

# 4

## Marine and estuarine reservoir effects in central Queensland: determination of $\Delta R$ values

### Introduction

This chapter forms the first of two chapters addressing technical issues critical to the rest of the study. Uncertainty in radiocarbon ages introduced by variation in marine and estuarine reservoir effects through space and time are a major issue in the investigation and dating of coastal archaeological deposits. In areas where no local studies have been undertaken reliance on generic regional correction values can reduce confidence in the accuracy of individual radiocarbon dates obtained on marine and estuarine samples (e.g. mollusc shell, fish bone etc) and the chronologies constructed on the basis of these dates. As a technical component of this study a series of five marine shell specimens live-collected between AD 1904 and AD 1929 and 12 shell/charcoal paired samples from archaeological contexts were radiocarbon dated to determine local  $\Delta R$  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.

The marine reservoir effect (also known as the oceanic reservoir correction factor, marine shell correction factor or surface ocean water reservoir effect) of  $450 \pm 35$   $^{14}\text{C}$  years calculated for Australia by Gillespie (1975, 1977, 1991; see also Gillespie and Polach 1979; Gillespie and Temple 1977) 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; Murray-Wallace 1996; Spennemann and Head 1996; Woodroffe et al. 1986:75, 77; Woodroffe and Mulrennan 1993). 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, 2004), no systematic evaluation of the applicability of this generalised marine reservoir effect has been undertaken in the region.



Figure 4.1 Map of Australia, showing places mentioned in the text. The boxed area indicates the southern Curtis Coast study area.

Since 1993, 20 archaeological sites have been test excavated in central Queensland under the auspices of the Gooreng Gooreng Cultural Heritage Project (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 100km from the coast (Figs 4.1–4.2). 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 ( $n=38$ ), while those from sites on the coast include wood charcoal ( $n=27$ ), marine shell ( $n=5$ ) and estuarine shell ( $n=32$ ) (see Ulm and Reid 2000, 2004 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).

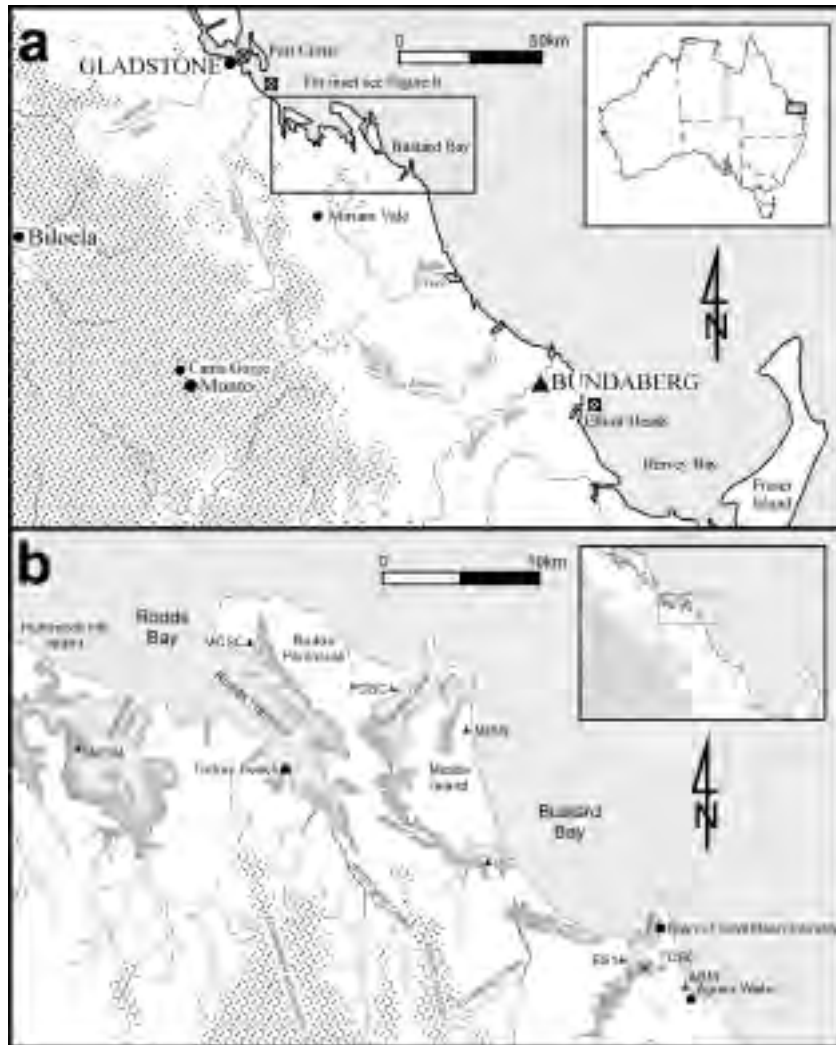


Figure 4.2 (a) Part of the central Queensland coast showing the location of ‘pre-bomb’ live-collected shell specimens (☒) and (b) estuaries and archaeological sites (▲) discussed in the text. SMCM=Seven Mile Creek Mound; MCSC=Mort Creek Site Complex; PCSC=Pancake Creek Site Complex; ISC=Ironbark Site Complex; ES1=Eurimbula Site 1; TCSC=Tom’s Creek Site Complex; ABM=Agnes Beach Midden.

## Background

A basic assumption of the radiocarbon dating method is that the concentration of  $^{14}\text{C}$  in the biosphere is uniform through space and time. Early in the development of the  $^{14}\text{C}$  method, however, it was recognised that certain environments exhibited much slower rates of mixing than the atmosphere, indicating significant variation within and between some  $^{14}\text{C}$  reservoirs. In particular, marine shells (which derive carbon principally from dissolved inorganic carbon in ocean waters) exhibited a systematic age difference from 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 mainly caused by incomplete mixing of upwelling water of ‘old’ inorganic carbonates from the deep ocean, where long residence times (>1,000 years) cause depletion of  $^{14}\text{C}$  activity through

radioactive decay, resulting in very old apparent  $^{14}\text{C}$  ages (Mangerud 1972). Estuarine reservoirs are even more complex with the interaction and incomplete mixing of  $^{14}\text{C}$  from both terrestrial reservoirs and marine reservoirs from tidal action (Little 1993; Robinson and Thompson 1981:50; Stuiver and Braziunas 1993:155). This is generally not the case in open coast contexts, where the effect of terrestrial runoff on near-shore  $^{14}\text{C}$  activity is attenuated by unrestricted circulation that ensures rapid mixing and distribution of atmospherically derived  $^{14}\text{C}$ . In estuarine environments, on the other hand, shellfish (and other estuarine organisms) can obtain a significant proportion of their carbon from  $\text{CO}_2$  dissolved in terrestrial rainwater runoff (i.e. enriched in  $^{14}\text{C}$  activity relative to depleted marine waters). The more atmospheric  $\text{CO}_2$  gained by marine and estuarine shells, the closer the  $^{14}\text{C}$  age value should be to the expected coeval terrestrial sample age. Fluctuations in  $^{14}\text{C}$  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; for example, 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  $^{14}\text{C}$  activity between individual estuaries, regardless of their proximity (Spennemann and Head 1996). The combined effect of these factors can create an estuarine reservoir age offset of up to several hundred years from the conventionally applied regional open surface water figure. For example, Kirch (2001) has documented strongly negative  $\Delta R$  values for shallow tropical lagoons in the Pacific with limited exchange with the open ocean. Paired samples from two sites in the Mussau Islands in the Bismarck Archipelago dated by Kirch (2001) indicate  $\Delta R$  values of up to  $-320$ , with a further pair from Ofu Island, American Samoa, yielding  $-230$ .

The potential magnitude of such factors in the southern Curtis Coast study area can be gauged by examining salinity profiles and intra-estuary circulation models. Extended periods of depressed salinity coinciding with periods of distinctly seasonal annual rainfall have been documented in many estuaries on the central Queensland coast. Although the major influences on water movement within these tributaries are prevailing tidal and weather conditions, freshwater inflow associated with periods of high intensity rainfall can cause heavy runoff, which produces short-to-medium-term fluctuations in estuary salinity and turbidity (Olsen 1980a:5). Olsen (1980a) notes that tidal flushing of estuaries is generally high, except for a period of depressed salinity between January and March, representing 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 of pre-AD 1955 ('pre-bomb') live-collected shells 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 ( $^{230}\text{Th}/^{234}\text{U}$ ) 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 have been live-collected prior to AD 1955 ('pre-bomb') and the date and location of collection known with confidence. After AD 1955 ('post-bomb') natural levels of  $^{14}\text{C}$  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 AD 1955 may require correction for fossil fuel depletion resulting from large-scale fossil fuel combustion beginning in the late nineteenth century (Aitken 1990; 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 305mm thick excavation units). Results of paired samples can therefore be difficult to interpret because variation could result from (1) temporal variation in ocean properties 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.

In recent years, regional marine reservoir effect has commonly been expressed as  $\Delta R$  (e.g. Erlandson and Moss 1999; Higham and Hogg 1995; Ingram 1998; Ingram and Southon 1996; Kennett et al. 1997; Phelan 1999; Reimer and Reimer 2000). Stuiver et al. (1986; Stuiver and Braziunas 1993) modelled global marine  $^{14}\text{C}$  activity using a simple box diffusion global carbon cycle model of marine reservoir responses to variation in atmospheric  $^{14}\text{C}$  activity. Regional deviations from the modelled marine calibration curve ( $\Delta R$ ) were calculated using radiocarbon ages on live-collected marine shell samples of known historical age (Stuiver et al. 1986:Table 1).  $\Delta R$  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 modelled global marine calibration curve (Q); therefore  $\Delta R = P - Q$  (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  $450 \pm 35$  years using radiocarbon ages of six shell specimens live-collected between AD 1875 and AD 1950 from four locations around the Australian coast. 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 (Table 4.1, Fig. 4.1). The six shells returned a weighted apparent mean age of  $475 \pm 35$  ( $D^{14}\text{C} = -57.7 \pm 4\text{‰}$ ), which was reduced to  $450 \pm 35$  ( $D^{14}\text{C} = -55 \pm 4\text{‰}$ ) after correction for the fossil fuel dilution effect (Gillespie 1991; Gillespie and Polach 1979; Gillespie and Temple 1977; 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  $D^{14}\text{C}$  values that had been 'age corrected for  $^{14}\text{C}$  decay from year of live collection and 1950' (Gillespie and Polach 1979:410) (i.e. the reservoir age of  $450 \pm 35$  is the error-weighted mean of the conventional radiocarbon age minus the age of the samples in AD 1950 plus fossil fuel correction, see Robinson and Thompson 1981:47) (see Gillespie 1977; Gillespie and Polach 1979; Gillespie and Temple 1977).

Stuiver et al. (1986:Table 1) used these results (uncorrected for fossil fuel dilution) to calculate the  $\Delta R$  correction for Australian waters of  $-5 \pm 35$  for application to marine calibration curves (e.g. Stuiver and Braziunas 1993:Fig. 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  $\Delta R = -5 \pm 35$  value had been calculated from the  $D^{14}\text{C}$  reported by Gillespie and Polach (1979:411) after removing an age-correction (see Stuiver et al. 1986:1021). This statement is incorrect, however, because the age-corrected  $D^{14}\text{C}$  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  $\Delta R = -5 \pm 35$  value reported by Stuiver et al. (1986:Table 1,

Fig. 10B; Stuiver and Braziunas 1993:Fig. 14) is thus not the weighted mean of the difference between the age-corrected  $^{14}\text{C}$  ages (rather than the conventional  $^{14}\text{C}$  ages) and the global marine model based on the known historical ages of the specimens. In Table 4.1 the reported radiocarbon ages were calculated from the reported  $\text{D}^{14}\text{C}$  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 (1985a:Table 1) owing to rounding factors. This error was also repeated in the original version of Reimer and Reimer's (2000) internet *Marine Reservoir Correction Database* but has since been corrected at my suggestion.

Table 4.1 Original 1970s series of radiocarbon dates obtained on live-collected marine shell samples from Australian waters presented by Gillespie (1977; Gillespie and Temple 1977).  $\delta^{13}\text{C}$  is an assumed value of  $0\pm 2$  (Gillespie and Polach 1979:410). Historical ages of shell samples were converted to equivalent global marine model ages using data from Stuiver et al. (1998a).  $\Delta\text{R}$  was calculated by deducting the equivalent marine model age of the historical age of the shell sample from the  $^{14}\text{C}$  age of the shell sample (after Stuiver et al. 1986:1020).  $\Delta\text{R}\sigma = \sqrt{(\sigma_{\text{historical age}})^2 + (\sigma_{\text{marine model age}})^2 + (\sigma_{^{14}\text{C age}})^2}$  (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 deltooides*; Kr=*Katelysia rhytiphora*.

SITE	LAB. NO.	SAMPLE	HISTORICAL AGE (YEAR AD)	MARINE MODEL AGE	$\text{D}^{14}\text{C}^{\text{a}}$ (‰)	$^{14}\text{C}$ AGE (YEARS BP) <sup>b</sup>	$\Delta\text{R}$ ( $^{14}\text{C}$ YEARS)
Torres Strait	SUA-354/1	Mo	1875 $\pm$ 3	476 $\pm$ 6	-58 $\pm$ 8	553 $\pm$ 68	77 $\pm$ 68
Torres Strait	SUA-354/2	Pb	1875 $\pm$ 3	476 $\pm$ 6	-56 $\pm$ 10	536 $\pm$ 85	60 $\pm$ 85
Torres Strait	SUA-357	Pm	1909	451 $\pm$ 7	-49 $\pm$ 10	443 $\pm$ 84	-6 $\pm$ 85
Garden Is.	SUA-355	Pl <sup>c</sup>	1930	458 $\pm$ 10	-55 $\pm$ 10	474 $\pm$ 85	16 $\pm$ 85
Adelaide	SUA-393	Dd <sup>de</sup>	1937 $\pm$ 2	463 $\pm$ 8	-70 $\pm$ 10	596 $\pm$ 86	132 $\pm$ 87
Narooma	SUA-356	Kr	1950	473 $\pm$ 13	-58 $\pm$ 10	480 $\pm$ 85	7 $\pm$ 86
Error-weighted mean:							50 $\pm$ 33

a Value corrected for  $^{14}\text{C}$  decay between year of live collection and AD 1950 (Gillespie and Polach 1979:410) (see text).

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

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

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

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

Another source of difference in the results is the use of the 1986 calibration curve to calculate the  $\Delta\text{R}$  values presented by Stuiver et al. (1986:Fig. 10B, Table 1) and Stuiver and Braziunas (1993:Fig. 16). Stuiver and Braziunas (1993:155) state that no 'attempt was made to update the regional  $\Delta\text{R}$  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 BP interval, and they therefore recommend the use of the 1993 marine calibration curves (Stuiver and Braziunas 1993:Fig. 17A–N). In the recent *Marine Reservoir Correction Database*, however, Reimer and Reimer (2000) have recalculated worldwide  $\Delta\text{R}$  values using the 1998 calibration dataset. In the present study, I have recalculated previous  $\Delta\text{R}$  values for the six samples presented in Table 4.1 using the 1998 calibration curve. Using the 1998 instead of the 1986 model results in a reduction of ~20 years in the marine model ages and a corresponding change in  $\Delta\text{R}$  values.

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  $\Delta\text{R}$  standard deviation combines the error estimates of the  $^{14}\text{C}$  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  $\Delta\text{R} = +50\pm 33$  ( $T' = 1.90$ ;  $\chi^2_{5,0.05} = 11.07$ ) (Table 4.1).

## 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 (Bowman 1985a, 1985b; Bowman and Harvey 1983; Gill 1983; Rhodes et al. 1980); (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; Head et al. 1983; Horsfall 1987; Hughes and Djohadze 1980; Luebbbers 1978; Ross et al. 2000; Thom et al. 1981); and (4) dating of 'post-bomb' live-collected shells (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 shells live-collected in 1903 by Charles Hedley offshore from Mapoon, c.80km north of Weipa (Table 4.2) (Rhodes et al. 1980). Note that the  $^{14}\text{C}$  ages reported in Table 4.2 have had the age-correction for difference in time between live collection in AD 1903 and AD 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 also reinforced the general applicability of the Gillespie value, with all results statistically indistinguishable from the original value (see Bowman 1985a, 1985b; Bowman and Harvey 1983; Gill 1983).

Table 4.2 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 4.1 for details of calculations.

SITE	LAB. NO.	SAMPLE	HISTORICAL AGE (YEAR AD)	MARINE MODEL AGE	$^{14}\text{C}$ AGE (YEARS BP)	$\Delta R$ ( $^{14}\text{C}$ 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:						52±42

### Radiocarbon dating of coral cores with clear growth bands

Reimer and Reimer (2000) have recently calculated two  $\Delta R$  values for the central Queensland coast from high precision  $\Delta^{14}\text{C}$  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 c.200km east of Gladstone (22°S, 153°E) and spans 323 years from AD 1635–AD 1957 (Fig. 4.1). The core site is well-flushed by open ocean waters. The radiocarbon record exhibits pronounced variation between AD 1680 and AD 1730 that does not correspond to variation documented for atmospheric radiocarbon from tree-ring studies (Druffel and Griffin 1993). Druffel and Griffin (1993) argue that these variations are attributable to changes in source waters and vertical mixing in the western Coral Sea, related to long-term changes in the nature of El Niño/Southern Oscillation (ENSO) events. The second core site is at Heron Island, c.60km east of Gladstone (22°S, 152°E), spanning 106 years from AD 1849–AD 1955. Reimer and Reimer (2000) calculated  $\Delta R$  values by averaging biannual  $\Delta^{14}\text{C}$  data from AD 1800–AD 1900 for Abraham Reef and for AD 1849–AD 1899 for Heron Island (Table 4.3). The results are indistinguishable and combine to give a  $\Delta R = +11 \pm 7$  ( $T'=0.13$ ;  $\chi^2_{1,0.05}=3.84$ ).

Table 4.3  $\Delta R$  values for Abraham Reef and Heron Island coral cores (after Reimer and Reimer 2000). Samples: *Porites australiensis*. See caption for Table 4.1 for details of calculations.

SITE	LAB. NO.	SAMPLE	HISTORICAL AGE (YEAR AD)	MARINE MODEL AGE	<sup>14</sup> C AGE (YEARS BP)	$\Delta R$ ( <sup>14</sup> 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:						11±7

### *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 investigations, 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 <sup>14</sup>C age of charcoal samples assumed to be temporally equivalent because of archaeological association. These shell / charcoal pairs came from five sites on the New South Wales coast and one site each in the Northern Territory, Victoria and Tasmania. The age difference between the shell and charcoal samples ranged from -820 to +725, with a mean of 283 years (shells older than charcoal). Variance from the expected 450±35 value discussed above was attributed primarily 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 paired samples 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 Gillespie and Temple's (1977) mean of 283 years indicated that the marine reservoir effect for this region may be less than the Gillespie value of 450±35 years. However, the apparent similarity of this figure to that derived from paired shell / charcoal samples by Gillespie and Polach (1979) was probably 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  $\Delta R = -364 \pm 69$ , with an apparent age difference of only 40 <sup>14</sup>C years. This result is much lower than expected and most probably 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 but no further research was conducted. Data presented by Ross et al. (2000) from Peel Island in Moreton Bay, southeast Queensland, indicated potentially significant deviations from the open ocean  $\Delta R$  value but full results are not available.

### *Dating 'post-bomb' live-collected shell specimens*

Another approach to determining regional variation in marine reservoir effect has been to date post-AD 1950 ('post-bomb') live-collected shells (Table 4.4). Gillespie and Polach (1979:Table 5; see also Gillespie 1977:Table 4) presented results of three such dates on samples collected from Queensland in AD 1973 (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 water depth of 25m offshore from Edward River on the Gulf of Carpentaria in AD 1978. Differences indicated variation in <sup>14</sup>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-AD 1950 alteration to carbon reservoirs resulting from nuclear detonations.

Table 4.4 Post-AD 1950 live-collected shell (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

### 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 specimens have met with limited success. The general agreement of studies of 'pre-bomb' live-collected shells with the original Gillespie value has encouraged researchers to apply the original value rather than more recent calculations. Many researchers have thus either applied the erroneous  $\Delta R = -5 \pm 35$  value (e.g. Hiscock and Hughes 2001) or rejected the use of any marine reservoir estimate (e.g. O'Connor 1999; Veitch 1999). The  $\Delta R$  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  $\Delta R$  values available for northeast Australia to recommend a  $\Delta R = +11 \pm 5$  (revised value after Torres Strait values were corrected for age, and the Mapoon samples were added at my suggestion).

## The present study: methods

A search of the Queensland Museum and Australian Museum malacology collections for pre-AD 1955, live-collected shells from the coast between Hervey Bay and Rockhampton resulted in the identification of 13 specimens representing three species from three locations with sufficient documentation for the purposes of this study. Five specimens from three locations were selected for radiocarbon analysis (Fig. 4.2, Table 4.5). A single sample from each location was dated by conventional liquid scintillation counting (LSC) and a duplicate sample from the Gladstone and Port Curtis 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 (Hogg et al. 1998; Tanaka et al. 1986). Two of the three species dated (*Donax deltooides* and *Anadara trapezia*) are common in coastal Aboriginal archaeological deposits in the area (Ulm and Lilley 1999).

Table 4.5 Radiocarbon ages obtained on 'pre-bomb' live-collected marine shell samples from central Queensland. Samples: Dd=*Donax deltooides*; At=*Anadara trapezia*; Vs=*Volachlamys singaporina*. See caption for Table 4.1 for details of calculations.

SITE	LAB. NO.	SAMPLE	HISTORICAL AGE (YEAR AD)	MARINE MODEL AGE	$\delta^{13}C$ (‰)	$^{14}C$ AGE (YEARS BP)	$\Delta R$ ( $^{14}C$ YEARS)
Elliott Heads	Wk-6994	Dd	1925±5	455±5	-0.6±0.2	400±60	-55±60
Port Curtis 1	Wk-8457	Vs	1929	458±5	0.3±0.2	460±60	2±60
Port Curtis 2	NZA-12120	Vs	1929	458±5	0.9±0.2	570±60	112±60
Gladstone 1	Wk-8456	At	1904	453±10	0.3±0.2	480±50	27±51
Gladstone 2	NZA-12119	At	1904	453±10	-0.8±0.2	360±60	-93±61
Error-weighted mean:							1±26

No pre-AD 1955 live-collected shells were from fully estuarine contexts in the study area, so 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  $\Delta R$  through time because the dating of live-collected specimens (see above) is valid strictly for the period of collection (i.e. the recent past). Twelve shell/charcoal pairs from seven archaeological sites representing five separate estuaries and the open beach were submitted for dating (Table 4.6). The samples were either identified during excavation where associations between samples were obvious (e.g. where charcoal was located *in situ* inside shell valves) 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). For all estuarine pairs, *A. trapezia* was selected as the shell component of the paired samples to reduce variation introduced by differences in the relationship of particular species to the carbon cycle. *A. trapezia* samples ranged from 10–40mm long with an average of 25mm. Inglis (1992) found that *A. trapezia* attains a size of 20–30mm in length within 12 months with large individuals (>40mm) growing less than c.1mm/year up to 70–80mm. The majority of samples are thus likely to have had relatively short life-spans (<2 years), although sufficient to minimise short-term variation in reservoir conditions. The shell component of the pair from the open beach consisted of *D. deltooides* in the absence of other shell material suitable for dating. The dated sample consisted of valves of mature shellfish averaging 37mm in length, indicating an age of <10 months (Murray-Jones 1999). Only the largest blocky fragments of charcoal available were selected for dating although no attempt was made to identify the species of wood involved (cf. Higham and Hogg 1995). For technical details on sample pretreatment procedures see Chapter 3.

## Results

### Live-collected known-age samples

A single 19.6g specimen of *D. deltooides* (Lamarck 1818), variously known as pipi or eugarie, was dated. T.L. 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) (Fig. 4.2, Table 4.5). A more precise record of the time of live collection is not available, and a collection date of AD 1925±5 is assumed in calculating an equivalent model marine age of 455±5 years. *D. deltooides* 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 radiocarbon age determination of 400±60 BP (Wk-6994) is equivalent to  $\Delta R = -55 \pm 60$  (Table 4.5).

Two specimens of *Volachlamys singaporina* (Sowerby 1842), commonly known as the Singapore scallop or Cuming's scallop, were dated. They 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 (16–22m) at Port Curtis just southeast of Gladstone (Australian Museum C369716) (Fig. 4.2; Table 4.5). Coordinates (23°55'S, 151°23'E) place the collection site offshore of the mouth of the Boyne River. *V. singaporina* 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 (8.8g, 1.7g, 1.5g, 0.6g). The largest sample was conventionally dated to 460±60 BP (Wk-8457), equivalent to  $\Delta R = +2 \pm 60$ , while the second largest sample was dated by accelerator mass spectrometry (AMS) to 570±60 BP (NZA-12120), equivalent to  $\Delta R = +112 \pm 60$ . The two dates are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of 515±42 BP ( $T' = 1.68$ ;  $\chi^2_{1;0.05} = 3.84$ ), equivalent to  $\Delta R = +57 \pm 42$  ( $T' = 1.68$ ;  $\chi^2_{1;0.05} = 3.84$ ).

Two specimens of *A. 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) (Fig. 4.2, Table 4.5). 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 intertidal 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 (1862–1926) 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 mudflats in southeast Australia and is strongly associated with the presence of seagrasses (Inglis 1992; Murray-Wallace et al. 2000; Sullivan 1961). The small size of the four individual specimens (11.5g, 4.3g, 4.6g, 4.5g) led to the adoption of the same dating strategy as that for *V. singaporena* (see above). The largest sample was conventionally dated to 480±50 BP (Wk-8456), equivalent to  $\Delta R = +27 \pm 51$ , while the second largest sample was dated by accelerator mass spectrometry (AMS) to 360±60 BP (NZA-12119), equivalent to  $\Delta R = -93 \pm 61$ . The two dates are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of 431±38 BP ( $T' = 2.36$ ;  $\chi^2_{1;0.05} = 3.84$ ) equivalent to  $\Delta R = -22 \pm 39$  ( $T' = 2.28$ ;  $\chi^2_{1;0.05} = 3.84$ ).

The five  $\Delta R$  calculations presented in Table 4.5 are indistinguishable at the 95% confidence level from the two averaged coral  $\Delta R$  values for central Queensland presented in Table 4.3 (Reimer and Reimer 2000) and combine to give an error-weighted mean of  $\Delta R = +10 \pm 7$  ( $T' = 7.17$ ;  $\chi^2_{6;0.05} = 12.59$ ). 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 Australian value of  $\Delta R = +11 \pm 5$  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  $\Delta R$  values (Table 4.5) with the seven used to calculate the northeast Australian value (Tables 4.1–4.3) changes this value to  $+12 \pm 7$  ( $T' = 12.16$ ;  $\chi^2_{11;0.05} = 19.68$ ).

## Archaeological shell / charcoal paired samples

### *Seven Mile Creek*

Four shell/charcoal paired samples were dated from the Seven Mile Creek Mound (SMCM) (see Chapter 6 for site details) (Fig. 4.2, Table 4.6). The eight dates indicated extremely rapid accumulation of the dense shell matrix over a period of less than 350 years between c.3,900–3,600 cal BP. The deposit thus presented an ideal opportunity to examine localised marine reservoir factors over a relatively short time-span at the beginning of the known chronology of human occupation of the region. The paired samples were selected at intervals down the 90cm deep densely packed shell deposit from a single 50cm × 50cm column. 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  $\Delta R$  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 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 (7–10cm) and was probably introduced through percolation down the midden profile, infilling the interstices in the porous shell matrix. If this pair is excluded, the stratigraphically lower three pairs show good agreement with an error-weighted mean of the remaining three values yielding  $\Delta R = -155 \pm 55$  ( $T' = 1.23$ ;  $\chi^2_{2;0.05} = 5.99$ ). This value is significantly different from the generalised local open ocean value of  $\Delta R = +10 \pm 7$  ( $T' = 8.65$ ;  $\chi^2_{1;0.05} = 3.84$ ) calculated above. This result based on replicated paired samples provides strong evidence that between c.3,900–3,600 cal BP the Seven Mile Creek estuary exhibited a  $\Delta R = -155 \pm 55$ .

### Round Hill Creek

Analyses were undertaken on three separate shell/charcoal pairs from archaeological sites bordering Round Hill Creek (Fig. 4.2, Table 4.6). 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 1980a:17), with freshwater influxes significantly depressing salinity during the wet season. This suggests that there may be complex hydrological factors operating periodically to introduce large volumes of dissolved atmospheric CO<sub>2</sub> into the estuary system. On this basis it was predicted that the estuarine shell dates would reflect uptake of terrestrial carbon mobilised 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 30–40cm below ground surface (see Chapter 12 for site details). The lens was bulk sampled from the section of the test pit and returned to the laboratory for sorting. The charcoal sample comprises small fragments from the 3mm sieve. The paired samples exhibit an apparent difference of 790 <sup>14</sup>C years, with a  $\Delta R$  value of  $+458 \pm 174$  (Table 4.6). 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 the 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 and charcoal samples 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 (see Chapter 13 for site details) (Fig. 4.2, Table 4.6). The first pair (Wk-7838/Wk-7686) came from a dense layer of shell c.22cm below ground surface. The layer consisted almost exclusively of *A. trapezia* and the rock oyster *Saccostrea glomerata*, with occasional fragments of blocky charcoal that were recovered from the 3mm sieve residue for dating. The paired samples exhibit an apparent difference of 90 <sup>14</sup>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. This was 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 =  $99.5 \pm 0.6$ ). The shell component of the sample returned a <sup>14</sup>C age of  $620 \pm 50$  BP. If the charcoal sample is assumed to exhibit a <sup>14</sup>C age of 0 (=AD 1950), the paired samples exhibit an apparent difference of  $\geq 620$  <sup>14</sup>C years with  $\Delta R = \geq +620$  (Table 4.6). Because assignment of an absolute value for  $\Delta R$  is not possible this result is excluded from further consideration.

### Middle Creek

Although Middle and Pancake Creeks are joined together by a narrow channel (see Fig. 4.2), they exhibit different morphological attributes and very different hydrological patterns (Olsen 1980a) 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 southern margin of Middle Creek (see Chapter 9 for site details), consisting of whole shells and charcoal fragments collected from the 3mm sieve residue. Although the pair returned an apparent age difference of 390  $^{14}\text{C}$  years, a  $\Delta R$  value could not be calculated because the charcoal age is modern at one sigma (Table 4.6).

Table 4.6 Shell/charcoal paired samples from the southern Curtis Coast.  $^{14}\text{C}$  ages obtained on charcoal samples were reduced by  $41 \pm 14$  years to correct for  $^{14}\text{C}$  variation between northern and southern hemispheres (McCormac et al. 2002). An estimate of the atmospheric calibration curve error, derived from an average of estimated error in the  $1\sigma$  span of the age, was also included. Therefore, atmospheric age  $\sigma = \sqrt{(\sigma^{14}\text{C age}^2 + \sigma_{\text{southern hemisphere offset}}^2 + \text{average of calibration curve error}^2)}$  (Gillespie 1982). Note that the incorporation of southern hemisphere offset error in this formula assumes that each atmospheric conventional radiocarbon age derives from an independent secondary reservoir (see Jones and Nicholls 2001 for discussion). The  $1\sigma$  range of the  $^{14}\text{C}$  value was converted to the equivalent global marine model  $1\sigma$  range using atmospheric ages interpolated from INTCAL98 to the same calendar year as MARINE98 (Stuiver et al. 1998a).  $\Delta R$  was calculated by deducting the mid-point of the equivalent marine model age of the charcoal determination from the  $^{14}\text{C}$  age of the paired marine shell sample.  $\Delta R\sigma = \sqrt{(\sigma_{\text{marine model age}}^2 + \sigma_{\text{marine shell age}}^2)}$  (Gillespie 1982). This method is illustrated for pair NZA-12117/Wk-8326 in Fig. 4.3.

SITE	LAB. NO.	SAMPLE	$^{14}\text{C}$ AGE (YEARS BP)	EQUIVALENT MARINE MODEL AGE	$\Delta R$ ( $^{14}\text{C}$ YEARS)
<b>Seven Mile Creek</b>					
SMCM	NZA-12272	charcoal	1260 $\pm$ 80	1592 $\pm$ 113	-
SMCM	Wk-8324	<i>A. trapezia</i>	3540 $\pm$ 80	3540 $\pm$ 80	+1948 $\pm$ 139
SMCM	NZA-12117	charcoal	3500 $\pm$ 60	3801 $\pm$ 71	-
SMCM	Wk-8326	<i>A. trapezia</i>	3610 $\pm$ 70	3610 $\pm$ 70	-191 $\pm$ 100
SMCM	NZA-12273	charcoal	3570 $\pm$ 60	3854 $\pm$ 70	-
SMCM	Wk-8327	<i>A. trapezia</i>	3780 $\pm$ 60	3780 $\pm$ 60	-74 $\pm$ 92
SMCM	NZA-12118	charcoal	3660 $\pm$ 60	3959 $\pm$ 76	-
SMCM	Wk-8328	<i>A. trapezia</i>	3750 $\pm$ 60	3750 $\pm$ 60	-209 $\pm$ 97
<b>Round Hill Creek</b>					
ES1	Wk-5215	charcoal	1600 $\pm$ 160	1932 $\pm$ 164	-
ES1	Wk-3944	<i>A. trapezia</i>	2390 $\pm$ 60	2390 $\pm$ 60	+458 $\pm$ 174
TCSC	Wk-7686	charcoal	540 $\pm$ 50	935 $\pm$ 35	-
TCSC	Wk-7838	<i>A. trapezia</i>	630 $\pm$ 50	630 $\pm$ 50	-305 $\pm$ 61
TCSC	Wk-7681	charcoal	modern	modern	-
TCSC	Wk-7682	<i>A. trapezia</i>	620 $\pm$ 50	620 $\pm$ 50	$\geq$ +620 $\pm$ 50
<b>Middle Creek</b>					
ISC	Wk-8557	charcoal	200 $\pm$ 140	627 $\pm$ 140	-
ISC	Wk-8558	<i>A. trapezia</i>	590 $\pm$ 60	590 $\pm$ 60	see text
<b>Pancake Creek</b>					
PCSC	Wk-6993	charcoal	700 $\pm$ 140	1059 $\pm$ 112	-
PCSC	Wk-6992	<i>A. trapezia</i>	800 $\pm$ 80	800 $\pm$ 80	-259 $\pm$ 137
<b>Mort Creek</b>					
MCSC	Wk-7458	charcoal	1970 $\pm$ 80	2279 $\pm$ 65	-
MCSC	Wk-6987	<i>A. trapezia</i>	2260 $\pm$ 50	2260 $\pm$ 50	-18 $\pm$ 82
MCSC	Wk-7458	charcoal	1970 $\pm$ 80	2279 $\pm$ 65	-
MCSC	Wk-7836	<i>A. trapezia</i>	2320 $\pm$ 50	2320 $\pm$ 50	+42 $\pm$ 82
<b>Open Coast</b>					
ABM	Wk-10969	charcoal	266 $\pm$ 87	609 $\pm$ 153	-
ABM	Wk-11280	<i>D. deltooides</i>	674 $\pm$ 47	674 $\pm$ 47	+65 $\pm$ 160

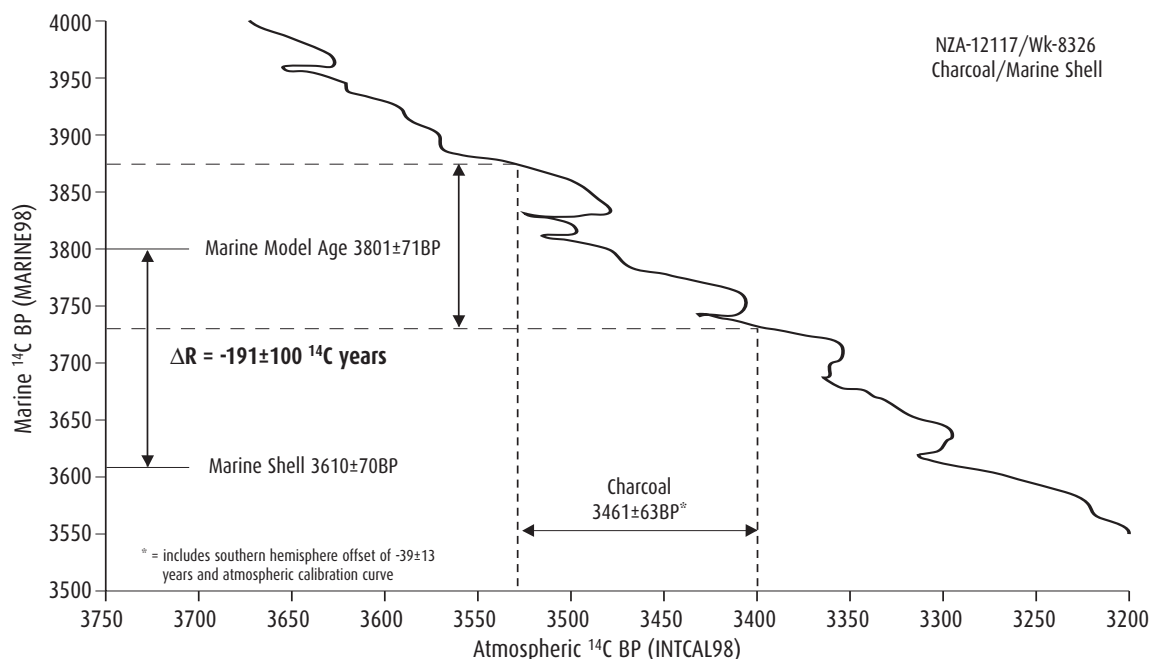


Figure 4.3 Example of  $\Delta R$  calculation method for pair NZA-12117/Wk-8326 (see caption for Table 4.6).

### 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  $^{14}\text{C}$  years with  $\Delta R = -259 \pm 137$  years (see Chapter 8 for site details) (Fig. 4.2, Table 4.6). 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, indicating a secure stratigraphic association. This site is located close to the broad entrance of the creek, which exhibits good tidal flushing and no obvious large terrestrial water input (Olsen 1980a). Terrestrial  $\text{CO}_2$  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 c.20–30cm below ground surface (Table 4.6) (see Chapter 7 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 be considered part of Rodds Harbour which has a high tidal range and thus good 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 an extremely dense layer 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  $^{14}\text{C}$  years, respectively. The values of  $\Delta R = -18 \pm 82$  and  $+42 \pm 82$  are indistinguishable at the 95% confidence level and combine to give an error-weighted mean of  $\Delta R = +12 \pm 58$  ( $T' = 0.27$ ;  $\chi^2_{1:0.05} = 3.84$ ).

### Agnes Beach

A single shell/charcoal pair (Wk-11280/Wk-10969) was obtained from the Agnes Beach Midden (ABM) on the high energy beach adjacent to the town of Agnes Water. It came from a discrete layer of *D. deltooides* and stone artefacts exposed in an eroding frontal dune (Fig. 4.2, Table 4.6). The charcoal sample is based on large blocky fragments of charcoal removed from the exposed lens. As the only stratified deposit containing organic material located on the open coast in the study area (see Ulm and Lilley 1999) the site presented an ideal opportunity to examine local open water marine reservoir factors. The paired samples exhibit an apparent difference of 408  $^{14}\text{C}$  years with a  $\Delta R$  value of  $+65\pm 160$  (Table 4.6). The large error estimate makes this value indistinguishable from the coral and live-collected shell  $\Delta R$  values presented in Tables 4.3 and 4.5 and combine with these to give an error-weighted mean of  $\Delta R = +10\pm 7$  ( $T' = 7.29$ ;  $\chi^2_{7;0.05} = 14.07$ ).

### Summary

As expected, the conventional radiocarbon age of estuarine shell samples was consistently older than that of paired charcoal samples (Table 4.6). Major discrepancies exist between the three sets of pairs from Round Hill Creek, with only one result ( $\Delta R = -305\pm 61$ ) considered free of obvious interpretation problems. If the pair from Eurimbula Site 1 (Wk-5215/Wk-3944) and the indeterminate results from the Tom's Creek Site Complex (Wk-7682/Wk-7681) and the Ironbark Site Complex (Wk-8558/Wk-8557) are excluded, the results from the other eight paired samples support the prediction that estuarine shell samples will exhibit a lower marine reservoir correction factor than the local open ocean value of  $\Delta R = +10\pm 7$ . Direct comparison of the  $^{14}\text{C}$  ages shows that shell samples are 90 to 390  $^{14}\text{C}$  years older than their paired charcoal sample. The open beach pair result from the Agnes Beach Midden provides further support for the regional applicability of the  $\Delta R = +10\pm 7$  based on coral and live-collected shell samples.

### Temporal variability or $\Delta R(t)$

The  $\Delta R$  values calculated above must be considered as a first approximation only because they do not account for variation in specific reservoir parameters (e.g. reservoir size and exchange rates between the atmosphere and ocean) through time. In the absence of additional information, it is assumed that temporal changes in  $\Delta R$  for a specific region must coincide with changes in the global mixed surface layer model ocean (Stuiver et al. 1998b:1135). Time-factored  $\Delta R(t)$  ( $t$ =time) for marine and 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. Ingram 1998; Kennett et al. 1997). Preliminary examination of  $\Delta R$  values of the Abraham Reef coral record through time, for example, indicates shifts from up to  $\Delta R = +39\pm 10$  in AD 1730 to  $\Delta R = -41\pm 8$  in AD 1950 (Paula Reimer, Centre for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, pers. comm., 2001; Druffel and Griffin 1993, 1995, 1999).

## Discussion

The five dates reported from pre-AD 1955 live-collected shell specimens from between the Elliott River and Gladstone combined with the two previous coral  $\Delta R$  values indicate, at least for the recent past, that open ocean reservoir influences are in the order of  $\Delta R = +10\pm 7$ . 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  $\Delta R$  values available for 'pre-bomb' live-collected Queensland shells and corals indicate that a generalised  $\Delta R = +12\pm 7$  ( $T' = 12.16$ ;  $\chi^2_{11;0.05} = 19.68$ ) is appropriate for open marine

contexts in northeast Australia and supersedes the erroneously calculated  $\Delta R = -5 \pm 35$  value recommended by Stuiver et al. (1986:Fig. 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 that mitigates the influence of  $^{14}\text{C}$ -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  $\Delta R = -155 \pm 55$  for Seven Mile Creek and  $\Delta R = +12 \pm 58$  for Mort Creek. Less confidence is placed in the  $\Delta R$  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  $\Delta R = -259 \pm 137$  for Pancake Creek, and  $\Delta R = -305 \pm 61$  for Round Hill Creek. Figure 4.4 schematically represents all the  $\Delta R$  values calculated in this study. The high level of variation observed in regional estuarine  $\Delta R$  values is best explained as a function of the structures of the carbon reservoirs in which the samples were formed. Many coastal archaeological sites, and all of those from which shell/charcoal paired dates are reported here, are in environments of restricted circulation: 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  $\Delta R$  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  $^{14}\text{C}$  throughout the estuary'.

The potential impact of differences in  $\Delta R$  between estuaries can be illustrated through a case study of the Seven Mile Creek Mound, the oldest dated open site on the central Queensland coast. Table 4.7 and Figure 4.5 present the calibrated results of four conventional radiocarbon dates of shell samples (*A. trapezia*) using four different  $\Delta R$  values:  $\Delta R = -5 \pm 35$  (recommended by Stuiver et al. 1986 and Stuiver and Braziunas 1993);  $\Delta R = +50 \pm 33$  (the corrected version of this value; see above);  $\Delta R = +10 \pm 7$  (calculated for the open ocean of the study region; see above); and  $\Delta R = -155 \pm 55$  (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  $2\sigma$  age-range. Table 4.7 shows overall variation in the central tendencies of the calibrated radiocarbon ages between the generalised Australian value of  $\Delta R = +50 \pm 33$  and the actual estuary-specific value of  $\Delta R = -155 \pm 55$  is in the order of 300 years. The difference between the regionally determined open ocean value of  $\Delta R = +10 \pm 7$  and the estuary-specific determined value is ~250 years.

The identification of variability in estuarine  $\Delta R$  values has significant implications for archaeology in Queensland. Some 25% (n=216) of all radiocarbon determinations from the state 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, more than 95% (n=21) of dates from the Keppel Islands are on marine shell (Rowland 1981, 1992; Ulm and Reid 2000).

This limited study demonstrates the potential for significant variation in local marine reservoir effect within the 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).

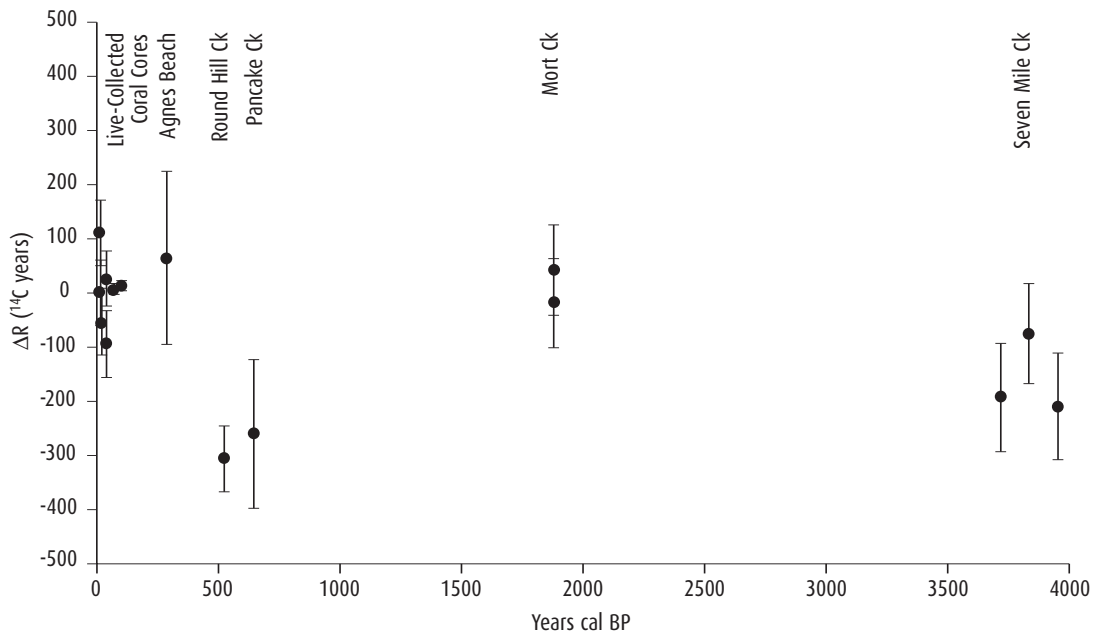


Figure 4.4  $\Delta R$  values calculated for the southern Curtis Coast.

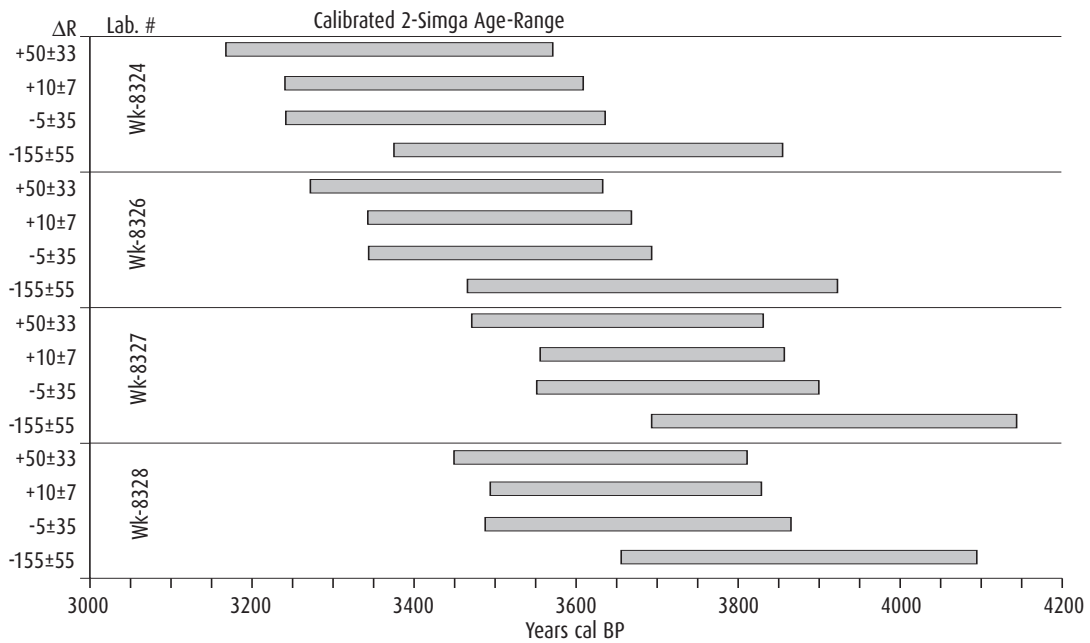


Figure 4.5 Calibrated radiocarbon age-ranges from the Seven Mile Creek Mound, using various  $\Delta R$  values (see Table 4.7).

Table 4.7 Calibrated radiocarbon ages from the Seven Mile Creek Mound, using various  $\Delta R$  values.

LAB. NO.	CALIBRATED AGE/S $\Delta R = +50 \pm 33$ (CAL BP)	CALIBRATED AGE/S $\Delta R = +10 \pm 7$ (CAL BP)	CALIBRATED AGE/S $\Delta R = -5 \pm 35$ (CAL BP)	CALIBRATED AGE/S $\Delta R = -155 \pm 55$ (CAL BP)
Wk-8324	3567(3362)3164	3606(3399)3235	3633(3429)3237	3850(3608)3372
Wk-8326	3630(3442)3269	3665(3470)3339	3690(3487)3338	3919(3684)3462
Wk-8327	3827(3637)3465	3855(3687)3550	3893(3700)3548	4140(3904)3688
Wk-8328	3808(3618)3444	3824(3651)3491	3859(3677)3485	4089(3867)3652

## Summary

A review of the literature on Australian marine reservoir effects indicates that the routinely applied  $\Delta R$  value of  $-5\pm 35$  for northeast Australia is erroneously calculated. The values determined in this study suggest a minor revision to Reimer and Reimer's (2000) recommended value for northeast Australia from  $\Delta R = +11\pm 5$  to  $+12\pm 7$ , and specifically for central Queensland to  $\Delta R = +10\pm 7$ , 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  $\Delta R$  value of more than  $-155\pm 55$  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  $^{14}\text{C}$  activity.

For the purposes of this study, the following  $\Delta R$  values will be applied in the calibration of marine and estuarine radiocarbon dates: local open waters (i.e. non-estuarine)  $+10\pm 7$ ; Seven Mile Creek  $-155\pm 55$ ; Mort Creek  $+12\pm 58$ ; Pancake Creek  $-259\pm 137$ ; and Round Hill Creek  $-305\pm 61$ . For estuaries where a specific  $\Delta R$  could not be determined (e.g. Middle Creek) the local open ocean  $\Delta R = +10\pm 7$  will be applied in default. In the absence of local high resolution  $\Delta R(t)$  records, temporal changes are assumed to coincide with changes in the modelled global ocean (Stuiver et al. 1998b:1135).