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Marine reservoir corrections for Moreton Bay, Australia

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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 ^{14}C years for the open ocean conforms to regional values established for northeast Australia of 12±10 ^{14}C years. Negative ΔR values of –65±61 ^{14}C years and –216±94 ^{14}C 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 ^{14}C age around 400 years older than the atmosphere (Gillespie and Polach 1979; Stuiver *et al.* 1986). However, studies worldwide have shown that variation in ^{14}C 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).

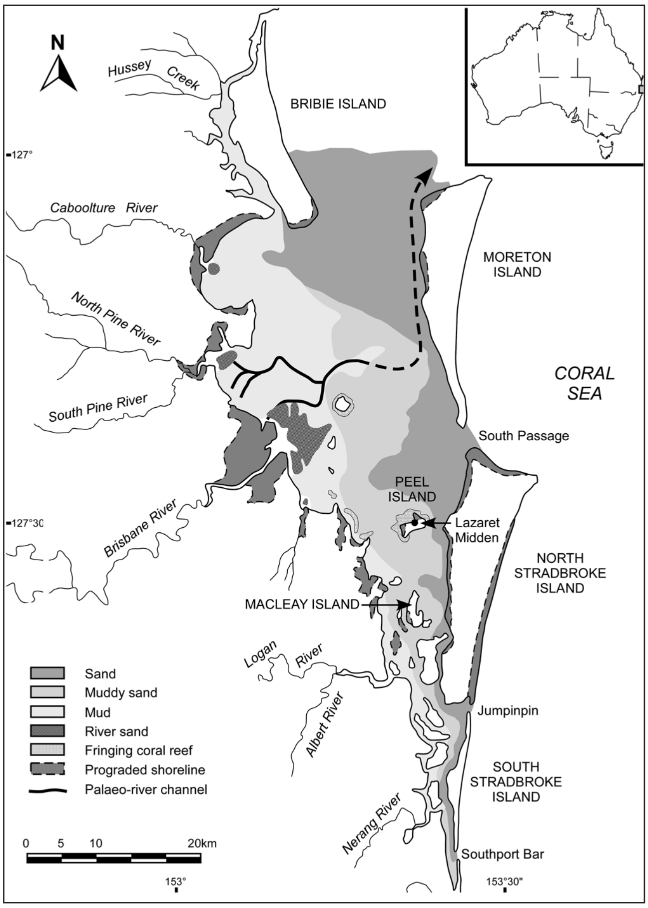

Figure 1. Moreton Bay, showing approximate position of the shoreline at 6000 BP (after Hekel *et al.* 1979: 8; Jones 1992: 31).

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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 ^{14}C years has been established; but values for adjacent estuaries diverge significantly with values of up to ΔR= –155±55 ^{14}C 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 ^{14}C ages by a generic Australia-wide 450±35 ^{14}C years recommended by Gillespie and Polach (1979) (e.g. Flood 1984) or adopted the northeast coast ΔR value c.12±10 ^{14}C 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 northeast 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 ^{14}C 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 ^{14}C depleted peats (cf. Keith *et al.* 1964). Additionally, whole shells were dated which, as Gillespie and Polach (1979: 414) acknowledge, provides an average ^{14}C signature over the growth period of the shell. *M. edulis* can live up to 24 years (Powell and Cummins 1985: Table 1), while most gastropods live <5 years (Frank 1969: 247). This 'inbuilt age' may be critical in the rapidly changing post-bomb environment.

Site	Lab. No.	Sample	Diet	Historical Age (year AD)	pMC (F^{14}C%)
Macleay Island	SUA-218/1	Mytilidae: *Mytilus edulis planulatus*	SF	1973	105.9±0.8
Macleay Island	SUA-218/2	Batillariidae: *Pyrazus ebeninus*	H	1973	104.6±0.8

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 ^{14}C atoms in the sample compared to that present in AD 1950 (Stuiver and Polach 1977).

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 ^{14}C 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 ^{14}C (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 CO_2 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). $\delta^{18}O$ and $\delta^{13}C$ 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 ΔR, 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). ΔR 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). ΔRσ 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 hirsutus*, 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 ΔR 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. ΔR 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. ΔR was calculated by deducting the marine model age of the atmospheric determination from the conventional radiocarbon age of the paired marine shell sample. ΔRσ 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 ΔR=26±23 ^{14}C years and –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 ΔR=9±19 ^{14}C years (Table 4).

Archaeological shell/charcoal pairs

The two shell/charcoal pairs from archaeological contexts returned ΔR 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 ΔR = 9±19 ^{14}C years presented above owing to the large uncertainty estimate. These results suggest that ΔR 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 (χ^2) test is used to

Site	Museum No.	Lab. No.	Sample	Diet	Historical Age (year AD)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	CRA (BP)	Equivalent Marine Model Age	ΔR (^{14}C yr)
Stradbroke Island	C13037/3	Wk-17806	Donacidae: *D. deltoides*	SF	September 1902	1.1±0.2	0.09±0.06	478±23	452±23	26±23
Stradbroke Island	C13037/4	Wk-17807	Donacidae: *D. deltoides*	SF	September 1902	0.7±0.2	–0.64±0.06	443±23	452±23	–9±23

Table 2. ΔR values from known-age pre-AD 1950 shells from Stradbroke Island. SF = suspension-feeder.

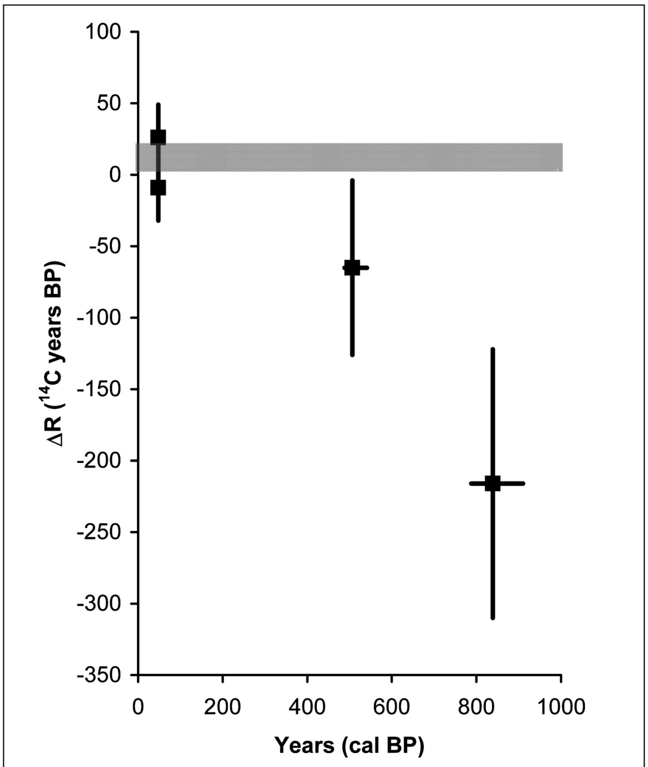
Site	Square/ XU	Depth (mm)	Lab. No.	Sample	Diet	δ13C (‰)	δ18O (‰)	CRA (BP)	Equivalent Marine Model Age	ΔR (^{14}C yr)
Lazaret Midden	B4/12	300	Wk-8009	charcoal	–	–27.2±0.2	–	500±50	905±35	
Lazaret Midden	B4/12	300	Wk-8013	Mytilidae: *T. hirsutus*	SF	0.7±0.2	–1.36±0.06	840±50	840±50	–65±61
Lazaret Midden	A/10	270	Beta-98031	charcoal	–	–25e±2e	–	970±60	1306±72	
Lazaret Midden	A/10	270	Beta-98032	Mytilidae: *T. hirsutus*	SF	1e±2e	–	1090±60	1090±60	–216±94

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

Description	No.	ΔR Pooled (^{14}C years)	χ^2 Test	$\chi^2/(n\text{-}1)$	ΔR with External Variance (^{14}C years)
Stradbroke Island known-age	2	9±16	T'=1.16; $\chi^2_{1:0.05}$=3.84	1.16	9±19
Lazaret Midden archaeological	2	-110±51	T'=1.82; $\chi^2_{1:0.05}$=3.84	1.82	-110±94
Known-age and archaeological	4	-2±16	T'=7.82; $\chi^2_{3:0.05}$=7.82	2.61	-2±103

Table 4. ΔR pooling statistics.

test the internal variability in a group of ΔR values. If $\chi^2/(n\text{-}1)$ is >1 the group has additional variability beyond measurement uncertainties, and the additional variance (σ_{ext}) and uncertainty are calculated and applied to the ΔR. The additional variance (σ_{ext}) is obtained by subtracting the ^{14}C measurement variance from the total population variance and obtaining the square root; therefore $\sigma_{ext}=\sqrt{(\sigma^2_{pop}-\sigma^2_{meas})}$. Any uncertainty including additional variance is calculated by $\sqrt{(E^2_{\Delta Rpooled}+\sigma^2_{ext})}$. When $\chi^2/(n\text{-}1)$ is ≤1 the weighted mean is used (see Mangerud *et al.* 2006: 3241-2 for details).



Discussion

The local open ocean value of ΔR = 9±19 ^{14}C years calculated for samples from Stradbroke Island conforms with expectations derived from calculations of ΔR 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 ΔR values from Peel Island within Moreton Bay of –65±61 ^{14}C years and –216±94 ^{14}C 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

◀ Figure 2. Moreton Bay ΔR plotted against the known-age of live-collected samples and the median of the calibrated age-range of terrestrial samples in archaeological pairs. Vertical error bars represent the estimated error in ΔR values and horizontal bars represent the 1σ spread in the calibrated age-ranges. The shaded zone shows the regional ΔR value of 12±10 ^{14}C years recommended for the northeast Australia (Ulm 2006). Radiocarbon ages on terrestrial samples in archaeological pairs were calibrated to calendar years using OxCal 4.0 (Bronk Ramsey 1995, 2001) and the SHCal04 dataset (McCormac *et al.* 2004). The median calibrated age takes account of the irregular probability distribution of calibration results (Telford *et al.* 2004).

passages along the eastern margin at South Passage, Jumpinpin 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.* 1998). High annual rainfall (1500 mm), a large catchment (18,000 km^2) and occasional cyclone events are responsible for large periodic freshwater inputs, depressing salinity and introducing large volumes of dissolved atmospheric CO_2 (Gabric *et al.* 1998; 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 $\delta^{13}C$ and $\delta^{18}O$ isotopic information where available. $\delta^{18}O$ is a highly sensitive indicator of change in water temperature and salinity, while the $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ values lower than that expected of marine environments. However, the $\delta^{13}C$ 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 $\delta^{18}O$ 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 $\delta^{13}C$ values has been noted by Spiker (1980) where photosynthetic activity enhances isotope exchange with atmospheric CO_2 resulting in more positive $\delta^{13}C$ 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 Polyak (1997: 888) have argued that increased wind turbulence may augment transfer of enriched $^{14}CO_2$ 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 for 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.

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Jomon sherds from Aomori, Japan, not Mele, Efate

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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

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