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**High-Resolution Radiocarbon Dating of Marine Materials in Archaeological Contexts:
Radiocarbon Marine Reservoir Variability between *Anadara*, *Gafrarium*, *Batissa*, *Polymesoda*
spp. and Echinoidea at Caution Bay, Southern Coastal Papua New Guinea**

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Abstract

The remains of shellfish dominate many coastal archaeological sites in the Pacific and provide a wealth of information about economy, culture, environment and climate. Shells are therefore the logical sample type to develop local and regional radiocarbon chronologies. The calibration of radiocarbon (^{14}C) dates on marine animals is not straightforward, however, requiring an understanding of habitat and dietary preferences as well as detailed knowledge of local ocean conditions. The most complex situations occur where terrestrial influences impinge on the marine environment resulting in both the enrichment and depletion of ^{14}C (Ulm *Geoarchaeology* 17(4):319–348, 2002; Petchey and Clark *Quat Geochronol* 6:539–549, 2011). A sampling protocol that combines a high-resolution excavation methodology, selection of short-lived samples identified to species level, and a tri-isotope approach using ^{14}C , $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, has given us the ability to identify ^{14}C source variation that would otherwise have been obscured. Here, we present new research that details high-resolution mapping of marine ^{14}C reservoir variation between *Gafrarium tumidum*, *Gafrarium pectinatum*, *Anadara granosa*, *Anadara antiquata*, *Batissa violacea*, *Polymesoda erosa* and Echinoidea from the Bogi 1 archaeological site, Caution Bay, southern coastal Papua New Guinea. These isotopes highlight specific dietary, habitat and behavioural variations that are key to obtaining chronological information from shell radiocarbon determinations.

Keywords: Radiocarbon; Marine reservoir correction; *Gafrarium*; *Anadara*; *Polymesoda*; Caution Bay; *Batissa*; Echinoidea; Lapita

1. Introduction

Archaeological sites in the Pacific tend to be problematic for radiocarbon dating because suitable materials such as charcoal or bone are often highly degraded, unidentifiable and/or scarce. It is therefore critical that archaeologists and Quaternary researchers obtain reliable calibrated ages from shell. This requires an understanding of geographical variability in the surface ocean marine ^{14}C reservoir caused by upwelling, ocean currents, and climate (Stuiver and Braziunas 1993), combined with knowledge of the habitat and dietary preferences of different shellfish (Tanaka et al. 1986; Ingram and Southon 1996; Hogg et al. 1998). For the last two decades, the ^{14}C community has recommended the selection of filter-feeding bivalves as the most suitable shellfish for dating, followed by carnivores and herbivores (Forman and Polyak 1997; Hogg et al. 1998; Petchey et al. 2004, 2008a). Deposit-feeding shellfish are not recommended (Dye 1994; Anderson et al. 2001). This preference for filter-feeding shellfish is based on the premise that such taxa predominantly consume suspended phytoplankton and dissolved inorganic carbon (DIC) from seawater (Tanaka et al. 1986). This simplistic view overlooks the very real possibility that metabolic carbon sources vary depending upon habitat and feeding mechanisms (cf. Keith et al. 1964; Dettman et al. 2004; Petchey and Clark 2011); in particular, many filter-feeding bivalves can alter their feeding strategies depending on water flow and sediment transport regimes, while others change feeding preferences as they mature (Broom 1982; Snelgrove and Butman 1994). It also overlooks the complexity of the near-shore environment where material derived from many varied sources of non-marine carbon are available.

Traditionally, research into variation within the regional marine ^{14}C reservoir (commonly referred to as delta R (ΔR), which is the difference between the modelled global average marine reservoir and the actual ^{14}C activity of the surface ocean at a particular location (Stuiver et al. 1998)) has concentrated on observed changes over wide geographic regions or periods of time (Dye 1994; Burr et al. 1998, 2009; Guilderson et al. 2000, 2004; Sikes et al. 2000; Petchey 2009; Petchey et al. 2004, 2005, 2008a, b; Petchey and Addison 2008; Petchey and Ulm 2012). Extensive studies of intra- and inter-species ^{14}C variability are few (see however, Hogg et al. (1998) and Cook et al. (2004) for evaluation of modern shellfish ^{14}C) and typically inconclusive except in environments known to have extreme shifts in ^{14}C . Examples of the latter include lagoons affected by hardwaters¹ (Petchey and Clark 2011) or ocean regions where upwelling of ^{14}C -depleted waters occur (Ingram and Southon 1996; Culleton et al. 2006) – both typified by very large and positive ΔR values. Lower values have been attributed to CO_2 absorption from the atmosphere and the incorporation of freshwater – either derived from river-borne organic debris from decaying plants and soil organics, or terrestrial runoff (Stuiver and Braziunas 1993; Southon et al. 2002; Ulm 2002).

Ascough et al. (2005) recently undertook a more detailed study of ^{14}C variation associated with life habitat and dietary differences of shellfish in coastal Scotland. Five species of shellfish from the intertidal zone with minimal carbonate rock and freshwater influence were tested; *Patella vulgata*, *Littorina littorea* (epifaunal grazers), *Mytilus edulis* (filter feeder attached to rock), *Ensis*, and *Cestroderma edule* (infaunal filter feeder). Although Ascough et al. (2005:438) concluded that there was no significant variation in the ^{14}C ages, a number of anomalies remained unexplained. Specifically, values for *L. littorea* and *E. ensis* were statistically variable.

¹ Hardwaters occur where large amounts of bicarbonate ions, generated by seepage through calcareous strata, result in excessively old ^{14}C ages.

Greater refinements to observations of shellfish environmental preferences have been obtained by the use of isotopes such as $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in combination with ^{14}C data (Culleton et al. 2006; Petchey et al. 2008b; Petchey and Clark 2011). Because most shellfish precipitate their shells in equilibrium with stable isotopes from the local environment, $\delta^{18}\text{O}$ can be used as an indicator of change in water temperature and salinity while the $\delta^{13}\text{C}$ reflects changes in water source and overall marine productivity. Typically, any input of freshwater within an ocean environment should result in the depletion of shell ^{13}C and ^{18}O (Keith et al. 1964:1781; Swart et al. 1983; Gat 1996:241, 255; Goewert et al. 2007), while increased productivity and CO_2 atmospheric absorption in reef locations may result in enrichment in ^{13}C (Weber and Woodhead 1971; Watanabe et al. 2006) and ^{14}C (Guilderson et al. 2000; Petchey et al. 2008b).

In this paper, we present research that investigates interspecies ^{14}C variation for archaeological shells collected from Bogi 1, a site in Caution Bay, Papua New Guinea (PNG). Our ultimate aim is to provide tools to achieve the most robust high-resolution chronology in the Pacific.

Setting

Caution Bay is located approximately 20 km northwest of Port Moresby along the southern coast of PNG (Figure 1a). An outer barrier reef forms the southwest (offshore) boundary of the bay providing protection from ocean swells (Coffey Natural Systems 2009:13.1). Oceanic circulation within the Gulf of Papua is dominated by a clockwise gyre, generated as the northwards-flowing Coral Sea Coastal Current enters along the eastern edge of Torres Strait and exits to the northeast (Woolfe et al. 1997). Petchey (2008a: Table 1) has calculated for shellfish generally an average ΔR of 6 ± 21 ^{14}C years for the region circled by the South Pacific Gyre (excluding Solomon Islands and Easter Island). Ongoing research by Ulm et al. (2007, 2009) for Torres Strait and Cape York Peninsula, and by Petchey et al. (2008a) for the Coral Sea, suggest that a slight enrichment in ^{14}C values in this region is likely. This enrichment is considered to be a consequence of higher rates of atmospheric–ocean surface ^{14}C exchange combined with minimal mixing with older subsurface waters in the shallow waters of Torres Strait and the Gulf of Carpentaria (cf. Petchey et al. 2008a; Ulm et al. 2009a, b). The mean hourly current speed in Caution Bay is 7 cms^{-1} – significantly slower than the faster-flowing currents ($\sim 25 \text{ cms}^{-1}$) that have been previously identified as causing upwelling favourable eddies elsewhere in the Pacific (Petchey 2009; Petchey and Ulm 2012). Satellite imagery of sea surface temperature show some indications of upwelled cold water associated with periods of prolonged southeast trade winds mainly to the east of Port Moresby (Coffey Natural Systems 2009:13.7). Two previously unpublished ΔR values for Abau and Yule Island to the east and west of Caution Bay confirm this picture of regional stability (see Table 1). Caution Bay itself is a mangrove-fringed embayment fed by the Lea Lea River 5 km from Bogi 1, as well as a number of smaller rivers, including the Vaihua River immediately backing the site (Figure 1b). These rivers drain a coastal hill region that is underlain by limestone, calcareous sandstones, mudstones and clay (see Mabbutt 1965; Speight 1965). Although wave scour and tidal currents tend to remove finer materials, larger particles are laid down on the inner tidal flats (Rowe et al. in preparation).

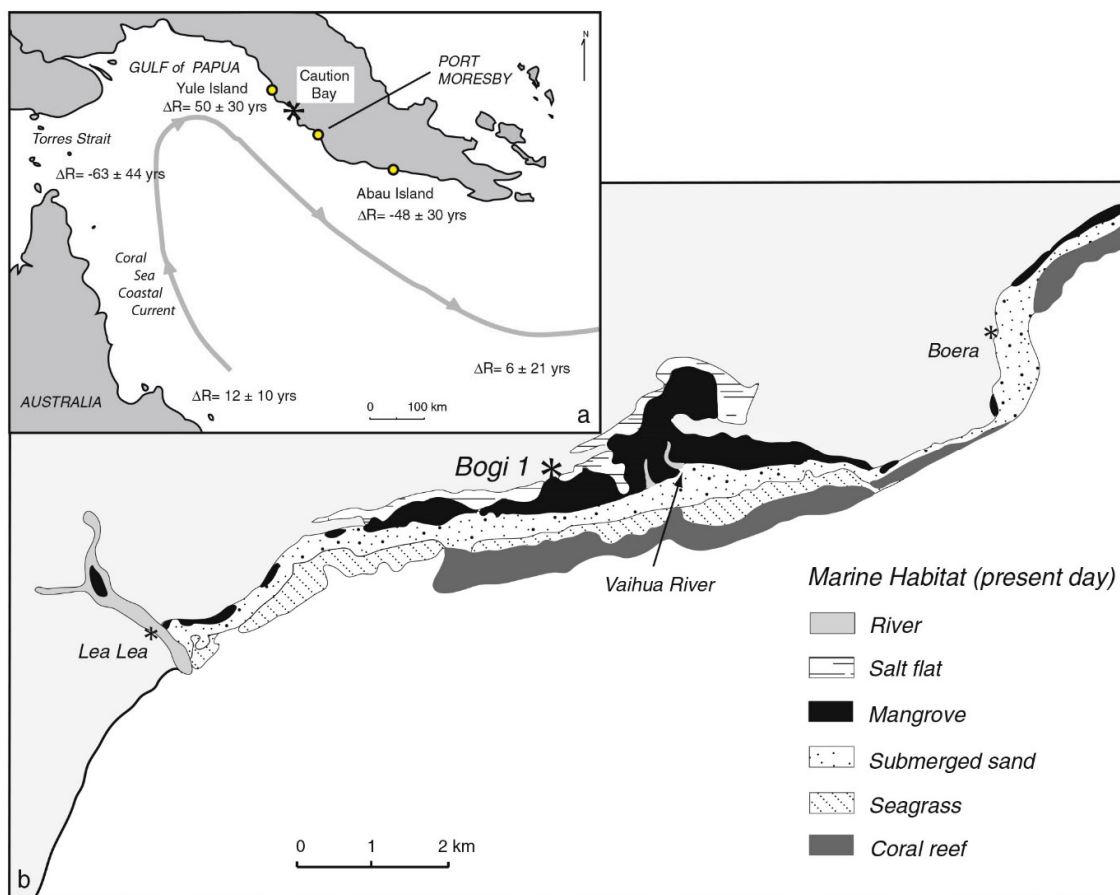


Figure 1. (a) Western south Pacific showing the location of Caution Bay, oceanic circulation (adapted from Woolfe et al. 1997) and regional ΔR values: East Australian average ΔR value from Ulm (2006); South Pacific Gyre average ΔR value from Petchey et al. (2008a); Torres Strait average ΔR value from Ulm et al. (2009a, 2009b). (b) Coastal marine habitats in Caution Bay and location of Bogi 1 (adapted from Coffey Natural Systems 2009)

Table 1. ΔR from pre-AD 1950 mollusc shells.

Location	Sample	Historical Age (AD)	$\delta^{13}C\%$ (± 0.2)	^{14}C age and error (BP) [$R_s(t)$]	Marine modelled age [$R_g(t)$]	ΔR (years) [$R_s(t) - R_g(t)$]	Identifier	Collector
Yule Island	<i>Bursa granularis</i>	1898	1.2	506 \pm 30	456 \pm 23	50 \pm 30	Wk-24841 [Bishop Museum]	Thaanum
Abau Island	<i>Gafrarium tumidum</i>	1944	-1.2	415 \pm 30	463 \pm 23	-48 \pm 30	Wk-24842 [Australian Museum sample AMC140963]	J. Gregory

The archaeological materials sampled for this research come from what is believed to be an archaeologically short-duration dense shell midden deposit—excavation units (XUs) 6-16a in Square C of Bogi 1 – dated to 2000–2150 cal BP. These XUs were chosen for analyses of ΔR variation between shell taxa because a series of preliminary radiocarbon determinations had here revealed a synchronous assemblage distinguishable from slightly older and younger ages below and above, respectively. Furthermore, the dense horizon of often whole shells represented by these XUs – underlain by further dense cultural shell from the same stratigraphic horizon but not sampled as a buffering cautionary measure – suggested good chrono-stratigraphic protection of sediments (i.e. of individual shell samples to be used for the present study) from potential unobserved post-depositional mixing with older (underlying) materials. XUs 6-16a are preceded by two additional midden concentrations dated to 2600–2900 cal BP and 3000–4200 cal BP; these earlier horizons are stratigraphically separated from each other, and from the XU 6-16a horizon, by distinctive layers of shell-poor sediments. The upper shell midden is sealed from later cultural activity by material dating to ~1500 cal BP (McNiven et al. 2011:3).

Method

The marine ΔR for a particular area can be calculated from shell/charcoal pairs such as those found in archaeological sites (Petchey and Clark 2011; Jones et al. 2007). For this type of calculation, it is essential that the age of shellfish death be known. This is determined by dating charcoal from short-lived, contemporaneous materials (see Petchey 2009 for ΔR guidelines).

The samples selected for analysis here include *Anadara granosa* (5.7% of the shellfish assemblage by weight from XUs 1-16a), *Anadara antiquata* (0.6%), *Gafrarium tumidum* (1.1%), *Gafrarium pectinatum* (0.4%), *Batissa violacea* (0.3%), *Polymesoda erosa* (0.4%) and unidentified Echinoidea (sea urchin) exoskeleton. This is a mix of filter-feeding, infaunal (burrow into the sediment), and estuarine bivalves typically recommended for dating (*Anadara* spp. and *Gafrarium* spp.), as well as shells not recommended for ^{14}C dating because they have higher tolerances for brackish conditions (*Polymesoda* sp. and *Batissa* sp.). Echinoids (sea urchins) are omnivorous and are generally considered to be acceptable for dating with caution, but have not previously been thoroughly investigated.

From each of the shells, we removed a 5-mm cross-section perpendicular to the edge, across multiple increments of growth to avoid intra-shell variations in ^{14}C caused by seasonal fluctuations and variable age of the shellfish (the Echinoidea were heavily fragmented and could not be identified to species level nor sampled in this manner). This method provided an average isotopic value over a maximum period of 5 year of growth (i.e. one increment in the Marine09 data set). The shell ^{14}C results were compared with dates on three samples of charred fruit, nut endocarp and culm (Wk-31047: 2097±27 BP; Wk-31049: 2114±27 BP; Wk-31050: 2101±27 BP), respectively, from contexts in direct association with the shells sampled from these same XUs (Table 2). These returned a pooled age of 2104±16 BP ($\chi^2_{2:0.05}=00.22<5.99$; no external variation). Charcoal not identified to species level, from various locations throughout the deposit, that have been excluded from the ΔR calculations include; Wk-31048 [2110±28 BP], Wk-30458 [2090±25 BP] and Wk-31051 [2192±25 BP]. These returned a pooled age of 2132±15 BP ($\chi^2_{2:0.05}=9.20<5.99$; external variation=49.74). Although this overlaps at 1 σ with the pooled results from the short-lived material (Wk-31047, Wk-31049 and Wk-31050), there is sufficient variability to justify removing them from the ΔR calculation. Anomalous charcoal results include; Wk-28266 [XU6 1603±30 BP] (a small fragment of charcoal coming from

the uppermost XU used in this study, in a stratigraphic area of contact with overlying deposits); Wk-28267 [XU8 1599±30 BP] (a small fragment of charcoal of undetermined plant component); Wk-28268 [XU11 1537±30 BP] (a small fragment of charcoal of undetermined plant component); and Wk-31046 [XU13 1.13±0.004 F¹⁴C] (a small fragment of charcoal almost certainly from burnt local grass obtained from the sieves rather than collected in situ). Three of these results date to ~1500 cal BP and indicate displacement of tiny charcoal fragments through the porous midden from upper layers down to XU13 (26.2 cm depth below surface). Wk-31046 probably reflects contamination at the time of collection (Table 2).

Radiocarbon dates were prepared and analysed at the University of Waikato Radiocarbon facility in New Zealand following standard accelerator mass spectrometry (AMS) protocols whereby the shells were washed in dilute HCl to remove surface contamination and charcoal samples were treated with a series of dilute HCl, NaOH and HCl washes prior to CO₂ collection. All shells were tested for recrystallization prior to dating using the Feigl staining technique (Friedman 1959). Graphite targets were processed by the reduction of CO₂ with H₂ in a reaction catalyzed by iron powder at a temperature of ~550°C. AMS targets were measured at the Keck Radiocarbon Laboratory, University of California, Irvine, and GNS Science, Wellington.

The ΔR for a specific location “(s)” is calculated from known-age shells collected prior to atmospheric bomb testing using the formula $R_s(t) - R_g(t) = \Delta R(s)$, where $\Delta R(s)$ is the difference between the actual ¹⁴C activity of the surface ocean at a particular location [$R_s(t)$] at that time, and the global average [$R_g(t)$] (as represented by the modelled marine ¹⁴C calibration curve Marine09 (Reimer et al. 2009)). To calculate ΔR values from archaeological terrestrial/marine pairs, an estimate of the Northern Hemisphere atmospheric calibration curve error (Reimer et al. 2009) over the 1 σ span of the radiocarbon age, including the calibration curve error, is used to derive the calculated marine modelled age [$R_g(t)$], $\sqrt{\sigma^{14}\text{C}}$.

For detailed information on how to calculate this see Ulm (2002). The calculated average marine modelled age for the short-lived charcoal samples is 2443±14 year. This has been subtracted from each shell ¹⁴C age [$R_s(t)$]. Each individual archaeological ΔR standard error is calculated by the formula

$$\Delta R\sigma = \sqrt{(\sigma_{R_g(t)})^2 + \sigma_{R_s(t)}^2}$$

$\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values were measured on gas splits taken during preparation of samples at the University of Waikato using a Europa Scientific Penta 20–20 isotope ratio mass spectrometer. Around, PNG the modelled $\delta^{13}\text{C}$ isotopic composition of the modern surface ocean DIC is approximately 1.5‰ (Tagliabue and Bopp 2008, Figure 2) while $\delta^{18}\text{O}$ is approximately 0.3‰ (LeGrande and Schmidt 2006, Fig. 1). These data were used as baseline values for Caution Bay.

Table 2. Shellfish context and isotopic information, Bogi 1, Square C.

XU	Depth below surface (cm)	Laboratory code	Material	Shell length (mm) ²	$\delta^{13}\text{C}$ ‰ (± 0.2)	$\delta^{18}\text{O}$ ‰ (± 0.2)	¹⁴ C age and error (BP) [Rs(t)]	ΔR (years) [Rs(t)-Rg(t)] ³	Comments
XU6	11.0	Wk-28266	Unidentified charcoal		-26.7		1603±30		Vertical displacement and unidentified species. Not used in ΔR equations.
	7.5–10.9	Wk-30326	<i>Gafrarium tumidum</i>	25.8	-0.4	-5.1	2507±25	64±39	Right valve
		Wk-32554	<i>Gafrarium pectinatum</i>	20.0	-0.3	-2.9	2524±27	81±40	Right valve
		Wk-30327	<i>Anadara granosa</i>	48.0	-4.5	-5.5	2397±25	-46±39	Left valve
		Wk-30328	<i>Anadara antiquata</i>	32.4	-2.7	-6.3	2427±25	-16±39	Right valve
SU8	13.8	Wk-28267	Unidentified charcoal		-25.0		1599±30		Vertical displacement and unidentified species. Not used in ΔR equations.
	12.8–14.9	Wk-30329	<i>Gafrarium tumidum</i>	32.4	0.0	-7.4	2501±25	58±39	Right valve
		Wk-32555	<i>Gafrarium pectinatum</i>	29.7	0.1	-3.6	2473±27	30±40	Left valve
		Wk-30330	<i>Anadara granosa</i>	49.7	-3.5	-10.0	2378±25	-65±39	Left valve
		Wk-30331	<i>Anadara granosa</i>	33.5	-4.0	-6.8	2358±25	-85±39	Right valve
		Wk-30332	<i>Anadara antiquata</i>	42.1	0.8	-4.7	2460±25	17±39	Right valve
		Wk-31037	Echinoidea exoskeleton	n/a	-0.1	-0.3	2439±25	-4±39	Fragment
XU10	17.2–19.5	Wk-30333	<i>Gafrarium tumidum</i>	24.0	-0.9	-5.2	2521±25	78±39	Right valve
		Wk-32556	<i>Gafrarium pectinatum</i>	30.1	0.1	-3.5	2512±26	69±39	Right valve
		Wk-30334	<i>Anadara granosa</i>	28.0	-3.7	-5.6	2326±25	-117±39	Right valve
		Wk-30335	<i>Anadara antiquata</i>	36.6	1.1	-4.3	2434±25	-9±39	Left valve
		Wk-32560	<i>Polymesoda erosa</i>	41.1	-0.3	-3.8	2299±29	-144±41	Right valve

² For whole values this is the valve length (after Claassen 1998:21) and for fragments this is the maximum axis.

³ Marine modelled age [Rg(t)]=2443±14 years based on the combined ¹⁴C result for Wk-31047, Wk-31049 and Wk-31050.

		Wk-32563	<i>Batissa violacea</i>	No data	-8.8	-4.0	2219±27	-224±40	Left valve
		Wk-31038	Echinoidea exoskeleton	No data	-2.1	-1.5	2451±25	8±39	Fragment
XU11(3)	22.0	Wk-28268	Unidentified charcoal		-27.1		1537±30		Vertical displacement and unidentified species. Not used in ΔR equations.
XU12a	21.7–23.5	Wk-30336	<i>Gafrarium tumidum</i>	27.9	-1.5	-5.6	2537±25	94±39	Right valve
		Wk-32557	<i>Gafrarium pectinatum</i>	30.9	0.3	-3.3	2530±26	87±39	Left valve
		Wk-30337	<i>Anadara granosa</i>	45.7	-6.0	-7.5	2373±25	-70±39	Left valve
		Wk-30338	<i>Anadara antiquata</i>	44.3	-0.6	-5.0	2448±25	5±39	Left valve
		Wk-32561	<i>Polymesoda erosa</i>	82.6	-12.4	-7.1	2295±27	-148±40	Left valve
		Wk-32564	<i>Batissa violacea</i>	No data	-9.4	-10.1	2253±27	-190±40	Right valve
		Wk-31039	Echinoidea exoskeleton	No data	1.0	-1.4	2459±25	16±39	Fragment
XU13	23.5–26.2	Wk-31046	Charcoal (monocot stem)		-13.6		1.13±0.004 F ¹⁴ C		Sample found after the pit was left open overnight. Not used in ΔR equations.
XU14	26.2–28.3	Wk-31047	Charcoal (carbonized fruit)		-27.0		2097±27		
		Wk-31048	Unidentified charcoal		n/a		2110±28		Unidentified species. Not used in ΔR equations.
		Wk-30340	<i>Gafrarium tumidum</i>	35.0	-0.3	-6.8	2498±30	55±42	Right valve
		Wk-32558	<i>Gafrarium pectinatum</i>	28.2	-0.1	-3.7	2467±26	24±39	Right valve
		Wk-30341	<i>Anadara granosa</i>	53.1	-4.7	-6.6	2425±29	-18±41	Right valve
		Wk-30342	<i>Anadara antiquata</i>	32.5	0.9	-3.7	2433±29	-10±41	Right valve
		Wk-32562	<i>Polymesoda erosa</i>	No data	-15.5	-9.2	2273±27	-170±40	Right valve
		Wk-31040	Echinoidea exoskeleton	No data	-1.0	-0.3	2467±25	24±39	Fragment

XU15a(1)	31.5	Wk-30458	Unidentified charcoal		-24.5		2090±25		Unidentified species. Not used in ΔR equations.
XU16a	30.5–33.4	Wk-31049	Charcoal (nut)		-23.8		2114±27		
		Wk-31050	Charcoal (monocot culm)		-24.1		2101±27		
		Wk-31051	Unidentified charcoal		-24.6		2192±25		Unidentified species. Not used in ΔR equations.
		Wk-30343	<i>Gafrarium tumidum</i>	29.7	-0.2	-7.3	2495±29	52±41	Right valve
		Wk-32559	<i>Gafrarium pectinatum</i>	27.6	-0.4	-4.5	2470±27	27±40	Right valve
		Wk-30344	<i>Anadara granosa</i>	53.8	-7.4	-7.4	2346±30	-97±42	Left valve
		Wk-30345	<i>Anadara antiquata</i>	40.2	0.9	-7.1	2453±29	10±41	Left valve
		Wk-31041	Echinoidea exoskeleton	No data	-1.0	-0.9	2452±25	9±39	Fragment

Results and discussion

The ΔR result for all shell species and echinoids from Caution Bay is -17 ± 7 years ($\chi^2_{34;0.05} = 151.45 < 48.60$) indicating that the natural variability in ^{14}C ages is much greater than the analytical uncertainty associated with the measurements. This range of values reflect the continuum expected in estuarine environments between the terrestrial freshwater systems and shellfish taxa that prefer brackish conditions (*B. violacea* and *P. erosa*) and those that prefer a more marine environment (*Anadara* spp., *Gafrarium* spp. and *Echinoidea*) (Table 3, Figure 3).

Batissa violacea ($\Delta R = -207 \pm 28$ years)

B. violacea is found in fresh and brackish waters near rivers, often buried with siphon projecting from the sediment, picking up detritus from the river. In periods of drought, they can live deep within the sediment, with no siphonal access to the surface, feeding from subterranean water (Poutiers 1998). It is hardly surprising therefore that *B. violacea* has an isotopic signature in keeping with a preference for warmer, brackish waters (Figure 3). The ^{14}C values similarly reflect input from terrestrial material.

Polymesoda erosa ($\Delta R = -154 \pm 23$ years)

Our stable isotope data for *P. erosa* is quite varied and reflect influences from both the marine and terrestrial reservoirs. Radiocarbon values are, however, statistically equivalent (Table 3, Figures 1 and 3). These shellfish are found within mangrove forests in the high intertidal zone, and consequently are only covered by the highest of the high tides. Animals occupying this region must cope with extreme environmental conditions, both in salinity and temperature, which could affect the isotopic values. However, the observed spread in values may also reflect a juvenile/adult distinction. Clemente and Ingole (2011) concluded that juveniles were more common at the low tide zone. Two out of the three samples measured here are clear adults (Wk-32561 = 82.6 mm length; Wk-32562 was measured on a broken valve in excess of 45 mm in length), while Wk-32560 has distinctive marine $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values and is only 41.1 mm in length.⁴

When *B. violacea* and *P. erosa* are removed from consideration the remaining marine/estuarine shellfish have a ΔR value of 9 ± 7 years, but still display variation beyond measurement uncertainty ($\chi^2_{29;0.05} = 57.91 < 41.34$; external variance=40). Closer inspection indicates that there is variability between the different genera and even between some species, but within each species the results are statistically indistinguishable (Table 3, Figure 3).

⁴ Morton (1988:110-111) differentiates juveniles as being ≤ 30 mm, while Gimin et al. (2005) put sexual maturity at 45 mm length.

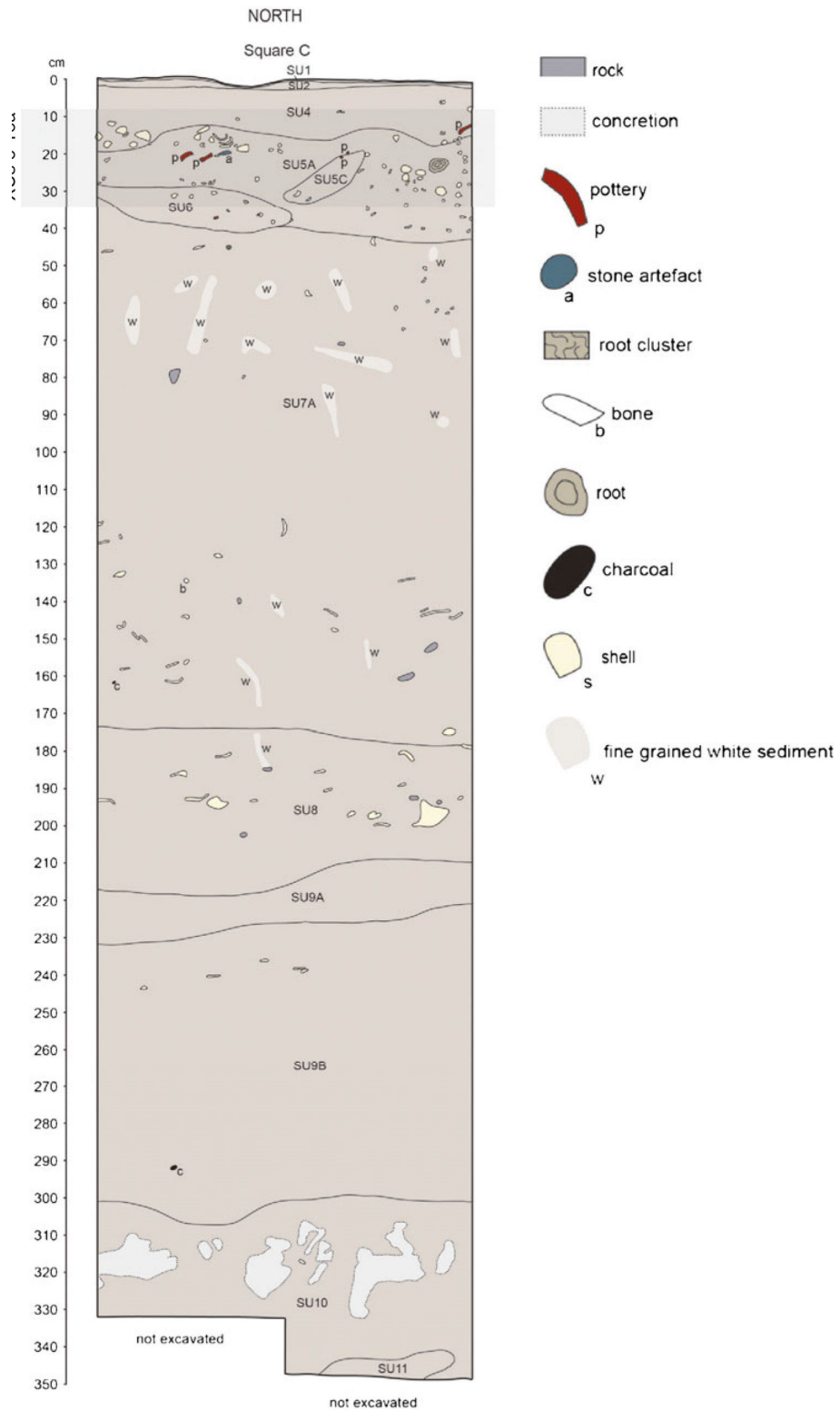


Figure 2. Stratigraphy of Square C, Bogi 1. Excavation units (XUs) 6-16a range from 7.5–33.4 cm depth.

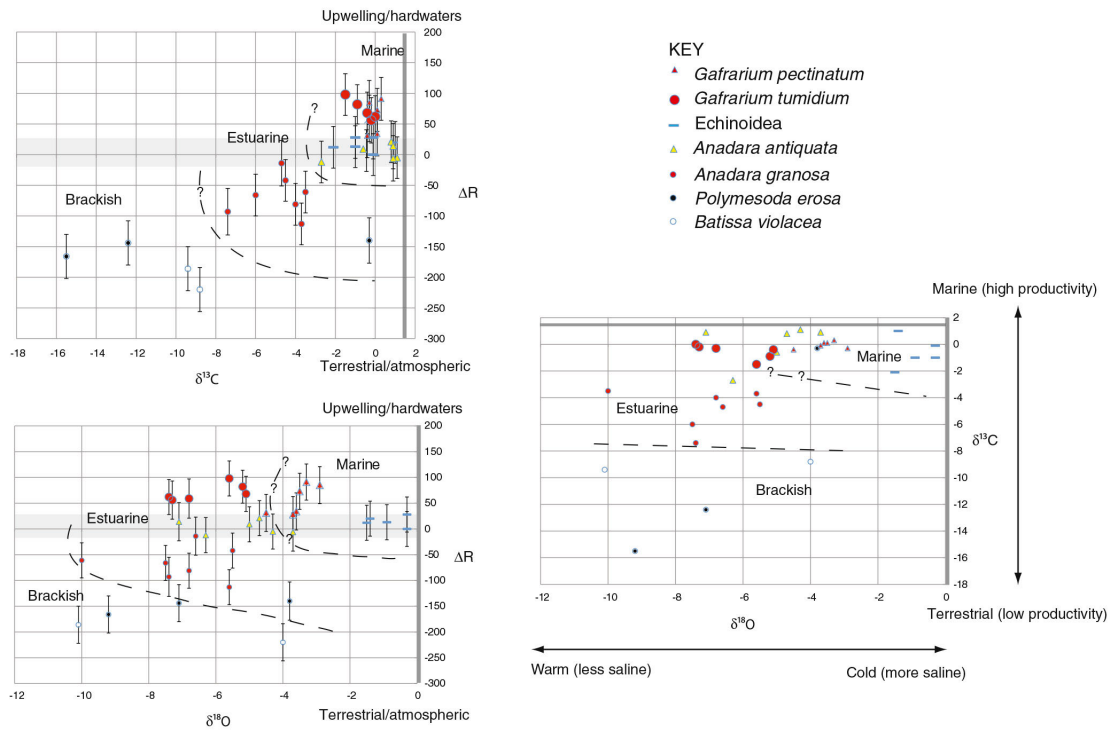


Figure 3. Measured $\delta^{18}O$, ΔR and $\delta^{13}C$ values for mollusc shells from Bogi 1, Caution Bay, southern PNG. At this location the modelled $\delta^{13}C$ isotopic composition of the modern surface ocean DIC is $\sim 1.5\%$ and $\delta^{18}O$ is $\sim 0.3\%$. The average ΔR value for shellfish across the Pacific Gyre region is 6 ± 21 ^{14}C years (see text for explanation). Average ocean isotope values are shown as grey bands

Table 3. Average ΔR for each shellfish and environmental divisions.

Shellfish/ Echinoidea	ΔR (years)	Chi squared statistics ⁵		Environmental division	Isotopic influence
		Species	Genera		
<i>Batissa violacea</i>	-207±28	$\chi^2_{1:0.05}=0.36<3.84$; no external variation		Associated with rivers	Brackish
<i>Polymesoda erosa</i>	-154±23	$\chi^2_{2:0.05}=0.24<5.99$; no external variation		Landward side of the high intertidal area	
<i>Gafrarium tumidum</i>	67±16	$\chi^2_{5:0.05}=0.83<11.07$; no external variation	$\Delta R = 60\pm 11$ ($\chi^2_{11:0.05}=3.94<19.68$; no external variation)	High intertidal	Estuarine
<i>Gafrarium pectinatum</i>	53±16	$\chi^2_{5:0.05}=2.72<11.07$; no external variation			
<i>Anadara granosa</i>	-71±15	$\chi^2_{6:0.05}=4.01<12.59$; no external variation	$\Delta R = -39\pm 11$ ($\chi^2_{12:0.05}=12.94<21.03$; external variation=22)	Mid-intertidal to marginally subtidal	
<i>Anadara antiquata</i>	-1±16	$\chi^2_{5:0.05}=0.55<11.07$; no external variation			Marine
Echinoidea	11±17	$\chi^2_{4:0.05}=0.28<9.49$; no external variation		Low intertidal/subtidal fringe	

⁵ To estimate the amount of uncertainty to be added to the ΔR value by the non-uniform ¹⁴C content of the shellfish the weighted mean for each group has been calculated using the Chi squared (χ^2) test. If the group has additional measurement variability (as indicated if $\chi^2/(n-1)$ is >1) we have added an additional uncertainty (external variance) to the ΔR . In this instance, the uncertainty is calculated by $\sqrt{(S^2_{\Delta R \text{ pooled}} + \sigma^2_{ext})}$, whereby the external standard deviation (σ_{ext}) is determined by subtracting the ¹⁴C measurement variance from the total population variance and obtaining the square root (e.g. $\sigma_{ext} = \sqrt{(\sigma^2_{pop} - \sigma^2_{meas})}$). When $\chi^2/(n-1)$ is ≤ 1 the uncertainty on the individual measurements explains the variations within the group of ΔR values and the weighted mean is used (see Mangerud et al. 2006:3241-3242 for detailed explanation).

Gafrarium spp. ($\Delta R = 67 \pm 16$ and $\Delta R = 53 \pm 16$ years)

The ΔR values for both *G. tumidum* and *G. pectinatum* are the largest of all shellfish and out of equilibrium with ocean values (Table 3), while $\delta^{18}\text{O}$ indicates that they prefer slightly warmer, less saline waters (Fig. 3). Studies show that *G. tumidum* is preferentially found in the high intertidal region within seagrass beds⁶ and mangrove forest (Baron and Clavier 1992; Tebano and Paulay 2000:9–10). This is confirmed by ethnographic observations from Caution Bay. Petchey and Clark (2011) have previously noted that *Gafrarium* spp. show a tendency to prefer inner-lagoon habits that are influenced by hardwaters. The impact of hardwaters on ^{14}C has been considered to be significant only in areas where water exchange with the open ocean is restricted, such as enclosed lagoons or estuaries (McKinnon 1999:94). Theoretically, input of freshwater should also result in the depletion of shell $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, but marine limestone $\delta^{13}\text{C}$ is close to 0 resulting in little offset from typical marine values (Keith et al. 1964:1758, 1781; Gat 1996:241, 255). Consequently, although the *G. tumidum* $\delta^{18}\text{O}$ results are depleted compared to other “marine” shellfish, there is no offset in $\delta^{13}\text{C}$. This supports the hypothesis that the ΔR results are elevated by hardwaters.

Anadara spp. ($\Delta R = -71 \pm 15$ and $\Delta R = -1 \pm 16$ years)

Petchey and Clark (2011) have previously noted that isotope values for *Anadara*, not differentiated to species level, from Tongatapu were highly variable and suggested caution when dating these shellfish. Our results also indicate that the ΔR data for *A. granosa* and *A. antiquata* are statistically cohesive within each species, but additional uncertainty (external variance) increases when evaluated as a group ($\chi^2_{12;0.05} = 12.94 < 21.03$; external variance = 22) suggesting habitat and/or dietary variation is possible (Table 3). Specifically, the isotopes for *A. antiquata* are typical of open ocean values, while *A. granosa* displays a preference for warmer, more terrestrial waters (Figure 3).

General habitat descriptions for *A. granosa* and *A. antiquata* indicate that both inhabit similar water depths (mid-intertidal to marginally subtidal), which are regularly exposed and submerged by tides (Fig. 1b). They also appear to have similar preferences for areas with an estuarine influence where waters are less saline (Broom 1985:6–7). Closer investigation however, indicates that each species has distinct habitat preferences. *A. granosa* is a good burrower and can be found on sandy mud bordering mangrove swamps, while *A. antiquata* prefers sandy-gravels and is a poor burrower—often preferring seagrass beds and shallow-lagoon bottoms (Tebano and Paulay 2000:13). Each species is adapted to cope with these differences; *A. antiquata* possesses a weak byssus to attach to rocks and sheltered crevices, coral gravel or shell hash, but *A. granosa* is unattached (Afiati 1994:18, 2007:105; Broom 1985:4–6; Tebano and Paulay 2000:6); nodules on the radial ribs of *A. granosa* increase contact with the surrounding mud and assist in keeping the animal from sinking (Lim 1966; Afiati 1994:232); *A. granosa* also has a short siphon that requires the animal to stay close to the surface. This last fact led Broom (1985:5, 8) to classify *A. granosa* as a surface deposit feeder since this would result in the ingestion of a mixture of detritus and benthic microalgae.

Anadara are highly adaptive shellfish that occupy niches in many different environments across the Pacific (Broom 1985:9–10). It is likely, therefore, that isotopic significant offsets will be similarly present for other *Anadara* species. Lim (1966) identified the following order of complexity in *Anadara* labial palps; *A. antiquata* < *A. anomala* + *A. trapezia* < *A. granosa* < *A. cuneata*. This was

⁶ Analysis by Honkoop et al. (2008) showed that much of the organic material in seagrass areas originates from decayed seagrass and algae-derived products.

attributed to environmental adaptations, with *A. cuneate* living in the muddiest locations. These observations, combined with our isotopic data, suggest that *A. trapezia* and *A. cuneata* will also have ΔR values offset from the ocean average.

Echinoidea ($\Delta R = 11 \pm 17$ years)

The isotopic results for the echinoids are uniformly tight and reflect a preference for colder, marine waters (Figure 3). Echinoids occupy a wide range of environmental niches from the low intertidal region and below (Figure 1b). This low intertidal zone is only exposed to air at the lowest of low tides and is primarily marine in character. Although these results are promising for adopting echinoids as a reliable ^{14}C sample material, it should be kept in mind that sea urchins are scavengers (Follo and Fautin 2001) and could ingest sediment of varying age.

Predicted applicability of calculated ΔR values over time

Throughout the Pacific relatively few studies have found a significant shift in the marine reservoir over time (though see McGregor et al. 2008:220; Yu et al. 2010) despite changes to human settlement and culture that have been attributed at least in part to environmental change (Haberle and David 2004; Allen 2006; Nunn 2007; Clark and Reepmeyer 2012). Coastal areas, and estuarine animals in particular, are very sensitive to small changes because of modification to marine and freshwater inputs (Tebano and Paulay 2000:13; Sabatier et al. 2010). It is in these environments, therefore, where evidence of change in ΔR values over time may be found in the future.

Palynological records from Caution Bay indicate that between 3300 and 1000 cal BP the mangrove forest community was well established along the coastline. Inland, the coastal thicket and forest dominated until 2000 cal BP, after which there is a decline in tree cover and a transition towards coastal scrub. Charcoal records also indicate an increase in burning between ~2000 and 1400 cal BP. After 1000 cal BP a spike in sedimentation resulted in less frequent tidal inundation, consequential changes to mangrove composition, and establishment of a saltmarsh and unvegetated mudflat (Rowe et al. unpublished data). These changes are almost certainly manifest in the distribution of shellfish – although *A. antiquata* is common today in the area around Boera Village, *A. granosa* is not. This may reflect a change in water conditions at this location. Preliminary investigation of the shellfish assemblage indicates that XUs 1-16a (representing the upper 35 cm of the deposit) are dominated by a core set of species (*Strombus luhuanus*, *Strombus gibberulus*, *Calliostoma* sp., Ostreidae, *A. granosa*, *Strombus* spp.), which account for 74.9% of the identified assemblage by weight. The consistent representation of shellfish taxa suggests that a relatively stable environment existed during the period in which XUs 1-16a accumulated. Studies of shellfish from older deposits at Caution Bay are still to be undertaken. It remains possible, however, that the precise ΔR values presented here for each species are specific to this period of occupation.

Conclusion

Using material from a high-resolution archaeological excavation we have identified species-specific marine reservoir offset (ΔR) values for *G. tumidum*, *G. pectinatum*, *A. granosa*, *A. antiquata*, *B. violacea*, *P. erosa* and Echinoidea from Caution Bay, southern PNG. This bay forms part of an open coastline, well-washed by ocean waters, with no upwelling or eddy disturbance. Because estuarine reservoir variations in this area are subtle, it is only through the use of a combination of ^{14}C , $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ that we have been able to tie our results to the specific dietary, habitat and behavioural traits that are key to interpreting shell radiocarbon determinations. Our results indicate significant terrestrial ^{14}C input into the shells of *P. erosa* and *B. violacea* because of their tolerance of brackish waters.

Gafrarium spp. show a preference for high intertidal estuarine environments that put them at risk from terrestrial carbon interference – in particular hardwaters, and they should not be routinely sampled for dating in areas with limestone bedrock and limited exchange with ocean water. Similarly, different *Anadara* spp. may occupy areas within the estuary that affect their ^{14}C values. This genus has evolved to occupy many niches as reflected in the isotopic values seen here for *A. granosa* and *A. antiquata*. This is the first time a species-specific ^{14}C variation has been identified.

The variation in shellfish ΔR values presented here, far from being a limitation to obtaining reliable calibrated ^{14}C dates on shell, should be recognized as reflecting our growing understanding of ^{14}C in nature. This in turn provides an opportunity for greater dating resolution and understanding of environmental influences than has hitherto been available in this region. In the absence of detailed intra-site calculation of ΔR values, we recommend a generic value for this coastline of southern PNG of 9 ± 40 ^{14}C years based on our results for *Gafrarium* spp., *Anadara* spp. and Echinoidea. Species-specific calculations will, however, allow better refinement of calibrated ages and we therefore recommend duplication of this study elsewhere. For the Caution Bay region in the period 2000–2150 cal BP, we recommend use of the following taxon-specific ΔR values: 67 ± 16 ^{14}C years for *G. tumidum*, 53 ± 16 ^{14}C years for *G. pectinatum*, -71 ± 15 ^{14}C years for *A. granosa*, -1 ± 16 ^{14}C years for *A. antiquata*, and 11 ± 17 ^{14}C years for Echinoidea. We do not currently recommend the use of *Polymesoda* or *Batissa* species for the development of archaeological site chronologies without careful evaluation of the potential ^{14}C offsets.

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