# $^{14}$C MARINE RESERVOIR VARIABILITY IN HERBIVORES AND DEPOSIT-FEEDING GASTROPODS FROM AN OPEN COASTLINE, PAPUA NEW GUINEA

Fiona Petchey[1] • Sean Ulm[2] • Bruno David[3] • Ian J McNiven[3] • Brit Asmussen[4] • Helene Tomkins[2] • Thomas Richards[3] • Cassandra Rowe[3] • Matthew Leavesley[5] • Herman Mandui[6] • John Stanisic[4,7]

**ABSTRACT.** Herbivorous and deposit-feeding gastropods are a major component of archaeological shell middens worldwide. They provide a wealth of information about subsistence, economy, environment, and climate, but are generally considered to be less than ideal for radiocarbon dating because they can ingest sediment while they graze, inadvertently consuming terrestrial carbon in the process. However, few studies of $^{14}$C activity in herbivores or deposit-feeding gastropods have been conducted into this diverse range of animals that inhabit many environmental niches. Here, we present results investigating $^{14}$C variability in shells belonging to the families Strombidae and Potamididae from the Bogi 1 archaeological site, Caution Bay, southern coastal Papua New Guinea (PNG). These shells make up 39.3% of the shell MNI[8] in the excavation units studied and some of these species are the most common taxa of neighboring sites. It would therefore be advantageous to establish if there are any $^{14}$C offsets associated with such animals, and identify those that can give reliable calendar ages. Our methodology combines a high-resolution excavation protocol, selection of short-lived samples identified to species level, and a tri-isotope approach using $^{14}$C, $\delta^{13}$C, and $\delta^{18}$O to evaluate the source of variability in shells. Our results indicate that considerable variation exists between different species of Strombidae with some inhabiting muddier environments that act as sinks for limestone-derived sediments with depleted $^{14}$C content. The magnitude of variation is, however, overshadowed by that measured in the mudwhelk, *Cerithidea largillierti*, which has the largest spread in $^{14}$C of any shellfish studied so far at Caution Bay. This animal ingests sediment within the estuary that contains $^{14}$C derived from both enriched and depleted sources.

## INTRODUCTION

For the last 2 decades, the radiocarbon community has recommended the selection of suspension-feeding bivalves as the most suitable shellfish for dating based on the principle that these taxa predominantly consume suspended phytoplankton and dissolved inorganic carbon (DIC) from seawater (Tanaka et al. 1986; Forman and Polyak 1997; Hogg et al. 1998). Herbivorous gastropods are considered less favorably because they can ingest sediment while they graze, increasing the uncertainty over where they get their carbon. Our current understanding of $^{14}$C offsets for herbivorous shellfish is based on a handful of studies, and the observations made are typically inconclusive except in environments known to have extreme shifts in $^{14}$C.

The most obvious offsets come from limestone coasts where ancient carbon can be incorporated into the shells. Dye (1994) and Anderson et al. (2001:37–9) recorded differences of up to 600 yr for herbivores *Nerita atramentosa* and *N. picea* (nerites) and omnivores *Cypraea caputserpentis* and *C. exarata* (cowries, now identified as belonging to the genus *Monetaria*) collected from areas with limestone bedrock, compared to those collected from volcanic coastlines around Hawai'i and Norfolk Island. A more detailed understanding of the position of herbivores in the $^{14}$C cycle comes from studies of modern specimens. Cook et al. (2004) measured $^{14}$C enrichment in *Littorina littorea* (peri-

winkle) and *Patella vulgata* (limpet) relative to seaweed and sediment from the intertidal area near the nuclear fuel processing plant at Sellafield, England. The $^{14}$C activities in the biota appear to reflect their positions in the foodchain and whether they grazed directly on seaweed (i.e. *L. littorea*) or algae on rocks (i.e. *P. vulgata*). Ascough et al. (2005) further evaluated this relationship using archaeological shell/charcoal samples from a site situated on a volcanic coastline on the west coast of Scotland. They investigated the $^{14}$C variability of 5 species of shellfish, including *P. vulgata* and *L. littorea*. In this environment, the limpets had $^{14}$C values similar to other shellfish, and although *L. littorea* showed some statistical variation that could have been caused by this genera's diverse habitat and feeding range,[9] Ascough et al. (2005:438) concluded that the variation did not exceed that which would be expected to result from measurement variability alone.

Studies into inter- or intraspecies $^{14}$C variability amongst herbivores are rare. Although inconclusive, Dye (1994:55–6) suggested the possibility of differences in 2 species of *Cypraea* spp. shells depending on whether they were found in the intertidal/splash zones (i.e. *C. exarata* had an apparent $^{14}$C age of 530 yr) or shallow offshore waters (cf. *C. caputserpentis* with an apparent $^{14}$C age of 250 yr), which was attributed to variable deposition of limestone-derived detritus in these areas. Hogg et al. (1998) also observed variation in the grazing turban snail *Lunella smaragda* depending on whether the animal was found in estuarine/subtidal or intertidal habitats in the same catchment area, and noted a similar pattern in suspension-feeding and carnivorous shellfish. They interpreted this as being caused by the complexity of this intertidal region, a zone subject to increased wave action and high aeration resulting in $^{14}$C enrichment.

There have been few studies undertaken looking at $^{14}$C variation in different types of mud snail. Deposit-feeding shellfish are considered to give the least reliable calendar ages by the $^{14}$C method because they directly ingest sediment (Dye 1994; Anderson et al. 2001). The pulmonate mud snail *Amphibola crenata* was studied from archaeological deposits at Shag River Mouth in New Zealand (Anderson et al. 1996:65) and showed up to 100 yr difference compared to other sample types—a pattern that was repeated in other sites (Anderson 1991). However, deposit-feeding shellfish remain a favorite dating sample in some areas because of their dominance in some middens, possibly at the complete exclusion of other taxa, and use as a chronostratigraphic and environmental marker (e.g. Sullivan and O'Connor 1993; Bradshaw 1995; O'Connor 1996; Hiscock 2008).

Most shell $^{14}$C reservoir studies are limited by a lack of specific environmental information; this is especially so for archaeological samples. Greater refinements to observations of shellfish environmental preferences have been obtained by the use of isotopes such as $\delta^{18}$O and $\delta^{13}$C in combination with $^{14}$C data (Culleton et al. 2006; Petchey et al. 2008b; Petchey and Clark 2011). $\delta^{18}$O indicates water temperature and salinity while $\delta^{13}$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 $\delta^{13}$C and $\delta^{18}$O, while increased productivity and $CO_2$ atmospheric absorption in reef locations may result in enrichment in $\delta^{13}$C and $^{14}$C. Recent multiple isotopic analysis of a range of suspension-feeding bivalves and Echinoidea from Caution Bay, Papua New Guinea, enabled variation in $^{14}$C results to be attributed to specific dietary, habitat, and behavioral traits (Petchey et al., in press). Of specific note was the enrichment of suspension-feeding *Anadara granosa* shells relative to *A. antiquata,* which is almost certainly related to a preference for burrowing in muddy substrates as indicated by specialized adaptations to the shell morphology of *A. granosa* (Petchey et al., in press).

---

[9]*Littorina* spp. can occupy a range of habitats from the high shoreline to the sublittoral fringe where they primarily graze on seaweed. *Patella vulgata* feed upon microalgal films (predominantly organic material, diatoms, and cyanobacteria) that coat rocky shores (Ascough et al. 2005).

We extend these observations from Caution Bay to 7 species belonging to the family Strombidae as well as the mangrove mud snail, *Cerithidea largillierti*. Strombidae are herbivores characteristically found on sand or slightly muddy bottoms in the intertidal or shallow subtidal zones (Beesley et al. 1998:675, 768). *Cerithidea* is a mangrove-dwelling gastropod that belongs to the same superfamily (Cerithioidea) as *Batillaria* and *Terebralia* sp. *Cerithidea* feed on mud detritus and decayed algae amongst the mangroves high in the intertidal region (Reid et al. 2008) (Figure 1b). *Cerithidea largillierti* shells in particular dominate many middens in the region—and in some sites is the only species to extend the full depth of the cultural sequences. A greater understanding of the range of ^{14}C variability, and the ability to obtain reliable calibrated ages, would therefore be a significant advantage to ongoing archaeological research.
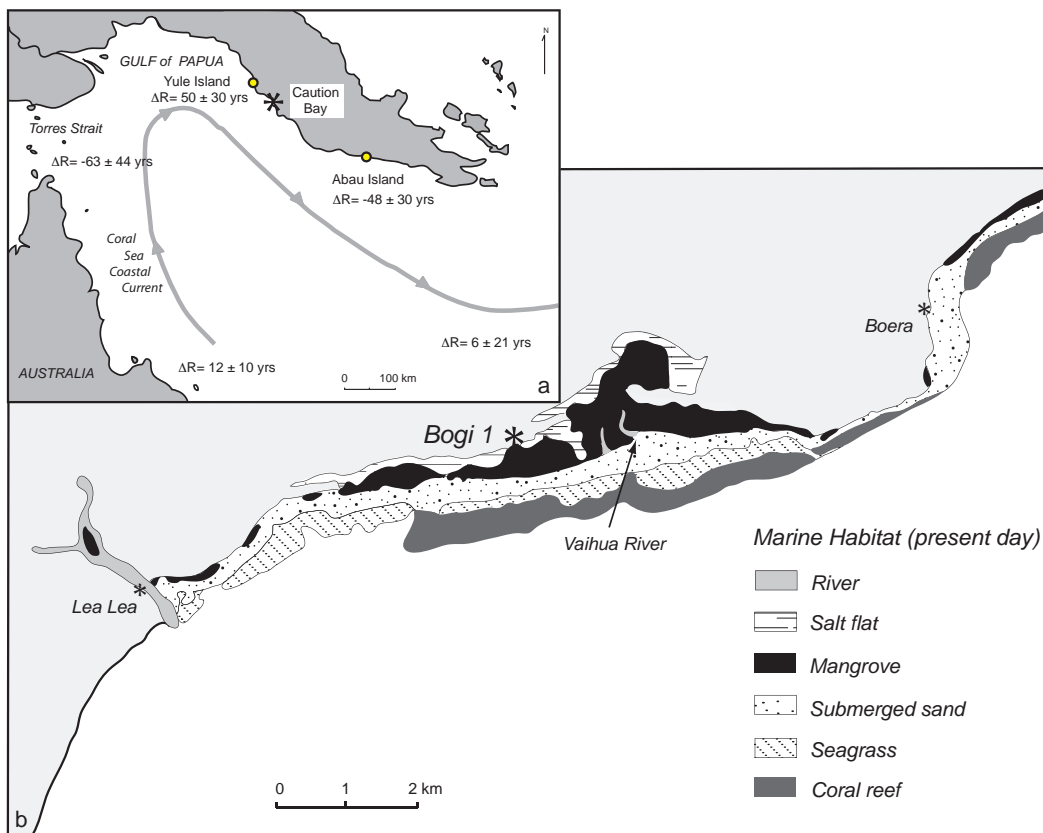


Figure 1  a) Western South Pacific showing the location of Caution Bay, oceanic circulation (adapted from Woolfe et al. 1997) and regional ΔR values: East Australian average ΔR of 12 ± 10 yr from Ulm (2006); South Pacific Gyre average ΔR of 6 ± 21 yr from Petchey et al. (2008a); Torres Strait average ΔR of –63 ± 44 yr from Ulm et al. (2009). b) Coastal marine habitats in Caution Bay and location of Bogi 1 (adapted from Coffey Natural Systems 2009).

## MARINE RESERVOIR VARIATION

Regional marine ^{14}C reservoir variation in shellfish is commonly referred to as Delta R (ΔR), which is the difference between the global average marine reservoir and the actual ^{14}C activity of the surface ocean at a particular location (Stuiver et al. 1998). Very large and positive ΔR values are typical

of shellfish collected from lagoons bordered by limestone geologies (Petchey and Clark 2011) or ocean regions where upwelling of $^{14}C$-depleted waters occur (Ingram and Southon 1996; Culleton et al. 2006). 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). The most common methods of calculating ΔR employ either known-age shells collected before atmospheric bomb testing, or terrestrial and marine $^{14}C$ samples excavated from archaeological sites. In both cases, it is essential that the age of shellfish death is known. For archaeological ΔR, this is determined by dating short-lived charcoal from contemporaneous contexts (commonly referred to as shell/charcoal pairs) (Stuiver and Braziunas 1993).

**SETTING**

Caution Bay is located ~20 km northwest of Port Moresby along the southern coast of Papua New Guinea (Figure 1). This bay forms part of an open coastline, well washed by ocean waters, with no upwelling or eddy disturbance (Petchey et al., in press). The coastline itself is underlain by limestone bedrock and fed by a number of small rivers, and although wave scour and tidal currents remove much of this material from the bay, larger particles are laid down on the innertidal flats (Mabbutt 1965). This hydrographic and sedimentary diversity is responsible for the range of ΔR values previously observed for different shellfish from this area (Petchey et al., in press). Suspension-feeding bivalves *Gafrarium* spp. tend to have slightly depleted $^{14}C$ signatures indicative of high intertidal habitats influenced by hardwaters, while $^{14}C$ and $^{13}C$ values for *Anadara granosa* are influenced by the ingestion of enriched terrestrial carbon sources in keeping with this species' preference for sandy mud bordering the mangrove swamp. *Anadara antiquata* and echinoids have isotope values closer to the global marine average (ΔR ~ 0) and comparable to that calculated by Petchey et al. (2008a) and Ulm (2006) for pre-AD 1950 shellfish collected in the region (Figure 1).

**SAMPLE SELECTION**

The archaeological materials sampled for this research come from 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 (McNiven et al. 2011). The $^{14}C$ dates reported in McNiven et al. (2011) represent a tiny subset of our dates this site.[10] A total of 35 Strombidae shells and 8 cerithiids were selected for comparison with 35 bivalves and echinoids previously sampled (Petchey et al., in press). Species selected include *Conomurex luhuanus* (25.9% of the shellfish assemblage by weight from XUs 6-16a), *Gibberulus gibberulus* (12%), *Canarium urceus* (1.5%), *Laevistrombus canarium* (1.4%), *Canarium labiatum* (0.6%), *Euprotomus aurisdianae* (0.3%), *Lambis* sp. (0.6%), and *Cerithidea largillierti* (3.7%).[11] Most of these shells were fragmentary, but where possible we sampled from the outer lip of the valve aperture. Any error introduced to our results should be minimal because most reef gastropods live <20 yr (Frank 1969:247), while most *Cerithidea* live <5 yr (Houbrick 1984). ΔR results were calculated by comparing the shell $^{14}C$ results with dates on 3 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 (Table 1). These returned a pooled age of 2104 ± 16 BP ($\chi^2_{2:0.05}$ = 0.22 < 5.99). Charcoal determinations from various locations throughout the deposit that have not been identified to species level are excluded from the ΔR cal-

---

[10]XUs 6–11 in Square C encompass statigraphic units (SUs) 4 (lower half), 5, and 6 (upper half) in McNiven et al. (2011).

[11]Strombid taxonomy currently recognizes former subgenera as genera in their own right. Previous names for these shells are *Strombus luhuanus*, *S. gibberulus*, *S. urceus*, *S. canarium*, *S. labiatus*, and *S. aurisdianae*.

culations. These include Wk-31048 [XU13; 2110 ± 28 BP], Wk-30458 [XU15a(1); 2090 ± 25 BP], and Wk-31051 [XU16a; 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 1σ with the pooled results from short-lived material (Wk-31047, -31049, and -31050), there is sufficient variability to justify removing them from the ΔR calculation. A number of anomalous charcoal results were also obtained: 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 F$^{14}$C] (a small fragment of charcoal almost certainly from burnt local grass obtained from the sieves rather than collected *in situ*). While 3 of these results date to ~1500 cal BP, continuity between $^{14}$C results of each shell species between layers supports our premise that tiny fragments of charcoal have been displaced 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.

$^{14}$C dates were prepared and analyzed 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 $CO_2$ 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 $CO_2$ with $H_2$ in a reaction catalyzed by iron powder at ~550 °C. Targets were measured at the Keck Radiocarbon Laboratory, University of California, Irvine. To calculate ΔR values from archaeological terrestrial/marine pairs, an estimate of the Northern Hemisphere atmospheric calibration curve (Reimer et al. 2009) over the 1σ span of the $^{14}$C age, including the calibration curve error, was used to derive the calculated marine modeled age (for details on how to calculate this see Ulm 2002). The calculated average marine modeled age for the short-lived charcoal samples is 2443 ± 14 yr. This has been subtracted from each shell $^{14}$C age [Rs(t)]. Each individual archaeological ΔR standard error is calculated by the formula $\Delta R\sigma = \sqrt{(\sigma_{Rg(t)}^2 + \sigma_{Rs(t)}^2)}$.

$\delta^{18}$O and $\delta^{13}$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 modeled $\delta^{13}$C isotopic composition of the modern surface ocean DIC is ~1.5‰ (Tagliabue and Bopp 2008) while $\delta^{18}$O is ~0.3‰ (LeGrande and Schmidt 2006). These data were used as baseline values for Caution Bay.

**RESULTS AND DISCUSSION**

Contextual and isotopic information for the shellfish analyzed are shown in Tables 1 and 2 and Figures 2 and 3. Overall, the isotopic values for the Strombidae gastropods are typical of animals living at the boundary between marine and estuarine environments (Figure 2). Across the family group (Table 2), there is considerable variation in ΔR (from 13 ± 31 to 156 ± 72 $^{14}$C yr; $\chi^2_{34:0.05}$ = 104.99 < 48.60), but this is reduced when each species is considered individually. However, even within species they tend to show more variation than the suspension feeding-bivalves previously investigated at the site (Petchey et al., in press) and additional uncertainty has been added to the ΔR of each strombid species to account for this. Two outliers are immediately apparent: *Laevistrombus canarium*, which has an elevated ΔR (156 ± 72 $^{14}$C yr), and *Conomurex luhuanus* with lower ΔR values (13 ± 31 $^{14}$C yr).

Table 1  Shellfish context and isotopic information, Bogi 1.

| Monash code | Depth below surface (cm) | Lab code | Material | δ¹³C ‰ (±0.2) | δ¹⁸O ‰ (±0.2) | ¹⁴C age ±1σ error (BP) [Rs(t)] | ΔR (yr) [Rs(t)– Rg(t)] |
|---|---|---|---|---|---|---|---|
| Bogi 1 Sq C XU6 | 7.5–10.9 | Wk-31010 | *Conomurex luhuanus* | 1.1 | –4.4 | 2529 ± 25 | 86 ± 39 |
| | | Wk-32565 | *Laevistrombus canarium* | 1.5 | –2.2 | 2713 ± 27 | 270 ± 40 |
| | | Wk-32571 | *Gibberulus gibberulus* | 1.9 | –2.3 | 2511 ± 27 | 68 ± 40 |
| | | Wk-32577 | *Euprotomus aurisdianae* | 1.0 | –2.7 | 2461 ± 27 | 18 ± 40 |
| | | Wk-32591 | *Lambis sp.* | 0 | –3.4 | 2557 ± 26 | 114 ± 39 |
| Bogi 1 Sq C XU8 | 12.8–14.9 | Wk-31011 | *Conomurex luhuanus* | 1.1 | –3.7 | 2390 ± 25 | –53 ± 39 |
| | | Wk-32566 | *Laevistrombus canarium* | –1.0 | –3.8 | 2510 ± 27 | 67 ± 40 |
| | | Wk-32572 | *Gibberulus gibberulus* | 1.7 | –5.4 | 2546 ± 27 | 103 ± 40 |
| | | Wk-32578 | *Euprotomus aurisdianae* | 0.6 | –3.2 | 2590 ± 27 | 147 ± 40 |
| | | Wk-32586 | *Canarium urceus* | 0.8 | –4.0 | 2579 ± 25 | 136 ± 39 |
| Bogi 1 Sq C XU10 | 17.2–19.5 | Wk-31012 | *Conomurex luhuanus* | 0.9 | –4.4 | 2485 ± 25 | 42 ± 39 |
| | | Wk-32582 | *Canarium labiatum* | 1.2 | –1.4 | 2491 ± 30 | 48 ± 42 |
| | | Wk-32567 | *Laevistrombus canarium* | 0.3 | –4.5 | 2687 ± 27 | 244 ± 40 |
| | | Wk-32573 | *Gibberulus gibberulus* | 1.4 | –5.5 | 2460 ± 27 | 17 ± 40 |
| | | Wk-32587 | *Canarium urceus* | 1.6 | –2.0 | 2492 ± 26 | 49 ± 39 |
| | | Wk-32592 | *Lambis* sp. | 1.1 | –2.6 | 2435 ± 25 | –8 ± 39 |
| | | Wk-33810 | *Cerithidea largillierti* | –7.1 | –3.3 | 2459 ± 25 | 16 ± 39 |
| | | Wk-33811 | *Cerithidea largillierti* | –7.3 | –4.8 | 2662 ± 25 | 219 ± 39 |
| Bogi 1 Sq C XU12a | 21.7–23.5 | Wk-31013 | *Conomurex luhuanus* | 1.7 | –5.0 | 2440 ± 25 | –3 ± 39 |
| | | Wk-32568 | *Laevistrombus canarium* | 0.4 | –4.6 | 2570 ± 27 | 127 ± 40 |
| | | Wk-32574 | *Gibberulus gibberulus* | 2.3 | –4.6 | 2474 ± 27 | 31 ± 40 |
| | | Wk-32579 | *Euprotomus aurisdianae* | 0.3 | –2.5 | 2501 ± 27 | 58 ± 40 |
| | | Wk-32583 | *Canarium labiatum* | 1.2 | –2.8 | 2462 ± 27 | 19 ± 40 |
| | | Wk-32588 | *Canarium urceus* | 0.4 | –4.7 | 2489 ± 25 | 46 ± 39 |
| | | Wk-32593 | *Lambis* sp. | 1.1 | –2.9 | 2492 ± 25 | 49 ± 39 |
| | | Wk-33812 | *Cerithidea largillierti* | –6.1 | –3.3 | 2152 ± 25 | –291 ± 39 |
| | | Wk-33813 | *Cerithidea largillierti* | –5.8 | –3.7 | 2471 ± 25 | 28 ± 39 |
| Bogi 1 Sq C XU13 | 23.5–26.2 | Wk-33814 | *Cerithidea largillierti* | –8.7 | –5.3 | 2209 ± 25 | –234 ± 39 |
| | | Wk-33815 | *Cerithidea largillierti* | –8.0 | –4.0 | 2355 ± 25 | –88 ± 39 |
| Bogi 1 Sq C XU14 | 26.2–28.3 | Wk-31047 | Charcoal (carbonized fruit) | –27.0 | — | 2097 ± 27 | |
| | | Wk-31014 | *Conomurex luhuanus* | 1.3 | –4.1 | 2447 ± 25 | 4 ± 39 |
| | | Wk-32584 | *Canarium labiatum* | 0.2 | –5.5 | 2531 ± 27 | 88 ± 40 |
| | | Wk-32569 | *Laevistrombus canarium* | 1.0 | –3.6 | 2558 ± 27 | 115 ± 40 |
| | | Wk-32575 | *Gibberulus gibberulus* | 2.4 | –2.6 | 2395 ± 27 | –48 ± 40 |
| | | Wk-32580 | *Euprotomus aurisdianae* | 0.6 | –3.6 | 2496 ± 31 | 53 ± 43 |
| | | Wk-32589 | *Canarium urceus* | 0.7 | –3.3 | 2446 ± 25 | 3 ± 39 |
| | | Wk-32594 | *Lambis* sp. | 0.5 | –3.7 | 2570 ± 26 | 127 ± 39 |
| | | Wk-33816 | *Cerithidea largillierti* | –6.7 | –2.8 | 2309 ± 25 | –134 ± 39 |
| | | Wk-33817 | *Cerithidea largillierti* | –3.2 | –2.5 | 2452 ± 25 | 9 ± 39 |
| Bogi 1 Sq C XU16a | 30.5–33.4 | Wk-31049 | Charcoal (nut) | –23.8 | — | 2114 ± 27 | |
| | | Wk-31050 | Charcoal (monocot culm) | –24.1 | — | 2101 ± 27 | |
| | | Wk-31015 | *Conomurex luhuanus* | 1.1 | –3.4 | 2444 ± 25 | 1 ± 39 |
| | | Wk-32570 | *Laevistrombus canarium* | 1.4 | –3.8 | 2558 ± 27 | 115 ± 40 |
| | | Wk-32576 | *Gibberulus gibberulus* | 2.3 | –3.2 | 2456 ± 27 | 13 ± 40 |
| | | Wk-32585 | *Canarium labiatum* | 0.8 | –4.0 | 2539 ± 28 | 96 ± 41 |
| | | Wk-32590 | *Canarium urceus* | 0.6 | –3.8 | 2485 ± 26 | 42 ± 39 |

Table 2 Average $\Delta R$ for each shellfish and environmental divisions. Rows highlighted in gray are reported in Petchey et al. (in press).

| Shellfish/ Echinoidea | Diet[a] | $\Delta R$ (yr) | Chi-squared statistics[b] Species | Genera | Environmental division | Isotopic influence |
|---|---|---|---|---|---|---|
| *Cerithidea largillierti* | DF | −59 ± 14 | $\chi^2_{7:0.05} = 122.30 < 14.07$; external variation = 159 | | High intertidal, in mangroves. | Estuarine |
| *Gafrarium tumidum* | SF | 67 ± 16 | $\chi^2_{5:0.05} = 0.83 < 11.07$; no external variation | $\Delta R = 60 ± 11$ ($\chi^2_{11:0.05} = 3.94 < 19.68$; no external variation) | High intertidal. | |
| *Gafrarium pectinatum* | | 53 ± 16 | $\chi^2_{5:0.05} = 2.72 < 11.07$; no external variation | | | |
| *Anadara granosa* | | −71 ± 15 | $\chi^2_{6:0.05} = 4.01 < 12.59$; no external variation | $\Delta R = −39 ± 11$ ($\chi^2_{12:0.05} = 12.94 < 21.03$; external variation = 22) | Mid-intertidal to marginally subtidal. | |
| *Anadara antiquata* | | −1 ± 16 | $\chi^2_{5:0.05} = 0.55 < 11.07$; no external variation | | | Marine |
| Echinoidea | O | 11 ± 17 | $\chi^2_{4:0.05} = 0.28 < 9.49$; no external variation | | Low intertidal/subtidal fringe. | |
| *Conomurex luhuanus* | H | 13 ± 16 | $\chi^2_{5:0.05} = 7.24 < 11.07$; external variation = 31 | | Intertidal and shallow subtidal to ~10 m. On sand, rubble and seagrass bottoms. | |
| *Laevistrombus canarium* | | 156 ± 16 | $\chi^2_{5:0.05} = 20.54 < 11.07$; external variation = 72 | | Intertidal and subtidal to ~55 m. On muddy sand and algal bottoms. | |
| *Gibberulus gibberulus* | | 31 ± 16 | $\chi^2_{5:0.05} = 8.32 < 11.07$; external variation = 37 | | Intertidal and shallow subtidal to ~20 m. On sand and seagrass bottoms. | |
| *Canarium labiatum* | | 63 ± 20 | $\chi^2_{3:0.05} = 2.38 < 7.81$; no external variation | | Intertidal and shallow subtidal to ~20 m. On seagrass and algal bottoms. | |
| *Canarium urceus* | | 55 ± 17 | $\chi^2_{4:0.05} = 6.28 < 9.49$; external variation = 34 | | Intertidal and shallow subtidal to ~40 m. On seagrass bottoms and sand. | |
| *Euprotomus aurisdianae* | | 70 ± 20 | $\chi^2_{3:0.05} = 5.64 < 7.81$; external variation = 42 | | Low intertidal and shallow subtidal to ~10 m. On seagrass bottoms and sand. | |
| *Lambis* spp. | | 71 ± 20 | $\chi^2_{3:0.05} = 7.70 < 7.81$; external variation = 53 | | Shallow subtidal to ~5 m. On sand and mud – various. | |

[a]Diet preferences: SF = suspension-feeder; H = herbivore; O = omnivore, DF = deposit feeder.

[b]To estimate the amount of uncertainty to be added to the $\Delta R$ value by the non-uniform $^{14}C$ content of the shellfish, the weighted mean for each group has been calculated using the chi-squared ($\chi^2$) 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 $\Delta R$. In this instance, the uncertainty is calculated by $\sqrt{(s^2_{\Delta Rpooled} + \sigma^2_{ext})}$, whereby the external standard deviation ($\sigma_{ext}$) is determined by subtracting the $^{14}C$ measurement variance from the total population variance and obtaining the square root (e.g. $\sigma_{ext} – \sqrt{(\sigma^2_{pop} – \sigma^2_{meas})}$). When $\chi^2/(n–1)$ is 1, the uncertainty on the individual measurements explains the variations within the group of $\Delta R$ values and the weighted mean is used (see Mangerud et al. 2006:3241–2 for detailed explanation).

Little habitat-specific information has been published for each of these shellfish, with all broadly recorded as living in a range of mud to rubble sediments at various depths (Table 2). The elevated $\Delta R$ values of most species compared to the South Pacific Gyre average of 6 ± 21 yr suggest they are ingesting sediment that is depleted in $^{14}C$ derived from the limestone bedrock. This appears exaggerated in *L. canarium*, which has a preference for muddier substrates (Carpenter and Niem 1998; Coleman 2003). This hypothesis is supported by an elevated $^{14}C$ signal combined with no obvious
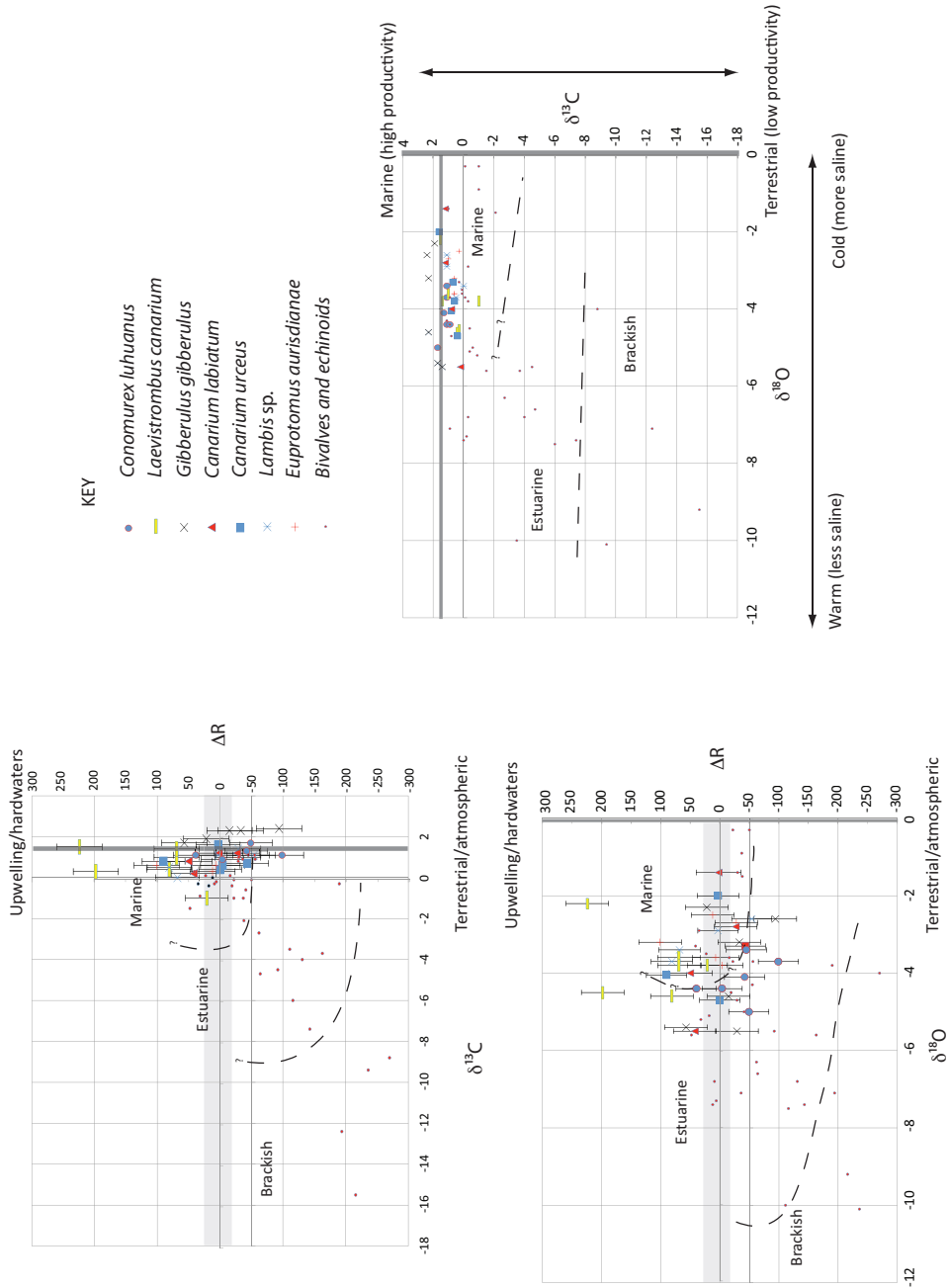
Figure 2 Measured δ¹⁸O, ΔR, and δ¹³C values for Strombidae shells plotted against bivalve and echinoid isotopes (Petchey et al., in press) from Bogi 1, Caution Bay, southern PNG. At this location, the modeled δ¹³C isotopic composition of the modern surface ocean DIC is ~1.5‰ and δ¹⁸O is ~0.3‰. The average ΔR value for shellfish across the Pacific Gyre region is 6 ± 21 ¹⁴C yr (see text for explanation). Average ocean isotope values (ΔR, δ¹⁸O, and δ¹³C) are shown as gray bands. Dashed lines delineate approximate boundaries between the isotopic values for shells from different marine environments based on observations in the present study.
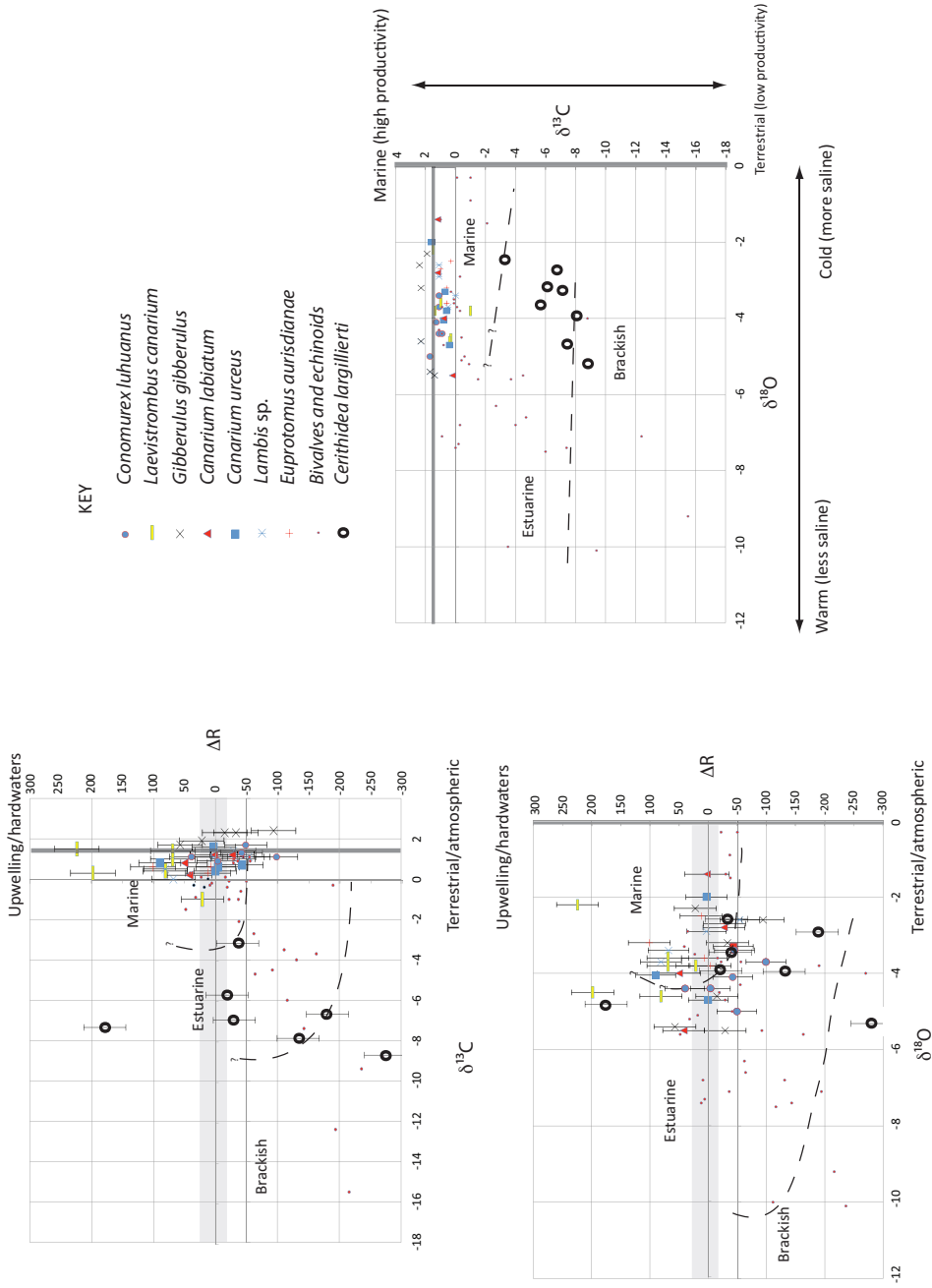
Figure 3  Measured δ18O, ΔR, and δ13C values for *Cerithidea largillierti* shells plotted against all shellfish isotopes measured to date from Bogi 1, Caution Bay. Average ocean isotope values are shown as gray bands. Dashed lines delineate approximate boundaries between the isotopic values for shells from different marine environments based on observations in the present study.

shift in $\delta^{18}O$ or $\delta^{13}C$ (marine limestone $\delta^{13}C$ is close to 0 resulting in little offset from typical marine values [Keith et al. 1964:1758, 1781; Gat 1996:241, 255]). Statistically, *L. canarium* has the most $^{14}C$ variability of all the Strombidae investigated and the $\chi^2$ statistics indicate that these shellfish do not form a cohesive group ($\chi^2_{5:0.05} = 20.54 < 11.07$). These results suggest caution when dating this animal. *Conomurex luhuanus*, on the other hand, prefers sandy environments and has a $\Delta R$ value closer to average ocean values (Figure 2).

*Cerithidea largillierti* (Figure 3) mud snails show more variation than all other shellfish combined ($\chi^2_{7:0.05} = 122.30 < 14.07$; external variation = 159). The $\delta^{13}C$ results for this species suggest input of terrestrial sources of carbon. Although there is a linear relationship between $\delta^{13}C$ and $\delta^{18}O$ (Figure 3), there is no apparent trend between either stable isotope with the $^{14}C$ results, which show considerable variation ($\Delta R$ values $-291 \pm 39$ to $219 \pm 39$ $^{14}C$ yr). This suggests these gastropods are eating carbon that originates from both enriched and depleted sources, giving them the widest spread in $^{14}C$ of any shellfish studied so far at Caution Bay. It is also impossible to predict any environmental trends using a combination of these 3 isotopes, making it impossible to correctly derive any calendar age for these animals.

**CONCLUSION**

A total of 78 $^{14}C$ analyses have now been undertaken on shellfish from Bogi 1, Caution Bay. This is the most comprehensive study of shellfish $^{14}C$ variation in an archaeological context published so far. The observations made here are in keeping with established theories of sample selection for $^{14}C$ analysis—specifically, that suspension-feeding bivalves have $^{14}C$ intake that is less variable than herbivorous gastropods and deposit-feeding shellfish. Moreover, while bivalves have adapted to occupy specialized environmental niches, as is reflected in their often narrow isotopic range, more variability is seen in the herbivorous and deposit-feeding gastropods because of their potential ingestion of sediment while they graze. This adds greater uncertainty to calendar ages derived from $^{14}C$ measurements obtained on these animals. However, our results indicate that amongst the herbivorous shellfish, habitat choice has significant impact on carbon content, with those animals that show a preference for muddy substrates returning the most variability. It is therefore essential that a greater understanding of species habitat and dietary preferences be obtained before undertaking any dating program.

For the Caution Bay region, we recommend the use of the following taxon-specific $\Delta R$ values: $63 \pm 20$ $^{14}C$ yr for *Canarium labiatum*, $13 \pm 31$ $^{14}C$ yr for *Conomurex luhuanus*, $31 \pm 37$ $^{14}C$ yr for *Gibberulus gibberulus*, $55 \pm 34$ $^{14}C$ yr for *Canarium urceus*, $70 \pm 42$ $^{14}C$ yr for *Euprotomus aurisdianae*, and $71 \pm 53$ $^{14}C$ yr for *Lambis* spp. We do not recommend dating of *Laevistrombus canarium* as this species shows significant variation in $^{14}C$. While our observations regarding Strombidae environmental and habitat effects on $\delta^{18}O$, $\delta^{13}C$, and $^{14}C$ isotopes can be applied elsewhere in the Pacific, we do not recommend using these specific $\Delta R$ values outside of Caution Bay because the exact impact of ingesting sedimentary carbon will depend on the available source material. At Caution Bay, depleted $^{14}C$ from limestone is responsible for the observed offset from the average ocean $\Delta R$, but in other environments it is possible that alternative terrestrial sources may be available (e.g. riverine input).

We do not recommend dating *Cerithidea* spp. or any other taxa belonging to the family Potamididae because 600+ yr of error could be introduced to any site chronology along this coastline. This reinforces previous research into the $^{14}C$ content of mud snails, and raises doubt over any chronological interpretations that rely on this sample type.

## ACKNOWLEDGMENTS

## REFERENCES

Anderson AJ. 1991. The chronology of colonisation in New Zealand. *Antiquity* 65(249):767–95.

Anderson AJ, Smith IWG, Higham TFG. 1996. Radiocarbon Chronology. In: Anderson AJ, Smith IWG, Allingham BJ, editors. *Shag River Mouth: The Archaeology of an Early Southern Maori Village*. Australian National University Research Papers in Archaeology and Natural History 27. Canberra: ANH Publications, RSPAS. p 60–9.

Anderson AJ, Higham TGF, Wallace R. 2001. The radiocarbon chronology of the Norfolk Island archaeological sites. *Records of the Australian Museum* (Supplement) 27:33–42.

Ascough PL, Cook GT, Dugmore AJ, Scott EM, Freeman SPHT. 2005. Influence of mollusk species on marine ΔR determinations. *Radiocarbon* 47(3):433–40.

Beesley PL, Ross GJB, Wells A, editors. 1998. *Mollusca: The Southern Synthesis. Fauna of Australia. Volume 5*. Melbourne: CSIRO Publishing.

Bradshaw E. 1995. Dates from archaeological excavations on the Pilbara coastline and islands of the Dampier Archipelago, Western Australia. *Australian Archaeology* 4(1):37–8.

Carpenter KE, Niem VH, editors. 1998. *FAO Species Identification Guide for Fishery Purposes. The Living Marine Resources of the Western Central Pacific. Volume 1. Seaweeds, Corals, Bivalves and Gastropods*. Rome: Food and Agriculture Organization of the United Nations

Coffey Natural Systems. 2009. PNG LNG Project. Environmental Impact Statement. Coffey Natural Systems Pty Ltd, Abbotsford, VIC 3067, Australia.

Coleman N. 2003. *2002 Sea Shells: Catalogue of Indo-Pacific Mollusca*. Springwood:Neville Coleman's Underwater Geographic Pty Ltd.

Cook GT, MacKenzie AB, Muir GKP, Mackie G, Gulliver P. 2004. Sellafield-derived anthropogenic 14C in the marine intertidal environment of the NE Irish Sea. *Radiocarbon* 46(2):877–83.

Culleton BJ, Kennett DJ, Ingram BL, Erlandson JM, Southon JR. 2006. Intrashell radiocarbon variability in marine mollusks. *Radiocarbon* 48(3):387–400.

Dye T. 1994. Apparent ages of marine shells: implications for archaeological dating in Hawai'i. *Radiocarbon* 36(1):51–7.

Forman SL, Polyak L. 1997. Radiocarbon content of pre-bomb marine mollusks and variations in the 14C reservoir for coastal areas of the Barents and Kara seas,

Russia. *Geophysical Research Letters* 24(8):885–8.

Frank P. 1969. Growth rates and longevity of some gastropod mollusks on the coral reef at Heron Island. *Oecologia* 2(2):232–50.

Friedman GM. 1959. Identification of carbonate minerals by staining methods. *Journal of Sedimentary Petrology* 29(1):87–97.

Gat JR. 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Science* 24:225–62.

Hiscock P. 2008. *The Archaeology of Ancient Australia*. New York: Routledge.

Hogg AG, Higham TFG, Dahm J. 1998. 14C dating of modern marine and estuarine shellfish. *Radiocarbon* 40(2):975–84.

Houbrick RS. 1984. Revision of higher taxa in genus *Cerithidea* (Mesogastropoda: Potamididae) based on comparative morphology and biological data. *American Malacological Bulletin* 2:1–20.

Ingram BL, Southon JR. 1996. Reservoir ages in eastern Pacific coastal and estuarine waters. *Radiocarbon* 38(3):573–82.

Keith ML, Anderson GM, Eichler R. 1964. Carbon and oxygen isotopic composition of mollusk shells from marine and fresh-water environments. *Geochimica et Cosmochimica Acta* 28(10–11):1757–86.

LeGrande AN, Schmidt GA. 2006. Global gridded data set of the oxygen isotopic composition in seawater. *Geophysical Research Letters* 33: L12604, doi: 10.1029/2006GL026011.

Mabbutt JA. 1965. Geomorphology of the Port Moresby-Kairuku area. In: Mabbutt JA, Heyligers PC, Scott RM, Speight JG, Fitzpatrick EA, McAlpine JR, Pullen R, editors. *Lands of the Port Moresby–Kairuku Area, Territory of Papua and New Guinea*. Melbourne: CSIRO Land Research Series No. 14. p 104–28.

Mangerud J, Bondevik S, Gulliksen S, Hufthammer AK, Høisæter T. 2006. Marine 14C reservoir ages for 19th century whales and molluscs from the North Atlantic. *Quaternary Science Reviews* 25(23–24):3228–45.

McNiven IJ, David B, Richards T, Alpin K, Asmussen B, Mialanes J, Leavesley M, Faulkner P, Ulm S. 2011. New direction in human colonisation of the Pacific. *Australian Archaeology* 72:1–6.

O'Connor S. 1996. Where are the middens? An overview of the evidence for shellfish exploitation along the northwestern Australian coastline. *Bulletin of the Indo-Pacific Prehistory Association* 15:165–80.

Petchey F, Anderson A, Zondervan A, Ulm S, Hogg A. 2008a. New marine ΔR values for the South Pacific subtropical gyre region. *Radiocarbon* 50(3):373–97.

Petchey F, Anderson A, Hogg A, Zondervan A. 2008b. 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):243–62.

Petchey F, Clark G. 2011. Tongatapu hardwater: investigation into the ¹⁴C marine reservoir offset in lagoon, reef and open ocean environments of a limestone island. *Quaternary Geochronology* 6:539–49.

Petchey F, Ulm S. 2012. Marine reservoir variation in the Bismarck region: an evaluation of spatial and temporal variation in ΔR and R over the last 3000 years. *Radiocarbon* 54(1):145–58.

Petchey F, Ulm S, David B, McNiven IJ, Asmussen B, Tomkins H, Dolby N, Aplin K, Richards T, Rowe C, Leavesley M, Mandui H. In press. High-resolution radiocarbon dating of marine materials in archaeological contexts: radiocarbon marine reservoir variability between *Anadara, Gafrarium, Batissa, Polymesoda* and *Echinoidea* at Caution Bay, southern coastal Papua New Guinea. *Archaeological and Anthropological Sciences*. doi:10.1007/s1250-012-0108-1.

Reid DG, Dyal P, Lozouet P, Glaubrecht M, Williams ST. 2008. Mudwhelks and mangroves: the evolutionary history of an ecological association (Gastropoda: Potamididae). *Molecular Phylogenetics and Evolution* 47(2):680–99.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4): 1111–50.

Southon J, Kashgarian M, Fontugne M, Metivier B, Yim WW-S. 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. *Radiocarbon* 44(1): 167–80.

Stuiver M, Braziunas TF. 1993. Modeling atmospheric ¹⁴C influences and ¹⁴C ages of marine samples to 10,000 BC. *Radiocarbon* 35(1):137–89.

Stuiver M, Reimer PJ, Braziunas TF. 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40(3):1127–51.

Sullivan M, O'Connor S. 1993. Middens and cheniers: implications of Australian research. *Antiquity* 67(257):776–88.

Tagliabue A, Bopp L. 2008. Towards understanding global variability in ocean carbon-13. *Global Biogeochemical Cycles* 22: GB1025, doi:10.1029/ 2007GB003037.

Tanaka N, Monaghan MC, Rye DM. 1986. Contribution of metabolic carbon to mollusc and barnacle shell carbonate. *Nature* 320(6062):520–3.

Ulm S. 2002. Marine and estuarine reservoir effects in central Queensland, Australia: determination of ΔR values. *Geoarchaeology* 17(4):319–48.

Ulm S. 2006. Australian marine reservoir effects: a guide to DeltaR values. *Australian Archaeology* 63:57–60.

Ulm S, Barham AJ, David B, Jacobsen G, Loch I, McNiven IJ, Petchey F, Rowland MJ. 2009. Marine carbon reservoir variability in Torres Strait, Stage II. AINSE Progress Report.

Woolfe KJ, Larcombe P, Whitmore G. 1997. The marine geology of the western Gulf of Papua, with special reference to the route of a proposed gas pipeline. Report to NSR Environmental Consultants Pty. Ltd.