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THE MARINE ΔR FOR NENUMBO (SOLOMON ISLANDS): A CASE STUDY IN CALCULATING RESERVOIR OFFSETS FROM PAIRED SAMPLE DATA

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ABSTRACT. It is necessary to calculate location-specific marine ΔR values in order to calibrate marine samples using calibration curves such as those provided through the IntCal98 (Stuiver et al. 1998) data. Where known-age samples are available, this calculation is straightforward (i.e. Stuiver et al. 1986). In the case that a paired marine/terrestrial sample calculation is performed, however, the standard calculation (i.e. Stuiver and Braziunas 1993) requires that the samples are treated as relating to isochronous events. This may not be an appropriate assumption for many archaeological paired samples. In this paper, we present an approach to calculating marine ΔR values that does not require the dated events to be treated as isochronous. When archaeological evidence allows the dated events to be tightly temporally constrained, the approach presented here and that described by Stuiver and Braziunas (1993) give very similar results. However, where tight temporal constraints are less certain, the 2 approaches can give rise to differing results. The example analysis considered here shows that a ΔR of –81 ± 64 ^{14}C yr is appropriate for samples in the vicinity of Nenumbo (Reef Islands, southeast Solomon Islands) around the period 2000–3000 BP.

INTRODUCTION

In order to calibrate marine samples using standard calibration curves, it is necessary to use a location-specific marine reservoir offset (ΔR). To calculate this value, it is necessary to either date pre-bomb marine samples of known age, or to date paired atmospheric and marine samples of otherwise unknown age. In the case that known-age samples are used, the ΔR calculation is easily calculated as described by Stuiver et al. (1986). Where paired archaeological samples are used, however, the problem is a little more complex because the temporal relationship between paired samples is not so precisely defined as for the known-age case. Despite this, the standard approach (e.g. Stuiver et al. 1986) to calculating a ΔR value for paired samples is based upon an assumption that the comparative samples relate to isochronous events. In many cases, this assumption may not be valid. In this paper, we discuss a Bayesian approach to calculating ΔR values that allows uncertainty in the temporal relationships among paired samples to be explicitly incorporated within the calculation procedure.

To provide a context for this discussion, we will consider the calculation of a suitable marine reservoir offset (ΔR) for the area in the vicinity of the main Reef Island Lapita site of Nenumbo, SE-RF-2 (Green 1976), on the basis of 4 charcoal dates and 2 shell dates (Table 1).

Table 1 Nenumbo SE-RF-2 dates.

Lab ID	Conventional ^{14}C age	Error	Provenance	Material	Reservoir
I-5747	2955	95	W-V-26	Charcoal	Terrestrial
I-5748	2775	100	W 35-36	Charcoal	Terrestrial
ANU-6477	2730	120	T-40	Charcoal	Terrestrial
ANU-6476	2850	130	U-40	Charcoal	Terrestrial
WK-7847	3100	40	X-30/X-29	*Tridacna maxima*	Marine
WK-7848	3080	40	X-28/Y-28-29	*Trochus niloticus*	Marine

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SE-RF-2 is situated on the small islet of Te Motu Taibä in the isolated Reef Islands group of small, low raised coral islands located 45 km northeast of the larger volcanic island of Nendö (Santa Cruz) and 430 km west of the next largest island of Makira in the eastern Solomons. Analysis of the SE-RF-2 date set provides the opportunity to develop a local marine ΔR value, which is central to dating the local archaeological sequence.

This case study represents a standard archaeological scenario. The archaeological record under analysis appears to represent a single phase of activity (Sheppard and Green 1991), and the available dates would normally be treated as samples that could be used to calculate regional ΔR values. However, under the standard paired sample analysis as described by Stuiver and Braziunas (1993) we model the dated phase of activity as corresponding to a single instant in time. This model is not strictly suitable for SE-RF-2, nor for many other archaeological applications of this type, as we cannot be certain that the dated events are strictly isochronous. The question then, is how do we implement a more suitable model?

THE DATA

All of the dated samples come from the main SE-RF-2 occupation layer, which consisted of numerous interlocking pit and posthole features cut into gray sandy layer over natural beach sand.

The 4 charcoal sample determinations have been previously published, and can be located by the grid square on the Figure 3 plan of Sheppard and Green (1991) as follows:

- **I 5747** - Grid square W-V-26, south-central portion - a pit or more likely a posthole of an internal fence alignment related to the occupation layer with the sample taken from an ash lens within the feature.
- **I 5748** - Grid square W 35-36 - an oven at the uppermost surface of the main occupation layer.
- **ANU 6476** - Grid square T-40 - small pit cut from the main occupation layer into underlying beach sand.
- **ANU 6477** - Grid square U-40 - large posthole or small pit feature in the main occupation layer cut into slightly larger pit in T-40 from which ANU 6476 sample was recovered.

The marine shell radiocarbon dates are new. Their contexts, fully contemporary and able to be paired with the samples above, are:

- **Wk 7847** - Grid square X-30 and part of X-29 - *Tridacna maxima* shell in a pit feature from main occupation layer cut into beach sand.
- **Wk 7848** - Grid square X, part 28 - *Trochus niloticus* shell in a large pit feature extending into Y-28-29, cut from the main occupation layer into the beach sand below.

STATISTICAL MODELS

In the standard approach to paired sample calculations, we have 2 conventional radiocarbon ages (CRAs), one relating to a sample associated with a terrestrial carbon reservoir and a paired sample associated with the local marine reservoir. In order to calculate the (unknown) local marine ΔR value, the terrestrial CRA is converted to a model marine ^{14}C age (Q_{at}) using a conversion curve (e.g. Stuiver and Braziunas 1993: Figure 15). This value is then subtracted from the paired marine CRA (P_{ma}) to derive the local ΔR value; i.e.

$$\Delta R = P_{ma} - Q_{at}$$

Under this scheme, the uncertainty associated with the ΔR estimate is quantified as $\sim N(\sigma_{\Delta R})$, where $\sigma_{\Delta R} = \sqrt{\sigma_{ma}^2 - \sigma_{at}^2}$.

Following this approach in the current example, we would calculate the ΔR estimate as follows. Initially, the atmospheric and marine samples (Table 1) are pooled separately following Ward and Wilson (1978: Case II) to derive the following mean values: 2838 ± 55 BP for the terrestrial and 3090 ± 29 BP for the marine. From these, we use the IntCal98 curves (Stuiver et al. 1998) to calculate a model marine age of 3180 ^{14}C yr as corresponding to the atmospheric sample. Thus, ΔR = 3090–3180 = –70 and $\sigma_{\Delta R} = 55^2 + 29^2$; i.e. ΔR = –70 ± 62 ^{14}C yr.

As discussed above, this calculation is appropriate when the paired samples are *known* to be isochronous. However, where this condition is not met it may be necessary to take into account any uncertainty regarding the relative timing of the dated events. One approach that has been adopted to address this issue is the use of the χ^2 statistic given by Ward and Wilson (1978) to establish whether the samples can be treated as effectively isochronous (e.g. Ulm 2002). However, this is an inappropriate use of that statistic and it should not be used in this capacity (Christen 1994; Jones 2001). Ward and Wilson's (1978) χ^2 statistic is designed to test the null hypothesis that events are isochronous. In the absence of strong, independent evidence that a date set relates to isochronous events, this is an unsuitable null hypothesis. Ward and Wilson's (1978) statistic is not intended to, and cannot, determine whether dated events are isochronous where this is otherwise uncertain.

An alternative approach to the standard paired samples calculation is to use a Bayesian calibration scheme that allows uncertainty in the relative timing of the samples to be included within the analysis. A Bayesian approach is useful as it allows prior understandings regarding the temporal relationship among the dated samples to be expressed, in an explicit way, in the chronometric analysis. Information of this kind is made explicit in the analysis via a probability distribution, called the *prior*, which weights the calibrated dates towards values in line with our prior expectations. Thus, we can express any prior understanding regarding the temporal relationships among the dated samples and are not required to treat them as being isochronous. This makes a Bayesian approach to calculating reservoir offset values from paired sample data preferable to that of the standard approach discussed above. In addition to the prior, a Bayesian analysis requires us to define a distribution called the *likelihood*. The likelihood describes the relationship between the measured ^{14}C data, the dated event, and the local reservoir offset(s). A calibrated value that makes the observed CRA a likely outcome of the ^{14}C observation process has a high likelihood. The prior and likelihood distributions together determine a new probability distribution known as the *posterior*. Sets of calibrated dates agreeing with the data, and at the same time plausible in the light of prior information, yield a large posterior probability. In Bayesian calibration, this posterior distribution is our analysis result. Formally speaking, the un-normalized posterior distribution is given by:

$$\text{posterior} = \text{likelihood} \times \text{prior} \tag{1}$$

If we can define a suitable likelihood and prior, then it is possible to calculate a posterior from which we can derive statistics of interest (local ΔR values in this case). Fortunately, suitable priors and likelihoods for the type of analysis we seek to perform here have been defined previously.

A standard definition of the ^{14}C likelihood suitable for use in Equation 1 is given elsewhere (e.g. Buck et al. 1991). For trying to calculate local ΔR values, we will certainly need to use a correlated reservoir offset (Jones and Nicholls 2001) and so should use a likelihood modified after the observation model given by Jones and Nicholls (2001).

Nicholls and Jones (2001) provide a prior suitable for calibration using temporal order constraints with archaeological data, and we will use that prior here. (See Nicholls and Jones [2001] for a detailed discussion of model specifics.) Under their calibration scheme, all analyzed dates are treated as coming from one of a number of phases that occur as a single series, and temporal constraints on the timing of each phase are set on the basis of the analyzed data. This is useful for estimating local ΔR values in the situation where samples related to both marine and terrestrial reservoirs are available and the samples can be confidently associated with serial phases of activity. In that case, the temporal phase constraints established by terrestrial CRAs will apply to marine samples associated with the same phase. These temporal constraints will act to limit the range of possible ΔR values associated with the marine samples and allow us to recover information regarding the local ΔR value. Here, the only assumption with respect to the relative timing of the analyzed CRAs is that the phase associations are correct; no further assumptions are made with respect to the relative timing of the analyzed CRAs. This situation reflects a realistic prior assumption with respect to analyses where we cannot reasonably assert that the analyzed CRAs are isochronous, but we are, however, confident that they relate to the same general phase of activity within the archaeological record.

The posterior given in Equation 1 is the joint probability of a number of parameters and it is usual to summarize this multidimensional distribution by considering the distribution of some meaningful statistic of direct interest (in this case the applied reservoir offset values would be such a statistic). To do this, we take the original joint posterior distribution given in Equation 1 and integrate out the uninteresting parameters in order to compute the "marginal distribution" for a statistic of interest. In practice, this is almost always performed via numerical integration on a computer, as the integrals usually cannot be done by hand. Typically, this type of numerical integration is performed through sample-based inference.

Sample-based inference is a numerical mode of analysis that allows us to form summarizing statements from the posterior density by sampling parameter sets from the posterior distribution (i.e. integrate out marginal posterior distributions of interest). As an example, histograms of sampled parameter sets are often used to summarize marginal posterior probability distributions.

The problem then is to generate samples from the posterior. In general, this is performed using Markov chain Monte Carlo (MCMC) algorithms, which employ Gibbs sampling or some more general Metropolis-Hastings algorithm. While this is a relatively straightforward exercise, it nonetheless requires specialist software or reasonable expertise to program from scratch. Here, we use the DateLab software system (Jones and Nicholls 2002), which implements both a Metropolis-Hastings MCMC sampler and a rejection sampler for generating sample sets from the posterior. The calculation of ΔR values from paired marine/terrestrial samples through Bayesian calibration is now a standard analysis function of DateLab (see the online manual at www.datelab.org for details).

Before proceeding with this analysis, it is useful to present a discussion of the SE-RF-2 archaeological record and establish that it is reasonable to associate the dated samples within one or more serial phases of activity.

ARCHAEOLOGICAL EVIDENCE FOR THE LENGTH OF OCCUPATION AT NENUMBO, SE-RF-2

Nenumbo, SE-RF-2 has been the subject of continuing analyses and publications since its excavation, first in 1972 and again in 1976. Before any excavation, a survey was made of its entire surface. The sherds of pottery and other cultural items in the top 3–5 cm of loose surface debris were systematically collected, sieved, and the results by category and number recorded within a 1-m grid while in the field (Green 1976:251–55; Sheppard and Green 1991). This made it possible to target the area selected for investigation and to relate the macroscale surface results for the whole site to the microscale portion of it (13.9%) that was eventually excavated.

Based on an analysis of the surface distribution of the potsherds, the total site area is estimated at between 800 m^2 (decorated sherds) and 1100 m^2 (plain sherds), of which 153.5 m^2 of a largely contiguous portion was excavated. Site size therefore lies in the single residential "hamlet" range of settlements among recorded Lapita sites, rather than the multi-unit residential settlements comparable to ethnographic "village" communities in the Solomons where rather larger zones with scatters of broken pottery fragments have been recorded (Irwin 1973; Green 1994:33–34).

The stratigraphy encountered at SE-RF-2 is fairly simple. Burnett and Fein (1977) studied soil samples taken from its 3 layers in detail. White coral beach sand forms the natural base, into which numerous structural features were cut. They were easily identified because they were filled with the same material as the overlying sandy charcoal-stained gray layer some 20 cm in thickness that everywhere constitutes the main cultural occupation in this locality. Above this layer is a modern garden soil, 25–30 cm thick, whose principal constituent derives from a weathered tephra (Burnett and Fein 1977). Its most likely origin is a fine airborne volcanic ash that covered both this Lapita site and a similar, but later, one. The ashfall seems to have occurred in the interval between 2400 and 500 BP, and it mantled most of the islands in the Main Reef group (Wall and Hansell 1976:26; Hughes 1981a:23). The probable source for this tephra is the nearby and still active volcano of Tinakula. Limited geological study of Tinakula, plus historic records of its recent activity, suggest that is normally not explosive enough to eject volcanic debris for any great distance away from the volcano itself (Hughes 1981b:27–28). The sector graben on the northwest flank, however, may be associated with a catastrophic explosion from which one could expect considerable airborne volcanic dust (Wyn Hughes, personal communication, 2002). Such an event might account for the tephra's basic to intermediate composition—responsible for the allophanic soils on the Reef and Santa Cruz islands (Wall and Hansell 1976:37).

It would appear that the gray sand occupation layer was once of a slightly greater thickness than it now has when viewed in section drawings. This is because its upper 5–8 cm has subsequently been incorporated into the slightly thicker tephra-based "gardening zone" that often extended to a depth of about 30 cm. There is then the expected indication of considerable vertical disturbance upward of material from the top of the gray sand occupation layer into the gardening zone above, and this same process brought some ancient cultural material to the site's surface as well, further reducing the size of those sherds. Thus, Green (1986) has argued that based on the vertical distribution of material among these layers, the occupation consists of a single component from which some material has been mixed into the overlying tephra by gardening, along with disturbance by the occasional tree fall and limited activity by land crabs.

A number of additional intersecting lines of evidence all support the deduction of a fairly brief 1-phase occupation event. Thus, no significant differences were found in the fishbone (Green 1986) or shellfish content (Swadling 1986) recovered from the black weathered tephra gardening zone and gray occupation layers. Pottery sherd size by spit/layer together with those of the surface show a steady decrease in size and number from the larger sherds (some of them fitting together) recovered from the gray layer. Smaller sherds occur in the gardening layer, with those on the surface being very small indeed (Green 1976, and unpublished data). No typological, stylistic, temper, or other content differences were detected in the items recovered from the 2 layers, again indicating the cultural contents constitute 1 assemblage.

The crispness of the spatial patterning exhibited by the surface sherd distribution displayed using a grayscale analysis fits well in general with the subsurface features and cultural content by category revealed through excavation (Sheppard and Green 1991: Figure 2 versus Figures 3, 6, 8, and 10). This suggests little post-depositional horizontal disturbance, just vertical migration upward of some of the underlying main occupation's cultural content. Refitting of a small number of potsherds (Parker 1981) between the northern and southern ends of the excavated area also suggests contemporaneous occupation and discard behavior, rather than horizontal disturbance. Finally, the distributions of marine shell, fishbones, chert pieces, obsidian pieces, and potsherds are all coherent and interrelated in terms of functional areas within the site and among its structural features, again suggesting these items were discarded during 1 short occupation interval.

The majority of the structural features revealed though excavation also exhibit coherent, readily interpreted patterns indicative of a low degree of recurring or successive constructions during the time of its occupation. In the southern food-processing and cooking zone, multiple stake or small postholes suggest a succession of 2 or 3 small cooking shelters may have been erected there. In the northern part of the excavation area, only a single long-occupied building is in evidence, one that has not been refurbished to any degree. The inference is that site usage lasted for the life span of 1 large (7 × 10 m) dwelling (Green and Pawley 1999). The complete rebuilding and thatching of similar structures in the Pacific more often occurs on a generational scale (R Walter, personal communication), and suggests a maximum for this structure. The distribution of artifacts is consistent with such a short duration in that the position of only 1 main structure is reflected.

Taking all this information together leads to the conclusion that SE-RF-2, a hamlet-sized community exhibiting only a single cultural component, is a Lapita settlement that involved only 1 central residential unit and to the south of it a related cooking and food-preparation zone. The site was occupied over the course of probably no more than a generation. An assessment of occupation length then would suggest an acceptable lower limit of <25 yr, or an upper one of perhaps 50 yr at the outside.

RESULTS

On the basis of the archaeological evidence given above, we would regard the Nenumbo, SE-RF-2 occupation as corresponding to a single general phase of activity with which we would associate all of the measured CRAs for this site. Thus, in terms of the models outlined above we regard the observed CRAs as deriving randomly from within this single phase of activity. We would further impose the constraint that the duration of this span of activity is <50 yr. We will call this Prior 1. In order to estimate the local ΔR value, we simply sample from the posterior distribution and summarize the sampled marine offset parameter. In this instance, the IntCal98 calibration data are used (Stuiver et al. 1998). In the case that the dates correspond to a terrestrial reservoir, we assume that no offset needs to be applied. When the dates relate to a marine offset for which we have no data, the marine offset (ΔR) is thus our prior for the marine reservoir and is uniformly distributed over $\pm\infty$. The necessary samples were generated using the Metropolis-Hastings sampler implemented in DateLab (Jones and Nicholls 2002) and are summarized in Figure 1. From these results, we can see that under Prior 1, the sampled local ΔR value can be summarized as being normally distributed with a value of -81 ± 64 ^{14}C yr. This result derives from reasonable prior assumptions regarding the relative temporal relationships among the dated samples and has not required us to assume that the samples are isochronous (and clearly they are not).

In order to explore the effect of changing our prior assumptions, it is interesting to consider a different prior model, under which we relax the constraint that the occupation duration for the Nenumbo SE-RF-2 site is <50 yr. Under this prior, we will allow the occupation duration to take any value. We

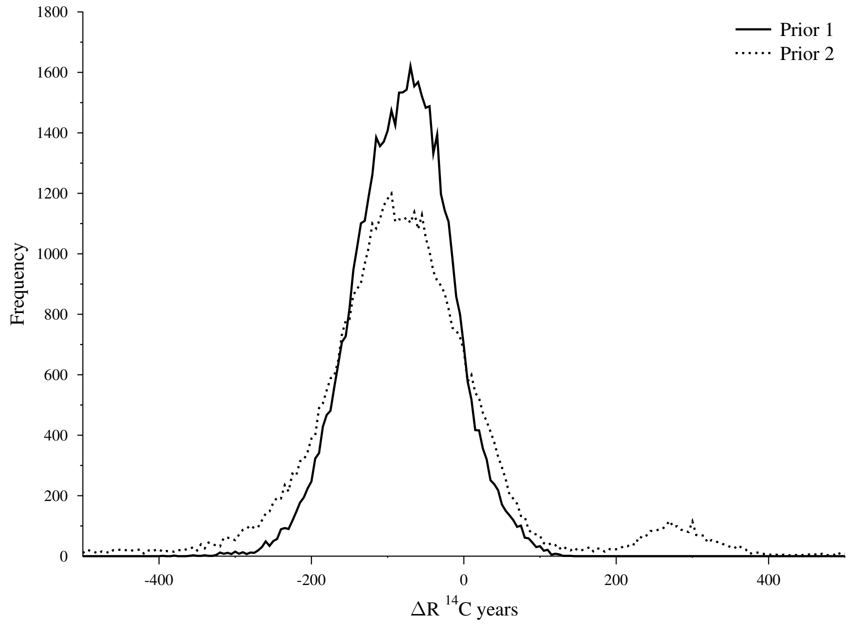

Figure 1 Distribution of sampled ΔR for Nenumbo, SE-RF-2, under Prior 1 and Prior 2

will call this Prior 2. Other than relaxation of this constraint, Prior 2 and its analysis is in every respect the same as Prior 1. Again, the sampled local ΔR value is summarized in Figure 1. Here, we can see that there is a clear difference between the 2 results. Under Prior 2, the sampled local ΔR value returns a bimodal distribution. While the dominant region of support is in the same region of that recovered under Prior 1, the distribution recovered under Prior 2 also allows for high-value positive offset values. This illustrates quite clearly that different prior assumptions can give rise to significantly different analysis results, and highlights the importance of establishing a suitable prior model for the data that reflects the archaeological record under consideration. Following the discussion above, we prefer to use Prior 1 and the associated ΔR estimate (–81 ± 64 ^{14}C yr) as being the most appropriate estimate for the area in the vicinity of the Nenumbo SE-RF-2 site in the period 2000–3000 BP.

CONCLUSIONS

The Bayesian calibration analysis presented in this paper represents a straightforward approach to calculating marine ΔR estimates for paired archaeological samples. It has the advantage over the standard approach that the estimate can accommodate uncertainty in the temporal relationship among the dated samples. Further, basic archaeological evidence relating to the relative timing of the dated events can be incorporated within the analysis in a natural manner. These calculations can be rapidly and easily undertaken using suitable software. In the current example, the DateLab software package (Jones and Nicholls 2002) was used.

The ΔR estimation approach presented here has shown that an estimate of –81 ± 64 ^{14}C yr is appropriate for the area in the vicinity of the Nenumbo, SE-RF-2 site in the period 2000–3000 BP. This differs from the figure of –70 ± 62 ^{14}C yr that would be calculated under the conventional calculation approach. Given that in many cases it is inappropriate to assume that paired archaeological samples are isochronous, this result suggests that more appropriate approaches to calculating archaeological ΔR values, such as that outlined in this paper, should be employed wherever possible.

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