±0.06)[b]	^{14}C CRA ± error (BP)	Pooled ^{14}C CRA ± error (BP)	Marine modelled age ($R_g(t)$)	ΔR (years) $R_s(t)-R_g(t)$
Ta'u Hospital, Ta'u Island, American Samoa								
Wk-21994	TU 1, Layer 5, 80 cmbs	*Turbo crassus* [shell]	2.75	−0.47	1020 ± 30		–	−14 ± 59
Wk-21993	TU 1, Layer 5, 75 cmbs	*Cocos nucifera* endocarp charcoal	−24.55	–	611 ± 30		1034 ± 51	
Teavau'ua (AHO-1), Anaho Bay, Nuku Hiva Island, Marquesas: Layer IV								
Wk-13833	TP5, Layer IV	*Pinctada margaritifera* [shell]	2.21	−1.17	1169 ± 36	1171 ± 24	–	38 ± 28
Wk-20133	TP 8, Layer IV	*Periglypta reticulata* [shell]	1.76	−1.26	1172 ± 30	[$\chi^2_{1:0.05}$=0.2<3.84]		
Wk-20135	TP11, Layer IV	cf. *Cocos nucifera* endocarp charcoal	−24.21	–	751 ± 31		1132 ± 15	
Wk-20134	TP11, Layer IV/IV^	cf. *Cocos nucifera* endocarp charcoal	−24.70	–	696 ± 31	725 ± 20 [$\chi^2_{2:0.05}$=1.59<5.99]		
OZI-974	TP8, Layer IV; Feature 13 (hearth)	Unidentified nutshell charcoal	27.7	–	730 ± 40			
Teavau'ua (AHO-1), Anaho Bay, Nuku Hiva Island, Marquesas: Layer IIIb								
Wk-20132	TP8, Layer IIIb	*Periglypta reticulata* [shell]	1.88	−0.74	710 ± 37		–	−16 ± 58
Wk-19116	TP9, Layer IIIb, Feature 6 (oven)	*Thespesia populnea* charcoal	−25.23	–	296 ± 34		726 ± 45	
Ureia (ATI-10), Aitutaki Island, southern Cook Islands: Zone G								
Wk-20130	TP1, top of Zone G	*Pinctada* sp. [shell]	2.48	−0.41	1093 ± 31		–	34 ± 56
Wk-23091	TP2, Zone G	*Holocentridae* sp. [fish]	−10.56	−14.70	1074 ± 30	1083 ± 22		
Wk-18402	TP1, base of Zone G, Feature 4 (postmold)	*Thespesia populnea* charcoal	−26.78	–	703 ± 29	[$\chi^2_{1:0.05}$=0.19<3.84]	1049 ± 52	
Wk-20568	TP5, Zone G	cf. *Cocos nucifera* endocarp charcoal	−23.44	–	709 ± 31	705 ± 21 [$\chi^2_{1:0.05}$=0.02<3.84]		

[a] Specimens identified as cf. *Cocos nucifera* are consistent with coconut endocarp in terms of surface features, thickness, and cross-section but because of the small size of the fragments, R. Wallace was not able to definitively exclude other possibilities.

[b] δ^{18}O and δ^{13}C reported relative to the VPDB (Vienna PeeDee Belemnite) standard. Values were measured on gas splits taken during preparation of samples for AMS analysis at the University of Waikato using a Europa Scientific Penta 20–20 isotope ratio mass spectrometer.

were calibrated using the Marine04 curve of Hughen et al., (2004). All radiocarbon determinations were calibrated using the OxCal program v3.10 (Bronk-Ramsey, 2005).

3. Results

Radiocarbon and stable isotope results for the archaeological samples are shown in Table 2. Comparison of data in Tables 1 and 2 indicates that there is no significant variation between any of the archaeological ΔR values and the regional values calculated from known-age, pre-AD 1950 shellfish at the level of precision used (see also Fig. 3). Moreover, the δ^{13}C and δ^{18}O values are typical for shellfish from the South Pacific Gyre waters with high productivity (Petchey et al., 2008b) and do not give any reason for us to suspect the incorporation of ^{14}C from non-marine sources in the shells. However, the precision of the ΔR values obtained from the archaeological pairs, as indicated by the standard error, is less than that of the known-age, pre-AD 1950 data. This is partly caused by wiggles in the terrestrial calibration curves, spreading the calibrated ^{14}C dates and masking subtle changes in ΔR value. It is likely, however, that the number of known-age, pre-AD 1950 ΔR values available is insufficient to document the actual level of variability present in the oceans surrounding these islands. Non-contemporaneity of the pairs may also be responsible for slight differences in the archaeological ΔR values compared to the known-age samples. In order to bolster the archaeological ΔR data we have plotted all radiocarbon determinations for each site, including unidentified charcoal, for comparison (Fig. 2a, b and c). These figures clearly show the greatest variability occurs amongst unidentified potentially longer-lived charcoal determinations. Ultimately, this provides further support for the ΔR values used.

4. Discussion

Analysis of radiocarbon results obtained from archaeological material indicate that there is no statistically significant variation between ΔR calculated from known-age, pre-AD 1950 shellfish and charcoal/shell pairs collected from archaeological sites in the Marquesas Islands (dated to around AD 1200), American Samoa (~AD 1300), or the southern Cook Islands (~AD 1200 and ~AD 1650). This is despite a wide range of evidence pointing to significant sea-level fluctuations, climatic impacts, and human-induced changes to the near-shore environments of these islands over the last 1000 years. We suspect this result is partly because most of the shellfish selected in this study have a narrow adaptive range and do not tolerate large changes in salinity and water quality (Haws, 2002). Consequently, change to the immediate environment will most likely result in the rapid loss of that species from that area, and any associated change to the ^{14}C signature of the water is unlikely to register in the shell of marine organisms. There is no recorded evidence of any such extinction in the archaeological shell record, however, and it is more likely that archaeological material is simply a less precise means of calculating ΔR than known-age, pre-AD 1950 shellfish, with the outcome that small changes in ΔR are masked. Any further attempts to refine the archaeological ΔR values will require larger numbers of determinations for evaluation (see Jones et al. (2007) and Petchey et al. (2005) for an alternative approach to calculating ΔR value that does not require the dated events to be tightly constrained and utilizes all radiocarbon determinations from a site).

We have found that locating suitable samples from undisturbed archaeological contexts is problematic because of the shallow, sandy nature of many Pacific sites. This can make it difficult to discern distinct boundaries between layers, such as between Layer 5 and 6 at the Ta'u Hospital site, and between Zones E and G at AIT-10. Coastal sites are also susceptible to disturbance by storm events as was the case at AIT-10, although usefully such events also provide a break between what otherwise might be longer duration stratigraphic units. Horizontal shifts in occupation, as occurred on the coastal flat at AHO-1, are also common throughout the Pacific as people followed the prograding shorelines.

The precision required when undertaking Δ*R* work also highlights the importance of limiting the influence of inbuilt age. The notion of inbuilt age in unidentified or long-lived charcoal species is well recognised (e.g., Anderson and Clark, 1999; Kirch, 1993:87). Moreover, by the early 1990s it was realized that to further reduce inbuilt age for high-resolution dating sequences it was necessary to select twigs for dating (Anderson, 1991:781; Schmidt, 1996:57). A recent study of radiocarbon determinations from the Cook Islands by Allen and Wallace (2007) has demonstrated that these concerns also apply in the tropical Pacific. In this study, un-calibrated wood charcoal samples identified to species gave radiocarbon results that were on average 64 ^{14}C years older than short-lived nutshell samples, with some unidentified samples being 300 or 400 years too old. We believe minor inbuilt age is partly responsible for the limitations in the ^{14}C chronology so commonly cited in the literature, and that careful selection of samples with specific emphasis on radiocarbon sample-type issues, as well as the use of sophisticated Bayesian modelling, will significantly refine ^{14}C chronologies even when dealing with relatively small numbers of ^{14}C dates.

The same caution should certainly be applied to the use of shell ^{14}C determinations. Since Dye (1994) first published anomalous Δ*R* values for shellfish from limestone coasts on O'ahu, Hawai'i, it has been widely documented that deposit-feeding shellfish can give anomalous ^{14}C results, and even ^{14}C determinations from shellfish with alternative dietary requirements may be suspect if collected within the vicinity of ancient limestone deposits, such as the case of the carnivorous *Conus* sp. shell from Mangaia (Wk-21062) (Table 1). Of course ideal sample types, such as identified short-lived twigs, nuts, or suitable shell species may not always be available. Where there is no other option, researchers must take into account the limitations in the radiocarbon data and incorporate these factors into their interpretations.

Our results indicate that in the South Pacific there is greater Δ*R* variability between the various island groups than that evident over time. In the central zone of the South Pacific Gyre, occupied by the southern Cook Islands (Fig. 1), the flow of the South Equatorial Current (SEC) is generally reduced, resulting in less mixing with older subsurface waters and negative Δ*R* values (Rougerie and Rancher, 1994:21–24; Guilderson et al., 2000; Petchey et al., 2008a). The Marquesas Islands are a different matter as they sit on the outer boundary of the South Pacific Gyre where the SEC flows faster. Martinez and Maamaatuaiahutapu (2004) have suggested that interaction between the SEC and the Marquesas island chain causes turbulent mixing and advection of water resulting in small to medium eddies which are upwelling-favourable (see Signorini et al., 1999; Rougerie and Rancher, 1994:16). These conditions are similar to, but on a smaller scale than, those thought to cause Δ*R* variability (from -29 ± 4 to 280 ± 80 ^{14}C years in shells collected pre-AD 1950) around the main island of Hawai'i where interaction between the island chain, the North Equatorial Current and the north-easterly trade winds cause large-scale eddies and upwelling (Petchey, 2009). Notably, the fringing reef at Anaho Bay is rare in the Marquesas and it is likely that oceanic conditions at this locality may not be typical of the more open coastlines. Consequently, the

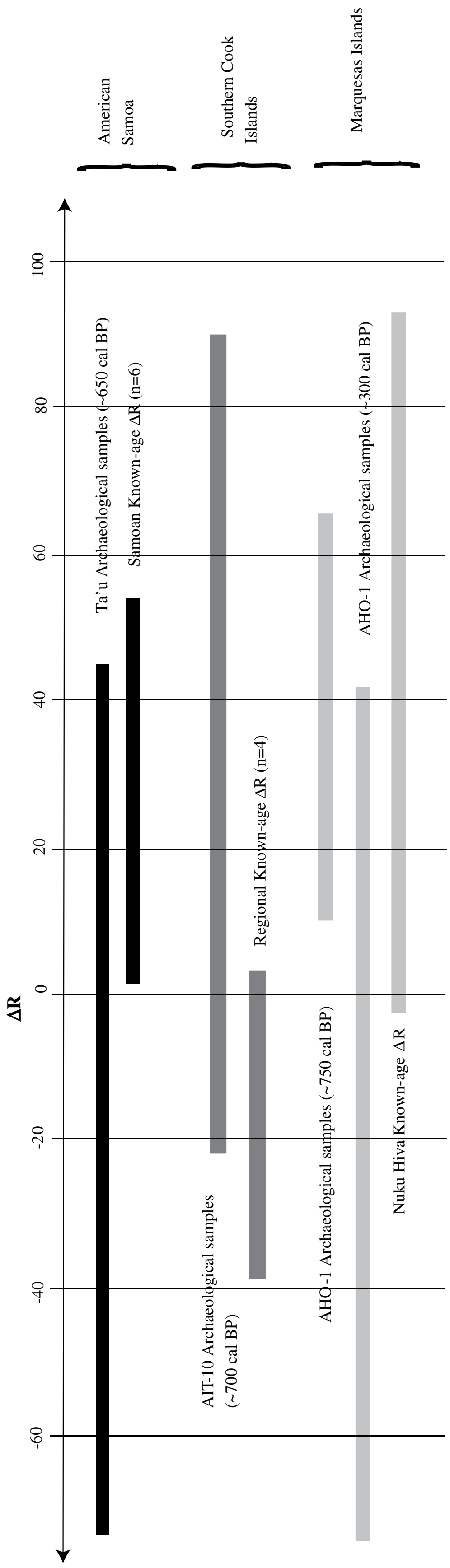

Fig. 3. Bar graphs comparing average (±1σ) known-age, pre-AD 1950 Δ*R* values and archaeological Δ*R* data by island group. Chi-square statistics for combined archaeological pairs and known-age, pre-AD 1950 Δ*R* values as follows: Samoan Archipelago, [$\chi^2_{1:0.05} = 0.42 < 5.99$]; southern Cook Islands, [$\chi^2_{1:0.05} = 0.76 < 5.99$]; Marquesas Islands, [$\chi^2_{2:0.05} = 0.42 < 7.81$].

regional validity of the Δ*R* value of 48 ± 48 ^{14}C years, obtained from coral collected from the fringing reefs, requires further testing.

5. Conclusion

Based on these results it is evident that Δ*R* values obtained from known-age, pre-AD 1950 shellfish should be used to correct archaeological and geological radiocarbon determinations from the Aitutaki, Ta'u, and Nuku Hiva islands dated to within the last 750 years. Whether Δ*R* values from known-age, pre-AD 1950 shellfish can be used to correct radiocarbon results from locations elsewhere in the Pacific requires further investigation. Current recommended Δ*R* values for the southern Cook Islands, Samoan Archipelago and Marquesas Islands are -18 ± 21 ^{14}C years, 28 ± 26 ^{14}C years and 45 ± 48 ^{14}C years respectively.

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References

Addison, D.J., 2008. Report on Archaeological Test Excavations at the New Ta'u Dispensary Site. A Project at Ta'u Village, Ta'u Island, Territory of American Samoa. Funded by the United States Department of the Interior (US DOI) Capital Improvement Projects. Prepared for: Justine Aetonu, Architecture and Engineering Division, Department of Public Works, American Samoa Government, Pago Pago, American Samoa 96799.

Addison, D.J., Asaua, T.S., 2006. 100 new dates from Tutuila and Manu'a: additional data addressing chronological issues in Samoan prehistory. Journal of Samoan Studies 2, 95–117.

Addison, D.J., Morrison, A. The Lapita settlement of Samoa: Is a continuous occupation model appropriate? In: McLaughlin, S. (Ed.), The Gotland Papers: Proceedings of the VII International Conference on Easter Island and the Pacific. Easter Island Foundation, Los Osos, in press.

Allen, M.S., 1998. Holocene sea-level change of Aitutaki, Cook Islands: landscape change and human response. Journal of Coastal Research 14 (1), 10–22.

Allen, M.S., 2002. Resolving long-term change in Polynesian marine fisheries. Asian Perspectives 41 (2), 195–212.

Allen, M.S., 2004. Revisiting and revising Marquesan culture history: new archaeological investigations at Anaho Bay, Nuku Hiva Island. Journal of the Polynesian Society 113 (2), 143–196. Table 6 and other errata, 113(3).

Allen, M.S., 2006. New ideas about late Holocene climate variability in the central Pacific. Current Anthropology 47 (3), 521–535.

Allen, M.S., Craig, J.A. The dynamics of Polynesian subsistence: insights from archaeofauna and stable isotope studies, Aitutaki, southern Cook Islands. Pacific Science 63(4), in press.

Allen, M.S., Steadman, D.W., 1990. Excavations at the Ureia site, Aitutaki, Cook Islands: preliminary results. Archaeology in Oceania 25, 24–37.

Allen, M.S., Wallace, R., 2007. New evidence from the East Polynesian gateway: Substantive and methodological results from Aitutaki, southern Cook Islands. Radiocarbon 49 (3), 1–17.

Anderson, A.J., 1991. The chronology of colonization in New Zealand. Antiquity 65, 767–795.

Anderson, A., 2001. The chronology of prehistoric colonization in French Polynesia, in: Stevenson, C.M., Lee, G., Morin, F.J. (Eds.), Pacific 2000: Proceedings of the Fifth International Conference on Easter Island and the Pacific, Easter Island Foundation, Los Osos, pp. 247–252.

Anderson, A., Clark, G., 1999. The age of Lapita settlement in Fiji. Archaeology in Oceania 34, 31–39.

Anderson, A., Sinoto, Y., 2002. New radiocarbon ages of colonization sites in east Polynesia. Asian Perspectives 41 (2), 242–257.

Anderson, A., Conte, E., Clark, G., Sinoto, Y., Petchey, F., 2000. . Renewed excavations at Motu Paeao, Maupiti Island, French Polynesia: preliminary results. New Zealand Journal of Archaeology 21, 47–66.

Anderson, A., Higham, T., Wallace, R., 2001. The radiocarbon chronology of the Norfolk Island archaeological sites. Records of the Australian Museum. Supplement 27, 33–42.

Ascough, P., Cook, G., Dugmore, A., 2005. Methodological approaches to determining the marine radiocarbon reservoir effect. Progress in Physical Geography 29 (4), 532–547.

Bard, E., 1988. Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: paleoceanographic implications. Paleoceanography 3, 635–645.

Bronk-Ramsey, C., 2005. OxCal Program v3.10. Radiocarbon Accelerator Unit, University of Oxford.

Burr, G.S., Beck, J.W., Jull, A.J.T., Pandolfi, J., Taylor, F., Corrège, T., 2006. Modern to late glacial reservoir ages of South Pacific corals. 19th International Radiocarbon Conference, Oxford, England, 3–7th April. Program and Abstracts, 78 pp.

Cleghorn, P.L., Shapiro, W.A., 2000. Archaeological data recovery report for the proposed Ta'u road reconstruction at Fag ā and Fitiuta, Ta'u Iland, Manu'a, American Samoa. Pacific Legacy Incorporated, Kailua, Hawai'i.

Chubb, L.J., 1930. Geology of the Marquesas Islands. Bernice P. Bishop Museum Bulletin 68, Honolulu, Hawai'i.

Cobb, K.M., Charles, C.D., Cheng, H., Edwards, R.L., 2003. El Nino/Southern Oscillation and tropical Pacific climate during the last millennium. Nature 424, 271–276.

Culleton, B.J., Kennett, D.J., Ingram, B.L., Erlandson, J.M., Southon, J.R., 2006. Intrashell radiocarbon variability in marine molluscs. Radiocarbon 48 (3), 387–400.

Deo, J.N., Stone, J.O., Stein, J.K., 2004. Building confidence in shell: Variations in the marine radiocarbon reservoir correction for the northwest coast over the past 3,000 years. American Antiquity 69 (4), 771–786.

Dickinson, W.R., 1997. Holocene paleoshoreline indicators in American Samoa. Unpublished report on file at the American Samoa Historic Preservation Office.

Dickinson, W.R., 2001. Paleoshoreline record of relative Holocene sea levels on Pacific islands. Earth-Science Reviews 55, 191–234.

Dickinson, W.R., 2003. Impact of mid-Holocene hydro-isostatic highstand in regional sea-level on habitability of islands in Pacific Oceania. Journal of Coastal Research 19, 489–502.

Dickinson, W.R., Green, R.C., 1998. Geoarchaeological context of Holocene subsidence at the Ferry Berth Lapita Site, Mulifanua, Upolu, Samoa. Geoarchaeology 13 (3), 239–263.

Druffel, E.R.M., Griffin, S., 1993. Large variations of surface ocean radiocarbon: evidence of circulation changes in the southwestern Pacific. Journal of Geophysical Research 98 (C11), 249–259. 20.

Dye, T., 1994. Apparent ages of marine shells: Implications for archaeological dating in Hawai'i. Radiocarbon 36, 51–57.

Fosberg, F.R., 1975. Vascular plants of Aitutaki. In: Stoddart, D.R., Gibbs, P.E. (Eds.), Almost-Atoll of Aitutaki: Reef Studies in the Cook Islands, South Pacific. Atoll Research Bulletin 190. Smithsonian Institution, Washington, DC, pp. 73–84.

Ganachaud, A., Kessler, W., Wijffels, S., Ridgway, K., Cai, W., Holbrook, N., Bowen, M., Sutton, P., Qiu, B., Timmermann, A., Roemmich, D., Sprintall, J., Cravatte, S., Gourdeau, L., Aung, T., 2007. Southwest Pacific Ocean circulation and climate experiment (SPICE)—Part I. Scientific Background. International CLIVAR Project Office, CLIVAR Publication Series No. 111. Seattle, WA, NOAA OAR Special Report, NOAA/OAR/PMEL.

Gehrels, W.R., 2001. Discussion. Journal of Coastal Research 17 (1), 244–245.

Graham, N.E., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., Xu, T., 2007. Tropical Pacific - mid-latitude teleconnections in medieval times. Climatic Change 83, 241–285.

Guilderson, T.P., Schrag, D.P., Kashgarian, M., Southon, J., 1998. Radiocarbon variability in the western equatorial Pacific inferred from a high-resolution coral record from Nauru Island. Journal of Geophysical Research 103 (C11), 24641–24650.

Guilderson, T.P., Schrag, D.P., Goddard, E., Kashgarian, M., Wellington, G.M., Linsley, B.K., 2000. Southwest subtropical Pacific surface water radiocarbon in a high-resolution coral record. Radiocarbon 42 (2), 249–256.

Guilderson, T.P., Schrag, D.P., Cane, M.A., 2004. Surface water mixing in the Solomon Sea as documented by a high-resolution coral ^{14}C record. Journal of Climate 17, 1147–1156.

Haws, M., 2002. The basics of pearl farming: a layman's manual. Centre for Tropical and Subtropical Aquaculture Publication No. 127. University of Hawaii.

Higham, T.F.G., Hogg, A.G., 1995. Radiocarbon dating of prehistoric shell from New Zealand and calculation of the ΔR value using fish otoliths. Radiocarbon 37, 409–416.

Hogg, A.G., Higham, T.F.G., Dahm, J., 1998. Radiocarbon dating of modern marine and estuarine shellfish. Radiocarbon 40, 975–984.

Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, G., Manning, S., Bronk-Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 Marine Radiocarbon age calibration, 0–26 cal Kyr BP. Radiocarbon 46, 1059–1086.

Hunt, T.L., Lipo, C.P., 2006. Late colonization of Easter Island. Science 311 (5767), 1603–1606.

Jones, M., Petchey, F., Green, R., Sheppard, P., Phelan, M., 2007. The marine ΔR for Nenumbo: a case study in calculating reservoir offsets from paired sample data. Radiocarbon 49 (1), 95–102.

Kalish, J.M., 1993. Pre- and post-bomb radiocarbon in fish otoliths. Earth and Planetary Science Letters 114, 549–554.

Keating, B.H., 1992. Geology of the Samoa Islands. In: Keating, B.H., Bolton, B.R. (Eds.), Geology and Offshore Mineral Resources of the Central Pacific Basin. Springer-Verlag, New York, pp. 127–178.

Keith, M.L., Anderson, G.M., Eichler, R., 1964. Carbon and oxygen isotopic composition of mollusk shells from marine and fresh-water environments. Geochimica et Cosmochimica Acta 28, 1757–1786.

Kennett, D.J., Ingram, B.L., Erlandson, J.M., Walker, P., 1997. Evidence for temporal fluctuations in marine radiocarbon reservoir ages in the Santa Barbara Channel, Southern California. Journal of Archaeological Science 24, 1051–1059.

Kennett, D.J., Ingram, B.L., Southon, J.R., Wise, K., 2002. Differences in ^{14}C age between stratigraphically associated charcoal and marine shell from the archaic period site of Kilometre 4, Southern Peru: old wood or old water? Radiocarbon 44, 53–58.

Kirch, P.V., 1993. Radiocarbon chronology of the To'aga site. In: Kirch, P.V., Hunt, T.L. (Eds.), Three Millennia of Polynesian Occupation in the Manu'a Islands, American Samoa. Contributions of the University of California Archaeological Research Facility No. 51. University of California, Berkeley, CA, pp. 85–92. The To'aga Site.

Kirch, P.V., 2000. On the Road of the Winds. University of California Press, Berkeley, CA.

Kirch, P.V., Yen, D.E., 1982. Tikopia: The Prehistory and Ecology of a Polynesian Outlier. B.P. Bishop Museum Bulletin 238, Honolulu.

Linacre, E., Geerts, B., 1998. Movement of the South Pacific Convergence Zone. http://www-das.uwyo.edu/~geerts/cwx/notes/chap12/spcz.html (accessed December 2008).

McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 southern hemisphere calibration 0–11.0 cal kyr BP. Radiocarbon 46, 1087–1092.

Mangerud, J., Bondevik, S., Gulliksen, S., Hufthammer, A.K., Høisæter, T., 2006. Marine ^{14}C reservoir ages for 19thcentury whales and molluscs from the North Atlantic. Quaternary Science Reviews 25, 3228–3245.

Martinez, E., Maamaatuaiahutapu, K., 2004. Island mass effect in the Marqueasas Islands: time variation. Geophysical Research Letters 31, L18307.

Moriwaki, H., Chikamori, M., Okuno, M., Nakamura, T., 2006. Holocene changes in sea-level and coastal environments on Rarotonga, Cook Islands, South Pacific Ocean. The Holocene 16 (6), 839–848.

Nunn, P.D., Britton, J.M.R., 2001. Human-environment relationships in the Pacific Islands around AD 1300. Environment and History 7, 3–22.

Paterne, M., Ayliffe, L.K., Arnold, M., Caioch, G., Tisnérat-Laborde, N., Hatté, C., Douville, E., Bard, E., 2004. Paired ^{14}C and ^{230}Th/U dating of surface corals from the Marquesas and Vanuatu (sub-equatorial Pacific) in the 3000 to 15,000 cal yr interval. Radiocarbon 46 (2), 551–566.

Petchey, F., 2009. Dating marine shell in Oceania: issues and prospects. In: Fairbairn, A., O'Connor, S., Marwick, B. (Eds.), New Directions in Archaeological Science. Terra Australis 28. ANU E Press, Canberra, pp. 157–172.

Petchey, F., Addison, D., 2008. Radiocarbon dating marine shell in Samoa – A review. In: Addison, D.J., Asaua, T.S., Sand, C. (Eds.), Recent Archaeology in the Fiji/West-Polynesia Region. Otago Anthropology Monograph Series 21. Otago University, Dunedin, pp. 79–86.

Petchey, F., Clark, G. A marine reservoir correction value (ΔR) for the Palauan archipelago: Environmental and oceanographic considerations. Journal of Island & Coastal Archaeology, in press.

Petchey, F., Phelan, M., White, P., 2004. New ΔR values for the southwest Pacific Ocean. Radiocarbon 46, 1005–1014.

Petchey, F., Green, R., Jones, M., Phelan, M., 2005. A local marine reservoir correction value (ΔR) for Watom Island, Papua New Guinea. New Zealand Journal of Archaeology 26 (2004), 29–40.

Petchey, F., Anderson, A., Hogg, A., Zondervan, A., 2008a. The marine reservoir effect in the Southern Ocean: an evaluation of extant and new ΔR values and their application to archaeological chronologies. Journal of the Royal Society of New Zealand 38 (4), 243–262.

Petchey, F., Anderson, A., Zondervan, A., Ulm, S., Hogg, A., 2008b. New marine ΔR values for the South Pacific Subtropical Gyre region. Radiocarbon 50 (3), 373–397.

Phelan, M.B., 1999. A ΔR correction value for Samoa from known-age marine shells. Radiocarbon 41 (1), 99–101.

Pirazzoli, P.A., Montaggioni, L.F., 1988. Holocene sea-level changes in French Polynesia. Palaeogegraphy, Palaeoclimatology, Palaeoecology 68, 153–175.

Reimer, P.J., Reimer, R., 2001. A marine reservoir correction database and on-line interface. Radiocarbon 43, 461–463.

Reimer, P.J., McCormac, F.G., Moore, J., McCormick, F., Murray, E.V., 2002. Marine radiocarbon reservoir corrections for the mid- to late Holocene in the eastern subpolar North Atlantic. The Holocene 12 (2), 129–135.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Bronk-Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal Kyr BP. Radiocarbon 46 (3), 1029–1058.

Reith, T.M., Hunt, T.L., 2008. A radiocarbon chronology for Samoan prehistory. Journal of Archaeological Science 35, 1901–1927.

Rick, T.C., Vellanoweth, R.L., Erlandson, J.M., 2005. Radiocarbon dating and the "old shell" problem: direct dating of artifacts and cultural chronologies in coastal and other aquatic regions. Journal of Archaeological Science 32, 1641–1648.

Rolett, B.V., 1998. Hanamiai: prehistoric colonization and cultural change in the Marquesas Islands (East Polynesia). Yale University Publications in Anthropology 81. Yale University Department of Anthropology & Peabody Museum, New Haven, CT.

Rougerie, F., Rancher, J., 1994. The Polynesian south ocean: Features and circulation. Marine Pollution Bulletin 29 (1-3), 14–25.

Schiffer, M.B., 1987. Formation processes of the archeological record. In: Rowell, R.M., Barbour, R.J. (Eds.), Advances in Chemistry Series 225. University of New Mexico Press, Albuquerque, NM.

Schmidt, M.D., 1996. Radiocarbon dating New Zealand prehistory using marine shell. Unpublished PhD thesis, University of Waikato.

Signorini, S.R., McClain, C.R., Dandonneau, Y., 1999. Mixing and phytoplankton bloom in the wake of the Marquesas Islands. Geophysical Research Letters 26 (20) 3121–2124.

Sikes, E.L., Samson, C.R., Guilderson, T.P., Howard, W.R., 2000. Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation. Nature 405, 555–559.

Sinoto, Y.H., McCoy, P.C., 1975. Report on the preliminary excavation of an early habitation site on Huahine, Society Islands. Journal de la Société des Océanistes 31, 143–186.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., Yim, W.W,-S, 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. Radiocarbon 44, 167–180.

Spennemann, D.H.R., 1987. Availability of shellfish resources on prehistoric Tongatapu, Tonga: effects of human predation and changing environment. Archaeology in Oceania 22, 81–96.

Spennemann, D.H.R., Head, M.J., 1998. Tongan pottery chronology, ^{14}C dates and the hardwater effect. Quaternary Geochronology 17, 1047–1056.

Spriggs, M., 2001. Who cares what time it is? The importance of chronology in Pacific archaeology. In: Anderson, A., Lilley, I., O'Connor, S. (Eds.), Histories of Old Ages: Essays in Honour of Rhys Jones. Pandanus books. Research School of Pacific and Asian Studies, Australian National University, Canberra, pp. 237–249.

Spriggs, M., Anderson, A., 1993. Late colonization of East Polynesia. Antiquity 67, 200–217.

Stoddart, D.R., 1975. Scientific studies in the southern Cook Islands: Background and bibliography. In: Stoddart, D.R., Gibbs, P.E. (Eds.), Almost-Atoll of Aitutki: reef Studies in the Cook Islands, South Pacific. Atoll of Aitutaki: Reef Studies in the Cook Islands, South Pacific. Atoll Research Bulletin 190. Smithsonian Institution, Washington, D.C, pp. 1–30.

Stuiver, M., Pearson, G.W., Braziunas, T.F., 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. Radiocarbon 28 (2B), 980–1021.

Stuiver, M., Braziunas, T.F., 1993. Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10000 BC. Radiocarbon 35, 137–191.

Suess, H.E., 1955. Radiocarbon concentration in modern wood. Science 122, 415–417.

Suggs, R.C., 1961. The archeology of Nuku Hiva, Marquesas Islands, French Polynesia. Anthropological Papers 49(1). American Museum of Natural History, New York.

Sutton, D.G., 1994. Conclusion: origins. In: Sutton, D.G. (Ed.), The Origins of the First New Zealanders. Auckland University Press, Auckland, pp. 243–258.

Tanaka, N., Monaghan, M.C., Rye, D.M., 1986. Contribution of metabolic carbon to mollusc and barnacle shell carbonate. Nature 320, 520–523.

Tomczak, M., Godfrey, J.S., 2001. Regional Oceanography: An Introduction. Version 1.0. Elsevier Science Ltd., Oxford. http://www.es.flinders.edu.au/~mattom/regoc/pdfversion.html (accessed November 2007).

Ulm, S., 2002. Marine and estuarine reservoir effects in central Queensland, Australia: determination of ΔR values. Geoarchaeology 17 (4), 3119–3348.

Wood, B.L., Hay, R.F., 1970. Geology of the Cook Islands. New Zealand Geological Survey Bulletin 82, 103.

Yoneda, M., Hirota, M., Uchida, M., Uzawa, K., Tanaka, A., Shibata, Y., Morita, M., 2001. Marine radiocarbon reservoir effect in the western north Pacific observed in archaeological fauna. Radiocarbon 43, 465–471.

Yonekura, N., Ishii, T., Saito, Y., Maeda, Y., Matsushima, Y., Matsumoto, E., Kayanne, H., 1988. Holocene fringing reefs and sea-level change in Mangaia Island, Southern Cook Islands. Palaeogeography, Palaeoclimatology, Palaeoecology 68, 177–188.