Research Reports

Marine reservoir corrections for Moreton Bay, Australia

SEAN ULM, FIONA PETCHY and ANNIE ROSS

Keywords: ΔR, marine reservoir effects, marine shell, radiocarbon dating, Moreton Bay

Abstract

We present the first direct assessment of marine reservoir effects in the Moreton Bay region using radiocarbon dating of known-age, pre-AD 1950, shell samples from the east coast of Stradbroke Island and archaeological shell/charcoal pairs from Peel Island in Moreton Bay. The resulting ΔR value of 9±19 14C years for the open ocean conforms to regional values established for northeast Australia of 12±10 14C years. Negative ΔR values of –65±61 14C years and –216±94 14C years for southern Moreton Bay highlight the potential for larger offsets over the last ~900 years. These may be linked to changing terrestrial inputs and local circulation patterns.

Moreton Bay is a large, shallow, subtropical, semi-enclosed triangular embayment formed between the large sand islands of Stradbroke and Moreton Islands and the mainland coastline of Australia (Figure 1). The bay extends c.90 km north-south and c.30 km east-west and contains some 360 islands. Radiocarbon dating of marine samples from Moreton Bay forms the basis of archaeological and geomorphological chronologies used to model changes in Aboriginal occupation (McNiven 2006; Ulm and Hall 1996), sea-level change (Flood 1981, 1984; Lovell 1975), the development of fringing coral reef systems (Hekel et al. 1979: 17; Ward et al. 1977) and the establishment of intertidal and subtidal shellfish communities (Flood 1981: 21; Hekel et al. 1979: 9). However, despite a heavy reliance on radiocarbon marine shell ages to construct archaeological and geomorphological chronologies, there has been no systematic evaluation of the local applicability of the generalised marine reservoir value for ocean surface waters in the region.

Radiocarbon ages obtained on contemporaneous terrestrial and marine samples are not directly comparable.

Shells and other organisms that have grown in marine environments exhibit older apparent radiocarbon ages caused by the uptake of carbon which has already undergone radioactive decay through long residence times in the deep ocean. On average, the ocean surface (<200 m) has an apparent 14C age around 400 years older than the atmosphere (Gillespie and Polach 1979; Stuiver et al. 1986). However, studies worldwide have shown that variation in 14C activity in near-shore marine and estuarine environments depends greatly on local and regional factors, such as hinterland geology, tidal flushing and terrestrial water input (e.g. Dye 1994; Southon et al. 2002; Stuiver and Braziunas 1993).

Regional differences in marine reservoir effect are most commonly determined through radiocarbon dating pre-AD 1950 known-age marine specimens (e.g. shell, coral, otoliths) (e.g. Bowman and Harvey 1983; Gillespie and Polach 1979; Southon et al. 2002) or dating shell and charcoal paired samples from contemporaneous archaeological contexts (e.g. Gillespie and Polach 1979; Ulm 2002). The marine reservoir effect is conventionally expressed as ΔR, which is the difference between the conventional radiocarbon age of a sample of known-age from a specific locality and the equivalent age predicted by the global modelled marine calibration curve (Hughen et al. 2004; Stuiver et al. 1986).

Figure 1. Moreton Bay, showing approximate position of the shoreline at 6000 BP (after Hekel et al. 1979: 8; Jones 1992: 31).
Marine and estuarine reservoir differences are a major issue in the investigation and dating of coastal archaeological and geomorphological deposits where these factors can result in calibration errors of up to several hundred years. For central Queensland, a local open ocean ΔR of 11±10 14C years has been established; but values for adjacent estuaries diverge significantly with values of up to ΔR= –155±55 14C years documented (see Ulm 2002 for detailed discussion). In this case, the blanket application of the regional ΔR value would produce calibrated ages approximately 200 years too young. In the absence of local studies of marine reservoir effects, researchers in the Moreton Bay region have either reduced marine 14C ages by a generic Australia-wide 450±35 14C years recommended by Gillespie and Polach (1979) (e.g. Flood 1984) or adopted the northeastern coast ΔR value c.12±10 14C years recommended by Ulm (2006) and Reimer and Reimer (2008) (e.g. McNiven 2006). For well-equilibrated open waters in the Eastern Australian Current, the northeastern coast value is likely to approximate local open ocean values, but studies elsewhere suggest that the waters within embayments like Moreton Bay itself could reflect local input and hydrological conditions (e.g. Little 1993).

As a preliminary assessment of the potential impact of marine carbon variability in the Moreton Bay region, two marine shells live-collected in 1902 and two shell/charcoal paired samples from archaeological contexts were radiocarbon dated to determine local marine and estuarine reservoir values.

Previous ΔR research in the Moreton Bay region

Gillespie and Polach (1979: Table 5; see also Gillespie 1977: Table 4) reported two determinations on shells live-collected in 1973 from Macleay Island in southern Moreton Bay as part of a broader study of the suitability of dating marine shell (Figure 1, Table 1). Differences in the radiocarbon activity (expressed as pMC) may be taken as a general indication of variation in 14C activity of source waters and therefore also local and regional oceanographic processes (Hogg et al. 1998). The two determinations show good agreement and are slightly lower than those reported for contemporaneous open water coral cores off the central Queensland coast from Lady Musgrave Island (111.95±0.21 pMC), Heron Island (112.45±0.21 pMC) and Abraham Reef (111.13±0.21 pMC) (Druffel and Griffin 1995).

These data are difficult to interpret, however, because of the absence of any regional modelling of post-AD 1950 alteration to the marine carbon reservoirs resulting from nuclear detonations (Reimer et al. 2004). Nonetheless, they suggest the possibility of a lag in registering a peak marine bomb signature in Moreton Bay compared to the well-equilibrated waters of the western Pacific Ocean. The selection of the whelk Pyrazus ebeninus, a grazing gastropod, could be problematic because this shellfish may have ingested carbon from a variety of sources, including 14C depleted peats (cf. Keith et al. 1964). Additionally, whole shells were dated which, as Gillespie and Polach (1979: 414) acknowledge, provides an average 14C signature over the growth period of the shell.  

Table 1. Post-AD 1950 live-collected shell (Gillespie and Polach 1979: Table 5). SF = suspension-feeder. H = herbivore. pMC (Percent Modern Carbon) represents the proportion of 14C atoms in the sample compared to that present in AD 1950 (Stuiver and Polach 1977).

| Site          | Lab. No. | Sample  | Diet | Historical Age (year AD) | pMC (F14C%)
|---------------|----------|---------|------|--------------------------|-----------
| Macleay Island SUA-218/1 | Mytilidae: | SF | 1973 | 105.9±0.8
| Macleay Island SUA-218/2 | Batillariidae: | H | 1973 | 104.6±0.8

Materials and methods

Two known-age, pre-AD 1950 shell samples and two archaeological shell/charcoal paired samples provide our data. All shell samples are suspension-feeding bivalves which are considered the most reliable sample material for ΔR studies (Hogg et al. 1998; Forman and Polayak 1997).

Pre-AD 1950 known-age shells

Two valves of the pipi Donax (Plebidonax) deltoides (Lamarck, 1818) from different individuals were dated (Table 2). Kesteven (Walker 1983) collected these samples from the ‘outer beach’ of north Stradbroke Island (Figure 1) in September 1902 and they were presented to the Australian Museum by Charles Hedley (Australian Museum Reg. No. C13037). The collection date is equivalent to a model marine age of 452±23 14C years. D. deltoides is a short-lived (<4 years), shallow-burrowing, suspension-feeding littoral sand dweller on high energy surf beaches (Beesley et al. 1998: 346-8; King 1976, 1985; Lamprell and Whitehead 1992; Murray-Jones 1999).

A 5 mm cross-section was removed perpendicular to the edge of each shell across multiple increments of growth to avoid intra-shell variations in 14C (Culleton et al. 2006) and provide an average value for the shell margin (i.e. to approximate the time of death as closely as possible). Sample preparation for accelerator mass spectrometry (AMS) determinations (including CO2 production) was undertaken by the University of Waikato Radiocarbon Dating Laboratory. AMS dating was conducted by the Rafter Radiocarbon Laboratory of the New Zealand Institute of Geological and Nuclear Sciences (IGNS). δ18O and δ14C values were measured on gas splits taken during preparation.
of samples for AMS analysis at the University of Waikato using a Europa Scientific Penta 20-20 isotope ratio mass spectrometer. To calculate $\Delta R$, the historical age of each shell sample (i.e. year of death) was converted to an equivalent global marine modelled age using the MARINE04 calibration dataset (Hughen et al. 2004). $\Delta R$ values were calculated by deducting the equivalent global marine model age at the time of death of the shell sample from the conventional radiocarbon age obtained (Stuiver et al. 1986). $\Delta R \sigma$ is the one-sigma estimate of uncertainty in the conventional radiocarbon age of the shell sample.

Archaeological shell/charcoal pairs

Two shell/charcoal paired samples were dated from the Lazaret Midden located on the north margin of Peel Island in southern Moreton Bay (Figure 1, Table 3) (Ross 2001; Ross and Coghill 2000; Ross and Duffy 2000). Excavation of four 50 x 50 cm squares revealed a dense deposit of shell and fish bone spanning the last c.1200 years. The pairs are associated with hearth features, providing secure stratigraphic contexts for the samples. Charcoal samples were paired with valves of the short-lived (<10 years) Trichomya hirsuta, a suspension-feeding mussel which lives attached to substrata in the lower intertidal to upper subtidal zone (Beesley et al. 1998: 251; Creese et al. 1997: 230).

A key limitation of $\Delta R$ studies employing archaeological marine/atmospheric samples is the assumption that the paired samples are contemporaneous. The difficulty of identifying such samples and the lack of independent age confirmations has led to scepticism over marine reservoir values calculated in this way (e.g. Gillespie and Polach 1979; Petchey and Addison 2005: 79). The Lazaret Midden pairs presented here are from apparently secure stratigraphic contexts without obvious post-depositional disturbance, were collected from the same small excavation units and conform to the age-depth sequence for the site (excluding the disturbed surface layer, see Prangnell 2002: 35). In the absence of other information the samples are assumed to be coeval.

Whole shells were dated by conventional liquid scintillation counting undertaken by the University of Waikato Radiocarbon Dating Laboratory and Beta Analytic Inc. $\Delta R$ values for pairs were calculated by converting the charcoal $^{14}$C age to the equivalent global marine model age using atmospheric ages interpolated from SHCal04 (McCormac et al. 2004) to the same calendar year as MARINE04 (Hughen et al. 2004) (for procedure see Reimer et al. (2002) and Ulm (2002)). The intersections of the one-sigma range of the conventional radiocarbon age of the atmospheric (charcoal) sample with the MARINE04 calibration curve, interpolated between available data points, provided maximum and minimum marine model ages. The midpoint of these values was taken as the model marine age. The estimated uncertainty in the marine model age includes both the range of the maximum and minimum marine model ages and an estimate of the average uncertainty of the atmospheric calibration data in the one-sigma range of the atmospheric age. $\Delta R$ was calculated by deducting the marine model age of the atmospheric determination from the conventional radiocarbon age of the paired marine shell sample. $\Delta R \sigma$ includes the estimated uncertainty in the marine model age and the marine radiocarbon age. For an alternative method using sample-based Bayesian inference that allows uncertainty in the dated events to be incorporated see Petchey et al. (2005) and Jones et al. (2007).

Results

Results are presented in Tables 2–4 and Figure 2 and outlined below.

Pre-AD 1950 known-age shells

AMS dating of the two samples of $D. deltoides$ collected in 1902 returned radiocarbon ages of 478±23 BP (Wk-17806) and 443±23 BP (Wk-17807) which are equivalent to $\Delta R=26±23$ $^{14}$C years and $\Delta R=9±23$ $^{14}$C years respectively (Table 2). The two ages are indistinguishable with an error-weighted mean of 461±17 $^{14}$C years, equivalent to $\Delta R=9±19$ $^{14}$C years (Table 4).

Archaeological shell/charcoal pairs

The two shell/charcoal pairs from archaeological contexts returned $\Delta R$ values of $-65±61$ $^{14}$C years and $-216±94$ $^{14}$C years which combine to yield an error-weighted mean with additional variance of $-110±94$ $^{14}$C years (Table 4). This value cannot be distinguished from the local open ocean value of $\Delta R = 9±19$ $^{14}$C years presented above owing to the large uncertainty estimate. These results suggest that $\Delta R$ activity in the last 500 years approximated modern values, but with the possibility of a shift to more negative values in the last millennium indicated by the $-216±94$ value around 850 years ago (Figure 2).

The pooling statistics (Table 4) are based on Mangerud et al. (2006: 3241) where the Chi squared ($\chi^2$) test is used to

<table>
<thead>
<tr>
<th>Site</th>
<th>Museum No.</th>
<th>Lab. No.</th>
<th>Sample</th>
<th>Diet</th>
<th>Historical Age (year AD)</th>
<th>$\delta^{14}$C (%)</th>
<th>$\delta^{18}$O (%)</th>
<th>CRA (BP)</th>
<th>Equivalent Marine Model Age</th>
<th>$\Delta R$ ($^{14}$C yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stradbroke Island</td>
<td>C13037/3</td>
<td>Wk-17806</td>
<td>Donacidae: $D. deltoides$</td>
<td>SF</td>
<td>September 1902</td>
<td>1.1±0.2</td>
<td>0.9±0.06</td>
<td>478±23</td>
<td>452±23</td>
<td>26±23</td>
</tr>
<tr>
<td>Stradbroke Island</td>
<td>C13037/4</td>
<td>Wk-17807</td>
<td>Donacidae: $D. deltoides$</td>
<td>SF</td>
<td>September 1902</td>
<td>0.7±0.2</td>
<td>-0.64±0.06</td>
<td>443±23</td>
<td>452±23</td>
<td>-9±23</td>
</tr>
</tbody>
</table>

Table 2. $\Delta R$ values from known-age pre-AD 1950 shells from Stradbroke Island. SF = suspension-feeder.
test the internal variability in a group of ∆R values. If \( \sum/c2/(n-1) > 1 \) the group has additional variability beyond measurement uncertainties, and the additional variance \( \sum/c540/_{\text{ext}} \) and uncertainty are calculated and applied to the ∆R. The additional variance \( \sum/c540/_{\text{ext}} \) is obtained by subtracting the \( \sum/c540/^{14}C \) measurement variance from the total population variance and obtaining the square root; therefore \( \sum/c540/_{\text{ext}} = \sqrt{\sum/c540/^{14}C_{\text{pop}} - \sum/c540/^{14}C_{\text{meas}}} \).

Any uncertainty including additional variance is calculated by \( \sqrt{\sum/c545/^{14}C_{\text{pooled}} + \sum/c545/_{\text{ext}}} \). When \( \sum/c545/^{14}C_{\text{pooled}}/(n-1) \leq 1 \) the weighted mean is used (see Mangerud et al. 2006: 3241-2 for details).

### Table 3. ∆R values from paired shell/charcoal samples from the Lazaret Midden, Peel Island. e=estimated value only.

<table>
<thead>
<tr>
<th>Description</th>
<th>No.</th>
<th>∆R (14C years)</th>
<th>χ² Test</th>
<th>χ²(n-1)</th>
<th>∆R with External Variance (14C years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stradbroke Island known-age</td>
<td>2</td>
<td>9±16</td>
<td></td>
<td>1.16</td>
<td>9±19</td>
</tr>
<tr>
<td>Lazaret Midden archaeological</td>
<td>2</td>
<td>-110±51</td>
<td></td>
<td>1.82</td>
<td>-110±94</td>
</tr>
<tr>
<td>Known-age and archaeological</td>
<td>4</td>
<td>-2±16</td>
<td></td>
<td>2.61</td>
<td>-2±103</td>
</tr>
</tbody>
</table>

### Table 4. ∆R pooling statistics.

The local open ocean value of \( \sum/c545/^{14}C = 9±19 \) 14C years calculated for samples from Stradbroke Island conforms with expectations derived from calculations of ∆R in open ocean contexts to the north, confirming the general uniformity of marine reservoir effects in areas dominated by the Eastern Australian Current (Figure 2). The two negative ∆R values from Peel Island within Moreton Bay of \(-65±61 \) 14C years and \(-216±94 \) 14C years, while not significantly different owing to the large error estimates, indicate enrichment of the local marine reservoir relative to the modelled surface ocean (Hughen et al. 2004). A range of factors that could contribute to these values are discussed below.

### Discussion

The local open ocean value of ∆R = 9±19 14C years calculated for samples from Stradbroke Island conforms with expectations derived from calculations of ∆R in open ocean contexts to the north, confirming the general uniformity of marine reservoir effects in areas dominated by the Eastern Australian Current (Figure 2). The two negative ∆R values from Peel Island within Moreton Bay of \(-65±61 \) 14C years and \(-216±94 \) 14C years, while not significantly different owing to the large error estimates, indicate enrichment of the local marine reservoir relative to the modelled surface ocean (Hughen et al. 2004). A range of factors that could contribute to these values are discussed below.

### Hydrology and circulation patterns

Moreton Bay is dominated by semi-diurnal tides entering the bay through the northern opening and three smaller...
passages along the eastern margin at South Passage, Jumpingpin and Southport Bar (Figure 1). Although tidal flushing is generally high, with average residence time estimated at 50 days, there is marked variability in tidal exchange between the deep northern section and the poorly flushed shallow southern section which exhibits residence times in excess of the overall bay average (Gabric et al. 1995). High annual rainfall (1500 mm), a large catchment (18,000 km²) and occasional cyclone events are responsible for large periodic freshwater inputs, depressing salinity and introducing large volumes of dissolved atmospheric CO₂ (Gabric et al. 1995; Milford and Church 1977). Dissolved inorganic carbon may also be introduced from groundwater discharge, including through swampy peat environments, along the margins of Stradbroke Island (Hadwen 2006).

We have attempted to differentiate between these sources using δ¹³C and δ¹⁸O isotopic information where available. δ¹⁸O is a highly sensitive indicator of change in water temperature and salinity, while the δ¹³C value of marine shells is thought to predominantly reflect changes in water source and overall marine productivity (Culleton et al. 2006; Kennett et al. 1997). Marine carbonates have high δ¹³C values c.0±2‰ (Stuiver and Polach 1977: 358), whereas freshwater values are typically depleted 5–10‰ compared to mean ocean water (Keith et al. 1964). Marine shellfish which incorporate a significant proportion of carbon derived from plant or soil sources should exhibit δ¹³C values lower than that expected of marine environments. However, the δ¹³C value available for *T. hirsutus* (Wk-8013) of 0.7±0.2 per mil is well within the range expected for marine samples (Stuiver and Polach 1977: 358), suggesting little input from terrestrial carbon sources. Conversely, the δ¹⁸O value for Wk-8013 (–1.36 ‰) is more depleted than the open ocean marine shells from Stradbroke Island (0.09 and –0.64 ‰) as would be typical for less saline waters (Culleton et al. 2006: 390; Dettman et al. 2004; Keith et al. 1964). Although the data are too limited to draw any firm conclusions, a similar discrepancy in δ¹³C values has been noted by Spiker (1980) where photosynthetic activity enhances isotope exchange with atmospheric CO₂, resulting in more positive δ¹³C values than is typical for estuarine waters (see also Petchey et al. 2008).

The combination of high freshwater inputs, well-aerated shallow waters and poor tidal flushing extending residence times might help explain the observed ΔR values. Forman and Poljak (1997: 888) have argued that increased wind turbulence may augment transfer of enriched ¹⁴C from the atmosphere reducing the reservoir effect (resulting in negative ΔR values) by 100 to 200 years (see also Hogg et al. 1998).

‘Old Wood’ effect

As the charcoal used in the archaeological pairs was not identified, it is possible that the reported charcoal ages are too old for the context. An ‘old wood effect’ can arise where firewood comes from wood lying in the environment (including driftwood) or where the older central sections of large trees are burnt (McFadgen 1982; Schiffer 1986). However, in the study area, wood generally decomposes rapidly in exposed humid environments (see Swift et al. 1979: 317). Thus any ‘old wood effect’ is unlikely to be greater than one to two decades, so it cannot account for the apparent difference between ΔR values inside and outside Moreton Bay.

**Change in marine reservoir effects through time**

Although only a small number of data points are available, the ΔR values presented here suggest that ΔR approximated current values during at least the last 500 years, with the possibility of lower ΔR values ~800–900 years ago (Figure 2). Several studies have indicated temporal variation in ΔR for the eastern Australian sea board. The Abraham Reef coral record off the central Queensland coast shows shifts in ΔR over the last 350 years of up to 80 years (Druffel and Griffin 1993, 1995, 1999) while the modelling of Franke et al. (2008) suggests minimum shifts of 300 years over longer timescales. These long-term effects are potentially compounded in embayments where changes in residence times and circulation patterns may change profoundly through time in response to geomorphological processes. As an example, marked changes in sedimentation and circulation patterns are documented in a change in the dominant coral species at Peel and Mud Islands from the clean water *Acropora* species to the mud-resistant *Favia* species since 3710±250 BP (Flood 1984: 130; Hekel et al. 1979; Jones et al. 1978: 13) (see Figure 1).

**Conclusion**

We recommend a ΔR value of 9±19 open waters in southeast Queensland, based on dating of known-age shell samples from Stradbroke Island. Determination of ΔR values inside Moreton Bay from archaeological shell/charcoal pairs is complicated by spatial and temporal variation in circulation and sedimentation patterns and terrestrial inputs. As a first approximation, ΔR values inside and outside Moreton Bay can be considered as similar for the recent past, although there are indications that marine reservoir conditions were not constant in Moreton Bay in the past and are strongly related to changing hydrological conditions. Further studies of paired shell/charcoal samples from a range of contexts and time periods will clarify patterns identified here.

**Acknowledgements**

Ian Loch (Australian Museum) provided the live-collected specimens for this study. The Australian Institute of Aboriginal and Torres Strait Islander Studies funded excavation and radiocarbon dating of the Lazaret Midden. Paula Reimer (Queen’s University of Belfast) patiently provided advice and encouragement. We thank the University of Waikato’s Radiocarbon Dating Laboratory and International Global Change Institute for hosting Ulm
during the writing of this paper. For advice and support, thanks to Alan Hogg, Daniel Rosendahl and Marion Holdaway. For constructive comments on the manuscript we thank Colin Murray-Wallace and Peter White.

References


King, M. 1976 The Life-History of the Goolwa Cockle, Donax (Plebidonax) deltoides, (Bivalvia: Donacidae), on an Ocean Beach, South Australia. Adelaide: Department of Agriculture and Fisheries.


McNiven, I. 2006 Late moves on Donax: Aboriginal marine


Jomon sherds from Aomori, Japan, not Mele, Efate

WILLIAM R. DICKINSON
and MARY ELIZABETH SHUTLER

Keywords: Jomon, Mele Plain, paleoshorelines

Abstract

The presence of Japanese Jomon sherds from Aomori in an artefact collection from Vanuatu has been attributed alternately to Jomon voyaging or to adventitious mingling of artefacts of different proveniences. The paleoshoreline history of Efate indicates that the site where the Jomon sherds were purportedly collected was submerged during Jomon time, making introduction of the sherds into Vanuatu by Jomon voyagers implausible. The anomalous sherds were probably taken directly from Japan to Paris, and inadvertently introduced there into the Vanuatu collection.

In a previous paper (Dickinson et al.1999), we showed from petrographic and microprobe evidence that cord-marked potsherds reportedly discovered as Vanuatu surface artefacts

WRD: Department of Geosciences, University of Arizona, PO Box 210077, University of Arizona, Tucson AZ 85721, USA; email: wrdickin@dakotacom.net; MES: College of Letters and Sciences, National University, 11255 N. Torrey Pines Rd., La Jolla CA 92037, USA