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WIGGLE-MATCH DATING OF TREE-RING SEQUENCES

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ABSTRACT. Given the non-monotonic form of the radiocarbon calibration curve, the precision of single ^{14}C dates on the calendar timescale will always be limited. One way around this limitation is through comparison of time-series, which should exhibit the same irregular patterning as the calibration curve. This approach can be employed most directly in the case of wood samples with many years growth present (but not able to be dated by dendrochronology), where the tree-ring series of unknown date can be compared against the similarly constructed ^{14}C calibration curve built from known-age wood. This process of curve-fitting has come to be called "wiggle-matching."

In this paper, we look at the requirements for getting good precision by this method: sequence length, sampling frequency, and measurement precision. We also look at 3 case studies: one a piece of wood which has been independently dendrochronologically dated, and two others of unknown age relating to archaeological activity at Silchester, UK (Roman) and Miletos, Anatolia (relating to the volcanic eruption at Thera).

INTRODUCTION

The use of wiggle-matching for the more precise dating of tree-ring sequences, where dendrochronology is not possible on its own, is not new (e.g. Ferguson et al. 1966; Clark and Renfrew 1972; Clark and Morgan 1983) but is a method which is being performed more and more frequently. The mathematical methods which can be employed (see for example, Christen and Litton 1995; Bronk Ramsey et al. 2001; Pearson 1986) are well worked out. The purpose of this paper is to look at the application of the technique to archaeological material of a form which might be found in archaeological sites. The method has been applied to such materials before (see for example, Friedrich et al. 2001; Lowe et al. 2001; Kilian et al. 2000; Wille et al. 2003; van de Plassche et al. 2001). It has also been applied to long sequences of floating tree-ring chronologies (see for example, Kromer et al. 2001; Manning et al. 2001; van der Plicht et al. 1995; Imamura et al. 1998; Guo et al. 2000; Slusarenko et al. 2001; Vasiliev et al. 2001; Hajdas et al., forthcoming; Slusarenko et al., forthcoming).

Here, we will look at the suitable requirements for a sample for this type of analysis through a process of simulation. We will then look at 3 specific examples to test the accuracy and precision of the technique in fairly typical archaeological contexts. The first of these samples is from a standing building and has actually been dendrochronologically dated, so it is a blind test of the method. The other two are from archaeological sites (Silchester, a Roman site in southern Britain) and Miletos (Late Bronze Age levels of the site in western Turkey). The Silchester sample and standing building sample are both wood (waterlogged in the case of Silchester) and the Miletos sample is charcoal—so these examples cover a range of material types and contexts.

SIMULATIONS

We have conducted a large number of simulations using the calibration program OxCal to see what kind of precision can be obtained through wiggle-matching. In doing this, we use the R_Simulate function of the program and perform each analysis 10 times in order to average over some of the inherent variability in such simulations.

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Figures 1 and 2 show examples from these simulations directed towards the investigation of what the optimum number of samples are in terms of the measurement precision available for a particular time period. In the particular case shown, good precision (total 95% confidence range of less than 20 yr) can be achieved with only 7 measurements at a measurement precision level of ±35 ^{14}C yr. The sample/precision requirements are very variable depending on the period concerned (essentially due to the details of the shape of the calibration curve). But high precision (20 calendar yr) is often achievable with individual sample precision of ±25 ^{14}C yr and less than a century of wood. The optimum spacing for measurements is usually 10 yr (reflecting the resolution and scale of wiggles in the calibration curve). Note: this work employed INTCAL98; the more smoothed and modeled nature of INTCAL04 will very slightly change conclusions when it is employed (as it lacks some of the largely decadal signal of INTCAL98), but we do not expect significant differences.

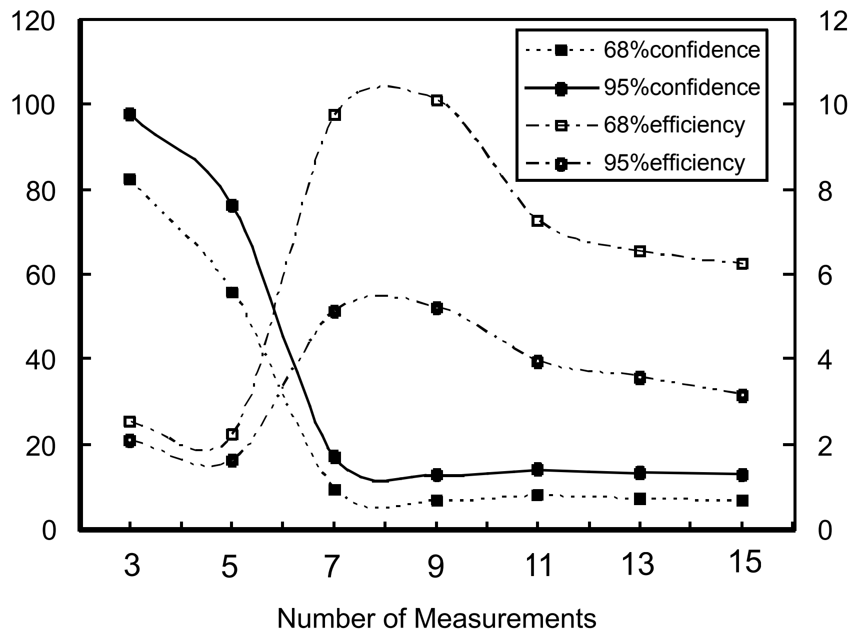

Figure 1 This figure shows the effect of increasing the number of measurements for a particular wiggle-match simulation; the starting date for this simulation was AD 1370; the sample intervals were set to 10 yr; and the precision was set to ±25 ^{14}C yr. The efficiency is defined as being $p^2/(r\ n)$, where *p* is the precision, *r* is the range, and *n* is the number of measurements. Using the efficiency measure or by looking at the ranges, it can be seen that about 7–9 measurements (spanning 70–80 yr) gives high precision for this particular period.

We can define an efficiency quotient (quality/effort) which is proportional to

$$p^2/(r\ n)$$

where *r* is the calibrated range after the wiggle-match and, therefore, $1/r$ is a suitable quality factor; *n* is the number of measurements and, therefore, proportional to the measurement effort; and *p* is the precision of the measurements, and the effort associated with this is assumed to be $1/p^2$.

This efficiency measure can be used to help in the estimation of the optimum number and precision of measurements for any given time range (see Figures 1 and 2).

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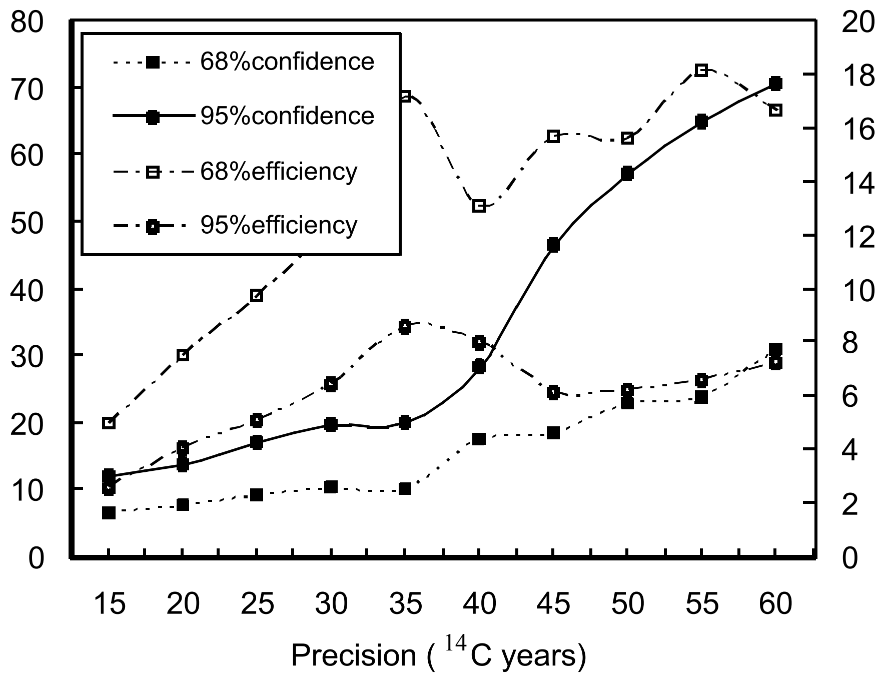

Figure 2 This figure shows the effect of changing the precision of measurements for a particular wiggle-match simulation; the starting date for this simulation was AD 1370; the sample intervals were set to 10 yr; and the number of measurements was fixed at 7. The efficiency is defined as being $p^2/(r\ n)$, where r is the range, n is the number of measurements, and p is the precision of the measurements. Using the efficiency measure or by looking at the ranges, it can be seen that in this case, even a precision of ±35 ^{14}C yr gives high resolution for this particular range.

Dating Methodology

The samples dated here were of wood and charcoal. The methods of sample pretreatment were the standard ones at Oxford for wood and charcoal (Hedges et al. 1989). In each case, we used acid/base/acid treatments. For wood, we followed this with a hypochlorite bleach to minimize the amount of lignin. We did not perform a solvent pre-clean on these samples—though, in retrospect, this might have helped to reduce the scatter in the blind test sample (see below).

All samples were graphitized following the method of Dee and Bronk Ramsey (2000) and the AMS dating followed the procedures described in Bronk Ramsey et al. (2004a).

Blind Test on Dendrochronologically-Dated Wood

This sample (oak) was provided by Dan Miles (Oxford Dendrochronology Laboratory) and had previously been dendrochronologically dated. The results are shown in Figure 3 with the fit to the calibration curve provided by the OxCal program (see Bronk Ramsey et al. 2001 for details of this method; the curve resolution is set to 1 and the INTCAL98 calibration curve used). The fit is good, though some of the later samples are slightly more scattered than one might expect (see comment above regarding pretreatment). Overall, the agreement between the samples and the curve passes a χ^2 test (minimum value 14.507 with 9 degrees of freedom with a threshold of 16.919 for 95% probability). The date for the mid-point of the last dated decade is fitted to 1065–1081 cal AD and, given

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the overall tree-ring sequence from the sample, we can deduce from this that the date of the outer ring of the sample should be 1072–1088 cal AD.

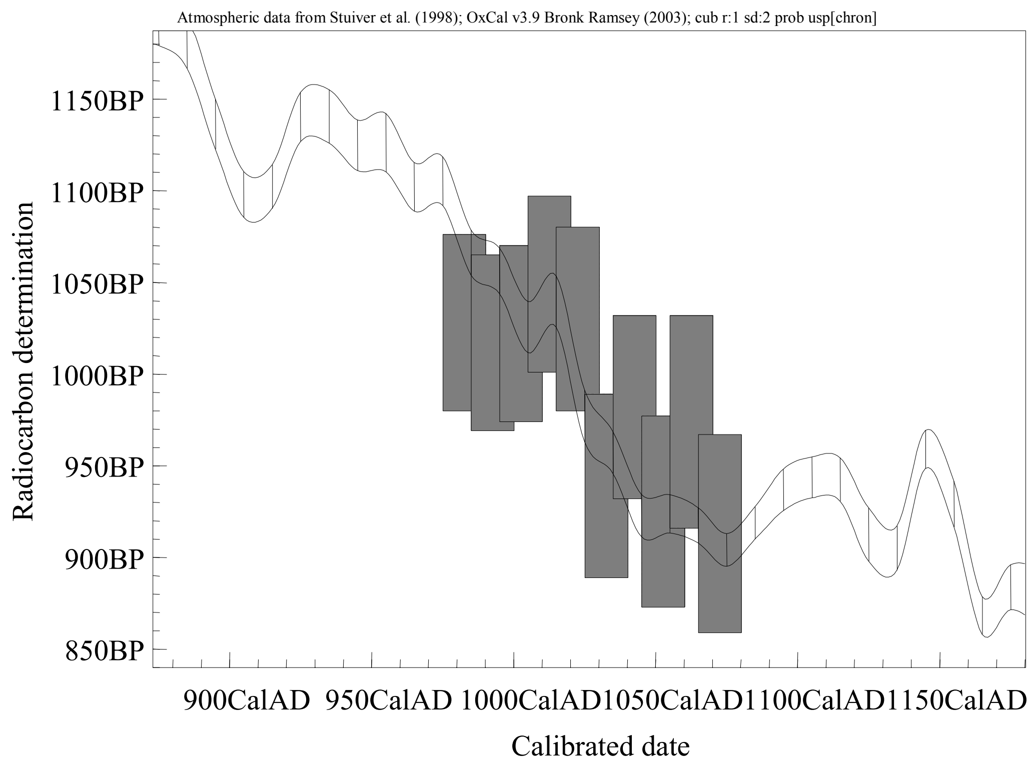

Figure 3 This figure shows the wiggle-match for the sample of dendrochronologically-dated wood which was used as a blind test of the method. The fit to the curve is good, though a little scattered at the right-hand side. The boxes show the 2-σ range of the ^{14}C measurement against the 95% confidence interval of the wiggle-matched sequence. In this case, the sample turned out to be from Salisbury Cathedral (see main text for a discussion of the result).

We subsequently obtained the dendrochronological date for the last ring of the sample, which is from Salisbury Cathedral in southern Britain: AD 1085 (Dan Miles, personal communication). This known dendrochronological age is within the 95% confidence range of the ^{14}C wiggle-match (1072–1088 cal AD).

Dating a Well in Late Roman Silchester

This sample (sill beam N18, oak), from pith through sapwood to a spring cutting date at the start of the 91st year of the sequence, belonged to Well 3011, found in Insula IX at the Late Roman site of Silchester (Clarke and Fulford 2002:143). It was supposed to be contemporaneous to the 3rd phase of the excavations and, thus, to belong to the 2nd–3rd centuries AD. The results of the wiggle-match are shown in Figure 4. The fit is very good for all but 1 sample and the overall agreement with the calibration curve passes a χ^2 test (minimum value 5.897 with 7 degrees of freedom with a threshold of 14.067 for 95% probability). The date for the mid-point of the last dated decade is fitted to 197–235 cal AD and, given the known number of additional rings from here to the terminal ring preserved on the sample, we can deduce from this that the date of the outer ring of the sample should be 202–240 cal AD.

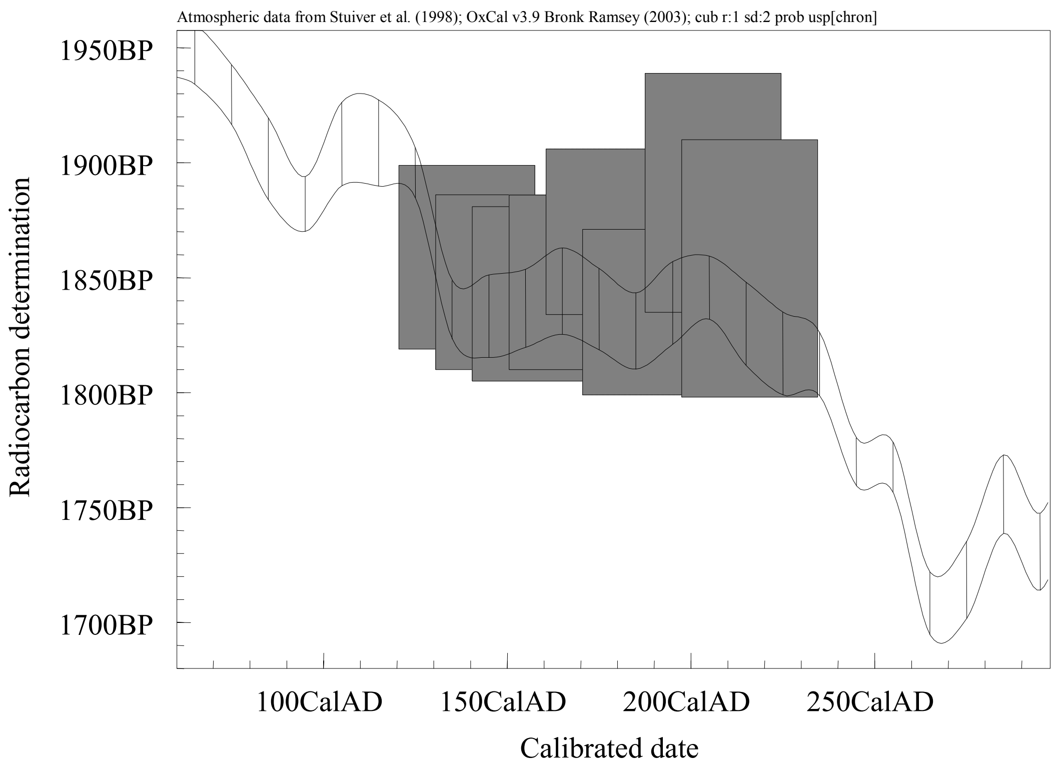

Figure 4 This figure shows the wiggle-match for the wood sample from Silchester. The fit to the curve is good with only the second point from the right being a marginal outlier. The boxes show the 2-σ range of the ^{14}C measurement against the 95% confidence interval of the wiggle-matched sequence.

Dating an Ornate Chair from Late Bronze Age Miletos

This sample (oak) is from an ornate chair found in a room of a sanctuary at Miletos (see also Bronk Ramsey et al. 2004b, these proceedings). Particles of Theran (Minoan) ash (identified by Max Bichler, personal communication) were sticking together with clay on the rim of a conical cup next to the chair. In the destruction deposit covering the burnt chair, there was a patch of ash containing particles of Theran tephra. Pottery, consistent with an LMIA date, was also found.

The dating of this sample offers a *terminus post quem* for the eruption of the volcano of Thera in the Aegean Sea and forms extra evidence to clarify the debate around the chronology of this event and the chronology of the LMIA cultural period in the Aegean. Current research considers the 2 most likely dates for this eruption to be either the mid- to later-17th century BC (Hammer et al. 2003; Manning et al. 1999, 2002; Manning and Bronk Ramsey 2003), or towards the end of the 16th century BC (Warren 1984, 1987, 1988, 1996; Bietak 2003). The results of the wiggle-match are shown in Figure 5. The fit is very good for all samples, and the overall agreement with the curve passes a χ^2 test (minimum value 2.896 with 6 degrees of freedom with a threshold of 12.592 for 95% probability). The date for the mid-point of the last dated decade is fitted to 1674–1651 cal BC; since there are 7 rings from the middle of this decade to the exterior of the sample, we can deduce from this that the date of the outer ring of the sample should be within the range 1667–1644 cal BC (see further in Bronk Ramsey et al. 2004b, these proceedings).

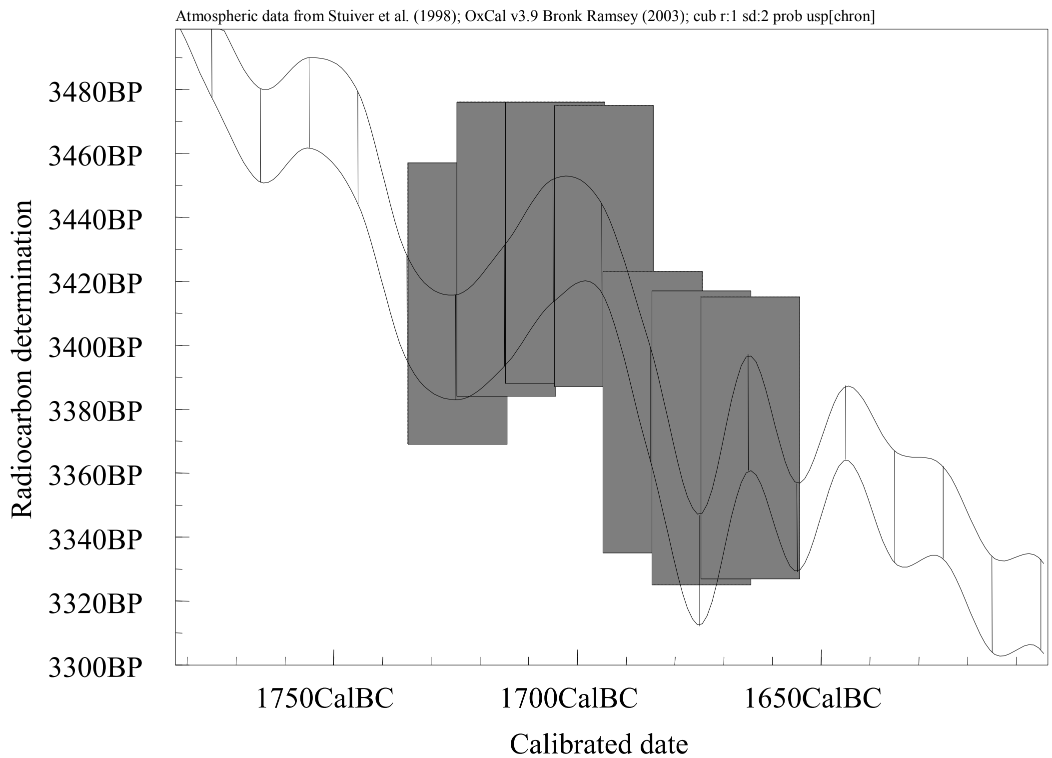

Figure 5 This figure shows the wiggle-match for the charcoal sample from Miletos. The fit to the curve is excellent. The boxes show the 2-σ range of the ^{14}C measurement against the 95% confidence interval of the wiggle-matched sequence.

CONCLUSIONS

We can see from the examples here, and from the simulations performed, that the wiggle-match dating of wood samples from archaeological contexts is a precise and accurate technique of dating, which could, in principle, be more widely applied. Overall 95% confidence ranges can be as short as a few decades. Such time-series wiggle-matching is really the only way to achieve high-precision calendar date estimates through ^{14}C dating. The critical caveat to justify the effort involved is that the dated sample must relate closely and specifically to the associated archaeology. Otherwise, one can have a well-dated piece of wood that serves no purpose.

The method is fairly labor-intensive since a number of ^{14}C determinations are needed for a single date. For this reason, the use of simulations to minimize the amount of work involved is important, and an "efficiency factor" can be used to help to find the optimum strategy.

In many cases, between 5 and 10 measurements at precisions of 25–30 ^{14}C yr are sufficient to achieve an overall 95% confidence range of less than 25 yr. This is many fewer measurements than would be needed to achieve the same precision by dating multiple samples from successive periods in a more general form of Bayesian wiggle-matching (sequence seriation matching, where the absolute time intervals between samples are not known). Thus, if the right material is available in suitable association, this technique should be the method of choice for high-precision dating of archaeological material.

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