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Marine and Estuarine Reservoir Effects in Central Queensland, Australia: Determination of ΔR Values

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Abstract

As a component of archaeological investigations on the central Queensland coast a series of five marine shell specimens live-collected between A.D. 1904 and A.D. 1929 and 11 shell/charcoal paired samples from archaeological contexts were radiocarbon dated to determine local ΔR values. The object of the study was to assess the potential influence of localised variation in marine reservoir effect in accurately determining the age of marine and estuarine shell from archaeological deposits in the area. Results indicate that the routinely-applied ΔR value of -5 ± 35 for northeast Australia is erroneously-calculated. The determined values suggest a minor revision to Reimer and Reimer's (2000) recommended value for northeast Australia from ΔR= +11 ± 5 to +12 ± 7, and specifically for central Queensland to ΔR= +10 ± 7, for near-shore open marine environments. In contrast, data obtained from estuarine shell/charcoal pairs demonstrate a general lack of consistency, suggesting estuary-specific patterns of variation in terrestrial carbon input and exchange with the open ocean. Preliminary data indicate that in some estuaries, at some time periods, a ΔR value of more than -155 ± 55 may be appropriate. In estuarine contexts in central Queensland, a localised estuary-specific correction factor is recommended to account for geographical and temporal variation in ^{14}C activity.

Introduction

The marine reservoir effect (also known as the oceanic reservoir correction factor, marine shell correction factor or surface ocean water reservoir effect) of 450 ± 35 ^{14}C years calculated for Australia by Gillespie (1975, 1977, 1991; see also Gillespie and Temple, 1977; Gillespie and Polach, 1979) is based on samples from Torres Strait and southern Australia. Several Australian studies have suggested the possibility of significant deviations in regional marine reservoir signature from this generalised value (e.g., Hughes and Djohadze, 1980; Woodroffe et al., 1986:75, 77; Woodroffe and Mulrennan, 1993; Murray-Wallace, 1996; Spennemann and Head, 1996). Additionally, Spennemann and Head (1996:35) note that the present "use of universal ocean reservoir factors not only potentially masks chronological variation, but potentially invalidates some observations in toto." However, despite routine dating of marine and estuarine shell from archaeological deposits in Queensland (see Ulm and Hall, 1996; Ulm and Reid, 2000), no systematic evaluation of the applicability of this generalised marine reservoir effect has been undertaken in the region.

Since 1993, 20 archaeological sites have been test excavated under the auspices of the Gooreng Gooreng Cultural Heritage Project in central Queensland (see Lilley and Ulm, 1995, 1999). Investigations have focussed on a coastal area centred on the Town of Seventeen Seventy and an inland area centred on Cania Gorge, approximately 100 km from the coast (Figures 1 and 2). Because this project constitutes the first detailed archaeological investigation in the region, a basic objective was to develop a cultural chronology for the two areas to enable systematic comparison within and between inland and coastal sequences as well as to relate findings to results from southeast Queensland (e.g., Ulm and Hall, 1996) and the Central Queensland Highlands (e.g., Morwood, 1984). To date, radiocarbon determinations from Cania Gorge have been based exclusively on wood charcoal samples (n=35), while those from sites on the coast include wood charcoal (n=22), marine shell (n=4) and estuarine shell (n=32) (see Ulm and Reid, 2000 for details). To examine the potential influence of local marine reservoir effect on the comparability of radiocarbon ages obtained on various sample materials, a limited program of dating live-collected marine shell specimens of known historical age and archaeological shell/charcoal paired samples was undertaken to improve confidence in calibration of ages from the study area and to ensure comparability between shell ages and between shell and terrestrial (charcoal) samples.

In addition to the significance of this study for interpretations of cultural chronologies in Australian coastal archaeology, the results have broader implications for studies of coastal geomorphology in eastern Australia. In recent studies there is a heavy reliance on marine radiocarbon ages to establish chronologies for sea-level change (e.g., Lambeck and Nakada, 1990; Larcombe et al., 1995), reef and coral cay development (e.g., Chivas et al., 1986), coastal dune sequences (e.g., Pye and Rhodes, 1985), and storm event frequency (e.g., Hayne and Chappell, 2001; Nott and Hayne, 2001).

Background

A basic assumption of the radiocarbon dating method is that the concentration of ^{14}C in the biosphere is uniform through space and time. Early in the development of the ^{14}C method, however, it was recognised that certain environments exhibited much slower rates of mixing than the atmosphere, indicating significant variation within and between some ^{14}C reservoirs. In particular, marine shells (which derive carbon principally from dissolved inorganic carbon in ocean waters) exhibited a systematic age difference to contemporary terrestrial samples on a regional basis which allowed calculation of a regionally-specific age offset. These differences have been documented primarily through the dating of marine shell specimens of known historical age (see Stuiver et al., 1986:Table 1; Reimer and Reimer, 2000).

Global variation in marine reservoir effects evident in marine shell carbonates are principally caused by incomplete mixing of upwelling water of 'old' inorganic carbonates from the deep ocean where long residence times (>1000 years) cause depletion of ^{14}C activity through radioactive decay, resulting in very old apparent ^{14}C ages (Mangerud, 1972). Estuarine reservoirs, however, are even more complex with the interaction and incomplete mixing of ^{14}C from both terrestrial reservoirs and marine reservoirs from tidal action (Robinson and Thompson, 1981:50; Little, 1993; Stuiver and Braziunas, 1993:155). This is generally not the case in open coast contexts where the effect of terrestrial runoff on near-shore ^{14}C activity is attenuated by unrestricted circulation that ensures rapid mixing and distribution of atmospherically-derived ^{14}C. In estuarine environments, on the other hand, shellfish (and other estuarine organisms) can obtain a significant proportion of their carbon from CO_2 dissolved in terrestrial rainwater runoff (i.e., enriched in ^{14}C activity relative to depleted marine waters). The more atmospheric CO_2 gained by marine and estuarine shells, the closer the ^{14}C age value should be to the expected coeval terrestrial sample age. Fluctuations in ^{14}C through time are amplified in estuarine contexts because of significant regional variability in rainfall magnitude and periodicity combined with the effects of relative sea-level changes on local circulation patterns, such as changes in sedimentation that limit the interaction of estuarine water bodies with the open ocean (e.g., entrance bars). Additional factors are also important in specific estuaries: hinterland geology (e.g., Dye, 1994; Ingram, 1998; Spennemann and Head, 1998) and intra-estuary variability in rainwater input and circulation patterns (Little, 1993). Given this dependent relationship, we would expect significant variation in ^{14}C activity between individual estuaries, regardless of proximity (Spennemann and Head, 1996).

The combined effect of these factors can create an estuarine reservoir ^{14}C age offset up to several hundred years from the conventionally-applied regional open surface water marine reservoir figure.

The potential magnitude of such factors in the central Queensland study area can be gauged by examining salinity profiles and intra-estuary circulation models. Extended periods of depressed salinity have been documented in many estuaries on the central Queensland coast coinciding with periods of distinctly seasonal annual rainfall. Although the major influences on water movement within these tributaries are prevailing tides and weather conditions, freshwater inflow associated with periods of high intensity rainfall can cause heavy run-off, which produces short-to-medium-term fluctuations in estuary salinity and turbidity (Olsen, 1980:5). Olsen (1980) notes that tidal flushing of estuaries is generally high, except for a period of depressed salinity between January and March suggesting significant terrestrial freshwater rainfall input (see also Lupton and Heidenreich, 1996 for similar data for catchments immediately south of the study area).

Regional differences in marine reservoir effect are generally determined through one or a combination of three major methods:

(1) direct radiocarbon dating pre-A.D. 1955 (pre-bomb) live-collected shell specimens of known historical age;

(2) radiocarbon dating shell/charcoal paired samples from high integrity archaeological contexts that are assumed to be contemporaneous; and,

(3) radiocarbon dating and/or paired radiocarbon and uranium-thorium ($^{230}Th/^{234}U$) dating of live corals or long-lived live shells with clear annual growth bands.

In the first method, marine shell specimens of known historical age must be live-collected prior to A.D. 1955 (pre-bomb) and that the date and location of live-collection is known with confidence. After A.D. 1955 (post-bomb) natural levels of ^{14}C activity in marine environments were enriched as a result of detonation of nuclear and thermonuclear weapons in the atmosphere (e.g., Druffel and Griffin, 1993, 1999; Peck and Brey, 1996). Even samples collected prior to A.D. 1955 may require correction for fossil fuel depletion resulting from large-scale fossil fuel combustion beginning in the late nineteenth century (Taylor, 1997:69). Dating shell/charcoal paired samples is also potentially problematic because it must be assumed that the samples selected are contemporaneous and that association is not simply the result of post-depositional processes or excavation procedures (see Ingram, 1998, for example, who assumes contemporaneity between shell/charcoal paired samples collected from 305 mm-thick excavation units). Results of paired samples can, therefore, be difficult to interpret because variation could result from (1) temporal variation in oceanography through time; (2) a lack of true association (contemporaneity) between the samples (e.g., old wood or taphonomic factors); and/or (3) localised reservoir signatures. Recent studies have demonstrated that examination and radiometric dating of certain coral species with well-defined annual growth structures can provide the most accurate determination of marine reservoir effects (Reimer and Reimer, 2000). Unfortunately, such studies are limited largely to tropical regions with long-term coral records.

Figure 1. Map of Australia, showing places mentioned in the text. The boxed area indicates the southern Curtis Coast study area.

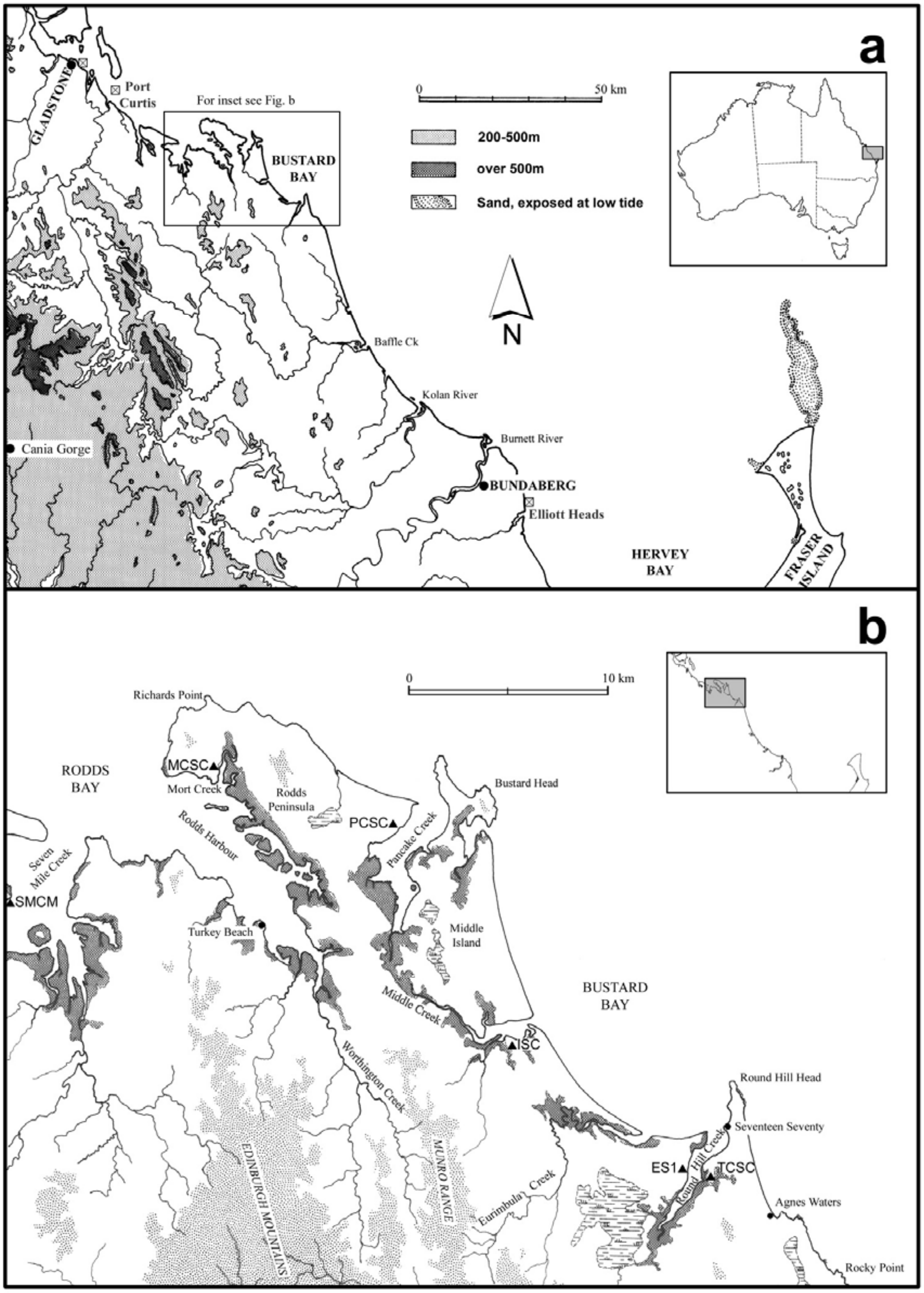

Figure 2. (a) Part of the central Queensland coast showing the location of pre-bomb live-collected shell specimens (☒) and (b) estuaries and archaeological sites (▲) discussed in the text.

In recent years, regional marine reservoir effect has commonly been expressed as ΔR (e.g., Higham and Hogg, 1995; Kennett et al., 1997; Ingram, 1998; Phelan, 1999; Reimer and Reimer, 2000). Stuiver et al. (1986; Stuiver and Braziunas, 1993; Stuiver et al., 1998b) modelled global marine ^{14}C activity using a simple box diffusion global carbon cycle model of marine reservoir responses to variation in atmospheric ^{14}C activity. Regional deviations from the modelled marine calibration curve (ΔR) were calculated using radiocarbon ages on live-collected marine shell samples of known historical age (Stuiver et al., 1986:Table 1). ΔR is the difference between the conventional radiocarbon age of a sample of known age from a specific locality (P) and the equivalent age predicted by the global modelled marine calibration curve (Q); therefore ΔR= P-Q (Stuiver et al., 1986:982).

Australian Marine Reservoir Studies: A Review

The Original Study

Gillespie (1977) established the conventionally-employed marine reservoir effect for marine shells grown in Australian waters of 450 ± 35 years using radiocarbon ages of six marine shell specimens live-collected between A.D. 1875 and A.D. 1950 from four locations around the Australian coast (Figure 1; Table I). Three samples were from the central Torres Strait and one each from Narooma in New South Wales, Adelaide in South Australia and Garden Island in Western Australia. The six shells returned a weighted apparent mean age of 475 ± 35 ($D^{14}C$= -57.7 ± 4‰), which was reduced to 450 ± 35 ($D^{14}C$= -55 ± 4‰) after correction for the fossil fuel dilution effect (Gillespie and Temple, 1977; Gillespie and Polach, 1979; Gillespie, 1991; see Mangerud and Gulliksen, 1975 for details of fossil fuel correction procedure). It is important to note that these values are not based on the conventional radiocarbon ages of the samples but rather calculated from $D^{14}C$ values that had been "age corrected for ^{14}C decay from year of live collection and 1950" (Gillespie and Polach, 1979:410) (i.e., the reservoir age of 450 ± 35 is the error-weighted mean of the conventional radiocarbon age minus the age of the samples in A.D. 1950 plus fossil fuel correction, see Robinson and Thompson, 1981:47) (see Gillespie, 1977; Gillespie and Temple, 1977; Gillespie and Polach, 1979).

Stuiver et al. (1986:Table 1) used these results (uncorrected for fossil fuel dilution) to calculate the ΔR correction for Australian waters of -5 ± 35 for application to marine calibration curves (e.g., Stuiver and Braziunas, 1993:Figure 17A-N). In a footnote, Stuiver et al. (1986:1021-Note e) state that the Australian sample ages reported in their paper as the basis of the ΔR= -5 ± 35 value had been calculated from the $D^{14}C$ reported by Gillespie and Polach (1979:411) after removing an age correction (see Stuiver et al., 1986:1021). This statement is obviously in error, however, because the age-corrected $D^{14}C$ results reported by Gillespie and Polach (1979) produce the same radiocarbon ages as those reported by Stuiver et al. (1986:Table 1) which are presented as conventional radiocarbon ages (i.e., age-correction removed). The ΔR= -5 ± 35 value reported by Stuiver et al. (1986:Table 1, Figure 10B; Stuiver and Braziunas, 1993:Figure 14) is, therefore, erroneous as the value presented is the weighted mean of the difference between the age-corrected ^{14}C ages (rather than the conventional ^{14}C ages) and the global marine model based on the known historical ages of the specimens. In Table I the reported radiocarbon ages were calculated from the reported $D^{14}C$ values after removing the age correction. Note that there are also slight discrepancies in these ages as reported by Stuiver et al. (1986:1020), Gillespie (1991:15), and Bowman (1985b:Table 1) due to rounding factors. This error was also repeated in the original version of Reimer and Reimer's (2000) world wide web Marine Reservoir Correction Database but has since been corrected at the suggestion of the author.

Another source of difference in the results is the use of the 1986 calibration curve to calculate the ΔR values presented by Stuiver et al. (1986:Figure 10B, Table 1) and Stuiver and Braziunas (1993:Figure 16). Stuiver and Braziunas (1993:155) state that no "attempt was made to update the regional ΔR determinations, because minor changes in calibration results for the last few centuries would result in corrections about equal to the rounding error (up to 5 yr) of the original data set." Stuiver et al. (1998b:1135) note that although calibration curves were again updated in 1998 (see Stuiver et al., 1998a), data are virtually identical for the 0-7,000 cal yr B.P. interval, and they therefore recommend the use of the 1993 marine calibration curves (Stuiver and Braziunas, 1993:Figure 17A-N). In the recent Marine Reservoir Correction Database, however, Reimer and Reimer (2000) have recalculated world-wide ΔR values using the 1998 calibration dataset. In the present study, I have recalculated previous ΔR values for the six samples presented in Table I using the 1998 calibration curve. The use of the 1998 instead of the 1986 marine calibration model results in a reduction of ~20 years in the marine model ages and a corresponding change in the ΔR value of the same magnitude.

The standard deviations reported with the model marine ages are derived from Stuiver et al. (1998a) combined with any estimate of error in the historical age of the year of live-collection of the sample. Similarly the ΔR standard deviation combines the error estimates of the ^{14}C age and the marine model age. Using these procedures and the methods outlined by Ward and Wilson (1978), I found that the six specimens formed a statistically indistinguishable group with an error-weighted mean of ΔR= +50 ± 33 (T'=1.90; $\chi^2_{5:0.05}$=11.07) (Table I).

Further Studies

Various studies have attempted to evaluate the applicability of the Gillespie correction factor to particular Australian regions. These studies have been based on four classes of data: (1) additional dating of pre-bomb live-collected shell specimens (Rhodes et al., 1980; Bowman and Harvey, 1983; Gill, 1983; Bowman, 1985a, 1985b); (2) radiocarbon dating of coral cores with clear growth bands (Reimer and Reimer, 2000); (3) shell/charcoal paired samples from archaeological and natural deposits (Gillespie and Temple, 1977; Luebbers, 1978; Hughes and Djohadze, 1980; Thom et al., 1981; Head et al., 1983; Horsfall, 1987; Ross, 2000); and (4) dating of post-bomb live-collected shell specimens (Gillespie and Polach, 1979; Rhodes et al., 1980). The following discussion will briefly review the results of these studies with a particular focus on Queensland and eastern Australian studies.

Dating Pre-Bomb Live-Collected Shell Specimens

Rhodes et al. (1980) tested the validity of the Gillespie correction for the Gulf of Carpentaria by dating two marine shell samples live-collected in 1903 by Charles Hedley offshore of Mapoon, ca.80 km north of Weipa (Table II) (Rhodes et al., 1980). Note that the ^{14}C ages reported in Table II have had the age correction for difference in time between live-collection in A.D. 1903 and A.D. 1950 calculated by Rhodes et al. (1980:Table 1) removed. The results are statistically indistinguishable from the six results produced by the original Gillespie study (T'=4.63; $\chi^2_{7:0.05}$=14.07). Prior to the present study, these are the only other live-collected specimens dated in Queensland since the original Gillespie (1977) study. Dating of live-collected specimens elsewhere in Australia has similarly reinforced the general applicability of the Gillespie value with all results statistically indistinguishable from the original value (see Bowman and Harvey, 1983; Gill, 1983; Bowman, 1985a, 1985b).

Table I. Original 1970s series of radiocarbon dates obtained on live-collected marine shell samples from Australian waters presented by Gillespie (1977; Gillespie and Temple, 1977). Historical ages of shell samples were converted to equivalent global marine model ages using data from Stuiver et al. (1998a). ΔR was calculated by deducting the equivalent marine model age of the historical age of the shell sample from the ^{14}C age of the shell sample (after Stuiver et al., 1986:1020). ΔRσ=√(σhistorical age^2+σmarine model age^2+σ^{14}C age^2) (Gillespie, 1982). The uncertainty in the marine model age includes estimated error in the calibration dataset (derived from Stuiver et al., 1998a). Error-weighted means are calculated using formulae in Ward and Wilson (1978). Samples: Mo=*Mactra obesa*; Pb=*Pinna bicolor*; Pm=*Pinctada margaritifera*; Pl=*Proxichione laqueata*; Dd=*Donax deltoides*; Kr=*Katelysia rhytiphora*.

Site	Lab. No.	Sample	Historical Age(year AD)	Marine Model Age	$\delta^{13}C$[a] (‰)	$D^{14}C$[b] (‰)	^{14}C Age (years BP)[c]	ΔR (^{14}C years)
Torres Strait	SUA-354/1	Mo	1875±3	476±6	0±2	-58±8	553±68	77±68
Torres Strait	SUA-354/2	Pb	1875±3	476±6	0±2	-56±10	536±85	60±85
Torres Strait	SUA-357	Pm	1909	451±7	0±2	-49±10	443±84	-6±85
Garden Is.	SUA-355	Pl[d]	1930	458±10	0±2	-55±10	474±85	16±85
Adelaide	SUA-393	Dd[ef]	1937±2	463±8	0±2	-70±10	596±86	132±87
Narooma	SUA-356	Kr	1950	473±13	0±2	-58±10	480±85	7±86
Error-weighted mean:								50±33

a Assumed value only (Gillespie & Polach, 1979:410).

b Value corrected for ^{14}C decay between year of live-collection and AD 1950 (Gillespie & Polach, 1979:410) (see text).

c Value calculated from the $D^{14}C$ presented by Gillespie & Temple (1977) and Gillespie & Polach (1979) after removal of the age correction (see text).

d Bowman (1985b:Table 1) reports as *Pinna bicolor*.

e Bowman (1985b:Table 1) reports as *Pinetoda margaritifera*.

f Gillespie & Temple (1977:29) and Gillespie & Polach (1979:411) report as *Conuber incei*.

Table II. Radiocarbon dates obtained on live-collected marine shell samples of known historical age from the Gulf of Carpentaria (Rhodes et al., 1980). Samples: A=*Anadara* sp.; Tt=*Telescopium telescopium*. See caption for Table I for details of calculations.

Site	Lab. No.	Sample	Historical Age (year AD)	Marine Model Age	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C Age (years BP)	ΔR (^{14}C years)
Mapoon	ANU-1828	A	1903	454±7	–	–	576±60	122±60
Mapoon	ANU-2092	Tt	1903	454±7	–	–	436±60	-18±60
Error-weighted mean:						–	506±42	52±42

Radiocarbon Dating of Coral Cores with Clear Growth Bands

Reimer and Reimer (2000) have recently calculated two ΔR values for the central Queensland coast from high precision $\Delta^{14}C$ results for annual and biannual coral (*Porites australiensis*) core samples presented by Druffel and Griffin (1993, 1995, 1999). The first core was from the outer edge of Abraham Reef, part of Swains Reef, located ca.200 km east of Gladstone (22°S, 153°E) and spans 323 years from A.D. 1635 - A.D. 1957 (Figure 1). The core site is well flushed by open ocean waters. The radiocarbon record exhibits pronounced variation between A.D. 1680 and 1730 that do not correspond to variation documented for atmospheric radiocarbon from tree ring studies (Druffel and Griffin, 1993). The second core site is at Heron Island, ca.60 km east of Gladstone (22°S, 152°E), spanning 106 years from A.D. 1849 - A.D. 1950. Reimer and Reimer (2000) calculated ΔR values by averaging biannual $\Delta^{14}C$ data from A.D. 1800 - A.D. 1900 for Abraham Reef and for A.D. 1824 - A.D. 1924 for Heron Island (Table III). The results are indistinguishable and combine to give a ΔR = +11 ± 7 (T'=0.13; $\chi^2_{1:0.05}$=3.84).

Dating Shell/Charcoal Paired Samples from Archaeological Sites

In the absence of live-collected specimens and well-dated coral cores, several studies have been made of stratigraphically-associated shell/charcoal paired samples. As part of early studies, Gillespie and Temple (1977:Table 4; see also Gillespie, 1977; Gillespie and Polach, 1979:Table 6) calculated the marine reservoir age for 37 marine shell samples from nine archaeological sites by comparing them with the ^{14}C age of charcoal samples assumed to be temporally equivalent because of archaeological association. These shell/charcoal pairs came from sites on the New South Wales coast, with one site each from the Northern Territory, Victoria, and Tasmania. The calculated age difference for the shell samples ranged from -820 to +725 relative to the calculated charcoal value with a mean age difference of 283 years (shells older than charcoal). Variance to the expected 450 ± 35 value derived from the live-collected historical specimens (see above) was primarily attributed to the lack of integrity of midden deposits, with the investigators concluding that "these middens are not ideal sites for the determination of past relationships between terrestrial and marine sample activities" (Gillespie and Polach, 1979:418). Hughes and Djohadze (1980) conducted a study of pairs from the Bass Point midden in south New South Wales finding a mean age difference of 270 years (shells older than charcoal). They suggested that the similarity of this result to the mean of 283 years derived from Gillespie and Temple's (1977) study indicated that the marine reservoir effect for this region may be less than the Gillespie value of 450 ± 50 years. However, the apparent similarity of this figure to that derived from paired shell/charcoal samples by Gillespie and Polach (1979) was likely fortuitous because of the contingent nature of local reservoir conditions outlined above. Studies by Head et al. (1983) and Luebbers (1978), on the other hand, have generally shown good agreement with the generalised correction factor.

In Queensland, only two limited studies of shell/charcoal paired samples are available. Horsfall (1987:404) presented a single pair from the Bramston Beach Midden 1 just south of Cairns indicating ΔR= -364 ± 69 with an apparent age difference of only 40 ^{14}C years. This result is much lower than expected and most likely resulted from a lack of contemporaneity between the shell and charcoal samples selected. Horsfall (1987:181) noted that this paired sample was part of a wider program of assessment of marine reservoir effect in north Queensland although apparently no further research was conducted. Data presented by Ross et al. (2000; Ross and Duffy, 2000) from the Peel Island Lazaret Midden in central Moreton Bay, southeast Queensland, indicated potentially significant deviations from the open ocean ΔR value although full results are not available.

Table III. ΔR values for Abraham Reef and Heron Island coral cores (after Reimer and Reimer 2000). Samples: *Porites australiensis*. See caption for Table I for details of calculations.

Site	Lab. No.	Sample	Historical Age (year AD)	Marine Model Age	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C Age (years BP)	ΔR (^{14}C years)
Abraham Reef	WH&AA Series	Coral	1850	487±8	–	–	500±6	13±10
Heron Island	WH&AA Series	Coral	1874	476±8	–	–	484±6	8±10
Error-weighted mean:						–	492±4	11±7

Table IV. Post-1950 live-collected shell specimens (Gillespie and Polach, 1979:Table 5; Rhodes et al., 1980:Table 1). Samples: Mep=*Mytilus edulis planulatus*; Pe=*Pyrazus ebeninus*; V=*Volachlamys* sp.; Ss=*Saccostrea succulata*.

Site	Lab. No.	Sample	Historical Age (year AD)	%Modern
Macleay Is.	SUA-218/1	Mep	1973	105.9±0.8
Macleay Is.	SUA-218/2	Pe	1973	104.6±0.8
Charon Point	ANU-1173	Ss	1973	116.0±0.7
Edward River	ANU-2099	V	1978	119.7±0.9

Dating Post-Bomb Live-Collected Shell Specimens

Another approach to determining regional variation in marine reservoir effect has been to date post-1950 (post-bomb) live-collected marine shells (Table IV). Gillespie and Polach (1979:Table 5; see also Gillespie, 1977:Table 4) presented results of three such dates on samples collected in 1973 from Queensland (two from Moreton Bay and one from near Mackay), while Rhodes et al. (1980:Table 1) report a single determination from a specimen collected from a depth of 25 m offshore from Edward River on the Gulf of Carpentaria in 1978. Differences indicated variation in ^{14}C activity of source waters and therefore also local and regional oceanographic processes. Although two of the four post-bomb specimens show good agreement, the results are difficult to interpret because of the lack of detailed regional modelling of post-1950 alteration to carbon reservoirs resulting from nuclear weapons detonation.

Summary

Attempts to investigate marine reservoir effects on the eastern Australian seaboard by dating shell/charcoal paired samples from archaeological sites and post-bomb live-collected shell specimens have met with limited success. The general agreement of studies of pre-bomb live-collected shell specimens with the original Gillespie value has encouraged researchers to apply the original value rather than more recent calculations. Many researchers have, therefore, applied the erroneous ΔR= -5 ± 35 value (e.g., Hiscock and Hughes, 2001) despite the summary of all values available in the Marine Reservoir Correction Database (Reimer and Reimer, 2000). The ΔR values from the coral cores at Abraham Reef and Heron Island currently provide the most detailed information for eastern Australian near-shore waters. Reimer and Reimer (2000) combined the seven independent ΔR values available for northeast Australia to recommended a ΔR= +11 ± 5 (revised value after Torres Strait values were corrected for age, and the Mapoon samples were added at the suggestion of the author).

The Present Study: Methods

A search of the Queensland Museum and Australian Museum malacology collections for pre-A.D. 1955, live-collected shell specimens from the coast between Hervey Bay and Rockhampton resulted in the identification of 13 specimens representing three species from three locations with sufficient levels of documentation for the purposes of this study. Five specimens from three locations were selected for radiocarbon analysis (Figure 2a; Table V). A single sample from each location was dated by conventional liquid scintillation counting (LSC) and a duplicate sample from both the Gladstone and Port Curtis sample groups was submitted for accelerator mass spectrometry (AMS) determination. The three live-collected species selected for this study are all filter-feeding bivalves with limited mobility and are consequently good candidates for examining local reservoir conditions. Several studies have indicated that detrital-feeders (such as grazing gastropods) are potentially problematic as ingested organic carbon from diverse sources can become incorporated into shell structures through metabolic action (Tanaka et al., 1986; Hogg et al., 1998). Notably, two of the three species dated (*D. deltoides* and *A. trapezia*) are common in coastal Aboriginal archaeological deposits in the area (Ulm and Lilley, 1999).

Table V. Radiocarbon ages obtained on pre-bomb live-collected marine shell samples from central Queensland. Samples: Dd=*Donax deltoides*; At=*Anadara trapezia*; Vs=*Volachlamys singaporina*. See caption for Table I for details of calculations.

Site	Lab. No.	Sample	Historical Age (year AD)	Marine Model Age	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C Age (years BP)	ΔR (^{14}C years)
Elliott Heads	Wk-6994	Dd	1925±5	455±5	-0.6±0.2	-49.1±7.1	400±60	-55±60
Port Curtis 1	Wk-8457	Vs	1929	458±5	0.3±0.2	-56.0±7.1	460±60	2±60
Port Curtis 2	NZA-12120	Vs	1929	458±5	0.9±0.2	-67.9±6.4	570±60	112±60
Gladstone 1	Wk-8456	At	1904	453±10	0.3±0.2	-58.2±5.7	480±50	27±51
Gladstone 2	NZA-12119	At	1904	453±10	-0.8±0.2	-44.0±6.5	360±60	-93±61
Error-weighted mean:								1±26

No pre-A.D. 1955 live-collected shell specimens were located from fully estuarine contexts in the study area, so that the study of possible estuarine marine reservoir effects relied on examination of shell/charcoal paired samples from excavated archaeological sites. In addition, paired samples are useful in examining variation in ΔR through time because the dating of live-collected specimens (see above) is valid strictly for the period of collection (i.e., the recent past). Eleven shell/charcoal pairs from six archaeological sites representing five separate estuary systems were submitted for radiocarbon dating (Table VI). Archaeological shell/charcoal paired samples were either identified during excavation where associations between samples were obvious (e.g., where charcoal was located in situ inside shell valves; see Figure 3) or selected in the laboratory after consideration of the integrity of the association between samples (e.g., samples derived from densely-packed layers of midden material where the possibility of post-depositional movement is reduced; see Figure 4). In all cases *A. trapezia* was selected as the shell component of the paired samples to reduce variation introduced by differences in the relationship of specific species to the carbon cycle. *A. trapezia* samples ranged from 10-40 mm long with an average of 25 mm. Inglis (1992) found that *A. trapezia* attains a size of 20-30 mm in length within 12 months with large individuals (>40 mm) growing less than ca.1 mm/year up to 70-80 mm. The majority of samples are, therefore, likely to represent relatively short life-spans (<2 years), although sufficient to minimise short-term variation in reservoir conditions. Only the largest blocky fragments of charcoal available were selected for dating although no attempt was made to identify the species involved (cf. Higham and Hogg, 1995).

All conventional radiocarbon determinations and sample preparation for AMS determinations (including CO_2 production) were undertaken by the University of Waikato Radiocarbon Dating Laboratory to reduce the effects of inter-laboratory variation in sample preparation and counting procedures. AMS dating was conducted by the Rafter Radiocarbon Laboratory of the Institute of Geological and Nuclear Sciences (IGNS). Charcoal samples were washed in hot 10% HCl to remove possible contaminants. Marine and estuarine shell samples were cleaned and washed in an ultrasonic bath before acid-etching (2M HCl) for 100 seconds to minimise the possibility of contamination through isotopic exchange between the sample and its environment. All archaeological shell samples were subjected to x-ray diffraction (XRD) analysis to establish the absence of recrystallised $CaCO_3$ (calcite) in the shell structure. All conventional samples were converted to benzene through hydrolysis and ^{14}C activity measured by liquid scintillation counting (LSC) (Higham and Hogg, 1997). For AMS samples CO_2 was converted to graphite before introduction to the mass spectrometer. Radiocarbon ages are reported as conventional radiocarbon ages (Stuiver and Polach, 1977) and the conventional ages include a laboratory error multiplier of 1.22 (Higham and Hogg, 1997).

Table VI. Shell/charcoal paired samples from the southern Curtis Coast. ^{14}C ages obtained on charcoal samples were reduced by 39±13 years to correct for ^{14}C variation between northern and southern hemispheres (McCormac et al., 2001). An estimate of the atmospheric calibration curve error, derived from an average of estimated error in the 1σ span of the age, was also included. Therefore, atmospheric age $\sigma = \sqrt{(\sigma^{14}C\ age^2 + \sigma southern\ hemisphere\ offset^2 + average\ of\ calibration\ curve\ error^2)}$ (Gillespie, 1982). The 1σ range of the ^{14}C value was converted to the equivalent global marine model 1σ range using atmospheric ages interpolated from INTCAL98 to the same calendar year as MARINE98 (Stuiver et al., 1998a). ΔR was calculated by deducting the mid-point of the equivalent marine model age of the charcoal determination from the ^{14}C age of the paired marine shell sample. $\Delta R\sigma = \sqrt{(\sigma marine\ model\ age^2 + \sigma marine\ shell\ age^2)}$ (Gillespie, 1982). This method is illustrated for pair NZA-12117/Wk-8326 in Figure 5. Double lines enclose individual shell/charcoal paired samples.

Site	Lab. No.	Sample	$\delta^{13}C$ (%)	^{14}C Age (years BP)	Equivalent Marine Model Age	ΔR (^{14}C years)
Seven Mile Creek						
Seven Mile Creek Mound	NZA-12272	charcoal	-26±0.2	1260±80	1592±113	–
Seven Mile Creek Mound	Wk-8324	*A. trapezia*	-0.9±0.2	3540±80	540±80	+1948±139
Seven Mile Creek Mound	NZA-12117	charcoal	-25.7±0.2	3500±60	3801±71	–
Seven Mile Creek Mound	Wk-8326	*A. trapezia*	-0.8±0.2	3610±70	3610±70	-191±100
Seven Mile Creek Mound	NZA-12273	charcoal	-23.4±0.2	3570±60	3854±70	–
Seven Mile Creek Mound	Wk-8327	*A. trapezia*	-1.2±0.2	3780±60	3780±60	-74±92
Seven Mile Creek Mound	NZA-12118	charcoal	-27.8±0.2	3660±60	3959±76	–
Seven Mile Creek Mound	Wk-8328	*A. trapezia*	-0.5±0.2	3750±60	3750±60	-209±97
Round Hill Creek						
Eurimbula Site 1	Wk-5215	charcoal	-25.3±0.2	1600±160	1932±164	–
Eurimbula Site 1	Wk-3944	*A. trapezia*	-0.8±0.2	2390±60	2390±60	+458±174
Tom's Creek Site Complex	Wk-7686	charcoal	-25.3±0.2	540±50	935±35	–
Tom's Creek Site Complex	Wk-7838	*A. trapezia*	-0.9±0.2	630±50	630±50	-305±61
Tom's Creek Site Complex	Wk-7681	charcoal	-27.2±0.2	modern	modern	–
Tom's Creek Site Complex	Wk-7682	*A. trapezia*	-1.2±0.2	620±50	620±50	≥+620±50
Middle Creek						
Ironbark Site Complex	Wk-8557	charcoal	-26.0±0.2	200±140	627±140	–
Ironbark Site	Wk-8558	*A. trapezia*	-0.3±0.2	590±60	590±60	see text

Complex						
Pancake Creek						
Pancake Creek Site Complex	Wk-6993	charcoal	-26.8±0.2	700±140	1059±112	–
Pancake Creek Site Complex	Wk-6992	*A. trapezia*	-0.3±0.2	800±80	800±80	-249±137
Mort Creek						
Mort Creek Site Complex	Wk-7458	charcoal	-26.5±0.2	1970±80	2279±65	–
Mort Creek Site Complex	Wk-6987	*A. trapezia*	-1.5±0.2	2260±50	2260±50	-18±82
Mort Creek Site Complex	Wk-7458	charcoal	-26.5±0.2	1970±80	2279±65	–
Mort Creek Site Complex	Wk-7836	*A. trapezia*	-1.4±0.2	2320±50	2320±50	+42±82

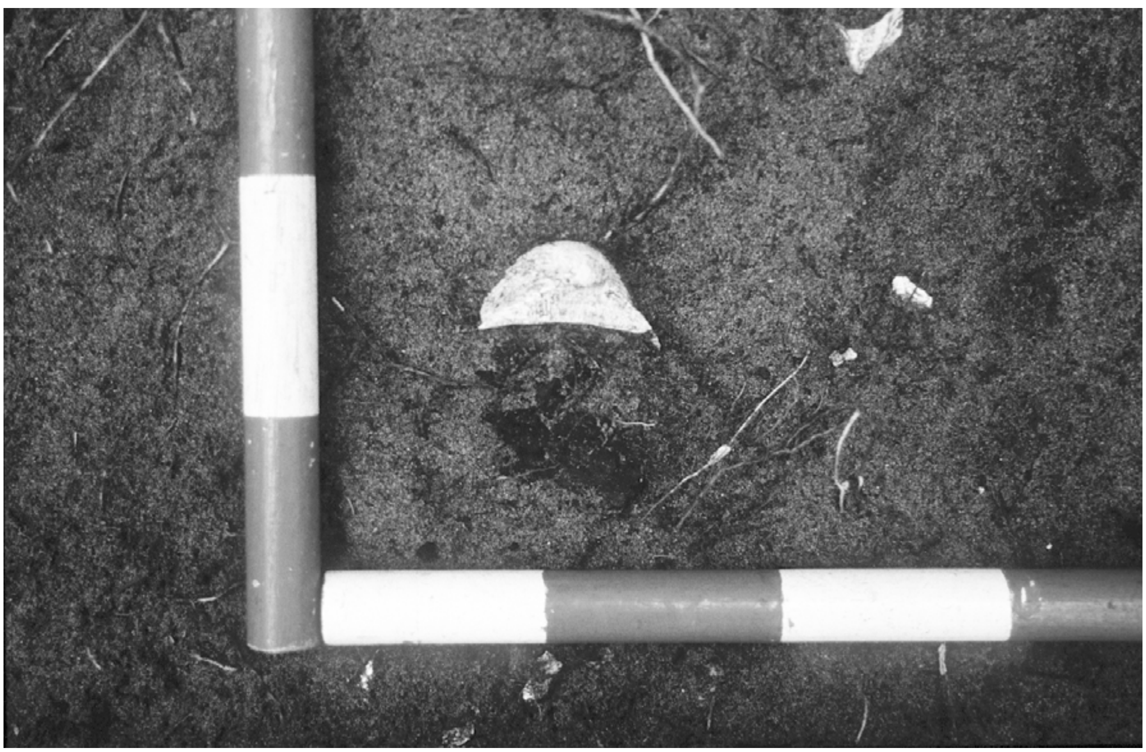

Figure 3. Shell/charcoal paired sample (Wk-7682/Wk-7681) from Tom's Creek Site Complex (Photograph: S. Ulm).

Figure 4. Compact shell deposit at the Seven Mile Creek Mound from which four shell/charcoal paired samples were dated (Photograph: S. Ulm).

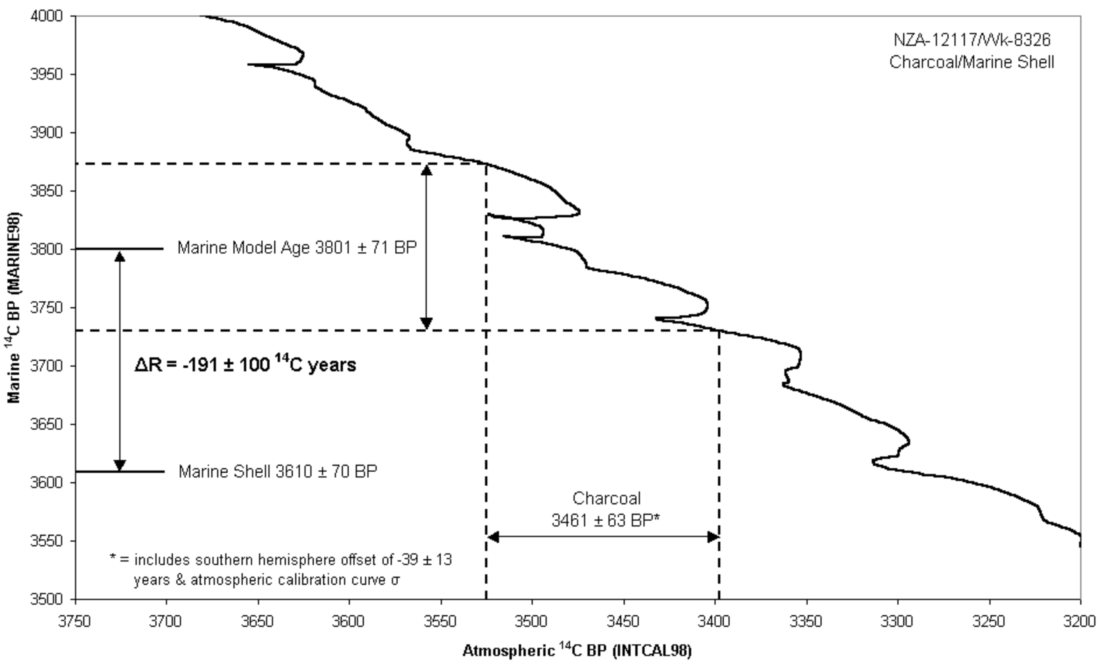

Figure 5. Example of ΔR calculation method for pair NZA-12117/Wk-8326 (see caption for Table VI).

Results

Live-Collected Known-Age Samples

A single 19.6 g specimen of *Donax deltoides* (Lamarck, 1818), variously known as pipi or eugarie, was dated. May collected this specimen, as well as five others, in the 1920s from Elliott Heads (24°04'S, 151°09'E) just south of Bundaberg (Queensland Museum MO63339) (Figure 2a; Table V). A more precise assignment of the time of live-collection is not available, and a collection date of A.D. 1925 ± 5 is assumed in calculating an equivalent model marine age of 455 ± 5 years. *D. deltoides* is a littoral sand dweller on high-energy beaches and would therefore be unlikely to be associated with estuarine water circulation patterns (Coleman, 1981; Lamprell and Whitehead, 1992). The result of 400 ± 60 yr B.P. (Wk-6994) is equivalent to ΔR= -55 ± 60 (Table V).

Two specimens of *Volachlamys singaporina* (Sowerby, 1842), commonly known as the Singapore scallop or Cuming's scallop, from Port Curtis were dated. These were from a collection of four small articulated shells (with the desiccated animal enclosed) collected by M. Ward and W. Boardman during dredging in July 1929 from shallow water (16-22 m) just southeast of Gladstone (Australian Museum C369716) (Figure 2a; Table V). Coordinates (23°55'S, 151°23'E) place the collection site off-shore of the mouth of the Boyne River. *V. singaporian* prefers shell debris habitats and occurs in shallow water throughout northeast Australia (Lamprell and Whitehead, 1992). The total shell weights for each of these specimens is low (8.8 g, 1.7 g, 1.5 g, 0.6 g). The largest sample was conventionally dated to 460 ± 60 yr B.P. (Wk-8457), equivalent to ΔR= +2 ± 60, while the second largest sample was dated by accelerator mass spectrometry (AMS) to 570 ± 60 yr B.P. (NZA-12120), equivalent to ΔR= 112 ± 60. The two dates are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of 515 ± 42 (T'=1.68; $\chi^2_{1:0.05}$=3.84), equivalent to ΔR= +57 ± 42 (T'=1.68; $\chi^2_{1:0.05}$=3.84).

Two specimens of *Anadara trapezia* (Deshayes, 1840), variously termed mud ark or Sydney cockle, were dated. These specimens came from a collection of four small valves live-collected pre-1904 from Gladstone (Australian Museum C018788) (Figure 2a; Table V). Coordinates (23°51'S, 151°16'E) place the collection site under the present eastern margin of the city of Gladstone. This area consisted of inter-tidal flats fronting Port Curtis before extensive land reclamation in the second half of the twentieth-century. The specimens were presented to the Australian Museum by Charles Hedley in 1904. The accompanying museum label simply dates the specimens as pre-1904. Hedley stayed briefly in Gladstone en route to a field excursion to Masthead Island in October-November 1904 (Hedley, 1906). The coincidence of the dates for the fieldtrip and the donation to the museum suggests the samples were collected during the 1904 fieldtrip. Furthermore, in a 1904 paper, Hedley (1904:206) described the distribution of *A. trapezia* (under the name *Arca lischkei*; see Murray-Wallace et al., 2000) as ranging from "Bass Straits [sic] to Moreton Bay" but in a subsequent paper as reaching "the tropics" (Hedley, 1915:51). For the purposes of this study, I therefore assume that the *A. trapezia* specimens were live-collected in October-November 1904. *A. trapezia* is common on intertidal mud flats in southeast Australia and is strongly associated with the presence of sea grasses (Inglis, 1992; Murray-Wallace et al., 2000). The small size of the four individual specimens (11.5 g, 4.3 g, 4.6 g, 4.5 g) led to the adoption of the same dating strategy as that for *V. singaporian* (see above). The largest sample was conventionally dated to 480 ± 50 yr B.P. (Wk-8456), equivalent to ΔR= +27 ± 51, while the second largest sample was dated by accelerator mass spectrometry (AMS) to 360 ± 60 yr B.P. (NZA-12119), equivalent to ΔR= -93 ± 61. The two dates are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of 431 ± 38 (T'=2.36; $\chi^2_{1:0.05}$=3.84) equivalent to ΔR= -22 ± 39 (T'=2.28; $\chi^2_{1:0.05}$=3.84).

The five ΔR calculations presented in Table V are indistinguishable at the 95% confidence level from the two averaged coral ΔR values for central Queensland presented in Table III (Reimer and Reimer, 2000) and combine to give an error-weighted mean of ΔR= +10 ± 7 (T'=7.17; $\chi^2_{6:0.05}$=12.59). This correction is currently the best estimate of variance in local open water marine reservoir effect from the modelled global marine calibration curve for the central Queensland coast. Although this new value is not significantly different from the generalised northeast Australia value of ΔR= +11 ± 5 recommended by Reimer and Reimer (2000), it is based on a larger number of independent local samples with reduced error estimates. Pooling the five new ΔR values (Table V) with the seven used to calculate the northeast Australian value (Tables I-III) results in a revision of this value to +12 ± 7 (T'=12.16; $\chi^2_{11:0.05}$=19.68).

Archaeological Shell/Charcoal Paired Samples

Seven Mile Creek

Four shell/charcoal paired samples were dated from the Seven Mile Creek Mound (SMCM) (see Ulm, 2000, 2001 for site details) (Figure 2b; Table VI). The eight radiocarbon dates available indicated extremely rapid accumulation of the dense shell matrix over a period of less than 350 years between ca.3,900–3,600 cal yr B.P. The deposit, therefore, presented an ideal opportunity to examine localised marine reservoir factors over a relatively short time-span at the base of the known chronology of human occupation of the region. The paired samples were selected at intervals down the 900 mm-deep densely-packed shell deposit from a single 500 mm x 500 mm column (Figure 4). Samples consisted of large articulated *A. trapezia* valves plotted during excavation paired with single fragments of blocky charcoal from the same excavation unit identified during excavation or during laboratory analysis of sieve residues. Single pieces of charcoal were used to avoid combining fragments representing possibly separate events (see Ashmore, 1999).

The four ΔR values are significantly different (T'=199.00; $\chi^2_{3:0.05}$=7.82). The charcoal date NZA-12272 is clearly at odds with the results of the other seven determinations available and indicates a lack of association with the paired shell sample (Wk-8324). This charcoal sample is derived from close to the top of the deposit (70-100 mm) and was probably introduced through percolation down the midden profile. If this pair is excluded, the stratigraphically lower three pairs show good agreement with an error-weighted mean of the remaining three values yielding ΔR= -155 ± 55 (T'=1.23; $\chi^2_{2:0.05}$=5.99). This value is significantly different from the generalised local open ocean value of ΔR= +10 ± 7 (T'=8.65; $\chi^2_{1:0.05}$=3.84) calculated above. This result based on replicate paired samples provides strong evidence that between ca.3,900–3,600 cal yr B.P. the Seven Mile Creek estuary exhibited a ΔR= -155 ± 55.

Round Hill Creek

Analyses were undertaken on three separate shell/charcoal pairs from archaeological sites bordering Round Hill Creek (Figure 2b; Table VI). The creek has a large catchment area and is broad and shallow with an entrance bar inhibiting complete tidal flushing. Significantly, Round Hill Creek is bordered by extensive freshwater wetlands on its southwest margins (see Olsen, 1980:17), with freshwater influxes significantly depressing salinity during the wet season. This suggests that there may be complex hydrological factors operating to periodically introduce large volumes of dissolved atmospheric CO_2 into the estuary system. On the basis of these factors, it was predicted that the estuarine shell dates would reflect uptake of terrestrially-derived carbon mobilized in freshwater runoff with dates more closely approximating results from the charcoal samples.

A single shell/charcoal pair (Wk-3944/Wk-5215) was obtained from Eurimbula Site 1 (ES1) on the west bank of Round Hill Creek from a discrete lens of *A. trapezia* located 300-400 mm below ground surface (see Ulm et al., 1999 for site details). The lens material was bulk sampled and returned to the laboratory for sorting. The charcoal sample is based on small fragments of charcoal recovered from the 3 mm sieve residue. The paired samples exhibit an apparent difference of 790 ^{14}C years with a ΔR value of +458 ± 174 (Table

VI). The shell age is much older than predicted and the most probable explanation for this wide discrepancy is a lack of a close temporal association between the shell and charcoal samples. Although the apparently discrete shell lens from which the samples derive appeared to be a secure stratigraphic context, it is possible that bulk sampling of the lens from the section resulted in contamination by more recent charcoal fragments. Alternatively, some or all of the fragmented charcoal selected for dating may have been intrusive – possibly introduced by tree root activity or crab burrowing which was noted during excavation (see Specht, 1985). Taylor (1987:Table 5.3) notes that contamination of the sample with <20% modern carbon would be sufficient to result in the observed discrepancy. Given the probable lack of association between the shell/charcoal sample this result is not considered as a reliable indicator of local reservoir conditions.

On the opposite side of Round Hill Creek, two separate shell/charcoal paired samples were submitted from the Tom's Creek Site Complex (TCSC) located at the confluence of Tom's Creek and Round Hill Creek (Figure 2b; Table VI). The first pair (Wk-7838/Wk-7686) came from a dense lens of shell ca.220 mm below ground surface. The lens consisted almost exclusively of *A. trapezia* and the rock oyster *Saccostrea commercialis* with occasional fragments of blocky charcoal that were recovered from the 3 mm sieve residue for dating. The paired samples exhibit an apparent difference of 90 ^{14}C years with $\Delta R = -305 \pm 61$. Unfortunately, no absolute result was obtained from the second pair (Wk-7682/Wk-7681) which consisted of a valve of *A. trapezia* packed with charcoal (Figure 3) because the very recent age of the charcoal did not allow a precise assignment of age to be made, although the sample is clearly younger than 200 years (%Modern= 99.5 ± 0.6) (Table VI). The shell component of the sample returned a ^{14}C age of 620 ± 50 yr B.P. (Wk-7682). If the charcoal sample is assumed to exhibit a ^{14}C age of 0 (=A.D. 1950), the paired samples exhibit an apparent difference of ≥620 ^{14}C years with $\Delta R = \geq +620$ (Table VI). Because assignment of an absolute value for ΔR is not possible, this result is rejected from further consideration.

Middle Creek

Although Middle and Pancake Creeks are joined together by a narrow channel (see Figure 2b), they exhibit different morphological attributes and very different hydrological patterns (Olsen, 1980) that require them to be treated as potentially separate estuarine carbon reservoirs. A single paired sample (Wk-8558/Wk-8557) was obtained from the Ironbark Site Complex (ISC) on the lower south margin of Middle Creek (see Reid, 1998 for site details), consisting of whole shells and charcoal fragments collected from the 3 mm sieve residue. Although the pair returned an apparent age difference of 390 ^{14}C years, a ΔR value could not be calculated because the charcoal age is modern at one sigma (Table VI).

Pancake Creek

A shell/charcoal pair (Wk-6992/Wk-6993) was obtained from the Pancake Creek Site Complex (PCSC) on the north bank of Pancake Creek, exhibiting an apparent age difference of 100 ^{14}C years with $\Delta R = -259 \pm 137$ years (Figure 2b; Table VI). The large error estimate associated with this value makes it indistinguishable from the generalised local open ocean value of $\Delta R = +10 \pm 7$. The paired sample consisted of a valve of *A. trapezia* tightly packed with blocky charcoal fragments suggesting a secure stratigraphic association. This site is located close to the broad entrance of the creek, which currently exhibits good tidal flushing and no apparently large terrestrial water input (Olsen, 1980). Terrestrial CO_2 dissolved in water stored in the beach ridges lining the north bank of the creek (possibly with long residence times) may have been introduced into shellfish beds in the intertidal zone.

Mort Creek

At the Mort Creek Site Complex (MCSC), a single blocky charcoal sample (Wk-7458) was paired with two separate shell samples (Wk-6987 and Wk-7836) of *A. trapezia* derived from the middle of a densely-packed shell lens located ca.200-300 mm below ground surface (Table VI) (see Carter et al., 1999 for site details). It was predicted that the result would show good agreement with the open ocean because the site is located near the mouth of Mort Creek (also known as Morris Creek), which can essentially be considered as part of the extensive Rodds Harbour, with a high tidal range and consequent high tidal flushing. Also, Mort Creek is a relatively minor estuary with a small catchment and does not have backing swamps suggesting minimal freshwater input. The samples were derived from a extremely dense lens of shell increasing the possibility of minimal post-depositional movement within the matrix. The two shell samples (Wk-6987 and Wk-7836) show good agreement with apparent age differences of 290 and 350 ^{14}C years, respectively. The values of ΔR= -18 ± 82 and +42 ± 82 are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of ΔR= +12 ± 58 (T'=0.27; $\chi^2_{1:0.05}$=3.84).

Summary

As expected, the conventional radiocarbon age of shell samples was consistently older than that of paired charcoal samples (Table VI). Major discrepancies exist between the three sets of pairs from Round Hill Creek with only one result (ΔR= -305 ± 61) considered free of obvious interpretation problems. If the pair from Eurimbula Site 1 (Wk-5215/Wk-3944) and the indeterminate results from Tom's Creek Site Complex (Wk-7682/Wk-7681) and the Ironbark Site Complex (Wk-8558/Wk-8557) are excluded, the results from other paired samples support the prediction that estuarine shell samples will exhibit a lower marine reservoir correction factor than the local open ocean value of ΔR= +10 ± 7. Direct comparison of the ^{14}C ages shows that shell samples are 90 to 390 ^{14}C years older than their paired charcoal sample.

Discussion

The five dates reported from pre-A.D. 1955 live-collected shell specimens from between the Elliott River and Gladstone combined with the two previous coral ΔR values indicate, at least for the recent past, that open ocean reservoir influences are in the order of ΔR= +10 ± 7. These results support the general conclusions of previous studies and are statistically indistinguishable from the five dates on live-collected shells from Torres Strait (Gillespie and Temple, 1977) and the Gulf of Carpentaria (Rhodes et al., 1980), although the error estimates are reduced. The error-weighted mean of all 12 ΔR values available for pre-bomb live-collected Queensland shells and corals indicate that a generalised ΔR= +12 ± 7 (T'=12.16; $\chi^2_{11:0.05}$=19.68) is appropriate for open marine contexts in northeast Australia and supercedes the ΔR= -5 ± 35 recommended by Stuiver et al. (1986:Figure 10A, Table 1). Relative consistency observed between determinations on live-collected specimens from northeast Australia is probably largely a function of the broad shallow continental shelf topography that mitigates the influence of ^{14}C-depleted deep ocean upwelling by ensuring mixing through wave and current action (Taylor, 1987:8).

These results stand in marked contrast to results obtained from estuaries on the basis of shell/charcoal paired samples from archaeological contexts. Results indicate estuary-specific values of ΔR= -155 ± 55 for Seven Mile Creek and ΔR= +12 ± 58 for Mort Creek. Less confidence is placed in the ΔR values calculated for other estuaries because of suspected problems of association (e.g., Round Hill Creek) or the existence of only a single paired result (Pancake Creek). However, as a first approximation, I suggest that ΔR= -259 ± 137 for Pancake Creek, and ΔR= -305 ± 61 for Round Hill Creek. Figure 6 schematically represents all the ΔR values calculated in this study. The high level of variance observed in regional estuarine ΔR values is best explained as a function of the structure of the carbon reservoir in which the sample was formed. Many coastal archaeological sites, and all of those from which shell/charcoal paired dates are reported in this paper, are in environments of restricted circulation; that is, they are located in estuaries where significant variation in terrestrial carbon input and exchange with the open ocean conditions might reasonably be assumed to deviate from that of the mixed surface layer of the ocean. Intra-estuary spatial variation in ΔR values is considered to be negligible. Studies by Hogg et al. (1998:184) found that tidally-dominated estuaries with catchments free of calcareous materials (such as those of the study area) "should exhibit a uniform distribution of ^{14}C throughout the estuary." These ΔR values are, however, a first approximation only because they do not account for variation in specific reservoir parameters through time. In the absence of additional information, it is assumed that temporal changes in ΔR for a specific region must coincide with changes in the global model ocean (Stuiver et al., 1998b:1135). Time-factored ΔR(t) (t=time) for estuarine environments can be calculated through large-scale studies of annual coral records and/or paired shell/charcoal samples from a variety of periods (e.g., Kennett et al., 1997; Ingram, 1998). Preliminary examination of ΔR values of the Abraham coral record through time, for example, indicates shifts from up to ΔR= +39 ± 10 in A.D. 1730 to ΔR= -41 ± 8 in A.D. 1950 (Reimer, personal communication, 2001).

The potential impact of differences in ΔR between estuaries can be illustrated through a case-study of the Seven Mile Creek Mound, the oldest dated open archaeological site on the central Queensland coast. Table VII and Figure 7 present the calibrated results of four conventional radiocarbon dates of shell samples (*A. trapezia*) using four different ΔR values: ΔR= -5 ± 35 (recommended by Stuiver et al., 1986 and Stuiver and Braziunas, 1993); ΔR= +50 ± 33 (the corrected version of this value; see above); ΔR= +10 ± 7 (calculated for open water of the study region; see above); and ΔR= -155 ± 55 (actual determined value for the Seven Mile Creek estuary based on shell/charcoal paired samples from the Seven Mile Creek Mound; see above). Conventional radiocarbon ages were calibrated with the CALIB (v4.3) computer program (Stuiver and Reimer, 1993) using the marine calibration dataset of Stuiver et al. (1998a). The calibrated ages reported span the 2σ age-range.

Table VII shows overall variation in the central tendencies of the calibrated radiocarbon ages between the generalised Australian value of ΔR= +50 ± 33 and the actual estuary-specific value of ΔR= -191 ± 37 is in the order of ~300 years. The difference between the regionally-determined open ocean value of ΔR= +10 ± 7 and the estuary-specific determined value is ~250 years.

The identification of variability in estuarine ΔR values has significant implications for archaeology in Queensland. For archaeological sites in Queensland, some 25% (n=216) of radiocarbon determinations are based on marine or estuarine shell samples (Ulm and Reid, 2000). In some coastal regions, the reliance on marine and estuarine shell samples for dating is often pronounced. For example, in sites dated in the Keppel Island group, more than 95% (n=21) dates are on marine shell (Rowland, 1981, 1992; Ulm and Reid, 2000).

Table VII. Calibrated radiocarbon ages from the Seven Mile Creek Mound, using various ΔR values (see text).

Lab. No.	^{14}C Age (years BP)	Calibrated Age/s ΔR= +50±33 (years cal BP)	Calibrated Age/s ΔR= +10±7 (years cal BP)	Calibrated Age/s ΔR= -5±35 (years cal BP)	Calibrated Age/s ΔR= -155±55 (years cal BP)
Wk-8324	3540 ± 80	3567(3362)3164	3606(3399)3235	3633(3429)3237	3850(3608)3372
Wk-8326	3610 ± 70	3630(3442)3269	3665(3470)3339	3690(3487)3338	3919(3684)3462
Wk-8327	3780 ± 60	3827(3637)3465	3855(3687)3550	3893(3700)3548	4140(3904)3688
Wk-8328	3750 ± 60	3808(3618)3444	3824(3651)3491	3859(3677)3485	4089(3867)3652

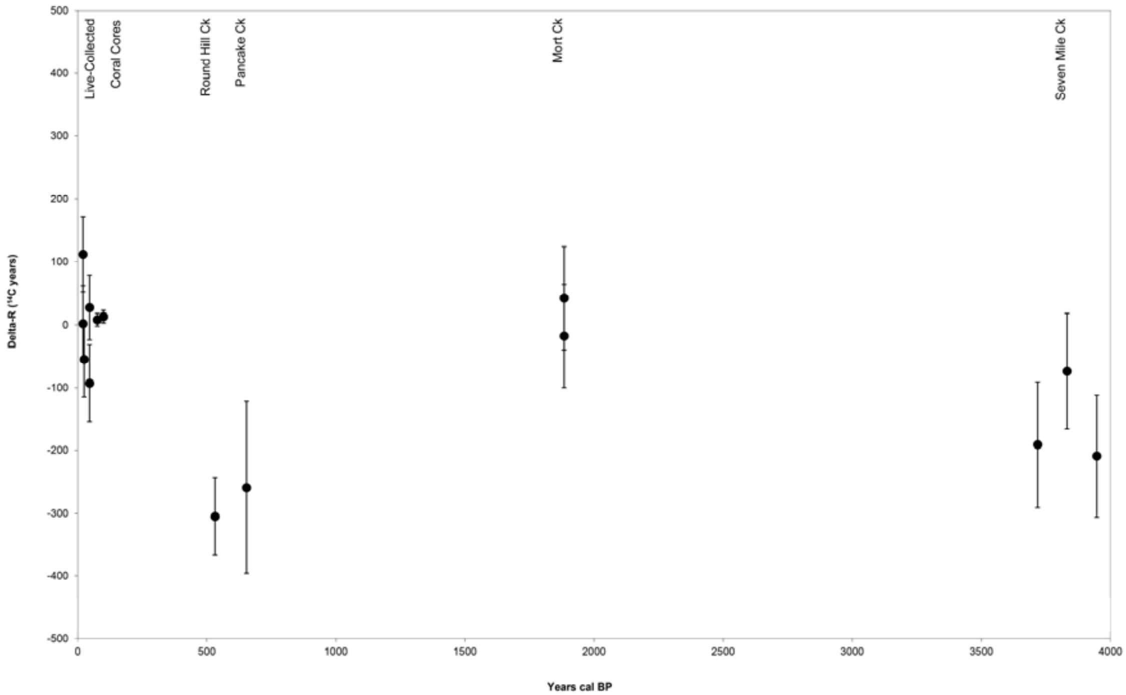

Figure 6. ΔR values calculated for the southern Curtis Coast.

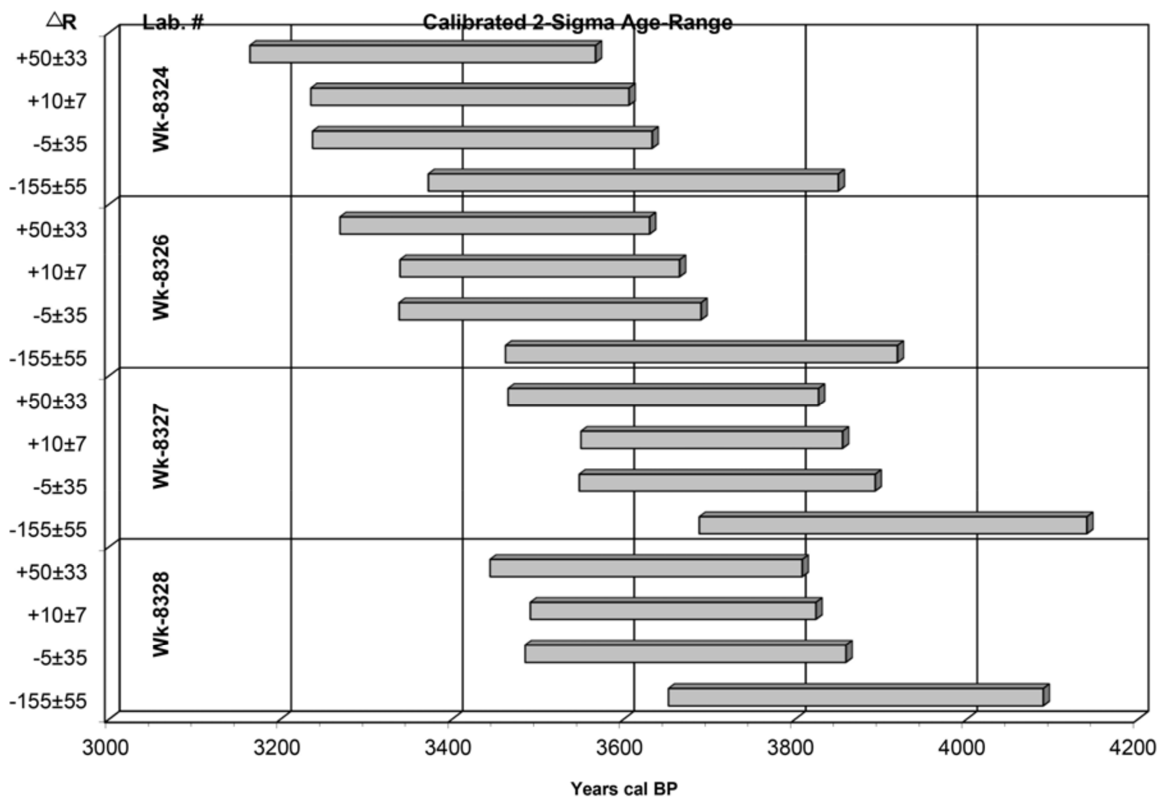

Figure 7. Calibrated radiocarbon age-ranges from the Seven Mile Creek Mound, using various ΔR values (see Table VII).

Conclusion

This limited study has clearly demonstrated the possibility of significant variation in local marine reservoir effect in the central Queensland study area. Clearly, radiocarbon age determinations based on marine specimens need to be considered in the context of local conditions (such as location, hydrology, geology, sedimentology). In confined areas such as estuaries, deviation of marine reservoir effect from global open ocean values may be pronounced. Possible adjustments of several hundred years to these determinations to take into account local marine reservoir effect has obvious implications for arguments for regional cultural change based on tightly-defined radiocarbon chronologies. In estuarine contexts in Queensland, a localised estuary-specific correction factor must be calculated that takes into account alterations in reservoir parameters through time (Spennemann and Head, 1996).

Sequences of radiocarbon dates have been employed widely in Australian studies to compare cultural chronologies at the local, regional and continental scales (e.g., Bird and Frankel, 1991; Holdaway and Porch, 1995; Ulm and Hall, 1996; Lourandos and David, 1998). Most studies have assumed rather than demonstrated, however, direct comparability between individual radiocarbon determinations. The assessment of the validity of individual dates and suites of dates has become increasingly important as cultural chronologies are progressively refined. Recent examples of these more particularistic studies include establishing the antiquity of human occupation in New Zealand (Higham and Hogg, 1997) and other Pacific islands and the onset of intense discard at midden sites around southeast Queensland (Ulm and Hall, 1996). Such issues have considerable ramifications for normative models of social and economic change in Aboriginal societies in the late Holocene where demonstrated contemporaneity between sites and regions is critical to the validity of abstract regional- and continental-scale models (e.g., Lourandos, 1997).

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