SHORT REPORTS

Australian Marine Reservoir Effects: A Guide to ΔR Values

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Introduction

Radiocarbon ages obtained on contemporaneous terrestrial and marine samples are not directly comparable. Samples grown in marine environments exhibit older apparent radiocarbon ages caused by the uptake of carbon which has already undergone radioactive decay through long residence times in the deep ocean. Variation in ^{14}C activity in marine environments, although related to changes in atmospheric activity, depends greatly on local and regional factors, such as hinterland geology, tidal flushing and terrestrial water input. Such factors are highly variable and can introduce uncertainties of up to several hundred years into dates obtained on marine samples in some parts of the world.

These issues have received much attention in Pacific archaeology where determinations on marine samples are routinely scrutinised (e.g. Anderson 1991; Spriggs and Anderson 1993) and major resources have been devoted to resolving regional marine reservoir correction factors (e.g. Dye 1994; Petchey *et al.* 2004; Phelan 1999). In Australia, however, only very limited investigations have been conducted despite routine dating of marine and estuarine shell (e.g. Bowman 1985; Bowman and Harvey 1983). For nearby areas regional offsets of up to 400 years have been documented (Petchey *et al.* 2004), highlighting a key problem in a country where marine shell from open coastal sites is routinely dated.

As a first approximation it is common practice in Australia to correct marine dates for marine reservoir effect by simply subtracting a generalised factor of 450±35 years to make them comparable to coeval terrestrial (e.g. charcoal) samples. This correction value was calculated by Gillespie in the 1970s (see Gillespie 1975; Gillespie and Polach 1979; Gillespie and Temple 1977). Since that time several 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; Ulm *et al.* 1999; Woodroffe *et al.* 1986:75, 77; Woodroffe and Mulrennan 1993).

In the last two decades researchers have gained a much more sophisticated appreciation of the complexity of global marine carbon reservoirs. One of the most significant innovations was the development of a global model of surface marine ^{14}C activity that enabled the calibration of radiocarbon dates obtained on marine samples, including the ability to account for regional differences from the global model with the input of a regional offset value, expressed as a ΔR value (Stuiver *et al.* 1986). Reimer and Reimer (2001, 2006) subsequently summarised all of the available global ΔR values in a world wide web database.

In this paper, I briefly discuss the principles of marine reservoir correction before presenting a guide to regional and subregional Australian ΔR values extracted from the Reimer and Reimer (2006) database and Ulm (2002).

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Background

A basic assumption of the radiocarbon dating method is that the concentration of radioactive carbon (^{14}C) in the biosphere is uniform through space and time. Early in the development of the radiocarbon dating method, however, it was recognised that marine shells exhibited a systematic age difference to contemporary terrestrial samples on a regional basis which allowed calculation of a regionally-specific age offset.

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 are even more complex with the interaction and incomplete mixing of ^{14}C from both terrestrial reservoirs and marine reservoirs from tidal action (e.g. Ulm 2002).

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

- direct radiocarbon dating pre-AD 1955 live-collected marine specimens of known historical age (e.g. shell, coral, otoliths);
- radiocarbon dating shell/charcoal paired samples from high integrity archaeological contexts that are assumed to be contemporaneous; and
- 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 recent years, regional marine reservoir effect has commonly been expressed as a ΔR value (e.g. Higham and Hogg 1995; Phelan 1999; Ulm 2002). Stuiver *et al.* (1986; see also Stuiver and Braziunas 1993; Stuiver *et al.* 1998; Hughen *et al.* 2004) 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 covering the last 10,000 years. 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 (you will also see this equation expressed as ΔR(s)=Rs(t)-Rg(t)) (Stuiver *et al.* 1986:982).

Once calculated, the ΔR value can be applied to marine calibration curves to calibrate dates obtained on marine shell (and other marine-derived sample materials such as fish bone,

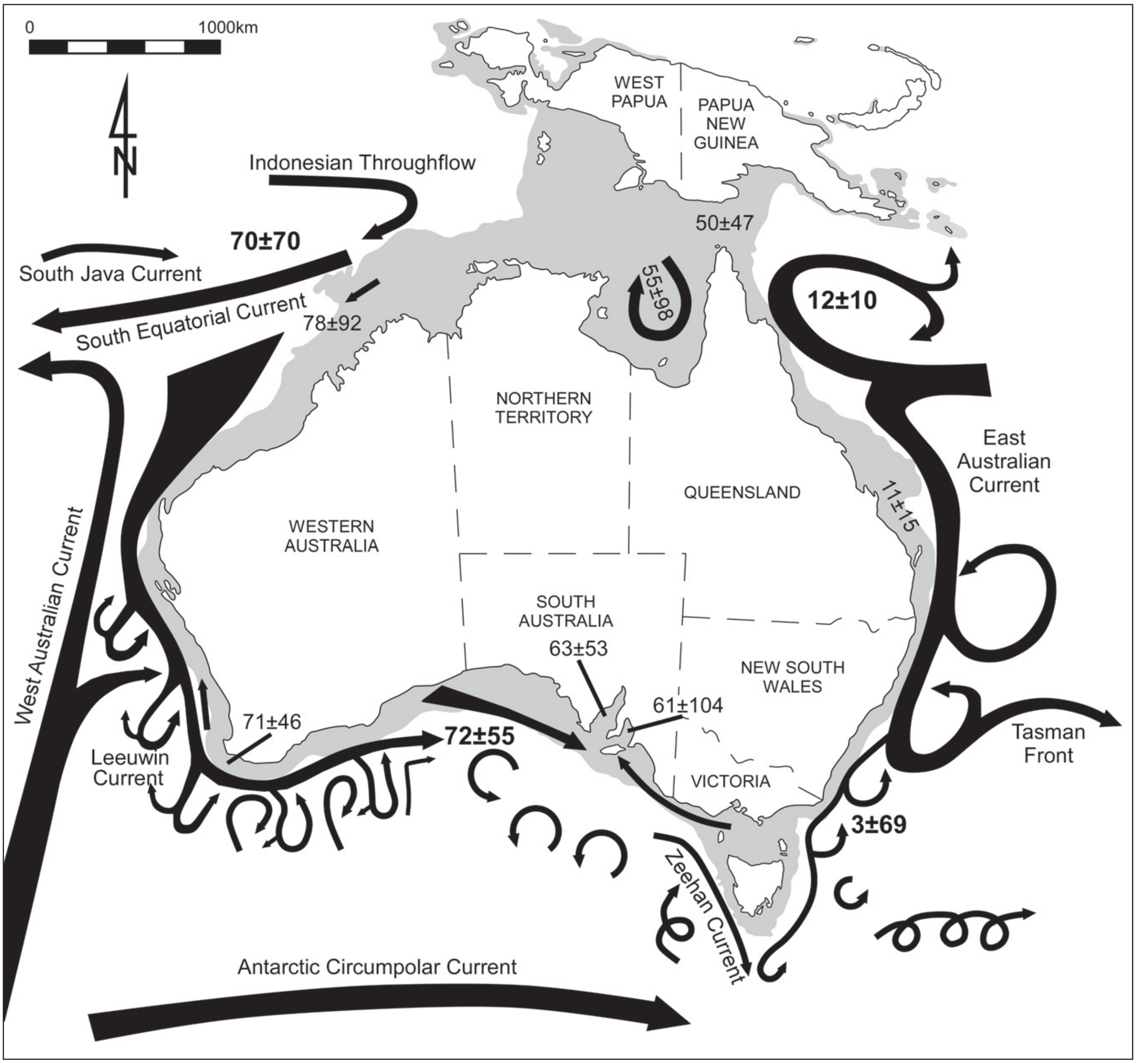

Figure 1 Map of Australia, showing rounded regional and subregional ΔR values. ΔR values in bold denote regional values. Those without bold are subregional values. Arrows indicate major surface ocean currents (after CSIRO 2000).

Table 1 Regional average ΔR values (after Reimer and Reimer 2006).

Region	# ΔR Values	Regional Average
Northeast Australia	10	12±10
Northwest Australia	8	70±70
South Australia	10	72±55
Southeast Australia	2	3±69

Table 2 Subregional average ΔR values (after Reimer and Reimer 2006).

Subregion	# ΔR Values	Subregional Average
Torres Strait	3	50±47
Gulf of Carpentaria	2	55±98
Kimberley Region	7	78±92
Southwest Western Australia	4	71±46
Spencer Gulf	5	63±53
Gulf of St Vincent	2	61±104
Central Queensland	7	11±15

coral, marine mammal bone etc) for specific regions. The ΔR value can also be used in widely available computer calibration programs such as CALIB (Stuiver and Reimer 1993) and OxCAL (Bronk Ramsey 1995).

Australian ΔR Values: A Guide

Reimer and Reimer's (2001, 2006) *Marine Reservoir Correction Database* of ΔR values includes the 33 data points available for Australian open coastal waters. In the current version of the database, Reimer and Reimer (2006) have calculated worldwide ΔR values using the latest calibration dataset of Hughen *et al.* (2004). This updates the original version launched in 2000 which was based on the 1998 dataset of Stuiver *et al.* (1998). Other significant changes to the database undertaken in early 2006 include the dropping of pre-calculated regional averages. Replacing this is a facility for the user to choose which particular samples to include in the calculation of a regional weighted mean ΔR value with its accompanying standard deviation or weighted mean measurement error. Reimer and Reimer (2006) now recommend that ΔR uncertainty be taken as the larger of the standard deviation and weighted mean measurement error values. This change has resulted in significant increases in ΔR uncertainty for some regional values, but more accurately represents uncertainty in source data.

The other advantage of the new system is that the user can be more discriminating about sample selection in calculating regional ΔR values. For example, users can exclude individual values based on deposit feeders (e.g. *Pyrazus* sp.) which have been shown to be less reliable than suspension feeders (e.g. *Donax* sp.) owing to the uptake of 'old' carbon in sediments (Hogg *et al.* 1998). It is therefore important to evaluate each sample before including it in the calculation of a regional weighted mean ΔR value.

The ΔR values presented in Reimer and Reimer's database are also progressively updated when new internationally agreed calibration datasets are published in *Radiocarbon* (around every 5–7 years). It is therefore important to refer to the database on a regular basis to calculate the most appropriate ΔR value to use for a particular locale.

Using data presented in Reimer and Reimer (2006), Figure 1 and Table 1 present pooled regional ΔR values for Northeast, Northwest, South and Southeast Australia. These regional values combine between two and 10 individual ΔR values and cover very broad geographical regions composed of potentially different marine reservoir conditions. Therefore, in addition to the regional ΔR values, Table 2 presents subregional ΔR values where two or more individual ΔR values are available for a specific area.

Discussion and Conclusion

The choice of a particular ΔR value to calibrate a particular radiocarbon date must be based on a consideration of the environment in which the sample material to be dated was formed (e.g. a shellfish grown in an estuarine environment vs an open beach environment etc). In terms of simple oceanographic conditions (i.e. a steady current, no seasonal upwelling etc) it is possible to predict the general magnitude of ΔR values from other values obtained within local prevailing currents and associated source waters; however, in cases where currents meet it can be difficult to assess without measurements. For example, ΔR values are very similar along the coast of Western Australia in the Leeuwin Current and again off the east coast where the Eastern Australian Current flows down as far south as New South Wales, where the Tasman Front breaks off (Figure 1). The region from New South Wales south, and especially along the southern coast of Victoria and all around Tasmania would be very difficult to predict owing to localised variation in currents and local upwelling.

A major limitation is a lack of data for estuaries where many archaeological samples originate. A study of ΔR values for a number of estuaries in central Queensland demonstrated estuary-specific values of up to ΔR= -155±55 (see Ulm 2002 for detailed discussion). In this case, the blanket application of the regional or subregional ΔR value would have produced calibrated ages approximately 200 years too young.

Another problem is the assumption that temporal changes in ΔR for a specific region coincide with changes in the global model ocean (Stuiver *et al.* 1998:1135). Time-factored ΔR(t) (t=time) values can be calculated through large-scale studies of annual coral records and/or paired shell/charcoal samples from a variety of time periods. Coral cores from central Queensland demonstrate that ΔR fluctuated by c.80 years over a 200 year period (see Druffel and Griffin 1999; Ulm in press).

A quick perusal of Figure 1 highlights major gaps in the availability of ΔR values for the Australian coast. These gaps pose significant issues for regions such as coastal New South Wales where numerous coastal shell midden deposits have been excavated and dated on the basis of marine shell samples with no local ΔR values available.

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