

NEW EVIDENCE FOR A MID- TO LATE-HOLOCENE CHANGE IN THE MARINE RESERVOIR EFFECT ACROSS THE SOUTH PACIFIC GYRE

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ABSTRACT. Holocene climate change in the South Pacific is of major interest to archaeologists and Quaternary researchers. Regional surface ocean radiocarbon (^{14}C) values are an established proxy for studying changing oceanographic and climatic conditions. Unfortunately, radiocarbon variability in the marine environment over the period of specific importance to human colonization of the remote Pacific islands—the last 3500 years—has been poorly studied. In order to build robust and accurate archaeological chronologies using shell, it is important to rectify this. In this paper, radiocarbon marine reservoir offsets (ΔR) are presented from eight archaeological sites, ranging in age from 350 cal BP to 3000 cal BP, and compared to coral datasets from the east Australian coastline. The results indicate that a significant decrease in the South Pacific Gyre ΔR occurred between 2600 and 2250 cal BP, most likely caused by changes in ocean circulation and climate. Accurately recording the timing of variability in reservoir offset is critical to untangling changes in society that took place in the Pacific, in particular, the development of Ancestral Polynesian Society.

KEYWORDS: archaeology, marine reservoir correction, South Pacific.

INTRODUCTION

The marine reservoir age “ R ” is the offset in ^{14}C age between the atmosphere and the global ocean with regional offsets from R termed the local marine reservoir age or ΔR (Stuiver et al. 1986). Calibration of marine ^{14}C dates involves application of a ΔR to the marine calibration curve (Marine13; Reimer et al. 2013) to account for these regional offsets. A ΔR can be calculated from “paired” (contemporaneous) terrestrial and marine samples excavated from archaeological sites or from isochrons such as tephra deposited offshore (e.g., Sikes et al. 2000). A regional reservoir offset can also be calculated from known-age shells or coral collected prior to atmospheric bomb testing (e.g., Petchey et al. 2008b), or from samples where independently measured calendar ages can be obtained, such as paired U/Th, ^{14}C dates (e.g., Clark et al. 2016a). No matter what materials are used for determining the ΔR , they must comply with a set of prerequisites (see Petchey 2009). For archaeological shell samples, the age is determined by dating short-lived—identified to species and/or element—“paired” terrestrial materials from contemporaneous contexts.

In the modern Pacific Ocean, a gradient exists between older reservoir ages in the tropical east and younger ages in subtropical regions and the tropical west that reflects the surface flow of the South Equatorial Current (SEC) (Petchey et al. 2008a; Burr et al. 2009) (Figure 1). This gradient is indicative of the upwelling of older ^{14}C -depleted waters in the east (Toggweiler et al. 1991; Ortlieb et al. 2011), the subsequent modification of the water by air-sea exchange, and a deepening thermocline as this water flows westward across the Pacific. Traditionally, R and ΔR for any given location have been assumed to be broadly constant over time (Stuiver et al. 1986). However, as more information becomes available this assumption does not hold up to scrutiny. Abrupt shifts have been recorded in early to mid-Holocene samples across the South Pacific (e.g., Paterne et al. 2004; Fairbanks et al. 2005; Yu et al. 2010; Ortlieb et al. 2011; Hua et al. 2015). Possible causes for these temporal reservoir shifts include a change in ^{14}C content and frequency of upwelled waters in the eastern tropical Pacific,

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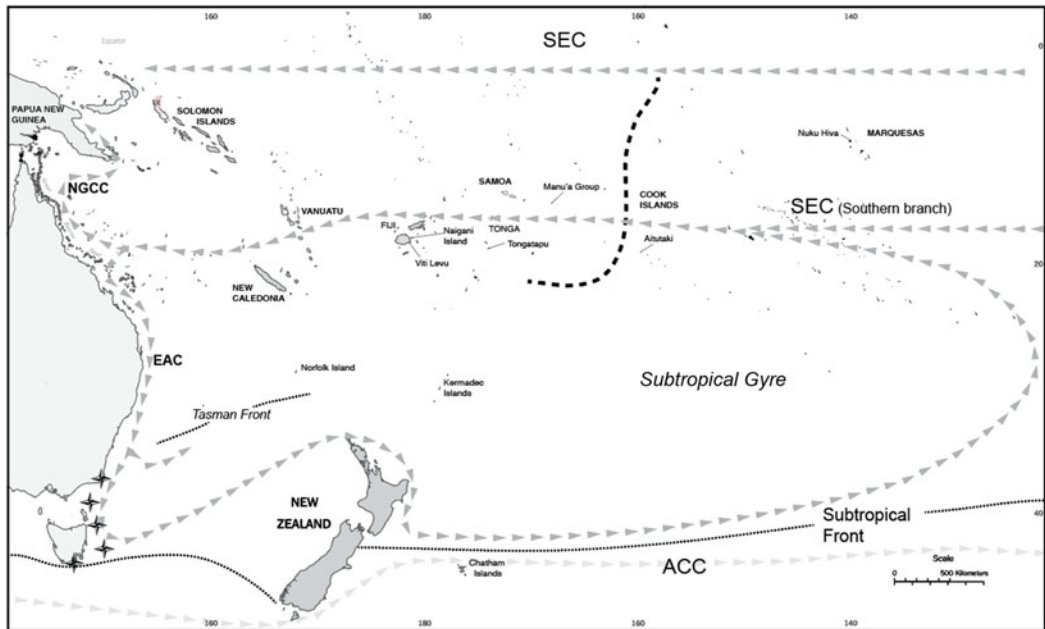


Figure 1 Map of the Pacific Ocean showing major circulation patterns and sites mentioned in the text. The dashed line shows the salinity front on the eastern edge of the Western Pacific Warm Pool. Surface currents: SEC = South Equatorial Current; EAC = East Australian Current; NGCC = New Guinea Coastal Current; ACC = Antarctic Circumpolar Current. Four-pointed stars represent black sampling locations from Komugabe-Dixon et al. (2016).

variation in ocean circulation associated with La Niña/El Niño conditions, change in the intensity of easterly trade winds, and movement of the Inter-tropical Convergence Zone (ITCZ) and the associated South Pacific Convergence Zone (SPCZ)—where northern and southern air masses converge and control the spread of these upwelled waters to western regions (Hua et al. 2015)¹.

Most research on this subject has concentrated on the early to mid-Holocene, with little work investigating change over the last 3500 years; the period of human settlement of the South Pacific (Kirch 1997; Kirch and Green 2001). Moreover, only 16 data points were reported in the references given above for this time period, and no values from central/western Pacific archaeological sources were considered. This is because reliable ΔR from archaeological sites has been limited by material availability and inherent problems with site disturbance (cf. Ortlieb et al. 2011; Clark et al. 2016b; Petchey et al. 2018), but also reflects disproportionate levels of funding for broad-scale paleoenvironmental research over archaeological interests. One study specifically designed to investigate the issue of change was undertaken by Petchey et al. (2009). Using “paired” terrestrial/marine samples from a range of archaeological sites, they noted little change in ΔR over the last 750 years for sites in American Sāmoa (dated to ca. 600 cal BP), the southern Cook Islands (ca. 670 cal BP), or the Marquesas Islands (ca. 380 and 670 cal BP). Generally, however, archaeological dating in this region has had to largely rely on ΔR values calculated from modern

¹During La Niña events, the SPCZ moves south-westward and limits old salty waters from the east reaching the western Pacific sites. In contrast, during El Niño events, the SPCZ moves north-eastward and the SEC strengthens, allowing more of these older waters to spread to the west (Hua et al. 2015:41).

(pre-AD 1950) validation studies (e.g., Petchey et al. 2008a, 2008b, Phelan 1999). A clever solution to overcoming the issue of disjunction between the terrestrial and marine samples was reported by Clark et al. (2016a) using U/Th, ^{14}C pairs from archaeologically derived *Acropora* spp. coral branches from Ofu Island, American Sāmoa, dated to ca. 2300 cal BP. The negative ΔR -value obtained (-101 ± 72 ^{14}C years) was interpreted as possibly being caused by spatial and/or temporal changes to the marine environment.

More recently, information for this period of interest has become available from a sequence of paired U/Th, ^{14}C dates from black coral collected from the southeastern coast of Australia (Komugabe-Dixson et al. 2016). Komugabe-Dixson et al. (2016:976-978) noted two distinct intervals when ΔR was significantly lower; between 4000 and 3300 cal BP ($\Delta R = -132 \pm 79$ ^{14}C years) and between 2700 to 1900 cal BP ($\Delta R = -156 \pm 79$ ^{14}C years). They attributed these negative values to increased penetration of well-ventilated gyre waters southward into the South Tasman Sea in response to strong and abrupt El Niño events that reduced upwelling in the southeast Pacific (as recorded by Ortlieb et al. 2011) and displaced the salinity front that separates fresher Western Pacific Warm Pool water from saltier and cooler waters in the east, enabling increased westward flow of gyre waters into the Tasman Sea. Interconnectivity between western and eastern sides of the South Pacific (Figure 1) means that significant reservoir changes should be expected in the central gyre as well and, therefore, adds further doubt to the validity of using a constant ΔR -value to calibrate marine shell ^{14}C dates from this region.

Held within the archaeological literature are a host of shell/charcoal ^{14}C pairs which can assist with this problem. Unfortunately, the interpretation of marine shell ^{14}C dates has been complicated by diet and habitat differences that rarely reflect open marine conditions. Research along the southern coast of Papua New Guinea at Caution Bay (Petchey et al. 2012, 2013) identified species-specific ΔR variation of up to 600 ^{14}C years in deposits dated to 2150–2000 cal BP. They attributed this to the possible incorporation of carbon from limestone in the hinterland but also observed that the magnitude of variation depended on the taxa dated. More recent research into shell taxa variation (Petchey et al. 2018) has provided methods to cull unreliable shell samples using $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ to identify carbon source. This has been successful in identifying estuarine-specific signals in some bivalves and, in areas where water has percolated through limestone, can help identify shells that are influenced by ^{14}C -depleted hardwater (Petchey and Clark 2011; Petchey et al. 2018). This work, combined with archaeological ΔR values reported in the literature, has enabled the reinvestigation of change in ΔR over time in the central Pacific Gyre region presented below.

METHOD

For this evaluation, sample pairs from published archaeological sources and from unpublished ΔR research by the author have been collated. All radiocarbon and stable isotope information is given in Table 1. Additional constraints to the archaeological dataset have been applied, as outlined below:

- 1. Region:** The region of interest is encircled by the South Pacific Subtropical Gyre, a circulatory system driven by the combined effects of the tropical trade winds and westerly winds in the subtropical regions, the combined results of which are the high-latitude eastward-flowing Antarctic Circumpolar Current (ACC) and the mid-latitude westward-flowing South Equatorial Current (SEC). The SEC transports water from the

Table 1 Archaeological ΔR terrestrial/marine pairs from the central South Pacific Gyre.

	Terrestrial data			Marine data					ΔR (^{14}C years)	
	Calendar age Mean (68% prob. range)*	Sample ID (age/CRA) Material	Site	^{14}C lab code	Conventional radiocarbon age \pm error (BP)	$\delta^{13}\text{C}$ (‰)	Classification#	Material	ΔR IntCal13 (68% conf.)	ΔR SHCal13 (68% conf.)
American Samoa	2468	2014-16 (U/Th = 2470 \pm 8)	Va'oto (AS-13-13), Layer IVb, Ofu Island	OZT-063	2566 \pm 27	-0.2	M/V	Coral: <i>Acropora</i> sp. abraded	-194 \pm 28	
	2375	2014-22 (U/Th = 2375 \pm 11)	Va'oto (AS-13-13), Layer VI, Ofu Island	OZT-064	2559 \pm 24	-0.3	M/V	Coral: <i>Acropora</i> sp. unmodified	-149 \pm 25	
	2796	2014-15 (U/Th = 2796 \pm 9)	Coconut Grove (AS-13-37), Layer III, Ofu Island	OZT-062	2984 \pm 16	0.4	M/V	Coral: <i>Acropora</i> sp. unmodified	-60 \pm 17	
	600 (650–550) cal BP	Wk-21993 <i>Cocos nucifera</i> charcoal (611 \pm 30)	Ta'u Hospital, Layer 5, Ta'u Island	Wk-21994	1020 \pm 30	2.8	G/V	Shell: <i>Turbo crassus</i>	-18 \pm 50	26 \pm 44
Tonga	730 (760–690) cal BP	Wk-21833 (821 \pm 30)	Heketa (HEK), 100–110 cm, Tongatapu Island	Wk-21953	1175 \pm 30	2.8	M/L	Shell: <i>Tridacna</i> sp. Juvenile	-22 \pm 42	9 \pm 38
				Wk-21955	1296 \pm 35	3.1	M/L	Shell: <i>Chama</i> sp.	98 \pm 46	130 \pm 42
	2590 (2710–2490) cal BP	Wk-23234 and Wk-28235 (Pooled result = 2492 \pm 22) <i>Cocos nucifera</i> charcoal	Talasiu (TAL), 55–80 cm, Tongatapu Island	Wk-22999	2767 \pm 37	2.2	M/L	Shell: <i>Tridacna</i> sp.	-92 \pm 66	-42 \pm 72
				Wk-23000	2726 \pm 30	2.8	M/L	Shell: <i>Tridacna</i> sp.	-132 \pm 63	-84 \pm 70
				Wk-23001	2682 \pm 30	3.5	G/L	Shell: <i>Conus</i> sp.	-176 \pm 63	-128 \pm 70
			Wk-48576	2753 \pm 17	2.7	M/L	Shell: <i>Pinctada</i> sp.	-100 \pm 72	-56 \pm 72	

Marquesas	670 (690–660) cal BP	Wk-20135 and 20134 (Pooled result = 725 ± 20) <i>Cocos nucifera</i> charcoal	Teavau’ua (AHO-1), Layer IV, Nuku Hiva, Marquesas	Wk-13833	1169 ± 36	2.2	M/V	Shell: <i>Pinctada margaritifera</i>	36 ± 38	76 ± 42
				Wk-20133	1172 ± 30	1.7	M/V	Shell: <i>Periglypta reticulata</i>	39 ± 32	80 ± 38
	370 (430–300) cal BP	Wk-19116 (296 ± 34) <i>Thespesia populnea</i> charcoal	Teavau’ua (AHO-1), Layer IIIb, Nuku Hiva	Wk-20132	710 ± 37	1.9	M/V	Shell: <i>Periglypta reticulata</i>	–26 ± 56	8 ± 58
Cook Islands	660 (680–660) cal BP	Wk-18402 and Wk- 20568 (Pooled result = 705 ± 21) <i>Thespesia populnea</i> and <i>Cocos nucifera</i> charcoal	Ureia, (ATI-10), Zone G, Aitutaku Island	Wk-20130	1093 ± 31	2.5	M/V	Shell: <i>Pinctada</i> sp.	–28 ± 34	16 ± 40
				Wk-23091	1074 ± 30	–10.6	—	Fish: <i>Holocentridae</i> sp.	–48 ± 32	–2 ± 40
Fiji	2820 (2860–2780) cal BP	Wk-23118 (2727 ± 35) Nutshell charcoal	Bourewa, Phase 6, Pit A1A/ A1D	Wk-23067	2969 ± 39	2.6	M/L	Shell: <i>Anadara scapha</i>	–95 ± 49	–65 ± 50
	2980 (3060–2880) cal BP	Wk-10294 (2852 ± 57) Grass, reed or palm frond	Naigani (VL 21/5), Sq A5, oven	Wk-10296	3110 ± 52	3.0	G/V	Shell: <i>Trochus</i> sp.	–72 ± 80	–30 ± 80

*Radiocarbon dates calibrated using IntCal13 (Reimer et al. 2013) in OxCal version 4.3.2 (<https://c14.arch.ox.ac.uk/>).

#M = Marine environmental influence; G = gastropod; V = Volcanic environment; L = Limestone environment. Lab prefixes: OZT – ANSTO, Australian Nuclear Science and Technology Organisation; Wk = University of Waikato.

gyre center and bifurcates on the east coast of Australia, feeding both the East Australian Current (EAC) and the New Guinea Coastal Current (NGCC) (Figure 1). This circulatory system is considered to create relatively stable surface conditions at the center of the gyre (Rougerie and Wauty 1993) but upwelling and mixing of water occur at the edge of the gyre and where large island chains disturb the flow of surface waters (Petchey et al. 2008). Consequently, we have avoided ΔR values from island locations at the edge of the gyre. This includes the Solomon Islands (Petchey et al. 2004, 2008a), Papua New Guinea (Petchey et al. 2012, 2013), Norfolk and Kermadec Islands, New Zealand and the Chatham Islands (Petchey et al. 2008b).

2. **Shell taxa:** Most shellfish precipitate their shells in equilibrium with the isotopic signature of dissolved inorganic carbon from the waters they live in (McConnaughey et al. 1997). This can, however, be complicated by dietary and habitat preferences of the animal studied. Many gastropods directly ingest sediment via algal grazing or by direct ingestion of the sediment. Therefore, ^{14}C results from algal grazing or herbivorous gastropods are only included if the island group in question is volcanic. In limestone locations, such as Tongatapu Island, only those bivalves with $\delta^{13}\text{C}$ values equivalent to, or higher than, the modern ocean average (ca. 1.7‰) are selected (cf., Petchey et al. 2018). This minimizes the likelihood of incorporating bicarbonate ions that incorporate ancient carbon from the calcareous strata.
3. **Context:** We have not considered any archaeological ΔR values calculated using Bayesian methodologies (e.g., Macario et al. 2015). Such methods enable the ΔR to be calculated from archaeological evidence that is temporally constrained despite strict contemporaneity being unknown (Jones et al. 2007). Few archaeological chronologies in the South Pacific have been constructed with sufficient numbers of stratigraphically secure dates to achieve sufficiently precise results using this approach (see however Petchey et al. [2015] who use this methodology for gastropod shells from the limestone island of Efate, Vanuatu).

Archaeological Samples (Figure 1, Table 1)

American Sāmoa (Manu'a Group): Three ΔR values derived from U/Th dated corals (*Acropora* spp.) have been identified from pre-2300 cal BP archaeological deposits on Va'oto, Ofu Island (Clark et al. 2016a). Two of the corals come from pre-colonization contexts and are unmodified; the third has been used as an abrader. Although mixing of the cultural deposit is likely (a second unmodified coral fragment from the exact same context as sample 2014-22 [2375 ± 11 cal BP] gave a different age [i.e., sample 2014-23; 2503 ± 7 cal BP; Clark et al. 2016b:270]), the use of U/Th to obtain a calendar age on the same ^{14}C dated sample negates the need for stratigraphic contemporaneity.

A single ΔR -value is reported by Petchey et al. (2009) using a *Turbo* spp. shell/charcoal pair from the Ta'u Hospital site, on Ta'u Island, dating from ca. 500 cal BP onwards. *Turbo* spp. gastropods are herbivorous with a recorded preference for calcium carbonate strata (Beesley et al. 1998:675, 768), but because Ta'u Island is the remnant of a basaltic caldera (Stearns 1944) this ΔR result is considered to be reliable.

Previously reported archaeological ΔR values from sites in Western Sāmoa (Kirch 1993; Cleghorn and Shapiro 2000) are excluded from this evaluation because the paired charcoals selected for dating were not identified as short-lived.

Kingdom of Tonga: Dating of Tonga is much more problematic because all main occupied islands are dominated by limestone (Burley 1998). Tongatapu is especially problematic because of the long residence time of water in the central Fanga Uta Lagoon which has contributed to a long-recognized hardwater effect for this island (Spennemann and Head 1998, Petchey and Clark 2011). ΔR research has been carried out at two archaeological sites; Talasiu, located within the eastern arm of the lagoon with material dated to ca. 2580 cal BP, and Heketa located on the ocean side of the lagoon, dated to ca. 1200 cal BP (Petchey and Clark 2011).

ΔR values obtained from *Tridacna* sp. and *Chama* sp. shellfish are available from Heketa. Both taxa dislike brackish waters and are found on reef flats (Hart et al. 1998, Beesley et al. 1998:309). *Turbo* and *Strombus* ^{14}C results reported by Petchey and Clark (2011) are not included in this evaluation since both may ingest sediment while feeding. A ΔR calculated from *Conus* sp. shell is also available from Talasiu. *Conus* are carnivorous reef-dwelling animals (Beesley et al. 1998:852–3) and therefore should more closely reflect ocean reservoir offsets, but no comprehensive ^{14}C study has been carried out on this animal so this value is included with caution. A large number of *Anadara* and *Gafrarium* shellfish ^{14}C dates have been obtained from the Talasiu midden. These may be affected by hardwater, as indicated by depleted $\delta^{13}\text{C}$ values for these shells (Petchey and Clark 2011:545), and are not considered further here. A single unpublished *Pinctada* sp. shell ΔR -value is also available for Talasiu (Wk-48576) and has a stable isotope value that confirms a marine influence ($\delta^{13}\text{C} = 2.7\text{‰}$).

Fiji Islands: Two archaeological ΔR values have been published for Fiji; one from the site of Bourewa, Viti Levu (Nunn and Petchey 2013) dated to between 2866 and 2613 cal BP (95% prob.), and a second from the site of Matanamuani on Naigani Island dated to between 3220 and 2860 cal BP (95% prob.) (Irwin et al. 2011). Nunn and Petchey (2013:29) identified one short-lived terrestrial/marine pairing from Bourewa; a sample of *Anadara scapha* from Pit A1A paired with nutshell charcoal from adjacent Pit A1D. Although limestone was noticed in the hinterland, the $\delta^{13}\text{C}$ ($2.6 \pm 0.2\text{‰}$) indicates this shellfish was likely influenced by fully marine sources. *Trochus*—an algal grazing gastropod (Beesley et al. 1998:683)—was dated from Matanamuani. This value is considered reliable because the island is predominantly volcanic, with the only limestone found on the opposite side of the island (Irwin et al. 2011).

Cook Islands: Aitutaki Island is a remnant volcanic cone (Stoddart, 1975) located in the southern Cook Islands. Initial occupation at the site of Ureia occurred ca. 725–520 cal BP (68% prob.) (Allen and Wallace 2007). Investigation of the regional reservoir offset around the Cook Islands, undertaken on material from Ureia, is reported by Petchey et al. (2009) and includes a ΔR obtained from a *Pinctada* sp. bivalve shell and another from *Holocentridae* sp. bone, an inshore fish species. Very little reservoir work has been undertaken using fishbone (see Petchey and Clark [2010:242] for reservoir work on *Scaridae* sp. fish remains from Palau), but it is thought that the ^{14}C predominantly reflects dietary protein sources that are in equilibrium with marine dissolved organic carbon.

Marquesas Islands: The Marquesas chain consists of ten main volcanic islands (Chubb 1930) at the eastern edge of the Pacific Gyre, of which Nuku Hiva Island is the largest. Reservoir offset values measured using *Pinctada margaritifera* and *Periglypta reticulata* shells from the site of Teavau'ua, Layer IV (661–518 cal BP) and Layer IIIb (543–153 cal BP, 95% prob.), are reported in Petchey et al. (2009).

ΔR Calculation

ΔR values for both ^{14}C and U/Th dated pairs (Table 1) have been calculated using the online tool found at <http://calib.org/deltar/> (Reimer and Reimer 2017), which first calibrates the terrestrial ^{14}C age with the appropriate calibration curve and then reverse-calibrates discrete points of the resulting probability density function with the marine calibration curve (Marine13; Reimer et al. 2013). Because the islands under consideration lie within the SPCZ, which merges with the ITCZ to the west (Figure 1), we have opted to use the Northern Hemisphere calibration curve (IntCal13; Reimer et al. 2013) following the recommendations of Petchey et al. (2009), though a gradient from north to south is likely (Buntgen et al. 2018) and a mixed Northern/Southern Hemisphere calibration may be more appropriate at certain time periods (cf., Marsh et al. 2018). ΔR values calculated using SHCal13 (Hogg et al. 2013) are also given in Table 1 for comparison. Calendar ages derived from U/Th measurements are similarly reverse-calibrated using the marine calibration curve. The new archaeological ΔR values are overlain on the black coral values from the east Australian coastline (Hua et al. 2015 and Komugabe-Dixson et al. 2016) and modern (pre-AD 1950) shell ΔR values from the South Pacific Gyre (Petchey et al. 2008; Ulm et al. 2009), both recalculated from published raw data using the online ΔR calculation tool.

RESULTS

The results are presented in Figure 2. Slightly more negative ΔR values occur between ca. 500 and 750 cal BP which give way to a positive inflection starting ca. 750 cal BP. The ΔR value of 98 ± 46 ^{14}C years for *Chama* sp. shell from Heketa could theoretically be influenced by hardwater and represents the potential danger of dating shell from such locations, but this trend towards higher ΔR values is also apparent in the more extensive coral datasets. Between 2600 and 2250 cal BP results from the archaeological samples follow the same trend as the coral datasets—towards lower ΔR (ΔR average = -160 ± 11 ^{14}C years [$\chi^2_{9;0.05} = 13.99 < 16.92$; GSD = 48]). The combined shell/coral average ΔR for the period between 3100 and 2600 cal BP increases to -48 ± 10 ^{14}C years ($\chi^2_{10;0.05} = 33.82 < 16.92$; GSD = 82). The same trend is evident when the SHCal13 calibration dataset is used to calculate the ΔR -value (Table 1). These results also suggest that there is no regional offset, with island groups from west of the salinity front (i.e., American Samoa and Tonga) found in both ΔR groupings.

DISCUSSION

Using material from archaeological contexts, comparable temporal ΔR trends have been identified in the central Pacific Gyre to those measured in coral from the southeast coast of Australia (Komugabe-Dixson et al. 2016; Hua et al. 2015) (Figure 2). Komugabe-Dixson et al. (2016:977–978) argued that considerable ENSO variability between the present day and 1000 years ago was responsible for the increased influence of ^{14}C -depleted water from equatorial waters and/or from the eastern boundary of the South Pacific where high ΔR values (between 355 ± 105 and 253 ± 207 ^{14}C years) were attributed to increased influence of upwelled ^{14}C -depleted water (cf., Ortlieb et al. 2011). It is possible that black coral from further south was differentially affected during periods such as the Little Ice Age (ca. AD 1600–1860) when the EAC was weakened and increased advection of cooler sub-Antarctic waters from the Subtropical Front caused an increase in the reservoir age and ΔR -value. Both shell and coral proxies have identified a

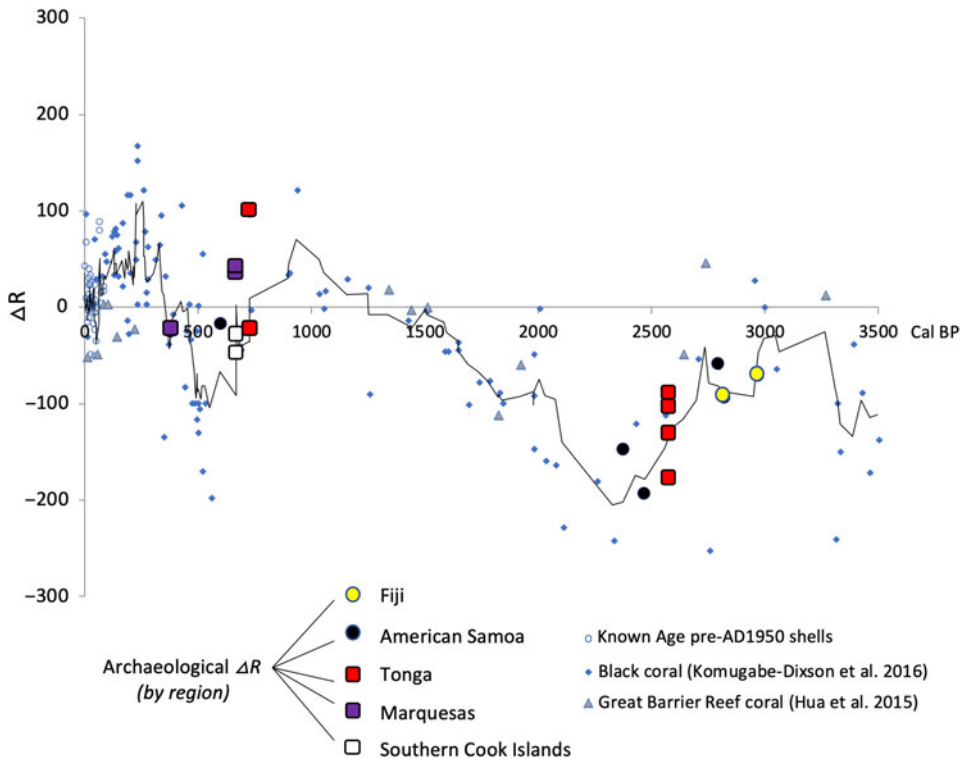


Figure 2 Change in ΔR across the South Pacific over the last 3500 years. Large squares and circles = archaeological ΔR values mentioned in text. Trendline based on a 4-point moving average.

significant negative shift in ΔR between ca. 2600 and 2250 cal BP. Komugabe-Dixon et al. (2016) attributed this change to strong and abrupt El Niño events. To the far eastern boundary, a similar depression in ΔR occurred between 5180 and 1160 cal BP, which Ortlieb et al. (2011) also interpreted as being caused by the increased influence of subtropical water and diminished coastal upwelling processes.

The shift to more negative ΔR values between ca. 2600 and 2250 cal BP occurs at a critical time in the Pacific—a time when sea-level was falling rapidly (see Dickinson 2001), interaction between different populations took place (Posth et al. 2018) and archaeological evidence points to significant cultural change that has been attributed to a developing Ancestral Polynesian Society (Kirch and Green 2001). Moreover, initial human colonization in West Polynesia followed close on the heels of falling sea-levels. To evaluate whether a regional forcing mechanism, independent of societal drivers, was primarily responsible for any societal changes (cf., Nunn and Carson 2015) it is necessary to obtain precise dates for these events. With the development of the first temporal model of changing ΔR , we are only now entering a phase where ^{14}C may be able to answer these questions. Recent dating of the early Polynesian site of To'aga, American Sāmoa (Petchey and Kirch 2019) using a time-dependent ΔR has highlighted the limitations of previous colonization models which have been put forward to account for apparent large gaps in the chronology caused by limited dating and widespread uncertainty in the reliability of shell dates.

An alternative to using ΔR when calibrating marine samples has recently been proposed by Butzin et al. (2017) who present simulations for spatial and temporal variability in the global marine reservoir age calculated from ocean circulation and temporally specific climate models. A regional marine reservoir age curve for the central South Pacific Gyre has subsequently been produced by Alves et al. (2019, fig 10c). While this model displays a similar pattern in reservoir age to the archaeological samples from the central South Pacific Gyre and black coral from the South Tasman Sea, it does not reproduce the very low values recorded in these datasets. This contradicts the findings of Alves et al. (2019:132–133) who noted that modeled data worked best in open-ocean areas of the Pacific, as evidenced by similarity to measured coral values recorded by Burr et al. (2015) for the Solomon Islands. This disjunction with the black coral/archaeological pairs could be caused by poor resolution and/or inaccurate inclusion of carbon cycle and ocean circulation changes in the reservoir age model (cf., Alves et al. 2019:136). Moreover, the Burr et al. (2015) dataset has only 6 measured values for the time period of interest here and originates from the edge of the gyre where ΔR variability is likely to be masked (Petchey et al. 2008b). This is clearly something to investigate further.

CONCLUSION

Evidence obtained from archaeological materials demonstrate that between 2600 and 2250 cal BP the marine ^{14}C reservoir offset (ΔR) across the central South Pacific Gyre was lower than the present. This observation matches coral U/Th, ^{14}C paired data collected from the east coast of Australia. This central South Pacific Gyre ΔR dataset fills a gap in ocean circulation and climate reconstructions between 3500 and 1000 cal BP—a key period that incorporates initial human settlement across the region and the subsequent development of Polynesian culture. The inclusion of shell ΔR values into extant datasets has been made possible because of advances in our understanding of ^{14}C uptake by shellfish, which has enabled the recognition of marine *versus* estuarine influences and, therefore, the exclusion of shells where the age has been affected by depleted ^{14}C from hardwater. To develop a more accurate and precise model of human colonization across this region it is essential that more ΔR values are obtained.

ACKNOWLEDGMENTS

This paper developed from an observation that reservoir ages calculated on coral from archaeological deposits in American Samoa did not conform to established geographical ΔR divisions for the region. This single observation enabled me to revisit the many marine ^{14}C reservoir projects undertaken over the last 15 years and provide context to information that appeared muddled. Special thanks go to all the Pacific archaeologists who have provided shell and charcoal samples for this research.

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