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# Radiocarbon wiggle-match dating in the intertidal zone

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## Abstract

Radiocarbon wiggle-match dating is a technique that can combine the versatility of radiocarbon dating with chronological information from tree-rings. This makes it useful in contexts where timbers are preserved, but dendrochronological dating is impossible. As intertidal and marine timbers are waterlogged, this can favour their preservation and hence allow wiggle-match $^{14}C$ dating, which can be of significant help in deriving relatively precise chronologies for a range of coastal structures. As the technique depends on making multiple radiocarbon measurements towards a single date, efficiency in application is the key and hence a number of practical considerations need to be taken into account in advance of conducting a dating programme. This paper discusses some of these practical concerns and reviews them in the context of the intertidal crannogs in the Firth of Clyde on the west coast of Scotland.

Keywords: Radiocarbon wiggle-match dating, Bayesian modelling, marine crannogs, site formation, taphonomy

## Introduction

Coastal and intertidal zones, with their potential for water saturation of archaeological contexts, and hence the retardation of the decay of organic materials (Bjordal et al. 1999; Weiner 2010), may present a set of chronology-building opportunities unavailable on a typical terrestrial site.

Foremost of these is the potential survival of timbers and hence the application of dendrochronological techniques that in some instances can provide an exact felling year (Baillie 1982; O'Sullivan 2003) and in other cases, sapwood-based felling estimates, or relative intra-site chronologies (Cavers and Crone 2017, *in press*). This is possible because trees of the same species will tend to react in a similar way to environmental conditions and so there will be a record of good and bad growth years that can be distinguished through visual and statistical analysis (Baillie 1995). However, many tree species, such as alder, are too sensitive to local environmental conditions and disturbances (Crone 2014), while other species, such as ash, can be too resistant to them (Baillie 1982) and so implementation of dendrochronological dating might not be possible on all sites containing timbers. Another substantial challenge to much of dendrochronology is the requirement for tree-ring sequences to be long enough for statistical confirmation of the observed trends, which often puts short sequences at a substantial disadvantage and so, in instances where the timbers are medium or short-lived (<100 years), it might be impossible to obtain dendrochronological dates (Baillie 1982). Hence, while it is preferential where it can be applied, dendrochronology might not always be versatile enough to take advantage of the preservation of timbers on archaeological sites.

The current paper discusses radiocarbon wiggle-match dating: a technique that can combine the radiocarbon dating technique with the chronological information provided by the annual growth of tree-rings (Bayliss 2007; Hamilton et al. 2007). As radiocarbon is more versatile than dendrochronology, wiggle-match dating can be applied to a broader range of tree species and also to short-lived samples, while still delivering a better degree of precision than that of individual radiocarbon determinations. This paper summarizes the technical basis of wiggle-match dating, some of the practicalities of the technique and discusses them with reference to the Clyde Estuary crannogs (Jacobsson et al. 2017, *submitted*).

## 2. What is wiggle-match dating?

Whenever a plant builds up a wooden stem, such as a tree-trunk, much of the material within the stem is physiologically dead on formation. If the woody stem grows annual rings, then each ring will contain a $^{14}C$ signature of the year in which it was first formed. This in turn permits the application of the wiggle-match dating technique: by taking several measurements across the tree-ring series it becomes possible to re-create a short section of the past radiocarbon trend and fit it to a radiocarbon calibration curve (Figure 1) (Bronk Ramsey et al. 2001). As a general recommendation, the internationally ratified radiocarbon calibration curve should be used (the most recent at the time of writing is IntCal13; Reimer et al. 2013).

The actual wiggle-match can be conducted using at least three different statistical approaches (Bronk Ramsey et al. 2001). The first of these, a least squares wiggle-match (e.g. Clark and Renfrew 1972), relies on finding the point at which the sum of the squares of distances between the measured series and the radiocarbon calibration curve is smallest. This technique is easiest to implement from a computational point of view, but it only ever produces a single point of fit, with no measure of uncertainty attached to it. The second alternative is the Bayesian wiggle-match (Bronk Ramsey et al. 2001), which places the individual determinations within a sequence model and provides exact values for the time elapsed between each of the samples (see e.g. Buck et al. 1996 for mathematical exposition). The Bayesian estimation of wiggle-matches has the advantage of providing a probability distribution for the date of interest. The third approach is Monte Carlo wiggle-match dating (Weninger 1997), which saw one of the early attempts to overcome the limitation of the least squares method, but, for a range of historical, practical and theoretical reasons, sees very infrequent application.

One of the key advantages of Bayesian wiggle-matches is that the probability distribution functions it provides are straightforward to carry over to site-level models of the kind discussed by. Litton and Buck (1995) and applied to data including wiggle-match determinations (e.g. Hamilton et al. 2007). Inclusion of wiggle-match determinations in formal statistical models permits their use to not only date a particular timber, but also to provide information on general site chronology or site formation processes. As many intertidal and coastal sites, from the submerged Mesolithic and Neolithic settlements (Andersen 1985; Galili et al. 2002) to the foreshore constructions of the Middle Ages (O’Sullivan 2003), have surviving wood, wiggle-match dating may be of great use to coastal and marine archaeology.

## 3. Practical concerns in wiggle-match dating

As wiggle-match dating requires multiple $^{14}$C measurements to produce a single date, efficient application is paramount. Therefore, it is best deployed where the improved precision it brings is necessary to deal with the archaeological questions encountered. In practice this means conducting a careful research design based on simulation (Bayliss 2009) and legacy or pilot data. The latter two sources of information are of particular use:

1) as the wiggle-match dates depend on fitting to the calibration curve, knowing which section of the curve a sample might belong allows for a more rational allocation of the dating resources,

2) knowing the section of the calibration curve also aids the sub-sampling strategy.

This second point relates directly to the question of how many tree-rings should be included in the sub-samples making up a wiggle-match date. In principle, single-ring sampling ought to be the preferred choice as it maximizes the chances of detecting any short-term radiocarbon variability and hence should provide better precision of the results. However, the resolution of the samples underlying the calibration curve is often lower than single-year and so sampling individual tree-rings can lead to a situation where the additional information not only fails to provide any meaningful improvement, but may also distort the quality of the fit (Jacobsson 2015). The general knowledge of when the dated timbers may have been felled also helps with the simulation stage of the research design, which involves evaluating the research investment necessary to answer the archaeological question through simulating a range of "what-if" scenarios. Knowing the general chronological location of the samples limits the range of the "what-if" scenarios to consider and hence cuts down on the time spent by the analyst on research design.

Simulation and the knowledge of the general positioning of a group of samples in time is also essential in estimating whether the precision necessary to address the archaeological questions can be obtained without sacrificing the accuracy of the results. While still of minor concern when working with routine precision determinations (*ca* 25—35 $^{14}$C years at 1$\sigma$), small systematic offsets between the calibration curve and the past radiocarbon trends are beginning to emerge as a major source of concern for projects that require very high chronological resolution. The offsets in question can arise due to a range of factors originating from the temporal variability of the carbon cycle leading to the emergence of short-term localized atmospheric $^{14}$C offsets (e.g. Manning et al. 2001; 2014), but may also stem from statistical properties of the wiggle-match dating model itself (Jacobsson 2015). These two potential sources of error mean that wiggle-match dating requires that attention must be paid to how precise the matches can be before the differences between the trends measured in the samples and the idealized picture of these trends in the calibration curve become non-negligible. The actual approach to defining such a "safe" precision zone can either take the form of an arbitrary cap on expected precision (in our experience, and based on limited simulation, 50–100 years at 95.4% probability for modelled ranges for wiggle-matches constitutes a reasonable cap) (Jacobsson 2015), or of simulation-based systematic sensitivity studies that seek to find exact "safe" values for a given part of the calibration curve in the face of a range of credible offsets. The latter approach, while preferable, requires a major time investment and hence might be difficult to carry out on a routine basis.

One other matter to consider at the stage of wiggle-match dating research design is whether the timbers dated retain the bark edge. If they do, the wiggle-match dates the felling of the timber. However, poor bark edge survival rates are common and some means of estimating the felling date are necessary. Most common of these is to take advantage of the distinction between sapwood and heartwood, which is common to a number of species. Heartwood forms as the wood gets older, with the sapwood transformed during the collapse and lignification of the vessels that were used for the transport of nutrients (Taylor et al. 2002). In some of the species displaying this distinction, such as oak, there tends to be a typical number of sapwood rings and hence, if the sapwood/heartwood boundary is preserved, it becomes possible to provide an estimate of how many rings are missing until the bark edge. There are three ways these estimates can be implemented in a wiggle-match:

1) The most straightforward way is to add the typical range of sapwood rings to the date for felling of the tree. This is a straightforward procedure and has the advantage of being consistent with the typical approach of the dendrochronological community (e.g. Cavers et al. 2011).
2) Adding only a typical range of sapwood rings has the disadvantage of assigning equal probabilities to numbers of rings that are common and extreme. This can be mitigated by using an empirical distribution based on sapwood rings observed in the species sampled (Bayliss and Tyers 2004; Hamilton et al. 2007).
3) An alternative is to apply a statistical model that would allow for possible biases emerging in sampling. This also has the advantage of making it possible to include further information in the model such as the number of heartwood rings, which correlate with different counts of sapwood rings (Miles 2005). The advantage of this approach is that it allows a greater degree of precision than the use of a uniform distribution implicit in the more traditional approach (1). The necessary models are implemented in recent versions of OxCal, starting with v4.0 (Bronk Ramsey 2009a).

Beyond these more general issues relating to the calibration curve and estimating the felling year, wiggle-match dating research design also needs to be conscious of sample taphonomy and how it might affect the dating results. All radiocarbon laboratories have procedures to deal with expected contaminants that may have an adverse effect on dating archaeological samples and these are under constant re-evaluation both through in-house quality assessment (QA) procedures (e.g. Naysmith et al., 2010) and international laboratory inter-comparison programmes (e.g. Scott et al. 2010), however, some samples might require extended pre-treatment protocols before reliable radiocarbon measurements are obtained (Hatte et al. 2001).

Besides the taphonomy of the individual samples, site formation processes also need to be taken into account when both designing and interpreting chronological studies. The matter of chronological associations is a general and long recognized issue when it comes to $^{14}$C dating of archaeological sites (Schiffer 1986). In the case of wiggle-match dating of timbers, any sample may have been re-used from an earlier structure (leading to an illusion of an older date), or may have been inserted during maintenance (introducing a risk of too young dates). Nevertheless, the higher precision afforded by wiggle-match dating can help to resolve this question as part of the dating design, or might make such questions the main focus of the dating design (see the case study below). Of course, integrating chronology and site formation process studies depends on the nature of the sites studied and so there are no universal guidelines on how this can be carried out and each project needs to be based on the understanding of the archaeological problems at hand and their relationship to the nature of the sites themselves. The case study of the Clyde crannogs illustrates how some of this plays out in practice.

## 4. Case study: the Clyde crannogs

There are at least four wooden platforms in the intertidal zone of the Firth of Clyde (the Clyde estuary) (Hale 2004) (Supplementary Figures. 1–5), whose interpretation of these sites hinges on their cultural and historical context. The close proximity of the terminus of the Antonine Wall (the northernmost Roman fortification in Britain) and the potential association of wetland sites with Roman material culture elsewhere in Scotland (Hunter 1994) have led some to posit that the Clyde crannogs were associated with the Roman occupation of Scotland (e.g. Sands and Hale 2002). If this was indeed the case, the interaction with the occupier could be one of the motives behind building these sites and ought to be taken into account whenever discussing the data derived from them. If, on the other hand, the sites pre- or post-date Roman activity in Scotland, their interpretation would need to be adjusted to a more appropriate historic context.

Prior to our wiggle-match dating study, eight legacy radiocarbon determinations were available for two of the Clyde crannogs: Dumbuck and Erskine Bridge crannogs. While three of these determinations might overlap with the construction of the Antonine wall in AD 142–162 and the period of Roman activity beginning with the invasion of Agricola in AD 80, the broad calibrated ranges of these radiocarbon dates allow for other associations, such as a connection to the settlement transformation in south-east Scotland in the 2nd century BC (Hamilton et al. 2015) (Fig. 2). Furthermore, even though the calibrated date ranges of the legacy dates from Erskine Bridge and Dumbuck crannogs overlap, it is still possible that the sites were not contemporary and thus they might not even be an expression of the same phenomenon.

Another issue to be tackled was the potential discrepancies between the ages of timbers within the legacy dates from both Dumbuck and Erskine Bridge crannog. The large uncertainties and occasional non-overlap in the dates from each site presented a risk of two potential dating complications:
1) the use of recycled timbers when building the platforms, and/or
2) the longevity or multiple re-use of the same locations.
As field observations at Dumbuck crannog indicated the second option to be improbable, the research design accounted for the possible presence of recycled timbers in the dated deposits, making the sites seem older than they were in reality. Because of this any attempt to resolve the higher-order historical questions would first require resolving the issues of site formation. To address this we developed a small-scale wiggle-match dating programme where at least two timbers from each of the dated features were chosen and more than one feature was dated at each of the two sites. A simulation study demonstrated that such a design, when applied to several features from each site, had a good chance of detecting timber recycling, provided a chance of identifying structure re-use and precision sufficient to deal with the archaeological question of when these sites were first built. What follows is a brief discussion of the results. The detailed information on the historical contexts, sampling decisions and the unmodelled radiocarbon data are available elsewhere (Jacobsson 2015; Jacobsson et al. 2017).

The first adjustment of the original research design came at the sampling stage. The exposed area of Dumbuck crannog consists of two main features: a circle of oak posts, from which we collected two timbers for wiggle-match dating, and a horizontal floor from which we collected three timbers for wiggle-match dating. While the two oaks from the circle of piles lived for long enough to match the research design of 50 years (a minimum of 53 and 56 years), two of the three horizontal timbers were shorter lived (28, 35 and 52 years minimum). This meant that the possibility existed that further sampling would be needed to solve the archaeological question of whether any of the Dumbuck timbers were re-used and when was the structure built. We were very fortunate in that this was not the case. Altogether 22 $^{14}$C determinations were commissioned on the new material from Dumbuck crannog (Supplementary Figure 6). At Erskine Bridge crannog, two of the authors (AH and PJ) sampled four long-lived timbers from two features exposed by erosion and three smaller stakes from what might have been a floor or a sub-floor. Twenty-five $^{14}$C determinations were carried out on these timbers (Supplementary Figure 7).

The results of the wiggle-match dating programme were unambiguous in that they showed that both Dumbuck and Erskine Bridge crannogs were built before any Roman incursion (Fig. 3): Dumbuck was built in *cal AD 5–55* (*95.4% Probability; Dumbuck construction Last*) and Erskine Bridge crannog was built in *330–215 cal BC* (*95.4% probability*; *Erskine construction Last*). In both instances the date ranges of the individual wiggle-matches within the sites overlapped, making a case against the notion of recycling from much earlier structures. Furthermore, the construction of both sites appears to lack any direct and immediate relationship with the developments in south-east Scotland following 200 cal BC and, what is perhaps more important, the two sites appear to be formed *370–235 years apart* (*95.4% probability*; *Dumbuck-Erskine Bridge difference*) (Fig. 4). This calculation was carried out using OxCal's Difference(); function, which allows calculating the time elapsed between two events of interest, which in this case were the construction estimates of the Dumbuck and Erskine Bridge crannogs.

These results were not achieved without some additional technical difficulties. At Dumbuck, all of the timbers spanning more than 40 years had one measurement that appeared to contain too little radiocarbon, given its expected date. As all these measurements came from a similar point in the sequences (3rd and 4th decades counting from the bark edge; see Supplementary Figure 8), the first place to look at the origin of the offset was the shape of the calibration curve. On inspection, it became clear that the expected location of these measurements corresponded to a wiggle in the calibration curve that could have been over-smoothed during the estimation of the calibration curve, as suggested by not only our, but also the local calibration measurements (see Jacobsson 2015 for more detail).

A more complex issue emerged at Erskine Bridge crannog where a large number of measurements from across the dated timbers seemed to have suffered from some form of systematic offset towards older uncalibrated radiocarbon ages. This affected the tree-rings that were exposed to the surrounding environmental matrix, either through their location in the outermost decadal block, or through the channels bored by shipworm (*Teredo navalis*) and decay. Hence, an outlier model (Bronk Ramsey 2009b) designed to account for the specific nature of this offset was implemented in all the affected samples. This had to be followed by a suite of sensitivity analyses that checked the assumption that a similar result would be attained if the assumptions that underpinned the outlier model were wrong (see Jacobsson et al 2017 *submitted* for more detail).

## 5. Conclusion

This paper presented the basics, some of the practicalities, and an application of radiocarbon wiggle-match dating in a coastal context. The technique is more versatile than dendrochronology, while producing results that are more precise than those of most routine single radiocarbon determinations. Hence, wiggle-match dating can be of great value in contexts where timbers are preserved, but, due to either the species composition of the assemblage or the limited longevity of the sampled timbers, dendrochronological results could not be attained.

Future developments will further improve the radiocarbon wiggle-match dating technique. On a fundamental level, the ongoing improvement in the radiocarbon calibration curve will provide substantial benefits to wiggle-match dating, both in terms of attainable precision and also greater reliability of results. Furthermore, a greater understanding of the chemical changes taking place in waterlogged wood (and for coastal applications in saline and brackish environments) could prove helpful in terms of avoiding the unexpected technical difficulties of the kind encountered when wiggle-match dating the Erskine Bridge crannog. The last improvement, applicable beyond the realm of wiggle-match dating, would be in better automatization of simulation studies, which would allow for a more comprehensive research design. Between these three improvements, the work on which is ongoing, and good awareness of the archaeological issues present in the different coastal and marine contexts, $^{14}$C wiggle-match dating can and will make substantial contributions to our understanding of human interaction at the boundary of land and sea.

## 6. Acknowledgements

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# Figures

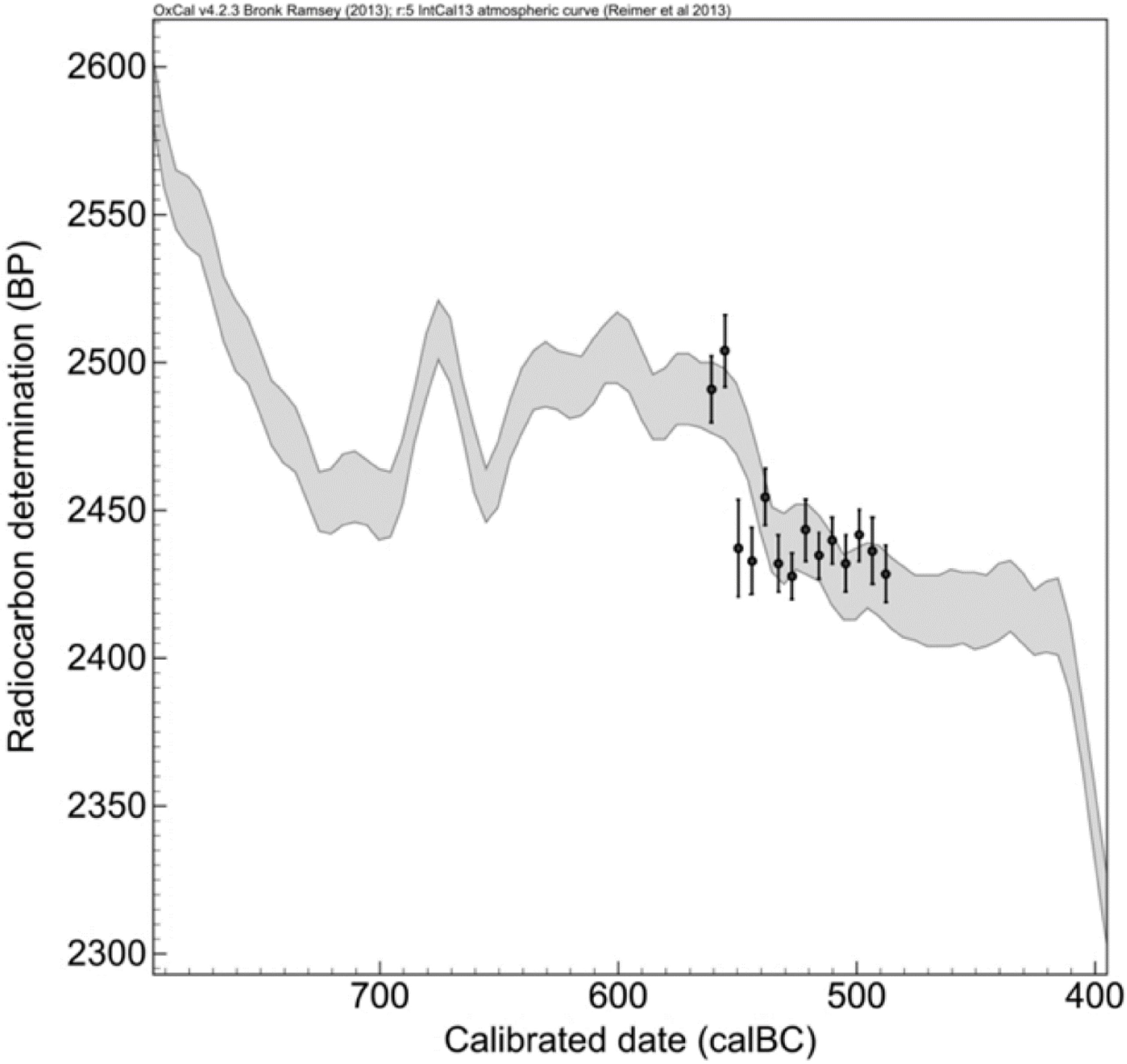

Figure 1 Basic premise of 14C wiggle-match dating of timbers. A series of radiocarbon determinations is carried out throughout the timber length and the results are fitted to an internationally ratified calibration curve. Data from (Cook et al., 2010).

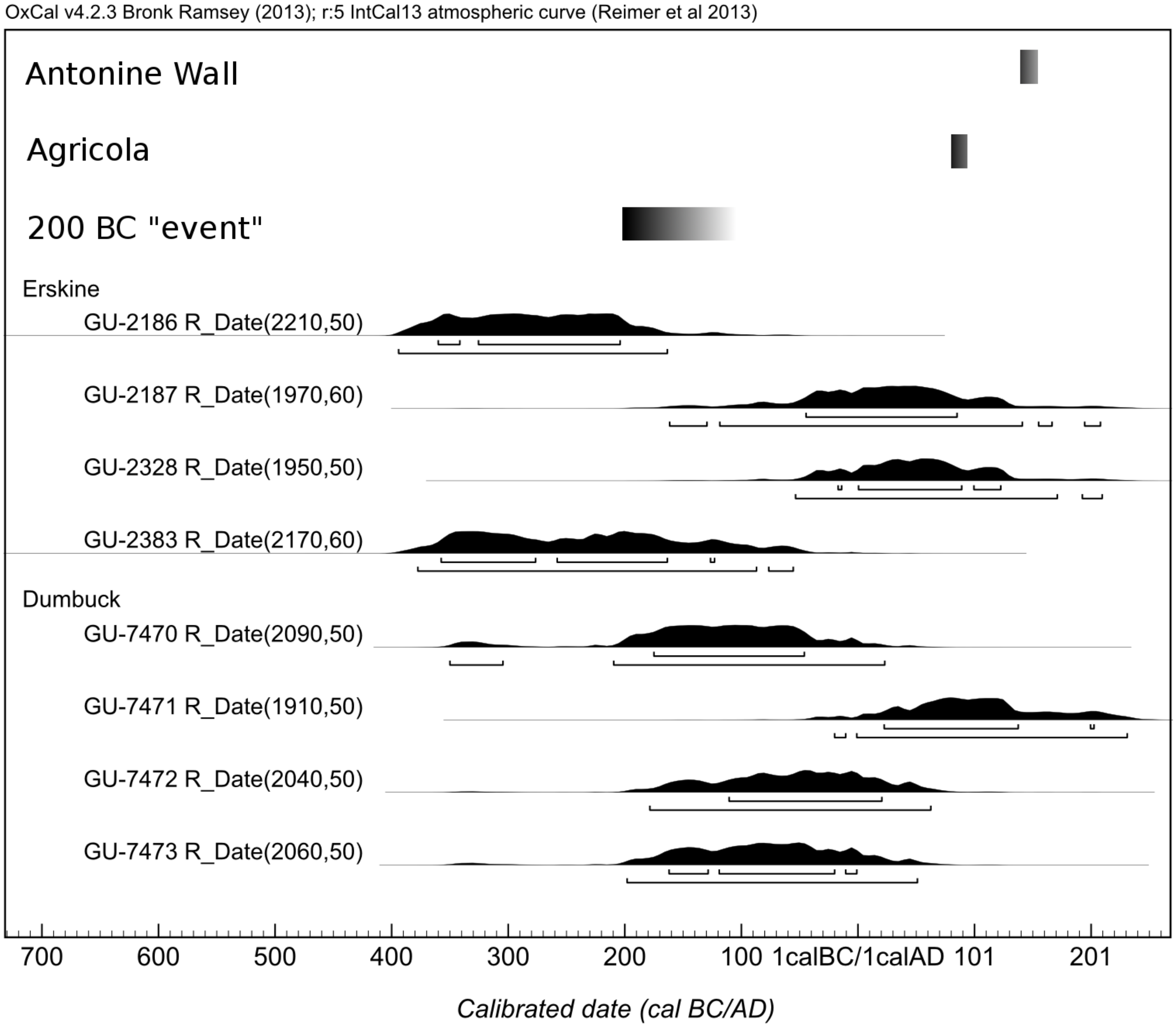

Figure 2 Legacy radiocarbon determinations from Dumbuck and Erskine Bridge crannogs visualized against the timing of the construction of the Antonine Wall, Agricola's invasion of Scotland and the settlement "event" happening around 200 cal BC. Data from Sands and Hale (2002).

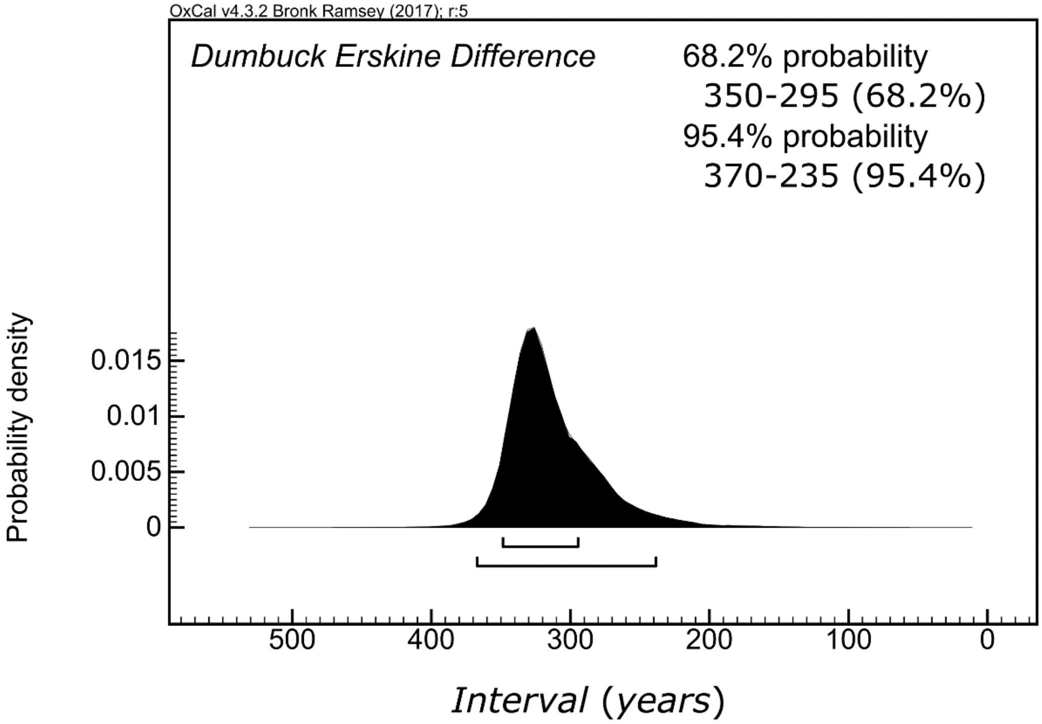

Figure 3 Wiggle-match based estimates of the construction of Dumbuck and Erskine Bridge crannogs visualized against the events from Figure 2.

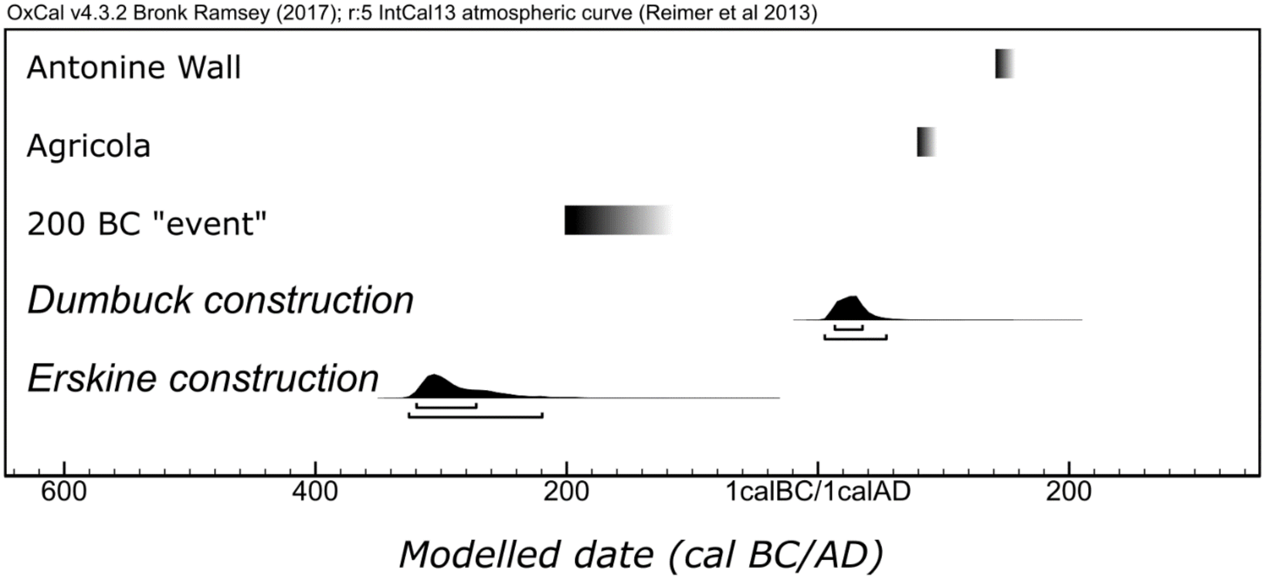

Figure 4 Estimate of the time elapsed between the construction of Dumbuck and Erskine crannogs.