# Improving the $^{14}C$ dating of south-west Scottish wetland sites

Piotr Jacobsson

MA(hons), MSc(R), FSA Scot

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# Abstract

This thesis discusses the adaptation of the wiggle-match dating technique and Bayesian chronological models to the practicalities of dating timbers from Iron Age Scottish wetland sites, with a focus on the area between the firths of the rivers Clyde and Solway. Wiggle-match dating technique relies on taking measurements from a sequence with an estimated, or known deposition rate, such as timbers, and fitting the resultant time series to an established calibration curve. Bayesian modelling entails combining various forms of information about the material dated to obtain a more comprehensive chronological understanding. These techniques are relevant to Iron Age wetland settlement in Scotland due to the lack of other methods that could produce high-precision dates on a routine basis; too few timbers from Scottish wetlands produce absolute dendrochronological dates and ordinary radiocarbon calibrations tend to have low precision during the period 750-200 BC, which covers the formative stages of both the Scottish Iron Age and wetland settlement tradition.

Effective use of the wiggle-match dating technique requires attention to aspects of technique, its practical implementation and suitable research design. As far as technical aspects are concerned, the work conducted within this thesis demonstrated the need to match the length of sample blocks of wood with the length of the measurements underpinning the calibration curve. Furthermore, presence of small offsets between the calibration curve and the actual past trend of radiocarbon has been identified; while these offsets have minimal impact on most radiocarbon applications, the wiggle-match dating technique is sensitive to them and hence conscious decisions need to be made at the stage of research design to avoid systematic bias in the results. Aspects of practical implementation have been explored through wiggle-match dating studies at four sites: Black Loch of Myrton, Cults Loch3, Dumbuck and Erskine Crannog. Results demonstrate that even on the most challenging parts of the calibration curve wiggle-match dating can succeed in producing modelled date ranges of less than 100 years and that, on more favourable parts of the curve, it can be used to aid the resolution of questions regarding site formation processes. Moreover, these case studies highlighted a number of practical issues such as propensity of decayed rings to produce radiocarbon results biased towards older ages. Efficient use of wiggle-match dating in archaeological contexts requires not only the technical and practical capacity, but also a strategic framework within which the methodology is to be employed. While the nature of this framework depends on the interpretations the researcher is interested in, this thesis suggests a focus on developing linkage between different sites, both wetland and terrestrial, so that the well-preserved deposits become informative of not only a single site, but also shed light on the local and regional developments.

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## Author's declaration

No part of the work presented in this thesis has been submitted for any other degree or qualification. The thesis is the result of my independent research, carried out between October 2012 and September 2015 at SUERC, University of Glasgow, under the supervision of Prof. Gordon Cook and Dr Derek Hamilton. Any material, published or otherwise, used in this thesis is given full acknowledgement.

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# 1 Introduction

Since the antiquarian surveys of the mid-19th century, over 400 confirmed or possible wetland sites have been discovered throughout Scotland (RCHAMS 2015), with a growing body of evidence suggesting the existence of further sites in hitherto unexplored parts of the country (Stratigos, forthcoming). At the moment, the overwhelming majority of these are identified as lake dwellings, or crannogs, although recent re-interpretation of the site at Black Loch of Myrton as a marsh settlement (Crone and Cavers 2015) indicates that these sites may be far more diverse. Likewise, most of the dating evidence points towards a period of greatest construction intensity during Scotland's pre-Roman Iron Age (750 BC–AD 80), but the activity continues into the early modern period (Crone 2012). In terms of both external appearance, as well as internal structure these sites vary, although the nature of this variability is still little understood. In very broad and general terms the sites in the Highlands tend to consist of stone mounds, while the ones in the lowland locations of south-west Scotland more often than not have the appearance of organic mounds (Henderson 1998b, 236), although there are exceptions from this overall picture, such as the stony Rough Island and Heron Island, both in the south-west (Henderson 2007b; Poller 2005, 231). The one factor that all these sites do have in common is their potential for excellent preservation of organic remains. Even the exposed and eroding marine crannogs in the Firth of Clyde still retain many of their 2000 year old structural timbers and on sites with favourable conditions, such as Oakbank, in Loch Tay, almost the entire mound is made of plant remains (Miller 2002). Therefore, the wetland sites have the potential to inform us about a range of prehistoric practices, from responses to ecological transformations, through the operational sequences involved in working with organic materials, to the basic elements of Iron Age architectural history. This in principle ought to lead to an extensive referencing to these sites, even more so as they coincide with a period of paucity of evidence on many of the terrestrial sites. As of the time of writing this has not happened, with only cursory comments being made in most syntheses of the period: wetland sites are mentioned on only 3 pages in Cunliffe's *Iron Age Communities* (2005) and 13 pages in Harding's *Iron Age in Northern Britain* (2004). So it can be said that at the moment the archaeological potential of Scottish wetland settlement remains unfulfilled.

This apparent paradox can be traced to a set of conditions rooted within both the history of research and the nature of the data themselves. For one thing, when contemporary Iron Age archaeology of Scotland emerged in the latter half of the 20th century, the exploration of wetland sites was on hiatus and, in any case, it was believed by many that these sites belonged to the Roman or later periods (Piggott 1953, 150-1). Hence, the framework developed lacked a place for wetland sites as a part of Iron Age community. This perhaps would not be so much of a problem had the nature of the sites themselves not reinforced the division. While much information on the terrestrial archaeology of Scotland was attainable through aerial survey (Cowley and Brophy 2001) or open-area excavation in the course of development mitigation (Phillips and Bradley 2004) wetland sites in general lie outside development focus areas and require a much greater investment per unit square of plan in terms of excavation and analysis costs than their counterparts on land. This, further exacerbated by the inherent richness of the wetland record, leads to a situation where an extensive but poor terrestrial assemblage is being compared with a very limited but rich wetland assemblage. The differences then lead to a situation where increase in knowledge on wetland sites does not contribute to the understanding of the Iron Age as a whole, as there is no form of linkage across the division induced by the preservation gradient. Hence a feeling of stamp collecting emerges for numerous aspects of Scottish wetland archaeology (Henderson 2007b, 231).

This stands in opposition to case studies from continental Europe, where wetland and terrestrial sites are integrated into narratives of the past through the concept of archaeological culture. The pile dwelling at Alvastra, Sweden, is treated as another pitted-ware pottery site with questions relating to that particular cultural grouping (Malmer 2002). Likewise, the Bronze Age fortified settlement at Biskupin, Poland, is presented as a Lusitz culture site first and wetland site second (Kostrzewski 1938; Piotrowski 1998, 98-99). Even in contexts where the role of culture-history was limited, alternative approaches were developed with the explicit focus on the relationship between wetland and terrestrial settlement, such as Miklyaevs historical geography which postulated area-wide syntheses and which is still pursued by the Russian wetland archaeologists (Mazurkevich et al. 2010, 61-3). Such strategies integrate the data of the wetland sites of continental Europe into a synthetic effort from the stage of research design and, as a result, the superior preservation makes a greater contribution to our understanding of prehistory.

Direct introduction of the European approach to Scottish crannogs and other wetland sites is impossible on account of the paucity of artefact remains that characterizes the Iron Age of northern Britain (Harding 2006, 78-9). Therefore, the development of culture-historical schemes, which would justify linking different sites into the same narratives, is hindered and so the logical premises for extrapolating from the rich wetland assemblages to the Iron Age as a whole are weak. In principle, this could be overcome through absolute chronology, but the technical means of developing sufficient chronologies are limited; dendrochronology cannot be expected to work for every structural feature and for much of the period radiocarbon dating is too imprecise to establish the required temporal connections.

The main aim of the project presented in this thesis was to develop a practicable approach to building absolute chronologies capable of establishing the temporal connections required for linking different Iron Age settlements. This entails a pursuit of the three interconnected questions of technique, practice and meaning:

1. The technical questions of the thesis were focused on whether the dating methods employed perform well during the Iron Age and whether satisfactory results can be attained within a viable investment.

2. The practical questions were focused on applying the technical results in the context of Scottish wetland archaeology. The main issues here were whether the technical approaches developed can be used to date single wetland sites, as well as identification of the limitations on the technique and recognition of any recurrent problems that future research design might need to take into account.

3. The final question was how to put the practical approach to work in such a way, as to make it meaningful to the understanding of the Iron Age. In its essence this relates to developing such research designs that have clear and attainable goals that at the same time provide meaningful insights into the Iron Age.

At the heart of this project are the wiggle-match dating technique and the Bayesian modelling of radiocarbon dates. The wiggle-match dating technique relies on the annual nature of tree-ring growth: because the cellulose of each ring only contains the carbon from the year it was formed, tree rings can be used to "build" a small section of a calibration curve that can be fitted to a ratified master curve. As the number of probable matches is limited, much greater precision can be attained than is the case for single dates. The main weakness of the technique is its reliance on a number of assumptions that are in some practical cases violated to the detriment of the date accuracy. Indeed, during the course of studying radiocarbon results from a known-age timber it became clear that there may exist small-scale offsets, which would have had their origin in the statistical uncertainty underpinning the calibration curve. In practice this means that there is a limit to how precise the wiggle-match date results can be before their modelled date ranges become inaccurate and, hence, there is an inherent limit to the practicable expectations of the technique. This loss of precision can be countered, to a degree, by the inclusion of the wiggle-matches in Bayesian statistical models which constrain some of the statistical scatter through the introduction of an overarching distribution. Bayesian modelling is also essential at the practical level of dating individual sites and features as it aids identification of outliers and proves helpful in determining possible timber re-use, or the addition of new elements to any given site.

The overall practical recommendations from the project can be divided into those relating to the timbers themselves and those pertaining to the nature of the radiocarbon calibration curve. Over the course of work on unknown samples it became clear that sometimes it is difficult to obtain an accurate measurement for the very decayed tree-rings, or that whole timber might have been re-used or otherwise subject to some form of systematic offset. Because of such possibilities sampling multiple timbers from features of interest is recommended for most conceivable wiggle-match dating scenarios.

The practical limitations stemming from the nature of the calibration curve are related to the reliability of the results as well as their precision. Besides the adverse effects of the small-scale offsets from the curve, the current study managed to identify situations where the high precision of the wiggle-matches, coupled with the shape of the calibration curve can lead to the emergence of analytical artefacts if caution is not exercised when building the models. However, once these obstacles are cleared, the evidence shows that it ought to be possible to attain modelled date ranges of at most 100 years during the most challenging part of the calibration curve during the earlier Iron Age (750–400 cal BC), and half that for the remainder of the period. This kind of precision is sufficient to infer links between sites based on their geographic proximity, or other similarities. Furthermore, it also means that for the sites built after 400 cal BC, it is possible to resolve some of the questions of site formation through wiggle-match dating.

Key to the efficient and meaningful deployment of the wiggle-match dating technique is the realization that absolute dating does not take place in a vacuum, but is related to other aspects of archaeological investigation. Wiggle-match dating research design hence ought to entail not only the evaluation of the practical and technical concerns, but also the way that project outcomes affect our understanding of past communities. With this awareness it is possible to anticipate what kinds of knowledge gains can be achieved and how to nest them within the broader Iron Age studies. The main role that wiggle-matching can play in this context is the development of linkage between sites, so that knowledge gains from these sites can inform the understanding of their local surroundings and also to the broader regional scales. The achievement of such aims benefits from explicit attention to the logic of archaeological inferences and the nature of archaeological data.

## 1.1 Thesis outline

This thesis consists of eight chapters, with the current introduction constituting Chapter 1.

Chapter 2 provides an introduction to the overall problems of Iron Age archaeology and a more thorough description of the division between wetland and terrestrial archaeologies in the context of the Scottish Iron Age. The review of the terrestrial archaeology of the Iron Age focuses on the extent of our knowledge and its current limitations. Specific attention is given to the nature of the artefact assemblages, environmental reconstructions, settlement record and the chronological basis. The section on wetland archaeology first outlines the history of research and then moves onto the discussion of the specific nature of waterlogged and submerged sites, and how this nature affects survival of material, as well as archaeological fieldwork. The final section of the chapter summarizes the principle of linkage between archaeological sites and events and presents three case studies demonstrating this principle in action and setting up the archaeological aims of the project.

Chapter 3 summarizes the background of the analytical and statistical techniques applied throughout the thesis. It begins with a brief justification as to why radiocarbon-based methods are believed to be the most viable when dealing with Scottish wetland sites and then moves on to summarize the principles of the radiocarbon dating technique. From this foundation the need for calibration is introduced, alongside the concept of the radiocarbon calibration curve and the relevant background to curve development. The final sections of the chapter explain the premises of wiggle-match dating and Bayesian statistics in their application to radiocarbon analysis.

Chapter 4 outlines the analytical and statistical methods used throughout the remainder of the thesis. It is divided into two sections, the first of which describes the laboratory procedure for sample pre-treatment from field collection to obtaining the radiocarbon measurement. The second section provides a summary and explanation of the various statistical techniques used throughout the latter chapters.

Chapter 5 lays down the foundations for applying the wiggle-match dating technique. It focuses on a series of 50 single-ring measurements from a known-age timber discovered in 2009 at Cults Loch 3, a crannog in south-west Scotland. The results of these measurements demonstrate that, for the time being it is inadvisable to use single-ring sampling for wiggle-matching unknown-age timbers from the Iron Age and also show that the technique may suffer from small biases when dealing with short sequences. This highlights an inherent risk whenever the precision of the unknown data approaches that of the calibration curve, the magnitude of which is evaluated in a set of simulation studies. These indicate that even on the 'more difficult'parts of the calibration curve modelled date ranges of less than 100 years can be achieved.

Chapter 6 applies the general principles of Chapter 5 to archaeological sites. In the first instance it summarizes the key practical issues that recur in the case studies. It then discusses legacy dates from two sites, Dormans Island and Loch Arthur, to demonstrate some of the basic challenges involved in dating Scottish wetland sites without the need to delve in the fine detail of wiggle-matching. The next site discussed is Black Loch of Myrton, where wiggle-matching is applied in a straightforward case of obtaining a construction date for a structure. The most important conclusion from this study is that circumstances may arise in which further resources need to be committed if the original research design proves insufficient, thus showing the importance of flexibility in research design. The third case study discusses the relative dating of structures 1 and 2 at Cults Loch 3. The two structures overlap in plan, but discerning their exact stratigraphic relationship proved impossible (Cavers and Crone, forthcoming). Resolving this question allowed the exploration of the limits of what is achievable on Scottish wetland sites. The final case study takes the wiggle-match dating technique beyond the confines of the most challenging part of the calibration curve (750–400 cal BC) and establishes construction dates for Dumbuck and Erskine Crannog, two intertidal structures in the Firth of Clyde. Here the technique managed to succeed in not only providing absolute dates but also in clarifying site formation questions despite a series of technical challenges. The key notion of throughout the chapter is that at site-level wiggle-match selection must always follow specific archaeological questions.

Chapter 7 discusses the development of wiggle-match dating research design from the perspective of extentding archaeological understanding. It does this by discussing the different roles that the wiggle-match dating technique and other high-precision chronologies can play in the context of Scottish wetland archaeology, based on the geographic scale on which the work is conducted. At the level of single sites chronological research can focus on the dating necessary for the development of interpretation at broader levels, but also, witihin an adequate research design, can focus on better understand site formation processes and cultural practices. On the local scale of individual loch, glen or firth, high-precision chronologies that can be derived through wiggle-match dating allow the assessment of contemporaneity and chronological succession of sites, hence making it possible to evaluate whether activity at different locations was connected. On scales broader than the immediate locality, dating provides the basis for relating sites to not only each other, but also to broader historical processes, thus providing context for the interpretation of the finds. In an ideal world the wiggle-match dated timbers have direct relevance to questions asked on all three scales of enquiry.

The final chapter, Chapter 8 concludes the thesis, summarizes the key recommendations, mentions the possibility of extrapolating the findings beyond the remit of the Scottish Iron Age, and outlines some of the directions for future research.

## 1.2 Focus area, chronological remit and some definitions

The focus area of this PhD is limited to the area between the firths of Clyde and Solway. This is dictated by three factors. First and foremost of these is sample availability. The south-west is the only part of the country where a variety of sites has been excavated, thus permitting access to samples from a range of well-understood contexts. Second is the issue of the imbalance of Iron Age research throughout the country; while this problem is now being mitigated, for several decades the south-west has been underrepresented in Iron Age archaeology, earning it a dubious distinction of being a black hole and an area of high priority in the Iron Age research Agenda (Haselgrove et al. 2001, Table 3). The third reason is that there is a sufficient diversity of stages of research on wetland sites in the south-west. This oscillates between survey, limited exploration and the full excavation of sites, thus providing an opportunity to apply the wiggle-match dating technique in a variety of contexts. Where relevant, case studies from beyond the focus area are discussed.

The main chronological remit of the project is between 800 BC and the period around the Roman invasion. This covers the whole of the pre-Roman Iron Age, which coincides with the most intensive periods of wetland construction in Scotland. Although post-Roman wetland settlement is well-known throughout Scotland, it is still uncertain whether it is in direct relationship to the earlier sites which form the main subject of this thesis (see Chapter 2.2). Nevertheless, later sites are discussed where relevant.

Throughout the thesis the term crannog is taken to denote a site that is some form of a lake dwelling, or an intertidal platform, in which case it is labelled as a marine crannog, but does not extend to the island duns of the Hebrides. While there are grounds for discussing the two monument classes together (Lenfert 2013), the construction and maintenance cycles of these structures would have been very different, leading to significant differences in dating approaches, if not archaeological interpretation. Even with the island duns excluded, the definition of the crannog followed throughout this thesis is vague and is intended only as succinct shorthand for the most prevalent recognized form of Iron Age Scottish wetland settlement. The term wetland settlement is taken to denote all sites where site formation processes are affected to a significant extent by water saturation, hence including crannogs, both submerged and on drained land, as well as marsh settlements. This use of the term is not precise and its meaning is closer to what is labelled as wet settlement (Menotti 2012, 13-4), however, the more precise term might not be intuitive for all readers of this thesis. The term theory has two meanings in the current thesis. In Chapters 3 and 5 it relates to theory as it is conceived in the natural sciences; a body of knowledge from which the properties of the phenomena studied can be deduced. In Chapters 2 and 7 the term theory is used in in the way it is encountered in archaeology, which is to denote the whole body of knowledge ranging from the philosophical considerations of the discipline to aspects of research design. Although this second use is far from satisfactory, it is pervasive in Anglo-American archaeology and hence it used throughout this thesis, to avoid the confusion that could emerge from the use of more specific terms such as metaarchaeology. Throughout this thesis the term radiocarbon age will refer to uncalibrated values and the term date to calibrated, modelled or calendar dates.

# 2 Terrestrial and wetland archaeologies of the Scottish Iron Age

Key to the meaningful exploration of any archaeological phenomenon is the ability to place it in context. Scottish Iron Age wetland settlement is no different in that it comes across as most relevant and valuable when it is integrated into period studies so that the superior preservation often encountered on these sites informs not only about itself, but also about its broader contexts. However, due to the history of research, as well as the nature of the data themselves, the integration of the terrestrial and wetland data sets in Scottish Iron Age archaeology is still limited. This chapter explores the origins of this apparent gap and also outlines how developing better absolute chronologies can lead to improving the linkage between the terrestrial and wetland archaeologies of the Scottish Iron Age. The chapter is divided into three main sections. The first section summarizes the terrestrial archaeological data from the Scottish Iron Age, according to type of data (artefacts, ecofacts, settlement and architecture) and also includes a summary of chronological schemes for the period. Such division of the material is to a large extent arbitrary and is introduced as a conceptual aid, not an interpretive basis. The second section outlines the nature of Iron Age wetland settlement data. It begins with a review of the history of research to the present before discussing the nature of the sites themselves. The latter part of the section stresses how the nature of wetland preservation can increase the complexity of site formation processes and this affects archaeological interpretation. The final section of the chapter introduces the theoretical premise of linkage between the two data sets and reviews some of the studies that have been successful in overcoming the wetland/terrestrial divide in the Scottish context. This will lay down the conceptual guides for a dating approach tuned to the problems of Iron Age wetland sites in Scotland. Throughout the review special attention is given to the area between the firths of Clyde and Solway, which constitutes the study area of Chapters 6 and 7. As much of this subsequent discussion is concerned with the Scottish mainland, the comments herein do not address the somewhat different archaeology of the Atlantic facade, unless stated otherwise.

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## 2.1 Terrestrial archaeologies of the Scottish Iron Age

The terrestrial archaeology of the Scottish Iron Age paints a picture where an increasing variability is becoming ever clearer; however, the causes of the variability remain hidden. Much of this uncertainty derives from the limited chronological characterization of the period, which in turn means that synchronic and diachronic variability cannot be teased apart. The resulting lack of historical understanding need not be a drawback in its own right, but it adds a layer of difficulty when wetland evidence is integrated into the wider picture.

### 2.1.1 Artefacts of the Scottish Iron Age

Artefacts are the traditional backbone of archaeological inference. If a sufficient number of artefacts are available, and if they display a sufficient range of stylistic variability, they can be grouped into classes. If these classes have some further meaning, for example chronological, they constitute types (Klejn 1982, 1-2). Since the $19^{\text{th}}$ century the ability to construct typologies has allowed archaeologists to describe synchronic and diachronic variability of the material record and hence the typological method, in whatever guise it comes, is often regarded as the preliminary concern in archaeology (Adams and Adams 1991; Klejn 1982; Read 2007). The Scottish Iron Age displays neither the quantities nor the variability of material culture necessary for the construction of a working typological system, leading to a situation where it is difficult to organize other forms of data into meaningful groupings.

The main reason for the lack of sufficient typologies in Scotland stems from the overall lack of pottery, which is found only in sparse quantities in the assemblages of the Scottish mainland and, where it is found, there is little stylistic variability (Harding 2004, 81, 107). There are some exceptions, such as Broxmouth, where first Cool (1982), and then MacSween (2013) managed to identify two ceramic types defined by wall thickness, temper and fabric. However, when compared to evidence from other sites in the region it becomes clear that it is difficult to implement the Broxmouth typological schemes throughout even the sites in its vicinity (MacSween 2013, 248-9).

Sites in the Atlantic zone are different to the mainland ones in that they can produce numerous pot-sherds and hence offer a better basis for typology building. However, their detail is still too limited to provide a detailed relative chronology (Mackie 1997; Young 1966) and the sequences themselves have been questioned (Lane 1990; Topping 1987).

Metalwork is another class of material culture that can be used to construct typologies, but in Scotland its finds are too rare to be used as cultural or chronological markers on a routine basis. Nevertheless, what exists is sufficient to suggest contact with communities beyond Scotland. For example, sometime after 800 BC a number of Hallstatt bronze swords were deposited throughout Scotland (O'Connor 2007, Figure 5). A few centuries later elements of La Tène material culture can be seen throughout the country, most often in the form of brooches (Coles and Livens 1958; Stevenson 1966), but also in the more spectacular finds, such as the Torrs pony cap (Harding 2002), or the Newbridge chariot (Carter et al. 2010). Hence, while the limited extent of the Iron Age metalwork available in Scotland precludes its use for the usual typological purposes, it does inform us that the country was not in complete isolation during the period.

Despite their limitations in supporting typology building, the artefacts that are available from the Scottish Iron Age can be used in other, non-typological, avenues of investigation, such as the study of technological choices (Dobres 2000; Lemonnier 1992). For example, the study of the 136 pot-sherds collected at Traprain Law during the 1996–7 excavations indicated that most of the raw material had been obtained within the vicinity of the site. Furthermore, there was a clear differentiation between the inclusions in different sherds indicating that a conscious technological selection was taking place, albeit its reasons remain unknown (Rees and Hunter 2000, 419-20). Studies such as Traprain are still few in number; nevertheless, there is a wealth of material culture that could benefit from them. The two most promising classes are the cannel coal bracelets and querns. The cannel coal bracelets are encountered on the continent (Baron et al. 2007), but are also plentiful on a number of sites throughout Scotland, for example at the enclosure at Braehead (Ellis 2007, 204-19). While still understudied, this group of artefacts can be assessed both in terms of their production techniques and raw material provenance and so provides a promising angle on technology and exchange (Baron et al. 2007). The study of querns is more advanced, albeit still limited. From a typological perspective, a quern transition between the saddle and rotary querns has been postulated for some time around 200 BC (Armit 1991, 190-5; Caulfield 1977), athough there is evidence that it may have begun earlier than that (McLaren and Hunter 2008, 105). While this limits the use of querns for chronological purposes, it does point at what might be a significant culture change. We know from their inclusion in domestic structures (eg. Buster and Armit 2013, 167) that querns may have been meaningful to the Iron Age people and so a change in their technology could have been associated with a shift in culture as a whole. Furthermore, McLaren and Hunter (2008, 117-9) identified some variability in the decoration patterns on the later, rotary querns, which might in some perspective provide some light on local cultural variability, albeit for the time being the extent of this exploration is still too limited.

The artefact record of the Scottish Iron Age can be characterized as defined by a lack of material that would lend itself well to the traditional typological analysis and therefore little can be determined about the relative chronology of the period based on its material culture. At the same time, the material is sufficient to study the technological, economic and social choices of the Iron Age communities, though more work will be required before significant conclusions are derived from this direction of research.

### 2.1.2 Environment and subsistence of the Scottish Iron Age

Questions of environment and subsistence have not received as much direct attention in Scottish Iron Age archaeology as in some other fields. Nevertheless, across disparate papers two main avenues of research emerge: the robustness of the subsistence economy and identifying abrupt climate change and its effects. It is important to remember that from an archaeological perspective the two are interrelated, as a robust subsistence economy can mitigate the effects of abrupt climate change (Button 2010, 376-95).

Iron Age subsistence strategies appear to be based on both farming and pastoralism, with some inclusion of wild resources and possible utilization of marine resources. The main crop of the period is barley. Sturdier than wheat (Miller 1997, 185-6), it is encountered at almost all Iron Age sites where archaeobotanical sampling has been implemented (eg. Carronbridge, (Johnston 1994, 270); Woodend, (Banks 2000, 251); Braehead, (Ellis 2007, 230); Rispain Camp, (Haggarty and Haggarty 1983, 37)). Besides barley, various wheat species (spelt, emmer and bread wheat) are also present on some sites (e.g. Carronbridge, Braehead or Rispain) however, in much smaller quantities, suggesting that it may have acted as a secondary crop (Ellis 2007, 230). The Iron Age also sees the first introduction of oats in Scotland (Boyd 1988, 104). Poor bone preservation on many Scottish sites makes it difficult to reach firm conclusions on the subject of animal husbandry. One site with a large, well-preserved bone assemblage is Broxmouth, where the caprines and cattle dominate, with a smaller contribution of pig. The presence of wild animals is limited (Cussans 2013, 468-9). Nevertheless, extrapolating from Broxmouth to the entirety of the Scottish Iron Age is unwarranted; for example at Dun Mor Vaul the animal bone assemblage was dominated by deer (McCormick and Buckland 2003) and the Iron Age deposits at High Pasture Cave are dominated by pig (Drew 2005). Given the evidence of ritual activity at High Pasture Cave (Birch 2005), the large proportion of pig is unsurprising, as this species is often associated with feasting (Serjeantson 2007, 91). What is less clear is the extent to which marine resources were consumed. On the one hand, isotopic evidence implies that at least in the Lowlands consumption of fish was negligible, which is in line with the rest of the British Isles (Jay and Richards 2007, 182). On the other hand, finds of fish-bones at sites such as Broxmouth are unambiguous evidence of deep-sea fishing during the

Iron Age (Russ et al. 2012). Taken together, the evidence suggests a diversity of species and the know-how necessary to diversify subsistence economy and so create a buffer against a range of potential disruptions. At the same time, the data remain dispersed and in the absence of systematic review it is difficult to assert whether robust strategies were indeed pursued.

Appropriate kinds of agricultural intensification can also help in developing a robust subsistence basis. Soil analyses from sites on Shetland and Orkney, such as Old Scatness, indicate that intensive midden cultivation has been practised since the Neolithic, leading to the development of pockets of very fertile soils in an otherwise marginal region (Guttmann et al. 2004, 61-2). However, we also know that this was not a universal choice, since, even in Shetland, less intensive techniques were used, as testified by the data from Jarlshof (Guttmann et al. 2008, 820). It is unfortunate that the Shetland sites are unique in their preservation of Iron Age paleosols, so while they indicate that the know-how necessary for intensive cultivation was present in some parts of Scotland, it is difficult to extrapolate this to the country as a whole.

The evidence for environmental change is more ambiguous, as for the most part the data indicate a high degree of local variability. The single event that stands out is the possible climatic deterioration around 750 BC, which is sometimes termed the sub-Atlantic transition (van Geel and Renssen 1998, 22), first defined on the basis of pollen core research conducted in Scandinavia and adapted into British conditions in the 1930s (Godwin 1934). Nevertheless, the scale and nature of this event remains uncertain, both due to uncertainty regarding its forcing mechanisms and the variability of proxies involved in its definition. In general, the most often cited cause for the downturn is reduced solar irradiation, as inferred from the shape of the radiocarbon calibration curve (Killian et al. 1995, 963-4). Yet our understanding of the processes behind past radiocarbon variability is still limited and so the alleged causal connection is still hypothetical at best (Wanner et al. 2008, 1803) (see Chapter 3 for more information on radiocarbon production). As regards the proxies underpinning the concept of the climatic downturn at 750 BC, they show a series of signs of a downturn happening at different times in different places and with different magnitudes, rather than a single catastrophic event. Some of this can be caused by the chronological uncertainties within the proxies themselves; for example, Wang et al. (2012) postulate climatic deterioration during the period of interest based on Oxygen isotopes within Hebridean limpet shells. However, the dating of the shells relies on an average global marine reservoir offset, which may not be applicable in that particular region (Ascough et al. 2009, 178). Pollen cores are the one proxy dated to a sufficient level that indicate the growth of peat around the time of the alleged transition (Langdon and Barber 2005, 564). Yet the dates from the cores show significant spatial and temporal variability; in parts of Ireland there appears to be a 100 year long delay in peat growth relative to the expected date (Swindles et al. 2007), while at Dartmoor it appears that a major downturn took place much earlier, in the late 2$^{nd}$ Millennium BC (Amesbury et al. 2008, 95).

The interpretation and detection of the environmental change is not made any easier by the fact that the main signal sought  the onset of blanket peat growth  can be disrupted by anthropogenic activity on a local scale (Davidson and Carter 2003; Edwards and Whittington 2003). The importance of local choices is observed in several Scottish case studies. For example, at Loch Farley (Sutherland), Tipping et al. (2008, 2384) identified an increase in wetness at 950 BC, but failed to identify any signs of abandonment. A similar scenario took place in west Glen Affric, where the period between 1030 and 770 BC witnessed an increase in pastoralism and limited cultivation, but there is no evidence of subsequent abandonment (Davies 2007, 2056). Such a localized approach also has the potential to shed light on important changes in later periods, as evidenced by differences in the nature of clearance between Stirlingshire and Dumbartonshire around 200 BC, where the former sees a more sudden change taking place (Dumayne-Peaty 1998, 205-10). In any case, there is not enough evidence at the moment to support the notion that the onset of the Iron Age is the result of a catastrophic climatic event.

### 2.1.3 Settlement and architecture

The settlement record is one of the greatest resources available to Iron Age studies in Scotland. This can be attributed to the research culture of Scottish archaeology, which follows the general British trend of giving special attention to field monuments (Daniel and Renfrew 1987, 70-2), as well as to the nature of the land itself: as much of Scotland is devoid of any tree cover and many areas have not been subject to modern deep ploughing, aerial photography becomes a more powerful tool than in many other European countries (Cowley and Brophy 2001, 61). The main limitation of Iron Age settlement archaeology in Scotland is the apparent lack of chronological meaning among the variety of forms observed in survey. As a result, it is often difficult to assemble the Scottish Iron Age settlement data into meaningful narratives.

The most frequent settlement form recorded for the Scottish Iron Age is the enclosure, perhaps due to its archaeological visibility. Enclosures can be defined through timber palisades; single, as was the case at the early stage of Dryburn Bridge (Dunwell 2007, 98-9), or multiple, as may have been the case at Mar Hall (Cavers et al. 2012), but more substantial systems of ramparts and ditches were also present. These rampart and ditch systems range from a single circuit surrounded by a single ditch, such as Woodend (Banks 2000), to more elaborate complexes with multiple circuits of enclosure, sometimes connected to one another, such as Hownam Rings (Piggott 1948) (Figure 2.1). Enclosures surrounded by a single rampart are often referred to as univallate, while ones surrounded by multiple ramparts are referred to as multivallate. The size of the enclosures is also variable. Some appear to have defined single homesteads, as may have been the case with the small enclosure at Scotstarvit (Bersu 1948), while others were much larger, like the hillfort on Burnswark Hill (Jobey 1978) (Figure 2.2). The Iron Age enclosures also varied with regard to their shape, from round, such as Mar Hall, through sub-oval, such as Dryburn Bridge, to rectilinear, such as Rispain Camp

(Haggarty and Haggarty 1983) (Figure 2.3). If an enclosure has a surrounding rampart and is located on a hill, it may be referred to as a hillfort by the National Monuments Record. However, this classification need not reflect a defensive function of the site (Poller 2005, 2-5). Sometimes, if the site is located on a promontory, advantage would have been taken of the surrounding topography and only the stretch of land granting access would have been enclosed, thus defining a promontory fort, as is the case at Carghiedown (Toolis 2007). In a number of cases, the ramparts have been burnt, leading to the melting of their stone component. Such sites are called vitrified forts (Cook 2010). Another specific form of enclosure is the dun. Duns are small circular enclosures made from stone, encountered throughout Scotland, but with a western bias (Harding 2004). In the south-west, some of these sites are referred to as homesteads and a concentration is present on the west coast of the Machars peninsula (Poller 2005, 250). Open sites are also present, though they are less apparent in aerial photography and often are discovered in the process of other archaeological activity. This was the case at Dalladies, where a group of roundhouses was discovered in the course of the excavation of a Neolithic long barrow (Watkins 1980). What is perhaps most important to remember when discussing these different types of settlement, is that their final form was often the result of modifications that accumulated over several generations. On some sites, such as the palisaded enclosure, at Braehead (Ellis 2007) (Figure 2.4), this is quite clear, as the successive palisades overlap. Oftentimes though there is no such information, for example at Mar Hall there are three concentric palisades, but we have no way of knowing whether they were part of the same design, or successive replacements.

While it is beyond any discussion that different enclosing features would require different forms of know-how and labour mobilization, they need not have typological currency, as illustrated by the story of the Hownam model, developed in the mid-1950s by Margaret Piggott as a means of a meaningful ordering of the settlement record. During her excavations at Hownam, Piggott realized that the palisaded enclosure at that site was followed by a ditched rampart, succeeded in turn by a multivallate enclosure (Piggott 1948, 220-2). Working within Hawkes's (1959) constrained ABC scheme of the Iron Age, she had to fit the whole development sequence into a 400-year period and proposed that the transition to the rampart was the result of a local shift in function of sites and attributed the second shift to the political instability of the Roman period. Subsequent open settlement was then seen as a product of Pax Romana (Piggott 1948, 223). This scheme appeared to be applicable to the next site she excavated, Hayhope Knowes (Piggott 1949), and by the 1960s it was accepted as a generalization applicable throughout the Scottish Iron Age. Yet the 1970s excavations at Dryburn Bridge and Broxmouth proved that the Hownam model is not universal (Armit 1999). At Dryburn Bridge, the settlement began as a palisaded enclosure, much as expected from the Hownam model. However, following the addition of an internal enclosure, Dryburn then developed into an open settlement, with no rampart phase (Dunwell 2007, 98). Broxmouth was even more decisive. It began as a palisaded enclosure, but soon afterwards houses were built over the original surrounding ditch. Thereafter, the

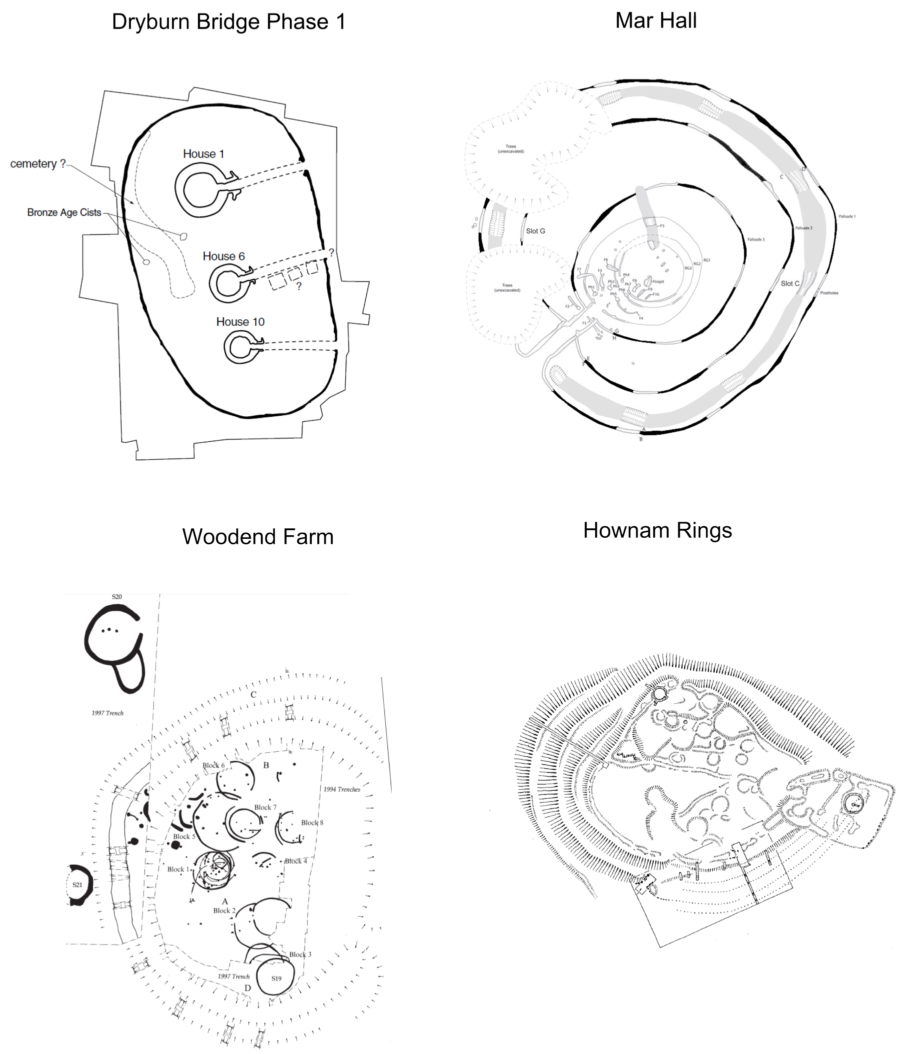



Figure 2.1: Different enclosure types: single palisade at Dryburn Bridge (Dunwell 2007, Illustration 66), multiple palisades at Mar Hall (Cavers et al. 2012, Figure 2), univallate enclosure at Woodend Farm (Banks 2000, Illustration 4), 4) and multivallate enclosure at Hownam Rings (Piggott 1948, Figure 2).

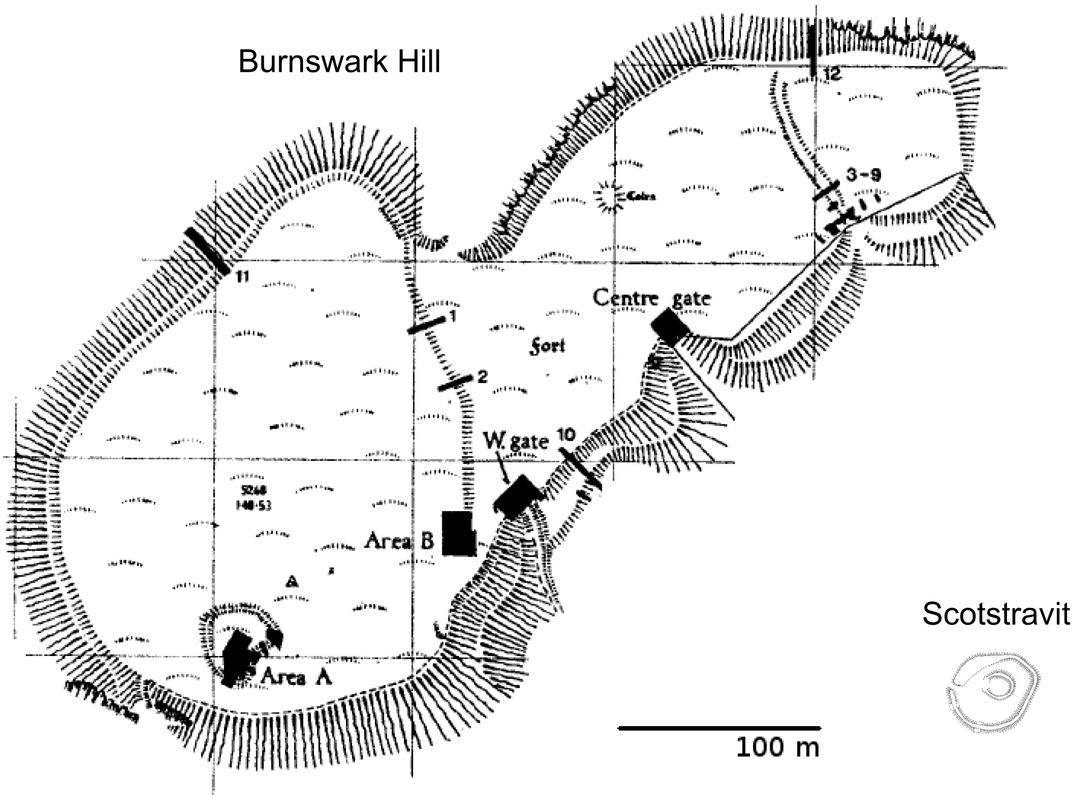



Figure 2.2: Comparison of enclosure sizes between Burnswark Hill (Jobey 1978, Figure 1) and Scotstravit (Bersu 1948, Figure 1).

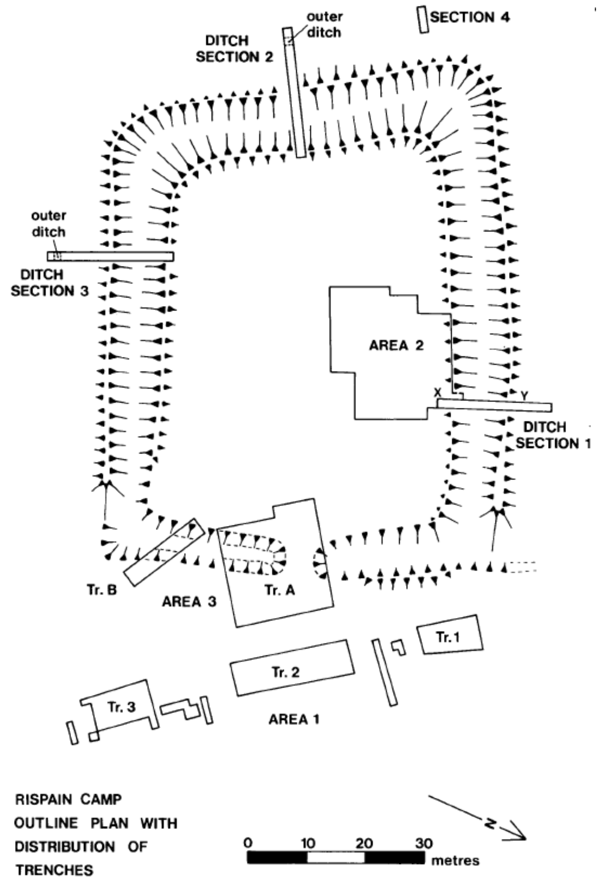



Figure 2.3: Rectilinear enclosure at Rispain Camp (Haggarty and Haggarty 1983, Figure 3).

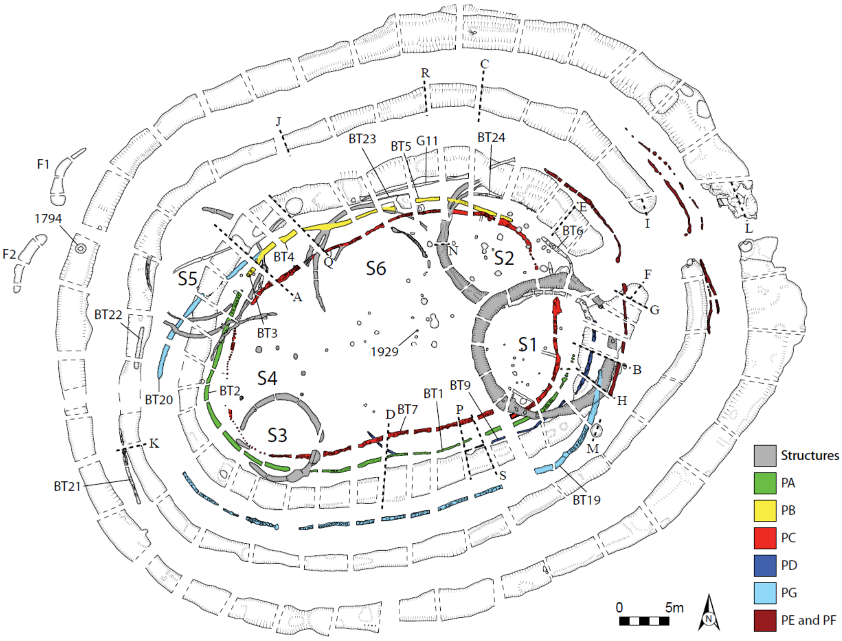



Figure 2.4: Overlapping palisades at Braehead (Ellis 2007, Illustration 3).

main enclosure phase took place with a series of ditches and ramparts added in somewhat close succession. In the subsequent phase, these fortifications are overbuilt by an open settlement, but after that in the final phase of Iron Age activity, the settlement of stone and timber roundhouses is surrounded by yet another rampart (Armit and McKenzie 2013, 17-9). Furthermore, the radiocarbon dating of both sites showed that they became open before the Roman incursion and also that the palisaded phase at Dryburn Bridge would have been contemporary with the multivallate phase at Broxmouth (Hamilton 2010; Hamilton et al. 2013). This leads to two important conclusions. First, the formal morphology of a site may not be informative of its chronology and hence cannot be used as a means of ordering sites through time. Second, the current shape of these sites may be an end point of an extended diachronic process and so does not need to represent the original intention of the builders.

One aspect of settlement in Iron Age Scotland that is unambiguous is the central position of the roundhouse in the sphere of domestic architecture. The main recognized division within the group has to do with the material utilized, with some of the structures built in wood and some with a substantial stone component. The latter kind of settlement dominates the Atlantic zone, where stone architecture had a long tradition and may have been a part of a shared cultural milieu of the Atlantic facade (Henderson 2007d). The zenith of the Iron Age stone architecture is the complex Atlantic roundhouse, a class of buildings referred to in most publications as brochs  monumental stone towers, which may have served as family seats (Armit 2002, 22). These sites concentrate in the Scottish north and west, but some are present in southern areas; in the south-west there are, for example, Teroy (Curle 1912) and Stairhaven (Wilson 1899) in Galloway. Furthermore, towards the turn of the first millennium cal BC stone built houses emerge in the south-east, as testified by the evidence from Broxmouth (Buster and Armit 2013).

The majority of roundhouses out-with the Atlantic zone were built in wood. These come in three forms: the post-ring, the ring-groove and the ring-ditch, as defined by their trace in the archaeological record. The post-ring structures are defined by the presence of a series of post-holes only; the ring grooves are similar, but they also have a shallow circular trench (groove) that is often interpreted as remnants of a wall trench. Ring-ditch houses have a more substantial ditch that may have been purpose dug, or a result of stalling cattle. These different types of wooden structures seem to have no chronological currency; for example at Dryburn Bridge all three are present (Figure 2.5) (Dunwell 2007). Another clear form of variability within the Iron Age roundhouse is the presence or absence of an extended entrance or a porch. Once again, the case of Dryburn Bridge demonstrates that these extension structures can co-occur on the same sites. There are also cases, such as Rispain in Galloway, where roundhouses had multiple entrances (Haggarty and Haggarty 1983). Current perspectives on roundhouses argue that these structures would have had meaning beyond that of basic accommodation or economic purpose and that they would have played an important part in representing and perpetuating Iron Age cosmologies (Cavers 2008). Regardless of one's attitude towards these interpretations, the size of some of these structures as well as their persistence is an indicator that they would have played a significant part in what has been termed as domestic monumentality that is taken to characterize the Iron Age (Cavers 2008, 20).

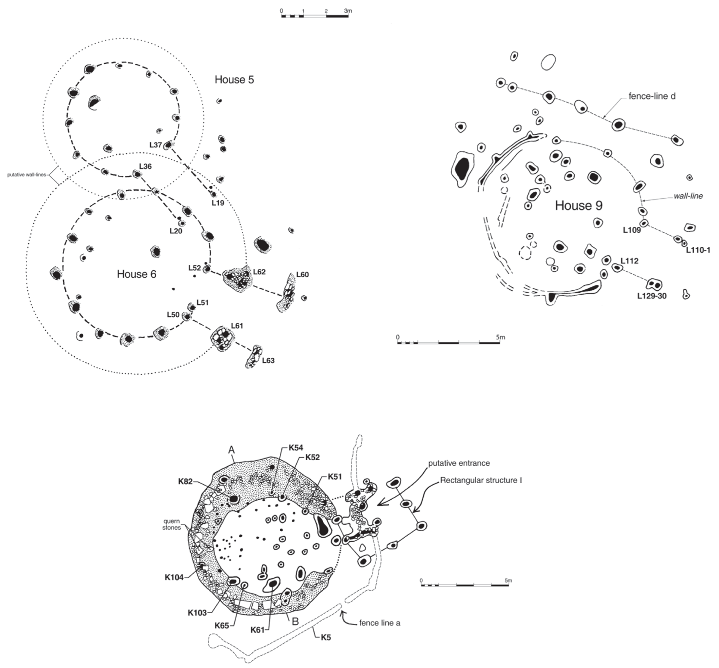



Figure 2.5: House types of the Scottish Iron Age: ring-post (upper left-hand corner); ring-groove (upper right-hand corner) and the ring-ditch (bottom). All examples from Dryburn Bridge (Dunwell 2007, Figures 21, 30-1).

The key challenge in understanding Iron Age settlement is that although it is undeniable that there would have been reasons for adding ramparts to an enclosure, or a porch to a roundhouse, our understanding of these reasons does not go beyond the very general notion of monumentality. This alone is important, for it shows the importance of labour mobilization as the heart of Iron Age social process (Sharples 2007), but, if our interpretations are to develop beyond the very general, we need to develop a better understanding of the causes, patterns and nature of the apparent variability.

### 2.1.4 Chronology of the Scottish Iron Age

As a result of the lack of material culture suitable for typological analysis (see section 2.1.1), radiocarbon dating is the basis for Scottish Iron Age chronology. Yet the presence of a calibration plateau and a large wiggle that cover the period between 750 and 100 cal BC means that for much of the Iron Age it is very unusual to obtain precise calibrated dates (for more detail see Chapter 3). The picture is further obscured by the lack of sites with sufficient numbers of reliable and contextualized radiocarbon determinations. Some of this can be attributed to many sites being excavated before the advent of the radiocarbon dating technique in the 1950s, or during the first three formative decades when the technique was still developing. Examples of such sites are Hownam Rings (see section 2.1.3 above), a key site with no absolute dating record, or Burnswark Hill, a large multi-vallated enclosure in Galloway, which, despite the large scale of the exposure, has only two unreliable determinations (Jobey 1978, 97). However, the main limitation comes from the frequent absence of suitable dating material. If radiocarbon dates are to be meaningful they must come from secure contexts and derive from samples relevant to the creation of the given context: seeds or charcoal from a floatation sample of a mixed deposit cannot be expected to provide a basis for a good site chronology. Yet on many Scottish Iron Age sites, only such poor samples are available; an example is Ayirolland one of the few Galloway homesteads excavated to date, where, despite an intensive sampling regime, no suitable radiocarbon dating material could be identified (Cavers and Geddes 2006). Nevertheless, where a site has been excavated in the recent past and suitable material was found in sufficient quantities, it can be expected that a suite of dates sufficient for chronological interpretation, or at least a more detailed dating project, will be available. This, for example, was the case at Mar Hall, on the shore of the Firth of Clyde (Cavers et al. 2012, 121).

There are also a handful of Iron Age sites in Scotland where Bayesian site models (see Chapter 3.3) have been developed. Perhaps the most detailed of these models has been built at Broxmouth, East Lothian (Hamilton et al. 2013). The three main aims at Broxmouth were to: 1) define when did activity on the site begin, end, and how long did it take; 2) define what were the dates of specific events, such as ditch infills, structure abandonments etc.; 3) aid the construction of the relative chronology for the site. To answer these sets of questions, a total of 123 $^{14}$C samples were submitted for analyses and were used alongside the 35 of the original 1980s determinations. The project was successful in fulfilling its aims, enabling amongst other things, the estimation of the frequency of the various construction and reconstruction events on the site and also the resolution of the order in which some of the earthworks were conducted, when stratigraphic information had not been available. In contexts such as Broxmouth, Bayesian modelling helps us appreciate the history of particular locales and increases our awareness of the richness of the Iron Age record. There are also cases where Bayesian approaches hint at possible transformations at greater scales, such as Hamilton's analysis of legacy radiocarbon dates from sites in the Scottish south-east and north-east England. In the process, he discovered that a class of small rectilinear enclosures, for example Fishers Road West, may have appeared in the record only around 200 cal BC, thus indicating some kind of cultural transformation (Hamilton 2010, 248-52). The ability to recognize such events means that radiocarbon chronologies can be used to define periods of cultural change in the Scottish Iron Age and hence form the basis for more refined archaeological periodization.

Periodization is in many ways fundamental to archaeological interpretation, as it places specific sites into their broader historic contexts (Pare 2008); the importance of periodization is illustrated by the shift in the interpretations of Stonehenge as it was relegated from the immediate pre-Roman period to the Neolithic. In terms of the continental Iron Age, it is the fine periodization that drives much of the interpretive understanding of the sites explored: from the time when the people assumed to be the elite of central European society turned toward the Mediterranean during Hallstatt C and D, through the break-down of the proto-urban Hallstatt world into the fragmented communities of warrior-farmers during La Tène I and II and the re-instatement of the urbanizing trend during La Tène III (Bogucki and Crabtree 2004), the wealth of the narrative and the depth of interpretation rely on historicity derived from periodization. This is because these changes are not just limited to art styles, or perhaps new fashions in settlement outline, but complex historic processes that affect the ways that humans act in the world. It is the lack of fine periodization that poses one of the main challenges facing Scottish Iron Age studies. The absence of diagnostic material culture and the challenges of radiocarbon calibration mean that archaeologists of the Scottish Iron Age cannot define the boundaries of various historical processes with the same ease as their continental or southern British colleagues, who are aided by wealth of typological material cross-correlated with Mediterranean imports and chronologies and, on some sites, such as Heuneburg, also by dendrochronology (Fernandez-Gotz and Krausse 2013).

Lack of fine chronologies means that most periodization schemes of the Scottish and northern English Iron Ages are focussed on long-term stability. Perhaps the most extreme example of this is Dennis Harding's notion of the long Iron Age (Harding 2004, 3-5), beginning around 800 BC, lasting until the second half of the first millennium AD and divided only based on the Roman interlude in the south. This framework of long-term stability and gradual change may be an accurate representation of the past; however, due to lack of sufficient chronologies, we are not yet in position to judge whether this was the case. Likewise, the ambiguity of the record means that more detailed models can be put forward without going against any evidence. For example, on the Atlantic facade, Euan MacKie (2008, 2010) divided the Iron Age in the first millennium BC into Early and Middle, with a transition sometime between 300 and 200

BC (his Late Iron Age coincides with the Roman Iron Age in the south). This division is motivated by a potential "peak" in the construction of monumental architecture in the Atlantic zone around 200 cal BC (Henderson 2007c), which can be traced in some of the earlier radiocarbon records and the introduction of the rotary quern (Armit 1991). Nevertheless, the chronology of the alleged "peak" in broch construction still needs improvement (?) and, even had this been resolved, it would still be questionable whether MacKie's periodization can be extended beyond the Atlantic facade. A creative approach to the problem of periods in the Scottish Iron Age was taken by Ralston and Ashmore (2007, 229) who put forward a scheme that combines the apparent increase in the wealth of material culture and the shape of the radiocarbon calibration curve. As a result, for them the divide between the Early and the Middle Iron Age happens earlier, sometime around 300 BC. The weakness of such approaches is that the periodization they produce is a composite of historical processes and non-cultural factors, such as the calibration curve, and therefore it is questionable whether they can be used as a guide to historical interpretation. These examples demonstrate how difficult it is to define a satisfactory periodization of the Scottish Iron Age; indeed one of the aims of the current thesis is to provide the means of improving the periodization of the Iron Age. Nevertheless, some working chronological outline is required by any piece of archaeological research, if only for heuristic purposes. Throughout the remainder of this dissertation a generalized western European division into an earlier and later Iron Age, with a turning point around 200 BC (Haselgrove and Moore 2007; Haselgrove and Pope 2007) is used. The choice is motivated by the presence of some notable transitions in the Scottish settlement record around this period, as evidenced by the peak in broch construction, or the development of the rectilinear enclosures in the south-east. At the same time it is treated only as a tentative proposition and a handy term for differentiating between large swathes of time.

### 2.1.5 Terrestrial Iron Age summary

Iron Age remains in Scotland are unusual in terms of post-Neolithic archaeology in general. On the one hand there is enough material to make the diversity of the period evident, but on the other there is little to bring this variability into coherent narratives on scales greater than a single site. The bulk of the evidence comes from the settlement record, which, while impressive in its diversity, seems to have no inherent ordering. Artefacts are present throughout the Scottish Iron Age, but their analysis requires non-traditional approaches and may not always be easy to integrate with other data. The evidence for environmental and economic processes is present, but once again, it is informative enough to act as a suggestion, but still too limited to be treated as a confirmation. Because of the combination of these and several other factors it is very difficult to say what happened in the Iron Age and why the material record took that particular form. This need not be a problem in itself, as the research of the past several decades shows that valuable insights into the past can be gained without such narrative. Nevertheless, lack of a more detailed historical framework bears heavy on our ability to build logical links to other archaeologies, including that of the Scottish wetlands.

## 2.2 Wetland archaeology in Scotland

The term wetlands is a neologism that emerged in the 1950s–1960s (Menotti 2012, 10) and the general grouping of these sites may have had little meaning for past people. In practice, the term wetland archaeology is applied to sites whose significant portions survive below the water table. Superior preservation at these locations often leads to a qualitative difference in the data, which in turn might be taken as a basis to see wetland archaeology as a separate sub-discipline (Coles 2004; van de Noort and O'Sullivan 2006). While important to the considerations of what constitutes an academic sub-discipline, this question is not pursued in this thesis, as it is not the disciplinary boundaries, but the integration of disparate archaeological narratives that are the main focus. Whenever the term wetland settlement is used, it is on the basis of preservation below the water table, or within water-saturated areas, such as the intertidal zone. It also includes submerged sites of the Highland zone, which in terms of fieldwork methods belong to underwater archaeology (Dixon 1991, 2004)  the choice to use the term wetland settlement in this case is dictated by the desire to avoid repeated use of the phrase wetland, intertidal and lacustrine settlement. In other words, throughout this thesis it is the survival of organic material below the water table or in water-saturated conditions that is implied by wetland settlement and not any form of past actuality.

It is the superior preservation that accounts for much of the divide between wetland and terrestrial archaeologies in Scotland. The two key challenges encountered on terrestrial sites are the often ambiguous nature of the data and the challenges to building detailed chronologies. Both these challenges are easier to negotiate in the wetland record, as the superior survival of organic remains ensures the presence of plentiful material for both radiocarbon dating and environmental analyses. At the same time, however, wetland sites come with their own distinct challenges in terms of fieldwork requirements and site formation processes. Together with the different histories of research, this creates a unique challenge of integrating very different kinds of data sets: while on land the general outlines of sites are often discernible with minimal investment, the organic survival is poor, making for limited knowledge gains in most cases. In the wetlands, discerning even the general outlines requires significant input and expertise, but the organic assemblages are much richer, making for greater potential knowledge gains. It is this qualitative difference in the data that constitutes the core of the interpretive rift between wetland and terrestrial records of the Scottish Iron Age.

### 2.2.1 History of wetland archaeology in Scotland

Scotland has one of the longest histories of concerted archaeological efforts aimed at understanding wetland settlement. Intentional surveys over drained areas began soon after the discoveries of Swiss lake dwellings in the mid-1800s, and by the end of the 19th century the study of Scottish lake dwellings stood well against any other archaeological effort in Europe (Midgley and Sanders 2012). However, the specific nature of Iron Age assemblages in Scotland meant that the early artefact-driven archaeology did not have the conceptual means to deal with these sites and, following the death of the pioneers, the subject receded to the level of an occasional excavation. The situation changed again with the advent of cheap diving and petrol-driven pumps, which made it possible to undertake new fieldwork in conditions that hitherto were inaccessible. Since then, the field began maturing with a growing realization as to the complexity of site formation processes and the diversity of the sites themselves. The long maturation of Scottish wetland archaeology stands in sharp opposition to the study of terrestrial Iron Age settlement where this process took place over several decades between the publishing of the Hownam model and its ultimate refutation in the 1990s.

Although at its onset Scottish wetland archaeology had a national range, reaching the Isle of Bute and Inverness-shire (Stuart 1865, 174-5), it soon focussed on a study area in the south-west. This was caused by the combination of two key factors. First, many lakes in the region had been drained in the recent past and hence the mounds were visible. By comparison, Highland sites were often underwater, while sites in eastern Scotland, if they exist, would have been long-drained and thus subject to more advanced decay (Stratigos ming). Another reason was that Rev. Wilson and William Maxwell, the most persistent researchers during the early period, were both based in Galloway (Munro 1882, 43; Wilson 1872, 1874). The work conducted at that time was concerned for the most part with identifying new sites and limited excavations aimed at recovery of artefacts. The reports were for the most part in the form of brief letters and second-hand accounts. Any synthetic effort had to wait until the latter part of the 19th century and the arrival of Robert Munro.

The early stages of wetland archaeology in Scotland came to an end with the excavation of Lochlea crannog in 1878–9. A project of a broader collective, the excavation ended up being directed by Robert Munro (1882, 76), who changed both the overall aims and excavation methodology. Whereas Maxwell and his colleagues were most often interested in only confirming the artificial nature of the site and retaining artefacts, Munro was intent on detailed recording and subsequent systematic analyses of the finds. Lochlea was followed by excavations at Lochspouts and Buiston (Munro 1882, 160-82, 190-239) and the trend towards more comprehensive analysis was followed by other researchers, such as Andrew Smith at Hyndford in 1898 (Munro 1899) and, to a degree, Bruce and Donnelly at Dumbuck and Langbank East in the early 1900s (Bruce 1900, 1908). The late 19$^{th}$ century also witnessed the extension of survey into the Highlands with the work of Rev. Odo Blundell (1909, 1913).

Munro was beyond doubt the most important 19th century Scottish wetland archaeologist. His achievements can be summarized into five main groups. First was the introduction of new excavation methods and recording standards, comparable to those of the mid-20th Century. While their importance was lost on Munro's contemporaries due to the lack of a conceptual need for such detail, they allow a limited re-interpretation of his findings. Second, he put forward the packwerk model for the construction of Scottish and Irish sites. According to this model brushwood was floated out onto the desired spot on the lake and sunk with stones. The process was then repeated until the desired mound formed. This was then revetted with a palisade to retain the mound in place (Munro 1894, 111-2). Since then the alternative model of a free-standing pile dwelling was developed (Dixon 2004), but many sites have been constructed using the packwerk method (**?**, forthcoming; Crone 2000; Henderson and Cavers 2011). Third, thanks to his excavation methods, Munro was in the position to appreciate the potential variability of Scottish lake dwellings. Thus, he was able to differentiate what Stuart has referred to as crannog proper, with a retaining palisade kept in place with morticed beams (Munro 1882, 259) and recognize the absence of such features at sites such as Lochspouts (Munro 1882, 164-5) or Hyndford (Munro 1899, 378). Munro's fourth set of achievements were in collating research conducted to date. His two main works, *Scottish Lake Dwellings* (1882) and *Lake Dwellings of Europe* (1890) contain an almost complete summary of wetland sites surveyed and excavated in Scotland by the time of their publication. While this knowledge would have survived as individual papers in the Proceedings of Antiquaries of Scotland, it is doubtful whether it would have been enough to motivate the renewal of Scottish wetland archaeology in the 1970s. Munro's final achievement is negative in nature. He proposed that crannogs are a response of the local elites to the social destabilization of the terminal period of Roman rule and the succeeding centuries (Munro 1882, 284), thus removing crannogs from the realm of Iron Age studies.

Following the deaths of Munro and Blundell, Scottish wetland settlement went on hiatus. Over the period between 1920 and the late 1970s only five new projects took place: at Lochend (Monteith and Robb 1937), Eadarloch (Ritchie 1942), Milton Loch 1 (Piggott 1953), Loch Glashan (Scott 1960) and Loch Arthur (Williams 1971). Of these, Milton Loch 1 was most influential; located in Dumfriesshire, the site yielded an extensive floor plan and was also the first of its kind to testify a deposition of an ard below the floors (Piggott 1953, 143-4). Ard deposition was encountered again at Cults Loch 3 (Cavers and Crone, forthcoming) and Oakbank in Loch Tay, Perthshire (Miller 1997, 146). Furthermore, during the course of the Milton Loch 1 excavation, a Pannonian-like brooch was discovered, leading Margaret Piggott to assign the site to the Roman age (Piggott 1953, 144-6), confirming Munro's beliefs about the beginnings of crannogs around the turn of the first millennia at the earliest. Hence, when formative debates of the Scottish Iron Age were developing on the back of the Hownam model, the wetland record appeared removed in time from the Iron Age. It was only in 1974, when the ard and one of the timbers from Milton Loch 1 were radiocarbon dated, that their Iron Age provenance became clear (Guido 1974). By this time, Scottish Iron Age studies were already on the eve of the collapse of the Hownam model and little time could be spared for wetland sites.

The 1970s saw a resurgence in crannog survey for its own sake, crowned at the end of the decade by the long-term underwater excavation project at Oakbank in Loch Tay. To a large extent the renewed growth of crannog research in this period was made possible because of new technological improvements. First of these was the availability of efficient petrol-driven pumps which make it possible to deploy water dredges for underwater excavations and make it possible to work below the water table when excavating on drained land. The other key development was the growing access to the self-contained breathing apparatus (SCUBA), which made underwater survey viable, as it was much easier to learn and required far fewer logistics to deploy than the traditional surface supplied diving equipment. SCUBA was first put to use in McArdle's (1972) survey of Loch Awe, which was followed by Nicholas Dixon's (1984) doctoral crannog survey in Loch Tay, coupled with underwater excavation at Oakbank. Oakbank excavations were inspired by the Swiss approach, whereby a site was excavated to a large extent by a permanent full-time team of underwater archaeologists working across the year from a semi-permanent base, allowing the provision of air to the divers from a low-pressure compressor, thus reducing the need for cylinders to a safety consideration only. Once the sites in reach of a given base have been excavated, recorded, and the remains covered for preservation, the base could be moved to a new location along the lake side (Geiser pers. comm. 2014), which is plausible given the continuous nature of the Neolithic settlement in the area. Oakbank excavation still awaits final publication and hence it is difficult to judge, but it contributed to the development of Dixon's (2007, 253) interpretation of the site as a pile dwelling, that re-opened the debate as to the nature of the substructure of the mounds. While this view does not enjoy universal acceptance (Cavers 2012), it provided the spark necessary to re-ignite the debate about the nature of crannog mounds. Furthermore, the data from Oakbank contributed to three PhD projects. The first of these, by Anne Crone (1988), was concerned with the dendrochronology of Oakbank. While an absolute date has not been obtained, the key problems of applying dendrochronology in Scottish wetland sites had been identified for the first time. The second project, by Rob Sands (1995) focussed on the tool marks left on the Oakbank timber assemblage. Sands' contribution lies in that he developed techniques for the collection of tool mark data without removal of the timber, as well as a methodology for tracing specific tools throughout the assemblage. Based on that, he was able to not only demonstrate the use of both bronze and iron axes on the site, but also made a case for groups of timbers being cut by the same tool in a period between re-sharpening. This ability to group material may yet prove very important to Scottish wetland archaeology. The third project was Jennifer Miller's (1997) analysis of the palaeobotanical assemblage. This work made three significant contributions. First, it demonstrated the presence of opium poppy and cloudberry at the site. As opium poppy had to be traded in at some point and cloudberry could only be collected from specific mountain areas, the closest of which was 20 miles away, these finds demonstrated that Oakbank was nested within a broad network of interactions and possible transhumance (Miller et al. 1998). Second, Miller postulated presence of particular activity areas within the site, based on the different elements of the assemblage. While a detailed site publication would be required to assess the validity of this, if such recognition could be achieved, it would have profound implications for our ability to understand the cosmology of Iron Age societies. Yet the most important contribution of Miller's work is that she demonstrated beyond any reasonable doubt that substantial amounts of identifiable organic remains survived at Oakbank and hence that crannogs, in principle, have the potential to mitigate the lack of specific environmental data encountered on terrestrial sites (see section 2.1.2). The late 1970s and early 1980s also witnessed research by Ian Morrison, culminating in the book *Landscape with lake dwellings* (1985), a short and accessible work that was the first to give such detailed attention to crannog function, providing a list of alternative reasons for their construction, from saving farmland to avoiding midges. However, *Landscape with lake dwellings* was too unspecific to be meaningful something that is not surprising given how the wetland archaeology of the period had almost no data other than limited survey and 19th century excavations to rely on.

The late 1980s to the early 2000s saw the diversification of wetland archaeology in Scotland. In 1989 Barber and Crone undertook a survey meant to confirm how many of the sites reported in the south-west were indeed crannogs (Barber and Crone 1993). It was in the course of this project that Crone renewed the excavations at Buiston, which provided rich structural, environmental and material culture assemblages (Barber and Crone 1993, 528). Thanks to these rich assemblages Crone (2000, 64-6) could obtain both absolute and relative dendrochronological determinations showing that the site was occupied for a period of only 100 years, during the course of which it witnessed as many as six refurbishment phases. Meanwhile, Dixon conducted survey and limited excavation in the Outer Hebrides as part of the Calanais research project. During the course of this work, so-called island duns stone-built Atlantic roundhouses located on islands were brought into the fold of the emerging Scottish wetland archaeology (Harding 2000). It was also this project that discovered that the submerged parts of Eilean Domhuill, on the Isle of Lewis, date to the Neolithic (Dixon 1991, 7). This extension of fieldwork beyond the central Highlands and south-west Scotland also took place through new student research undertaken throughout the 1990s. Alex Hale (1999) undertook a survey and limited excavation of intertidal sites in the firths of Clyde and Moray, confirming the existence of an Iron Age tradition of building sites in intertidal areas, thus adding to the diversity of known settlement forms. Michael Holley (1998) undertook a PhD project surveying the crannogs of the Inner Hebrides, which highlighted the important geographic differences between the small Hebridean lochs and those of the Highlands and pointed to different choices regarding raw materials, with the Hebridean sites being built to a large extent in stone. Meanwhile, Jon Henderson continued developing survey methodologies introducing the use of side-scan sonar, echo sounding and total stations (Henderson 1998a; Henderson and Burgess 1996).

It was in the process of the growth of Scottish wetland archaeology in the 1990s that the interpretive rift between wetland and dryland archaeologies became apparent. By

1998, Henderson and Sands recognized that integration of the data sets is slow. On similar premises, in the paper Islets through Time: the definition, dating and distribution of Scottish crannogs, Henderson (1998b) argued the need to begin differentiating Scottish crannogs, by making the case that one of the reasons for the lack of integration with the terrestrial record was the poor conceptualization of wetland site diversity. In an attempt to mitigate this, he proposed a classification, dividing crannogs into Highland, south-western, Hebridean and marine types: the Highland type consisted of stony mounds, the south-western type consisted of organic packwerk mounds, the Hebridean type consisted of island duns and marine crannogs included inter-tidal sites. This classification had two apparent weaknesses. First, some Hebridean-like sites appear in the south-west (Cavers 2010b, 97). This need not be a problem if Henderson's types were true working types, that is the kind of typological classifications that said something meaningful about the underlying historical processes (Klejn 1982) – the presence of Highland type mounds outside their core area could be informative. However, the real problem is that the complexity of site formation processes, as well as the potential for diversity within the groupings, meant that the model in question could do little to aid interpretation. As a result, the interpretive rift remained unbridged, but at the same time the reality of the underpinning diversity of wetland settlement began to dawn.

The early 2000s witnessed the continuation of previous trends, but also a growing maturation of the field. Two initiatives, the South-West Crannog Survey (SWCS, see Henderson et al. 2006) and the Scottish Wetland Archaeology Project (SWAP, see Crone and Clarke 2005), continued research into south-western sites that led to two small excavations at Loch Arthur and Dorman's Island (Cavers et al. 2011; Henderson and Cavers 2011), with the latter site providing the first absolute dendrochronological determination from a Scottish wetland site. Based on these experiences, 2009–10 saw the fieldwork component of the Cults Loch environs project where an artificial promontory, Cults Loch 3, was excavated in tandem with two nearby terrestrial sites a promontory fort (Cults Loch 4) and an enclosure (Cults Loch 5) (Cavers and Crone, forthcoming), making for a first concerted effort of integrating the evidence of wetland and terrestrial sites. This was then followed by the 2013 and 2015 field seasons at Black Loch of Myrton, which became the first Iron Age wetland site in Scotland to be confirmed as a marsh settlement rather than a lake dwelling (Crone and Cavers 2015) and so begging the question as to how many of the sites recognized as crannogs in 19$^{th}$ century surveys were actual lake dwellings. Important work also took place elsewhere. In Loch Tay, Dixon et al. (2007) dated 13 of the Loch's 18 crannogs, providing a good basis for future research (see Chapter 7). In Loch Ederline, Cavers and Henderson (2005) excavated at the Ederline Boathouse Crannog. These were intended to explore the Iron Age occupation of the site indicated by radiocarbon samples collected from the top of the mound during earlier survey; instead the trench that cut into the base of the mound uncovered deposits dating to the early medieval period. Although this discovery frustrated the original aim of the project, it did manage to deliver a clear case for the presence of stratigraphic inversions in Scottish wetland mounds and hence made a significant contribution to methodological awareness. In the 2010s, the geographic scope of wetland archaeology keeps growing. Lenfert (2013) has argued for a more holistic approach that considers the Outer Hebridean sites as part of the same phenomenon as the mainland settlement mounds. In the course of developing the empirical basis for this proposition, Lenfert (pers. comm. 2015) undertook numerous surveys throughout western Scotland and the isles, which, when published in full, will provide a much-needed update on the earlier work in the region. Another exploratory project is being undertaken by Michael Stratigos (forthcoming), who re-analysed 18$^{th}$ century maps and began identifying new sites in eastern Scotland. This research redresses some of the western bias of wetland site distribution, although it remains to be seen whether the eastern sites have the same chronological span as the western ones and hence whether they are a part of the same process. The 2000s also witnessed two PhD projects aimed at interpretation and synthesis. The first one, by Shelley (2009), focussed on medieval and early modern sites and demonstrated that such locations can have a multitude of functions and meanings even within a short time period. He also showed the importance of overarching contexts to the interpretation of specific local phenomena. The second project, by Graeme Cavers (2005), was concerned with the spatial relationships of crannogs in western Scotland. Cavers proposed the first clear historical model for the emergence of wetland settlement, whereby it would have been driven by the reshuffling of social power following the shift of settlement to the lowlands in the light of climatic deterioration at the Bronze to Iron Age transition. The main weakness of Caver's model is that it relies on the presence of crannogs in his study areas near to the Bronze/Iron Age transition and the presence of a substantial enough climatic downturn. As outlined in section 2.1.2, above, the evidence for the latter is far from unambiguous and, at the moment, the chronology of wetland settlement in the Iron Age is not sufficient to support the existence of crannogs near the very onset of the period (see Chapter 7.3) Nevertheless, Cavers' proposition is valuable in that it forms a problem-oriented program of specific research that articulates both wetland and terrestrial data.

Despite the apparent interpretive challenges and a feeling of unfulfilled potential (Crone 2007, 230; Henderson 2007a, 231, 240-1), achievements in wetland archaeology within Scotland are substantial relative to the small scale of investment. First of all, an overall chronological framework for the duration of the phenomenon has been established. It is clear at this point that there is no good evidence for continuity from the Neolithic sites such as Eilean Domhuill and that the majority of known sites would have been first constructed in the Iron Age. At the same time, there is also unambiguous evidence for the presence of crannogs in the early medieval period and beyond, albeit this spate of wetland activity may have been less intensive (Crone 1993, 245-9, 2012, 150). The relationship between wetland sites in Scotland and the remainder of the British Isles is also becoming clearer. With the exception of Black Loch of Myrton, most Scottish sites explored to date are islands that are to some extent artificial. This sets them apart from wetland sites of Iron Age England which are characterized by more extensive marsh settlements such as Sutton Common (van de Noort et al. 2007), or lake villages such as Glastonbury (Bulleid and St. George Grey 1917). Indeed, the only site on the island of

Great Britain that may be considered similar to Scottish crannogs is the early medieval Llangrose in Wales (Campbell and Lane 1989). The knowledge to date is also sufficient to evaluate the relationship to Irish wetland sites. Wetland settlement in Ireland can be traced back to the Mesolithic (Fredengren 2002), but its two main peaks come in the late Bronze Age and the early medieval period (Cavers 2006). The Late Bronze Age settlement ends around 800 BC and hence is in no way contemporary with any of the known Scottish sites (Crone 2012, 141-6). The only point where convergence between the two countries could be postulated is the early medieval period, when, despite chronological misalignments, conceptual similarities might exist between sites such as Buiston in Scotland and Coulure Demesne in Ireland, as both appear to have been based upon revetted-packwerk mounds (Crone 2000; O'Sullivan 2007). Yet, these mounds are different from the unrevetted mounds of the Scottish Iron Age period and hence beg the question as to whether the two forms should be considered in unison.

### 2.2.2 Nature of wetland sites in Scotland

The main differences between wetland and terrestrial sites are rooted in the preservation of the two kinds of record. Superior wetland preservation means that more in-depth analyses are possible, yet at the same time, this comes with greater logistical requirements and counterintuitive stratigraphic processes, which mean that it is difficult to say anything about the site itself without excavation. This stands in opposition to the terrestrial record of the Scottish Iron Age, where some basic site characteristics can be defined from aerial survey, but the excavated assemblages are often limited. It is because of these differences that the integration of the terrestrial and wetland records is so difficult.

Wetland preservation is a function of the specific effects of waterlogging upon the chemical, biological and physical decay factors (Dean et al. 1992; Sease 1994). As far as the chemical decay processes are concerned, the acidic nature of the water table will contribute to the deterioration of bones, often making little difference relative to a terrestrial site (Dixon 2004), although at some sites, such as Lochlea, numerous bones did survive and could be recovered even in the absence of modern excavation techniques (Munro 1882, 139-43). Acidity can also have adverse effects on crannog timbers, as it can contribute to cellulose degradation (Jordan 2001, 50). Biological decay processes denote the destruction of material through bacterial, fungal, plant or animal activity. While bacteria often will have little effect over the time-scales at work for the Scottish Iron Age, fungal attack can destroy timber at a rapid rate (Bjordal et al. 1999). However, fungal attack requires the availability of oxygen and hence waterlogging retards it (Jordan 2001, 48-9). Physical decay processes refer to the changes that take place for mechanical reasons, such as structural collapse or erosion. In wetland sites, waterlogging affects these processes because it reduces the weight of the archaeological remains (Dean et al. 1992; Sease 1994). Hence, a timber that would have collapsed under its own mass due to the chemical deterioration of cellulose will survive when below the water table. This in turn aids the formation of mounds containing the archaeological remains and thus affects further preservation, as well as the nature of the sites themselves.

Despite these advantages, wetland sites will not survive in perpetuity. Seasonal and long-term changes to the burial environment, as well as the continuing action of some of the decay agents, mean that over time, wetland sites are bound to deteriorate. As far as chemical decay is concerned, the key variables subject to these fluctuations are redox potential, which determines whether the archaeological material may oxidize (Figure 2.6). Lillie et al. (2007, 2008) demonstrated that both redox potential and acidity is subject to seasonal fluctuations in south-west Scottish lochs. This applies to sites such as Milton Loch 1, where seasonal water fluctuations cause intermittent drying of the location, but also to water-saturated sites, such as Barlockhart. In terms of biological attack, the two greatest impacts can be expected from nesting birds, identified for example at Cults Loch 1 (Lillie et al. 2008, 1896) and the mollusc, *Teredo navalis* (shipworm), which is common on the intertidal marine crannogs (Figure 2.7). The main adverse form of physical decay process comes from wave and tidal action that will affect sites that cut through the water surface, or have shallow enough components. Examples from Scotland include the damage from wave action to Dorman's Island (Henderson 2007b, 297-8) and tidal erosion at Erskine crannog in the Firth of Clyde (Hale 2000, 551). It is important to bear in mind that these continuing processes of chemical, biological and physical decay will not be uniform across any one site; instead, differential decay ought to be expected (Jordan 2001, 51), which sometimes leads to challenges in interpretation.

Figure 2.6: Effects of oxidation on preservation of organic remains in wetland sites. The oxidized matrix nearer the soil surface is less conducive to preservation and hence the stake has decayed (Crone and Cavers 2015, Figure 20b)

Figure 2.7: Timber from Erskine crannog with shipworm attack highlighted (Photo: author)

The combined effects of waterlogging on the chemical, biological and physical processes taking place on wetland sites make their formation processes different from what could be expected on a Scottish Iron Age terrestrial site. On most terrestrial sites in Scotland the major structural elements would decay and hence the remains above ground level, with the exception of earthen and stone ramparts, will be gone. The resulting sites will often be two-dimensional, except for instances where ditches, postholes or pits intersect. On a wetland site most of the material that is below the water level, as well as some above it, will survive to form a part of the site deposition matrix, so that the resulting sites are often three dimensional mounds. This characteristic of wetland sites has been put to use when attempting to identify new locations, from the Loch Dowalton surveys of the mid-1800s (Stuart 1865), to the modern surveys (Barber and Crone 1993; Stratigos ming). In general, it is useful to think of these mounds, both in terms of their interior and their external appearance, as the result of two complementary processes: construction/maintenance and collapse/decay. These elements are applicable to all archaeological sites (Schiffer 1996), but in the case of Scottish wetlands the decay process is slowed down, thereby allowing for a higher rate of material build-up.

Construction and maintenance are two inter-related processes that can be seen as events during which material has been added to the mound. In terms of primary construction three different modes have been postulated. The first is Munro's original Packwerk model, whereby the mound was built up by deposition of successive layers of brushwood (Crone 2007, 225-7). Mounds built this way, as well as the ones built using the related box-like variant encountered at Eadarloch in Loch Treig (Ritchie 1942), can be expected to have a core with little internal variability or cultural remains, save for the instances where some of the superstructure had subsided. In the second model sites begin as free-standing pile dwellings, with mounds forming as refuse is dumped from the platforms above and further piles and stones are added in the course of structure maintenance (Dixon 2007, 253). This kind of a mound can be expected to have a continuous record of material from above interspersed with more sudden collapse events. Note that as material accumulated the nature of the mound, and hence its maintenance patterns, will begin resembling those of a packwerk mound (Cavers 2007, 243). The third model is one whereby the original structure was built over a soft substrate. In some cases the substrate would become compressed under the weight of either the whole structure or its elements and sinking would begin, only to be countered by addition of further material, leading to mound accretion. This situation has been encountered in at least some marine crannogs such as Redcastle (Hale 2004, 151-2), on island duns such as Dun Bharabhat (Harding and Dixon 2000) and also in the marsh settlement at Black Loch of Myrton (Crone and Cavers 2015, 12-3). Wherever this process took place, the mound is built up of the construction layer and, where applicable, consecutive reconstruction episodes. Each type of mound structure would demand a different maintenance regime that would add material in a different way. On a packwerk mound this will entail the addition of groups of timbers as retaining palisades (Crone 2000, 64-6), while the pile dwellings might have had a more spread-out maintenance cycle, focussing on those timbers that became weakened. It is also important to appreciate that in their earliest stages, or over their life, sites may begin integrating these different construction methods. Hence, at Milton Loch 1, the central mound was in all probability built using the packwerk technique, but the surrounding area, interpreted as a jetty would have been built using the pile technique (Piggott 1953). At Lochend crannog in Coatbridge, on the other hand, it is possible to interpret the reported intensive deposition (Monteith and Robb 1937) as a construction on peat, of the kind encountered at Black Loch of Myrton, while the surrounding piles are the remains of a jetty similar to that from Milton Loch 1. It is also important to remember that structural concerns also control the deposition of refuse from the structure. While in a pile dwelling it is possible that the refuse midden was located below the platform, in a packwerk structure it would have had to be located either on top of the mound itself, in which case it would be dispersed or trampled into it, or into water around the mound. If there had been a consistent deposition area during an activity period then the midden formed this way could be expected to form a deposition pocket within the site, as appears to have happened with early medieval material at Ederline Boathouse (Cavers and Henderson 2005). Note that material deposition at a particular site need not coincide with its occupation. This is evidenced at Lagore crannog in Ireland, where a substantial amount of Iron Age and Roman finds were discovered underneath a structure that dated to the early medieval period (Guglielmi, forthcoming).

Collapse and decay are the reverse of construction and maintenance. Collapse will lead to the formation of pockets of material within a mound, while natural decay and sedimentation processes will affect the mound shape and the extent of its survival, which itself is a result of the development of a level of stability or a protective shell.

From an archaeological perspective, collapse events are most beneficial as they lead to the formation of deposits that are closest to the ideal of the time capsule, such as the remnants of the collapse event at Buiston (Crone 2000, 66). Nevertheless, it is reasonable to expect that such events would have been avoided during the use of the structure through in-built redundancy and active maintenance, so in most cases whatever collapse would have happened, it would have been controlled. One example of such controlled collapse is the interpretation of the timbers from Oakbank mound as collapsed structural piles that would have later been replaced (Dixon 2004). Once material has found its way to the mound either through construction, deposition or collapse, decay processes begin. Although the decay would have been retarded by waterlogging, the movement of water would, in most cases, still erode most timbers to stumps and disperse any loose material around the site. Hence, any remains that were not part of the crannog mound, or otherwise protected, will have been lost, making the reconstruction of superstructures difficult (Cavers 2012) It also means that the present layer of any given mound need not be the limit of its past extent, but only the limit of its current protective shell. This shell may develop in two ways. On the stony crannogs this is due to accumulation of stones around the core of the mound. As these are too heavy for the current to move, they will prevent further erosion (Miller 1997, 19). In the case of the sites surviving as organic mounds, the preservation may derive either from the interlocking of timbers, or through silting. It is also worth remembering that the less stony mounds are found for the most part in the smaller lochs of the south-west (Henderson 1998b, 236-7), which would have presented fewer survival challenges, at least as far as the currents are concerned. Whether this affects the distribution map of sedimentary as opposed to the stony mounds is beyond the scope of the current PhD. It is also important to remember that the stability of a site or its protective shell may be disrupted in an event at a later point in time, most often through drainage of lochs, at which point the physical support for the timbers is reduced, the sites compress, deflate and with time deteriorate to nothing as appears to have happened at Lochlea (Barber and Crone 1993, 527). A related case is the situation of partial drainage where the water level was lowered and the wave action began destabilizing and eroding the site, as was the case at Dorman's Island and Loch Arthur (Cavers et al. 2011; Henderson and Cavers 2011). Furthermore, it has also been observed that the advent of modern farming practices has led to increased runoff of fertilizers, causing changes to loch biochemistry that may be adverse to wetland site survival (Henderson 2007b, 295).

The combination of the construction, maintenance, collapse and decay processes creates two major differences between wetland and terrestrial sites. First, with the exception of some features, such as the subsidiary mound at Oakbank (Dixon 2004), or the pile halos at White Loch of Myrton (Henderson et al. 2003, 93-4), or at Milton Loch 1 (Piggott 1953), the shape and size of the mound need not correlate with any of the design intentions, often making discussion of the shape and size of the mound meaningless. This would not have been the case on terrestrial sites, where major structural elements are often visible in survey and hence at least some elements of the prehistoric decision process may be identified, even if they do not pertain to the whole history of the site. The second difference comes from the presence of pockets of survival within the mound, whose stratigraphic interpretation is not always straightforward. Perhaps the best example of this is the Ederline Boathouse crannog where the timbers on the top of the mound produced Iron Age dates, but some of the deposits at the base are early medieval; this could happen because while the other early medieval deposits on top eroded, the midden near the base of the mound has been protected enough to ensure survival (Cavers and Henderson 2005). Other cases of such pocket survival include the artefact deposit at Buiston (Crone 2000, 66), and perhaps the sheep carcasses discovered by Munro at Lochlea (Munro 1882, 78). At the same time, it does appear that some sites still contain elements of a more conventional deposition sequence of continuous lenses (alleged for Oakbank; Dixon 2004), or even superimposed structural remains (Cults Loch 3; Cavers and Crone, forthcoming). Such combinations of conventional stratigraphy with occasional inversion, survival of timbers from multiple occupation episodes and formation of pockets pertaining to particular deposition events stands in stark contrast to most terrestrial Scottish archaeology, where vertical accumulation is minimal and high decay and erosion rates ensure that discrete material grouping survive only in pits and ditches.

The preservation and deposition processes on wetland sites have far-reaching implications for archaeological research. Some of these are, to a degree, self-explanatory; the investment required at the post-excavation stage is much greater on account of better survival of organic material. Likewise, conservation of the remains can become more challenging if the assemblage has a significant wooden component. There are also differences in fieldwork methodology. When excavating sites above water, some means of controlling a water-table needs to be developed, most often by cutting a drainage pit into the deposit and pumping it out with a petrol-driven pump (Crone and Cavers 2015, 11) and underwater excavation adds a whole suite of further logistical complications. Nevertheless, the main challenges come not from these rather broad categories, but from the complexity of the sites themselves; as material might form discrete pockets and due to stratigraphic inversion being a real possibility, substantial part of a mound has to be excavated before site taphonomy can be understood (Cavers 2007; Crone 2007; Henderson 2007a). This can be bypassed by some research designs, but, in the long term, it is only through near-complete excavations that a thorough understanding of wetland site diversity can be established. Hence, although these sites carry far more information than their terrestrial counterparts, they also require greater effort if this information is to be accessed.

Besides affecting the quality of the evidence surviving within the crannog mounds themselves, the waterlogging process is also beneficial to the survival of information in the areas surrounding the site. This has been demonstrated by O'Brien et al. (2005) at Ballywillin crannog in Ireland, where a core was collected from the sediments just beside the crannog mound and analysed for plant macrofossils, pollen, spores, diatoms, chironomids (non-biting midges) and Coleoptera (beetles). The results indicated two distinct periods of disruption corresponding to pulses of activity on the crannog. The first was the woodland clearance, noticeable in the pollen record sometime after cal AD

620 and interpreted as the result of the original activity on the site. The second was the disruption in the nutrient levels in the lake around cal AD 1150, interpreted as the result of the expansion of the crannog mound. Hence, besides providing a different record on-site, wetland locations also provide a different array of possible off-site analyses, providing a broad array of possibilities for site-specific environmental studies.

### 2.2.3 Scottish Iron Age wetland settlement summary

Wetland sites in Scotland differ from their terrestrial counterparts in two substantial ways. First, their history of research is different. While the basis of Scottish Iron Age archaeology developed in the post-war period, Scottish wetland sites were relegated to a later chronological horizon and no attempt was made at integration. In the 1970s and 1980s, the true chronological scope of the wetland phenomenon was recognized, however, the challenge of integrating the two very different data sets has not yet been realized and the recognition of the problem only came in the 1990s. The integration problem itself stems from the difference in preservation: as the wetland mounds preserve their third dimension and protected pockets of material formed in discrete events and depositional processes, their composition can become very complex. Hence, to understand these sites, complete, or near-complete excavation is required, which carries with it significant costs. The other strategy, one of partial excavation is also possible, but the logical limitations of such exposures have to be appreciated when putting forward any archaeological interpretations. All of this stands in stark contrast with terrestrial sites, where major components can often be recognized from aerial photography and most interpretation occurs in plan. In the absence of the material culture that would bind the two archaeological records together in a single historical process, some form of alternative linkage has to be developed if the different settlement types are to begin complementing one another.

## 2.3 Linkage

The problem outlined in this chapter and underpinning the thesis on the whole is one of an interpretive rift that has emerged between the wetland and terrestrial archaeologies of the Scottish Iron Age. This section will outline the few studies which have bypassed this rift. In all cases this was made possible by the emergence of a phenomenon referred to throughout this thesis as *linkage*. In the current thesis linkage refers to forming justified connections between terrestrial and wetland sites and hence putting oneself in the position where knowledge gained in the wetland context can be used in the interpretation of the terrestrial remains. There are three case studies in Scottish wetland archaeology where wetland sites play a specific part in the interpretation of past historic events. In each of these cases there are either demonstrated or implied relationships with the terrestrial sites which make the results of the investigations meaningful.

The first of these studies is Matthew Shelley's PhD project on wetland settlement in eastern Scotland during the early modern period (2009). This volume presents numerous cases of particular island sites being involved in specific historic events and, thanks to documentary backing, it has been possible to both relate the physical remains to specific purposes at these sites and obtain a better grasp of the part they played in local communities. For example, Shelley was able to demonstrate the centrality of the ecclesiastical settlement on the Island of Cluny to its local surroundings, both in political and economic terms. Had his observations been followed by excavation and had this excavation come across well-preserved organic remains, we would be aware that they are the sum of feudal production and also we could use these data to improve our understanding of the economic underpinning of medieval ecclesiastical power in the region and its impact on the livelihoods of the population who lived on surrounding terrestrial sites. Shelley was able to make such statements because he had the advantage of working in the historic period. In the case of Clunie he found documentary information on when the island was used and for what purposes, thus relating any observations on the actual archaeology through the medium of this historical background. This kind of close linkage cannot be expected to work in prehistory. Nevertheless, Shelley's work shows that if entanglements between sites are worked out, then improving the knowledge on one of them improves the knowledge of the whole group.

A prehistoric example towards this end comes from the Cults Loch environs project, where two terrestrial sites and one crannog have been excavated and studied as a part of a single programme (Cavers and Crone, forthcoming). In the course of the radiocarbon analyses it became clear that one of the terrestrial sites, a promontory fort (Cults Loch 4), and the crannog (Cults Loch 3) were occupied within a similar time period in the 5$^{th}$ Century BC. The potential significance of this is discussed in Chapter 7; here it suffices to say that in the light of re-dating the crannog in the course of the current project, it is clear that in this case any discoveries on the economy from the wetland site would inform at least about the options available to whoever occupied the promontory fort. Thus, in the case of the sites at Cults Loch, an increase in knowledge about the crannog leads to an immediate increase in knowledge about the promontory fort. The linkage here was developed through spatial proximity and synchronicity of the two locations.

The third case study puts forward an interpretation for the onset of the crannog phenomenon that would also affect our understanding of their broader historic context. This is Graeme Cavers' *Crannogs and Later Prehistoric Settlement in Western Scotland* (2010b), based on his PhD thesis submitted to the University of Nottingham. Within it, Cavers suggests that crannogs emerged as a means of marking land ownership in the period of social re-negotiation following the end of the Bronze Age. The land issue is relevant to this scenario because it assumes a distinct environmental downturn forcing the abandonment of upland occupation. If this model could be demonstrated to be true, it would link to a large number of different settlements and add a new dimension to how we perceive the transition. Nevertheless, the linkage here is only one of potential for two reasons. First, we still do not know the date of earliest wetland settlement in the study region. Second, the correlated environmental events still need clarifying (see section 2.1.2, above). For actual linkage to take place, these relationships would have to be demonstrated. Still, if the argument could be defended, the existence of crannogs would add another layer to our understanding of the Bronze Age–Iron Age transition and let us view these sites as important to manifesting control over land. This, in turn, could be used to aid the interpretation of specific case studies, such as that of Cults Loch 3.

The case studies demonstrate instances where linkage was developed in spite of the lack of material culture. In Shelleys work, linkage was made possible through the presence of historic records. For Cults Loch, it was the spatial proximity and synchronicity that were essential. As for the third case study, according to which the development of Scottish wetland settlement was driven by the social changes caused by the climatic deterioration at the end of the Bronze Age, linkage is only a potential not because of any logical flaws, but due to insufficient empirical evidence for the climatic downturn and because of poor chronological control. If these uncertainties had been resolved, linkage would have taken place. Thus, the key is not to rely on the presence of favourable situations, but to be able to create these situations. In other words, the integration of wetland archaeology into Scottish Iron Age studies requires that we, as archaeologists, can create conditions for linkage. In the absence of material culture, this requires the utmost attention to absolute chronology.

## 2.4 Chapter summary

This chapter reviewed the Iron Age archaeology of Scotland in search of the reasons why wetland sites, with their superior organic preservation, are not well integrated into debates of the period. The main and continuing cause of this state of affairs is the inherent difference between the two assemblages, making them difficult to treat in the same fashion. While the terrestrial sites often carry little information due to decay and erosion, what remains available can be accessed with relative ease. Meanwhile, the wetland sites carry much more information, while having little that can be accessed without intensive excavation. Therefore, the efficient integration of these assemblages has to rely not on forms of parallel interpretation, but on the process of linkage, whereby improvement in knowledge in one, leads to improvements in the other. For the most of world prehistory, linkage is an unconscious phenomenon that can occur because its logical underpinnings are backed by the presence of overarching culture-historical narratives. Because of the paucity of diagnostic material culture in the Scottish Iron Age, spontaneous development of linkage cannot be expected and instead the process ought to become a calculated research aim. This in turn requires a conscious effort towards developing narratives and that can only be successful when backed by sufficient chronologies. As discussed in section 2.1.4, Iron Age chronologies and their meaning are vague at best. This vagueness emerges due to technical reasons: to develop the necessary chronologies that would enable linkage requires overcoming these technical challenges. The nature of these challenges and the approaches that can be used to overcome them is the subject of the next chapter.

# 3 Wiggle-match dating background

Chapter 2 argued that chronological improvement is one way to overcome the interpretive rift between wetland and terrestrial archaeologies of the Scottish Iron Age. The current chapter will focus on how to develop these chronologies. The workhorse method put forward is radiocarbon wiggle-match dating  the one technique that can be expected to work on all Scottish wetland sites, while producing sufficient precision. At the same time the technique itself, although 50 years old, is not in routine use on Scottish wetland sites. Indeed, it is one of the aims of this thesis to bring it to the stage of routine use.

The chapter is structured into three sections. Section 1 outlines the reasons for the use of radiocarbon as the basic means of dating wetland settlement. In principle this can be summarized in terms of a trade-off between precision and sample availability: although dendrochronology is in principle much better suited to the task, it can only be applied to very specific timbers that will not be present in all of the features of interest. The second section discusses the theory of the radiocarbon dating technique and the resultant need for calibration of radiocarbon determinations. The third section discusses the Bayesian analyses of radiocarbon determinations. This is necessary as radiocarbon determinations alone tell us little of chronology and they need to be calibrated and modelled to obtain the precision required. One form of modelling is the wiggle-match dating technique that relies on constructing a small curve of radiocarbon changes through time in a natural deposition sequence (such as tree rings in a timber) and fitting it to an overarching ratified calibration curve (Figure 3.1). Because the number of locations of fit is limited, the precision of the resultant date improves. At the same time the requirement for multiple radiocarbon measurements makes wiggle-match dating expensive. Hence, it needs to be shown as reliable under the conditions in which it is deployed, the number of samples ought to be optimized and an overall strategy for its use in archaeological contexts should be articulated. These subjects form the core of the current thesis and will constitute the bulk of Chapters 5 and 6.

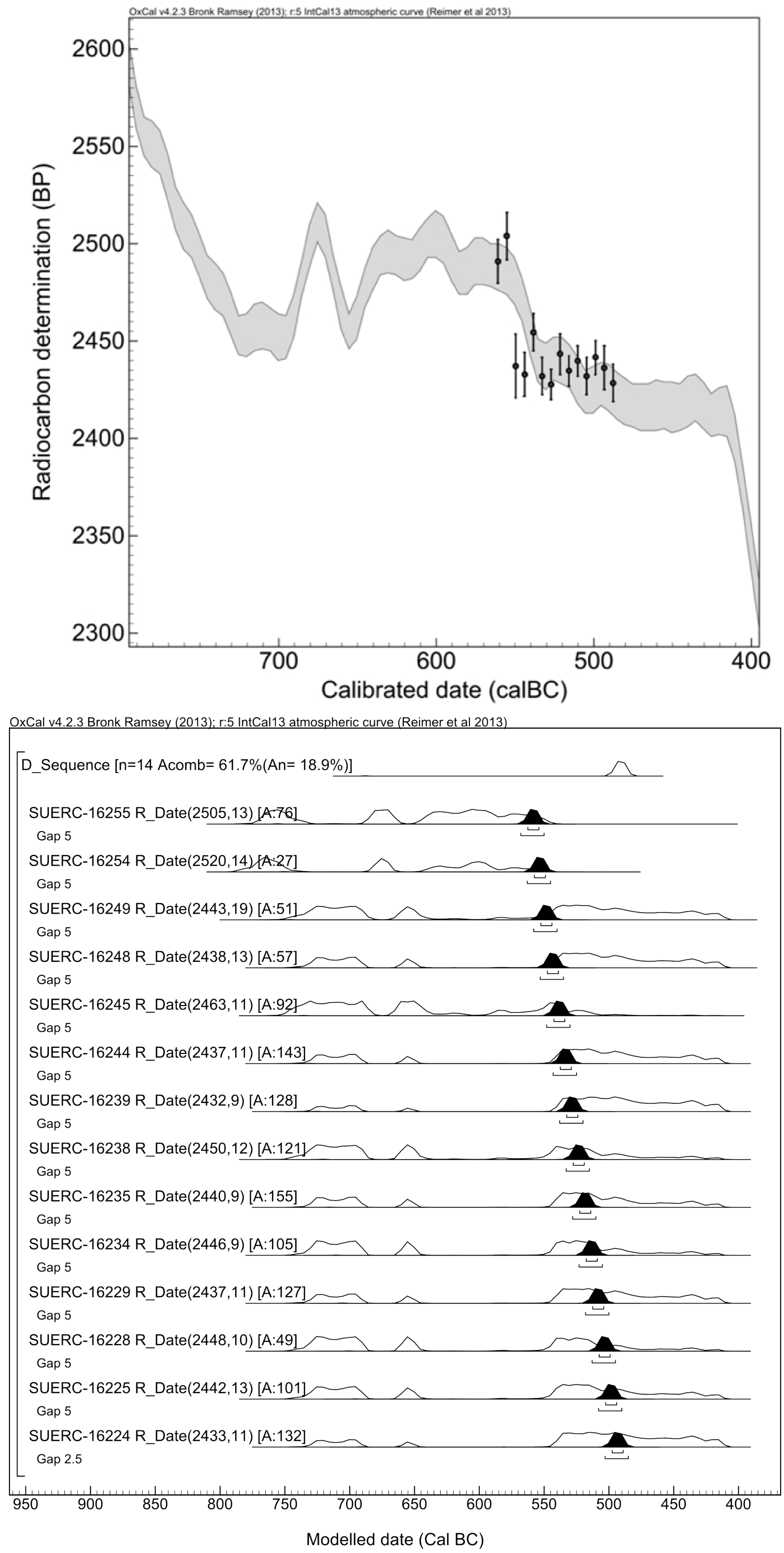



Figure 3.1: Radiocarbon wiggle-match dating: a series of measurements from an unknown age timber is composed into a small curve and matched to the master calibration curve (top). As the number of possible points of fit is limited, the precision of the estimate improves, indicated by the shift from the hollow black lines to the filled black area (bottom) (data from Cook et al. 2010).

## 3.1 Why radiocarbon?

Before any new chronology building takes place two questions need to be answered:

1. What is the minimum precision required by the research aims?
2. What is the availability of samples?

The latter is controlled by whether suitable material was present on site in the first place and how well it survived. In studying wetland settlement, datable samples ought to be available for each major structural event. As for precision, it depends on the level of detail required to improve the state of knowledge: the early radiocarbon results from Jericho told us something new about the earliest Neolithic even though they had errors of more than a hundred radiocarbon years (Kenyon 1956). Had similar dates been obtained for the same period today, they would tell us less about the absolute chronology of the site than typological comparisons. In the case of the Scottish Iron Age knowing specific centuries is often sufficient; this is the kind of resolution that will discern groupings of events. For example, with centennial precision (<100 years) it would be possible to determine whether the onset of wetland settlement coincides with the end of the Bronze Age and hence whether Cavers scenario according to which the two events are related holds (see Chapter 2.3) (Cavers 2010b). Furthermore it was centennial precisions that made the Cults Loch study possible (Cavers and Crone, forthcoming). From a cultural perspective this kind of centennial or better precision enables us to either confirm or reject synchronicity of sites, or at least their existence in memory of the preceding generations.

The centennial precision requirement defines which dating techniques can be used as the core methods. Luminescence can be rejected because its standard deviation interval oscillates between 5–10% of the sample age (Murray and Olley 2002, 14), which for the Scottish Iron Age would mean 95.4% confidence intervals of between 400 and 1000 years a problem that has been encountered during the dating of the palisaded enclosure at Braehead, Glasgow (Ellis 2007, 202-3). Archaeomagnetic dating can, in principle, attain very high precision in the range of several decades, but its success depends on the geographic location of the sample and its age (Aitken 1990, 251). This may not always be the case for the Scottish Iron Age: for example Cook (2010, 86) reports that the archaeomagnetic date from the hillfort at Dunnider had a range of about 350 years, which is too crude for the purposes outlined above. Thus tree-ring dating, or dendrochronology, and radiocarbon are left as the only viable alternatives that may fulfil the precision requirement.

Dendrochronology relies on comparisons between the characteristics of growth rings between timbers of the same species. If a given species is subject to growth-ring variability dependent to a large extent on major weather characteristics in a given year, it becomes possible to match it to known-age sequences from other locations and hence derive a date that may be precise to a particular felling season within a specific year, if the bark edge survives (Baillie 1982, 1995). In other cases if the sapwood-heartwood boundary (the boundary between the inner dead and outer living rings) survives, it is possible to discern the felling to a few decades (Baillie 1982, 57-60). The main requirements for the technique to work are that:

1. The tress should have lived for long enough. Baillie (1995) recommends at least 100 years, although in some cases exceptions can be made (EH 2006).
2. The ring-width variability has to be significant, but not too excessive, as in the latter case it becomes swamped with local noise that cannot be used for dating (Baillie 1982).

In practice, this means that oak is the only species present in the Scottish Iron Age assemblages that can produce reliable dendrochronological dates. Pine has not been used during that period (Crone and Mills 2002, 788), ash displays too little inter-annual variability and other species such as alder display too much ring-width variability. Furthermore, even oak needs to be subject to growing conditions similar to those in regions with already existing chronologies and the statistics are helped by larger assemblages (Baillie 1995).

It is rare that the requirements of dendrochronology are fulfilled on Scottish Iron Age wetland sites. In many locations oak is rare: at Oakbank Crannog it constituted 21% of the wood assemblage (Crone 1988, 56), at Cults Loch 3 only 47 oak timbers were recovered (Cavers and Crone, forthcoming) and at Black Loch of Myrton only eight oak timbers have been discovered so far (Crone and Cavers 2015, 15). Furthermore, many of the oak timbers used will have lived for too brief a period to be used in absolute dating. At Oakbank only four of the 41 useable oak samples had more than 100 rings, most of which display asymmetric growth that complicates measurements (Crone 1988, 134; Figure 17). The situation is not much different at Cults Loch 3, where from a group of 47 recovered oak timbers only 15 had more than 100 tree rings. Nevertheless, Cults Loch 3 has been dated (Cavers and Crone, forthcoming), but not all contexts of interest were covered (see Chapter 6.4). In any case, dendrochronology cannot be expected to work on a routine basis in Scottish wetland archaeology.

These limitations do not mean that dendrochronology is of little use on Scottish wetland sites. For one thing, where it does work, the very precise dates provide a major interpretive advantage. Furthermore, a broader range of species, including the often prevalent alder, can be arranged into relative site-chronologies (Crone 2014). While these do not provide an absolute date for the site and hence may not contribute to establishing relationships between sites, they can allow the exact reconstruction of site histories, as at Buiston crannog (Crone 2000, 51-3). There is also the possibility of using tree-ring data for purposes of environmental reconstruction. Although the traditional approach of using ring-width as an environmental proxy has been shown to have its limitations (Buntgen et al. 2009, 261-73), these can be overcome to an extent through stable isotope analyses[1]. In principle, if photosynthetic processes are hindered by a lack of water or energy, the tree will fractionate against heavier carbon isotopes. Likewise, if water is plentiful and photosynthesis moves at a low rate, the tree will fractionate against the heavier oxygen isotope. By combining these two proxies it is possible to derive high-resolution climatic reconstructions over the duration of the tree growth (McCarroll and Loader 2004), which may prove useful in addressing the uncertainties regarding climate in Scotland during the Iron Age (see Chapter 2.1.2).

Although dendrochronology is a powerful tool at the level of interpreting individual Iron Age sites in Scotland, its application to the construction of absolute chronologies is limited by the availability of suitable material. Hence, radiocarbon remains the only technique that may be able to deliver the required centennial precision on a routine basis. It does, however, suffer from its own limitations relating to the process of calibration that stems from the very theory of the technique. The success of the current project relies on overcoming these limitations.

## 3.2 Radiocarbon dating: basic theory and calibration

This section reviews the theory of the radiocarbon dating technique and the reasons why radiocarbon age determinations must be calibrated before they acquire chronological meaning. Calibration curve construction will also be considered. Sub-section 3.2.1 will outline the basic premises of the technique. Sub-sections 3.2.2 and 3.2.3 will discuss the problems of radiocarbon production and the global carbon cycle and why their variability leads to the need for calibrating radiocarbon dates. The final sub-section, 3.2.4 focuses on the data and construction of the calibration curve. This provides the background necessary to understanding the hidden challenges of wiggle-match dating technique, which will be discussed in Chapter 5.

### 3.2.1 Radiocarbon dating premises

The radiocarbon dating technique is based upon three empirical observations: the natural occurrence of $^{14}C$, the introduction of natural $^{14}C$ into the biosphere through photosynthesis and the exponential decay of $^{14}C$ in a sample after it is removed from the carbon cycle (Libby et al. 1949). Natural $^{14}C$ is produced through neutron bombardment of $^{14}N$ in the upper atmosphere and the new carbon atom then oxidizes to form $^{14}CO_2$ (Pandow et al. 1960), which can be absorbed by either the hydrosphere or the biosphere (Figure 3.2). In the latter case it is taken up by plants during photosynthesis and built into tissue. As long as the tissue remains alive its radiocarbon content is in equilibrium with the atmosphere, but upon death it begins to decay at a rate which is independent of the surrounding conditions. This means that by knowing

[1]Isotopes are atoms of the same element with different number of neutrons and hence different mass. While the chemical properties across isotopes are identical, heavier isotopes are slower to react or pass through constrained spaces.

how much $^{14}C$ a sample contained in the first place, how much $^{14}C$ it contains now and the decay rate of radiocarbon, we can estimate how much time has passed since the sampled organism died.

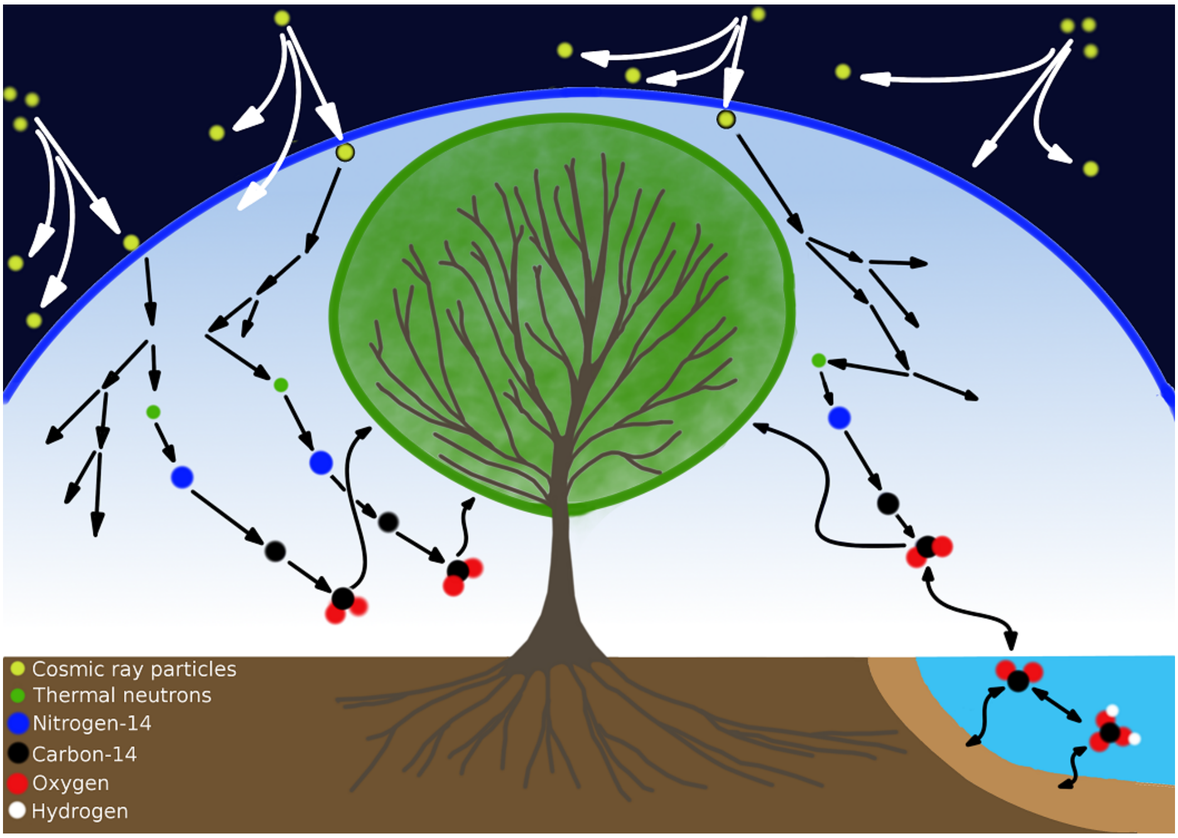



Figure 3.2: The principles of radiocarbon dating. Primary cosmic rays undergo a cascade of nuclear reactions upon first collisions in the Earths atmosphere. These collisions result in the production of a range of particles including thermal neutrons which can undergo a reaction with atmospheric $^{14}N$, leading to the production of $^{14}C$. This then oxidizes to $CO_2$, most of which is absorbed by the hydrosphere. However, some will make its way into the biosphere through photosynthesis.

Calculating the radiocarbon age depends on three variables: the radiocarbon content of the sample, a decay constant and the radiocarbon content at death (Figure 3.3). Current sample content can be evaluated by decay counting (radiometric analysis) or by direct atom measurement using accelerated mass spectrometry (AMS); in both techniques the amount of radiocarbon is estimated in relation to that of a standard (Aitken 1990, 93-4). The primary radiocarbon standard is Oxalic Acid II, issued by the US National Institute of Standards and Technology (former National Bureau of Standards) and is designed to emulate the atmospheric value of $^{14}C$ in 1950, had the industrial revolution not taken place (Stuiver 1983; Stuiver and Polach 1977, 356-7).

The decay rate of radiocarbon is derived from the half-life of 14C, which can be determined by counting the decays over time in a sample with a known number of atoms of the isotope of interest. Libbys team at first estimated the half-life of radiocarbon to be about 5700 years (Engelkemeir et al. 1949, 1833), but this was later revised to a conventional half-life of 5568 years (Aitken 1990, 93). The revision itself was refuted and in 1962 the half-life was corrected back to 5730 years (Godwin 1962). Since then

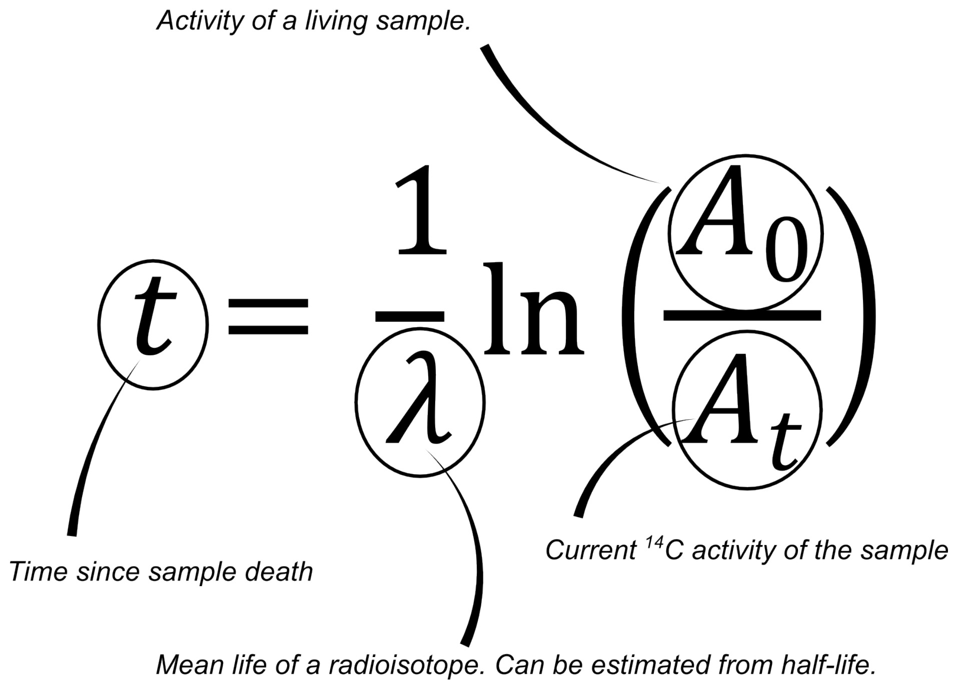



Figure 3.3: The radiocarbon age equation.

there were no corrections, despite some recent critiques (Chiu et al. 2007, 27). For consistency, an uncalibrated radiocarbon age is calculated from the observed radiocarbon counts using the conventional half-life of 5568 years (Stuiver and Polach 1977, 362-3). Note that, while relevant to a number of carbon-cycle applications, exact knowledge of the radiocarbon half-life is not of direct relevance to archaeological applications, due to the nature of the calibration process (as discussed in the subsequent sections of the current chapter).

The radiocarbon half-life can be considered as a known value and the current radiocarbon activity of a sample can be evaluated through measurement. However, the age equation also requires the living activity of the sample to be known ($A_0$). In the early years of radiocarbon dating it was assumed that radiocarbon concentrations in the atmosphere underwent little significant change prior to the Industrial Revolution, when large amounts of radiocarbon-depleted $CO_2$ started being released. However, by the mid-1950s it became apparent that this was not the case as significant deviations from the expected trend were first observed in pre-industrial tree-rings (de Vries 1958) and by the mid-1960s this phenomenon was confirmed by the early calibration measurements (Suess 1965). These early measurements showed that past radiocarbon activities displayed significant complexity, which itself can be attributed to the variability in the production and cycling of radiocarbon.

### 3.2.2 Radiocarbon production

Radiocarbon is produced by $^{14}N$ interaction with neutrons derived from cosmic rays. These rays are high-energy charged particles that originate from supernova explosions and over time diffuse throughout the galaxy. Upon entering the solar system, they slow down and those that make their way to Earth are broken down upon entering the atmosphere. These breakdowns result in a number of products, which include thermal neutrons that produce $^{14}C$ if they collide at an appropriate angle with $^{14}N$. Therefore, radiocarbon production is controlled by the presence of nitrogen and thermal neutrons (Beer et al. 2012, 161).

Atmospheric pressure controls nitrogen availability. The greater this pressure becomes, the more Nitrogen atoms will be present per unit volume. At the same time as the pressure increases going down through the atmosphere, the probability of encountering a thermal neutron begins to decrease. Hence, the optimal production is about 120mbar (Figure 3.4; Mak et al. 1999, 3382), corresponding to the stratosphere, which begins between 8 and 16km above sea level, depending on the latitude, and ends about 50km above sea level (Beer et al. 2012, 205-7). The number of neutrons available for the production of radiocarbon depends on the cosmic ray intensity in the local intergalactic spectrum (LIS) and the probability of cosmic ray penetration into the atmosphere. The LIS can be considered constant on $^{14}C$ time-scales (Masarik and Beer 2009, 8), but the probability of a cosmic ray making its way into the atmosphere is controlled by the activity of the sun and the Earths magnetic field.

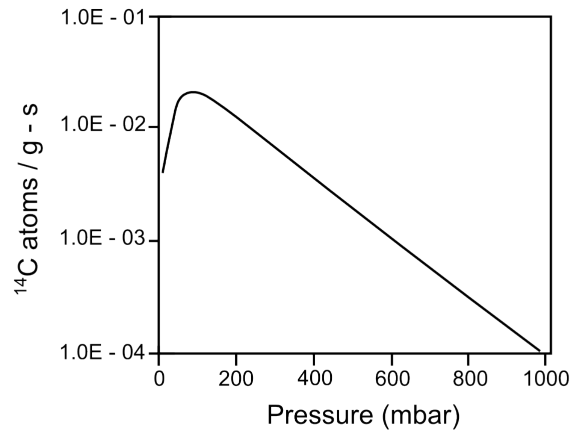



Figure 3.4: Estimated radiocarbon production rates at different atmospheric pressures. Mak et al. Re-drawn from 1999, Figure 1.

The Sun controls the number of cosmic rays in the Solar system. Solar activity qualitatively correlates with sunspot numbers: the more sunspot numbers are observed, the greater the solar activity and the fewer particles make it to the Earths stratosphere (Beer et al. 2012, 33-63). This is subject to multiple oscillations (Knudsen et al. 2009). For this project the 11-year Schwabe cycle, which is modulated by the longer 88 year Gleissberg cycle and the 22-year cycle of the Suns magnetic dipole, are the most relevant (Peristykh and Damon 2003).

The Earths geomagnetic field determines the minimum energy that a cosmic particle needs to penetrate into the stratosphere. In general, a cosmic particle will be accelerated in the direction of the magnetic field with energy proportional to the strength of the field at the time. Because the magnetic field runs parallel to the Earths surface at the equator and perpendicular at the poles, particles at higher latitudes are more likely to find their way into the atmosphere (Figure 3.5) (Beer et al. 2012, 68-73).

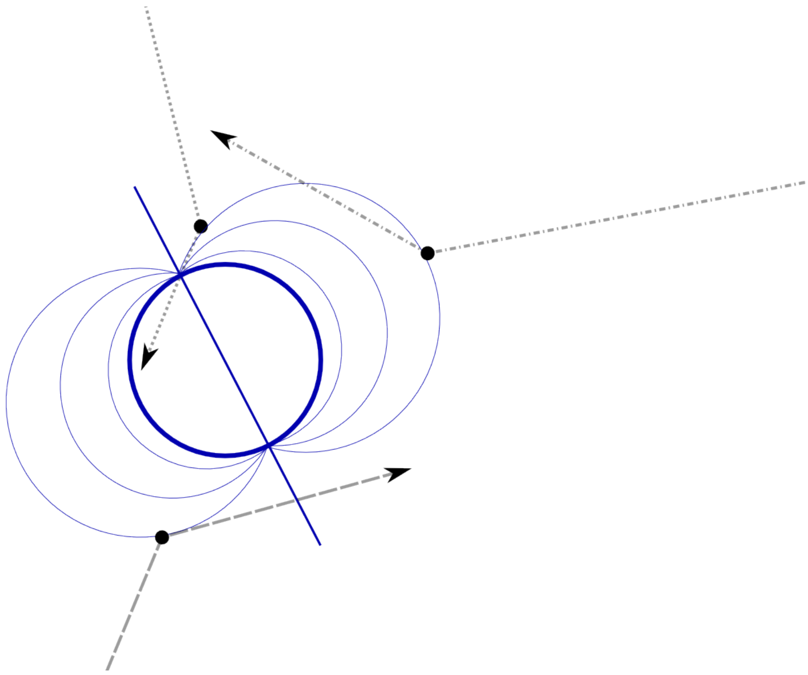


Figure 3.5: Geomagnetic effects on cosmic rays. Cosmic rays approaching the equator are more likely to be accelerated away into space, than the ones approaching the poles.

Even though the qualitative theory of natural radiocarbon production is well understood, the quantitative detail remains elusive. Uncertainties stem from the coupling between the solar and terrestrial magnetic fields, the stochastic nature of the astronomic and magnetic cycles involved and the lack of sufficient empirical measurements of $^{14}C$ production. Magnetic coupling means that any Earth-induced periodicities of less than 500 years will become swamped by the Sun while the terrestrial cycles are also influenced by the solar cycles (Love 2011, 259-60; Snowball and Muscheler 2007). Furthermore, the processes involved are stochastic in nature: while we have some estimates of their typical lengths, for the most part these are variable. This is best illustrated by the Schwabe cycles, which vary from nine to 13 years (Figure 3.6). Finally, there is the lack of reliable direct natural production measurements. Mak et al. (1999, 3384) conducted such measurements at ground level, but their results amounted to only half of the theoretical predictions. A more recent study involved measurements aboard commercial aircraft, however, here the results indicated production rates exceeding the theoretical estimates (Bronk Ramsey et al. 2007, 563). While it is tempting to reject the theoretical evaluations, these are in agreement with a number of empirical observations on other cosmogenic isotopes which would have to be rejected if the two radiocarbon production rate experiments were considered reliable (Masarik and Beer 2009, D11102-4).

Because of these limitations our primary method of estimating past production variability is through the study of radionuclide records themselves. This approach comes with two caveats: first, the resolution of our estimations will only be as good as the

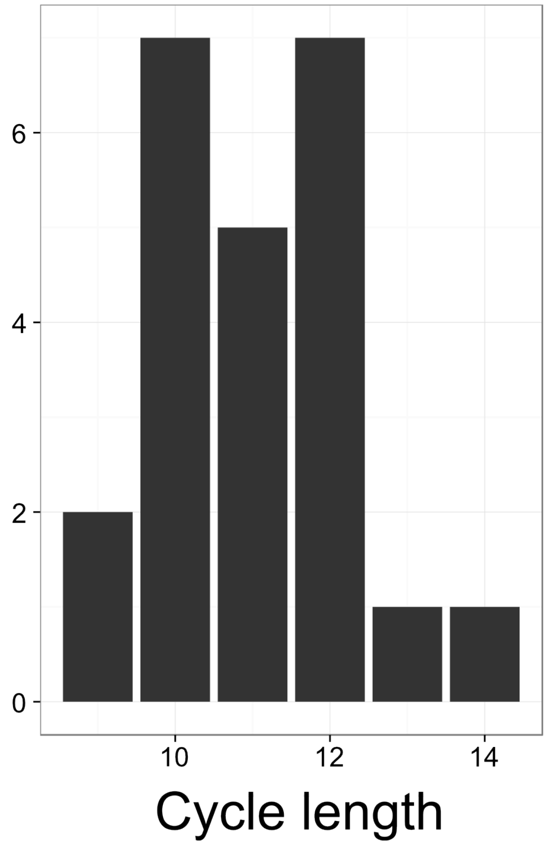



Figure 3.6: Lengths of historical Schwabe cycles in years. Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

resolution of the records themselves and second, there will be limits imposed by the nature of these records.

### 3.2.3 Global carbon cycle

Production variability accounts for fluctuations in how much $^{14}C$ is added into the stratosphere. However, the age equation is concerned with tropospheric concentrations, which are controlled in part by the global carbon cycle. This cycle attenuates the effects of short-term production variability, makes atmospheric concentrations sensitive to ocean dynamics and has the potential to introduce regional offsets.

Attenuation is the process of reducing the amplitude between the peak and the trough of radiocarbon production (Beer et al. 2012, 229). The key constraint is provided by how long an average radiocarbon atom stays in a given reservoir relative to production periodicity. As the average residence time of carbon in the atmosphere, 7.7 years, is just under a decade, much of the variability of the Schwabe cycle is lost. This, coupled with other carbon cycle effects, means that tree ring radiocarbon records as little as 4‰of the amplitude of the cosmic flux variability (Beer et al. 2012, 225-30).

The main force behind the carbon cycle is ocean dynamics, which exert great influence over atmospheric radiocarbon concentrations. The theoretical results backing this assertion come from the modelling results of Oeschgers team in the mid-1970s (Oeschger et al. 1975) and have been developed by their successors (eg. Joos et al. 2004). Oeschger recognized that carbon budgets can only be balanced if the gradients in diffusion rates between deep and shallow ocean waters are taken into account, implying that ocean dynamics affect atmospheric radiocarbon concentrations. Empirical evidence for the importance of ocean circulation is provided by the modulation of the Southern Hemisphere radiocarbon offsets by the El Niño Southern oscillation (Turney and Palmer 2007). Sensitivity to ocean dynamics also implies sensitivity to global climates. Large shifts in past atmospheric radiocarbon can be attributed to this, as illustrated by the increase in atmospheric radiocarbon content at the onset of the Younger Dryas, or during the Ice Ages (Hua et al. 2009, 2989; Hughen et al. 2004, 205), but note that alternative scenarios are possible (Goslar et al. 2000). However, during the Holocene, the major climatic swings have come to an end and the effects of ocean dynamics on atmospheric radiocarbon became more subtle (Hughen et al. 2004, Figure 3; Muscheler et al. 2004, 336).

### 3.2.4 Radiocarbon calibration curves

The complexity of the interactions between the production rates and circulation of radiocarbon make it impossible to make theoretical adjustments to age equations. Instead it is more practical to calibrate the $^{14}C$ determinations against a curve derived from measurements of known-age material . The earliest such curve was hand-drawn using measurements of dendro-dated Bristlecone pine (Figure 3.7) (Suess 1965). The 1970s saw the advent of more refined methods of joining the areas between the measurements, amongst which the use of piece-wise curves based on moving averages emerged as the preferred approach and remained in use until the early 2000s (Buck and Blackwell 2004). The same period also saw the proliferation of calibration data which led to confusion as to which curve was the correct one. This was mitigated during the 1982 Radiocarbon Conference with the agreement on the consensus calibration data sets (Klein et al. 1982). These were then replaced in 1986 by the Internationally Ratified Calibration data sets (Pearson and Stuiver 1986; Stuiver and Pearson 1986), which have since gone through a number of iterations named by their publication date (93, 98, 04, 09 and the current IntCal13; Pearson and Stuiver 1986; Reimer et al. 2004, 2009, 2013; Stuiver and Pearson 1986; Stuiver et al. 1998). Alongside the adjustments and extensions of the data sets, the methodology for inferring the shape of the curve and its uncertainty has developed through the history of IntCal. By IntCal98 these fused, so that following 1998 the term IntCal refers to a radiocarbon calibration curve built on ratified data sets using a ratified methodology (Stuiver et al. 1998, 1058). This sub-section discusses both the underpinning calibration data and the methodology in turn. It then turns to the subject of known offsets from the calibration curve, which are important for the discussion in the latter parts of Chapter 5 and also of general relevance to using the technical approaches put forward here in contexts other than Scotland.

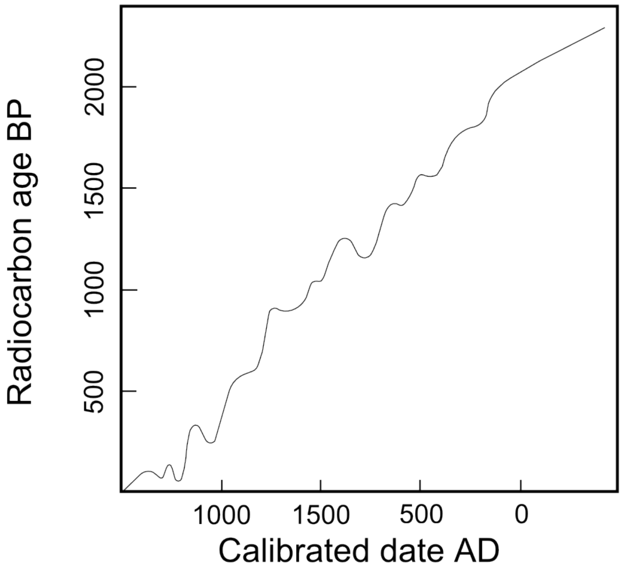



Figure 3.7: The Suess 1966 bristlecone calibration curve (modified from Stuiver and Suess 1966, Figure 1).

#### Calibration data sets

IntCal data for the mid-first millennium BC consist of decadal and bi-decadal blocks of dendro-dated timbers, most of which derive from the 1986 Belfast and Seattle measurements (Pearson and Stuiver 1986; Stuiver and Pearson 1986). In the period of interest, the Belfast series consists of decadal and bi-decadal blocks of rings from Irish oaks (Pearson et al. 1986, 912) and the Seattle series consists of decadal blocks of German and Irish oaks (Stuiver and Becker 1986, 863). In IntCal93 the accuracy of both series was questioned. The Belfast lab reported possible technical issues in the counting process (Pearson and Qua 1993), however, these have been refuted since (Reimer et al. 2004, 1032). The Seattle samples suffered radon contamination during counting and a correction had to be introduced. This was estimated at up to 40 radiocarbon years in IntCal93 (Stuiver and Becker 1993, 36-8), but this estimate was exaggerated and the correction was reduced to a maximum of 20 years in IntCal98 and beyond (Stuiver et al. 1998, 1127). It is also worth mentioning that the measurement of German oak from the early 2$^{nd}$ millennium AD, undertaken by ETH Zurich, showed a systematic drift towards older radiocarbon ages relative to all IntCal data, although it remains uncertain whether this is a genuine pattern or a function of storage and pre-treatment (Guttler et al. 2013; Wacker et al. 2009). Under the current curve, IntCal13, the mid-first millennium BC calibration data sets also include Heidelberg measurements of German oak (Kromer et al. 2010) and a series of measurements on Bristlecone pine, undertaken at UC Irvine (Taylor and Southon 2013).

All these data come from decadal or bi-decadal blocks of wood (ie. blocks of ten or twenty rings measured as single samples). This choice is driven by economic motives (Stuiver 1993, 67) and in the case of bristlecone pine practicality, as it is rare for individual bristlecone tree-rings to exceed fractions of centimetres (Leavitt and Bannister

2009, Figure 5). However, use of decadal blocks will attenuate much of the short-term variability introduced by the Schwabe cycle (Figure 3.8) (Beer et al. 2012, 260-1). IntCal93 recognized this problem and dealt with it by providing a series of finer calibration tables based on measurements on annual samples, but only for the period following AD 1520 (Stuiver 1993). IntCal98 took a different approach. The whole curve was drawn as a series of decades. Any effects of short-term variability were mitigated by adding a constant of 64 to the sample variance, which was supposed to offset any effects of solar variability (Stuiver et al. 1998, 1043). Since IntCal04 decadal smoothing has not been addressed in a direct fashion as a result of growing awareness of the complexities involved in curve estimation. The consequences of this loss of short-term variability are recognized (Reimer et al. 2013, 1883), but for the time being they are not yet addressed. As will become apparent in Chapter 5 this has ramifications for wiggle-match dating design.

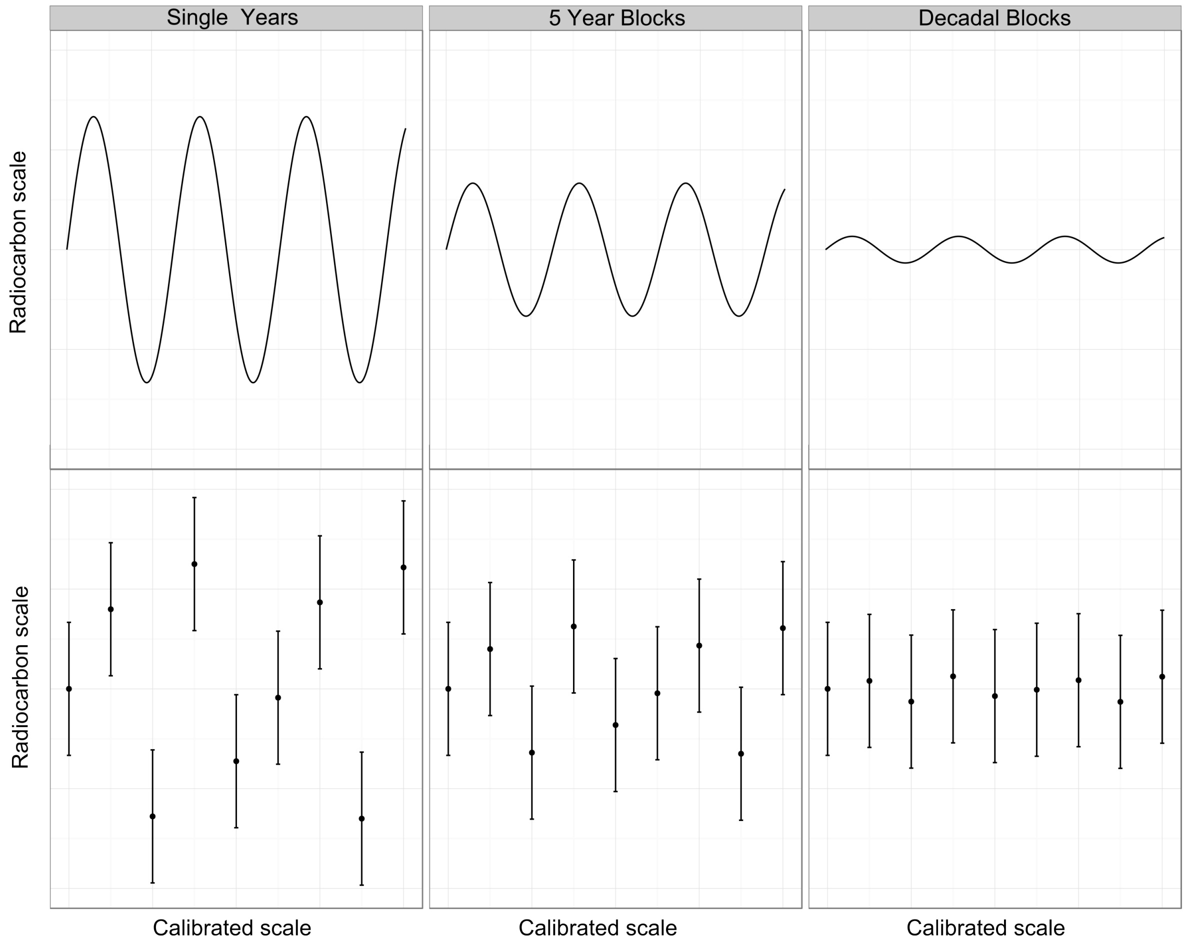



Figure 3.8: Schematic representation of the effects of attenuation of the 11-year cycle in radiocarbon archives. As sample length increases from single years to decadal blocks, the short-term variability becomes averaged. In effect the expected variability in radiocarbon determinations decreases. This effect can be estimated from the attenuation equation (Beer et al. 2012, Equation 14.6.1-1).

### Calibration curve inference

While a radiocarbon calibration curve cannot exist without the underpinning data, these data only represent points in time and the periods in between them have to be estimated. Because there is no direct measure of what is happening during these periods, they are subject to uncertainty additional to that of the measurement error (Figure 3.9) (Clark 1979; Niu et al. 2013). Piece-wise curves, such as IntCal98, dealt with this by applying moving averages to match the measurements (Clark 1975; Stuiver et al. 1998, 1042). The main drawback of this approach was that it obliterated much of the short term-variability and made the curve only suitable for samples which lived for a period comparable to the smoothing factor. Any short-lived samples had to be subjected to some kind of an ad-hoc procedure, such as the addition of a constant to the sample variance, in order to overcome the curve uncertainty issues. This changed in IntCal04 with the implementation of a random-walk approach, originally designed by Portugal Aguilar et al. (2000), developed by Christen and Nicholls (2000) and altered to the specifications of the International Working Group by Buck and Blackwell (2004). A random walk is a term from probability theory which describes a sequence of numbers, in which each next value is random, but into which a direction can be introduced through a drift parameter (Figure 3.10) (Isaac 1995, 103-4). In a random walk calibration curve the drift is set to account for radiocarbon decay through time and the variability seen in the calibration datasets is conceptualized as probabilistic deviations from the drift direction. The key is to deduce what are the possible values for each step of the walk, given the calibration data. Because there is no limit on how many data can be used to define the short-term changes, it is possible to use the covariance of a large number of measurements (IntCal04 used 100 values) and so use the long-term trend within them to obtain an estimate for any point within the range of the radiocarbon technique (Buck and Blackwell 2004, 1100). Hence, random walk methods can produce estimates which are both precise and display mathematical coherence.

There are different approaches to finding the values of the random walk. IntCal04 was numerical: it sought to estimate the best position for each of the steps of the random walk by fitting numbers to the data and choosing the best. This introduced some constraints, most of which had to do with accounting for the complex nature of the Pleistocene data sets. It also meant that the variance of the random walk had to be estimated beforehand and fixed throughout the entire execution (Blackwell and Buck 2008, 231). The two iterations of IntCal that followed 2004 used an MCMC approach (see section 3.3.5) to defining the curve (Heaton et al. 2009; Niu et al. 2013). This method tackles complex mathematical models by breaking them down into simpler ones and then sampling from their separated parameters, so the random walk estimation can simultaneously evaluate the expectation of each point on the curve and its associated variance. While the shift to simulation methods does not alter the geometry of the tree-ring dated sections of IntCal, it means that the methodology is in place to better estimate the curve variance as the number of data sets increases.

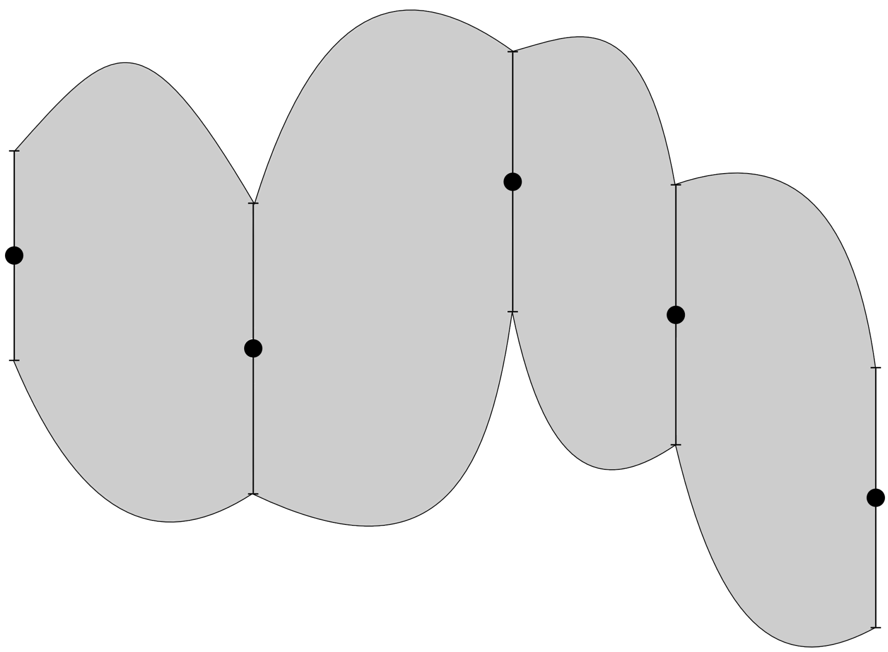


Figure 3.9: Schematic representation of the problem of curve inference. Because the periods between the measurements have no direct measurements, the path taken by the past radiocarbon trend can follow any possible route permitted by short-term variability. Modelled radiocarbon curves from IntCal04 onwards address this problem by studying covariance between a large numbers of measurements and using this information to limit the resulting uncertainties.

### Calibration curve accuracy

One of the main assumptions when using any given calibration curve is that it provides an accurate description of the past radiocarbon trend for a given place and time. At this point there are sufficient data from different parts of the world that demonstrate that this is not always the case. This sub-section reviews these data and provides a background for the more generalized discussion of offsets in Chapter 5.

In theory there are a number of mechanisms that can cause discrepancies between the local radiocarbon trend and a global calibration curve. The understanding of these mechanisms is dependent on the understanding and modelling of the carbon cycle. Many of the assumptions regarding homogeneity of tropospheric $^{14}$C refer to the Oescheger and other box models, which are interested in average values and not internal variability and so pay little attention to mixing within the atmosphere (Beer et al. 2012, 226). This, however, may not always be a good description of localized radiocarbon concentrations that are of interest in radiocarbon dating. For example, a significant increase in wave action will increase the interface between surface waters and the atmosphere in a particular area, which should lead to localized change in the mixing gradients between the two reservoirs. What is less certain is whether the change would be large enough to influence the results of $^{14}$C dating. Effects of such localized mixing gradients can be facilitated by movement of air masses or oceanic currents. For example, the daily rain cycle in the inter-tropical zone leads the repulsion of air masses and so forms a limit on tropospheric gas exchange between the hemispheres (Beer et al.

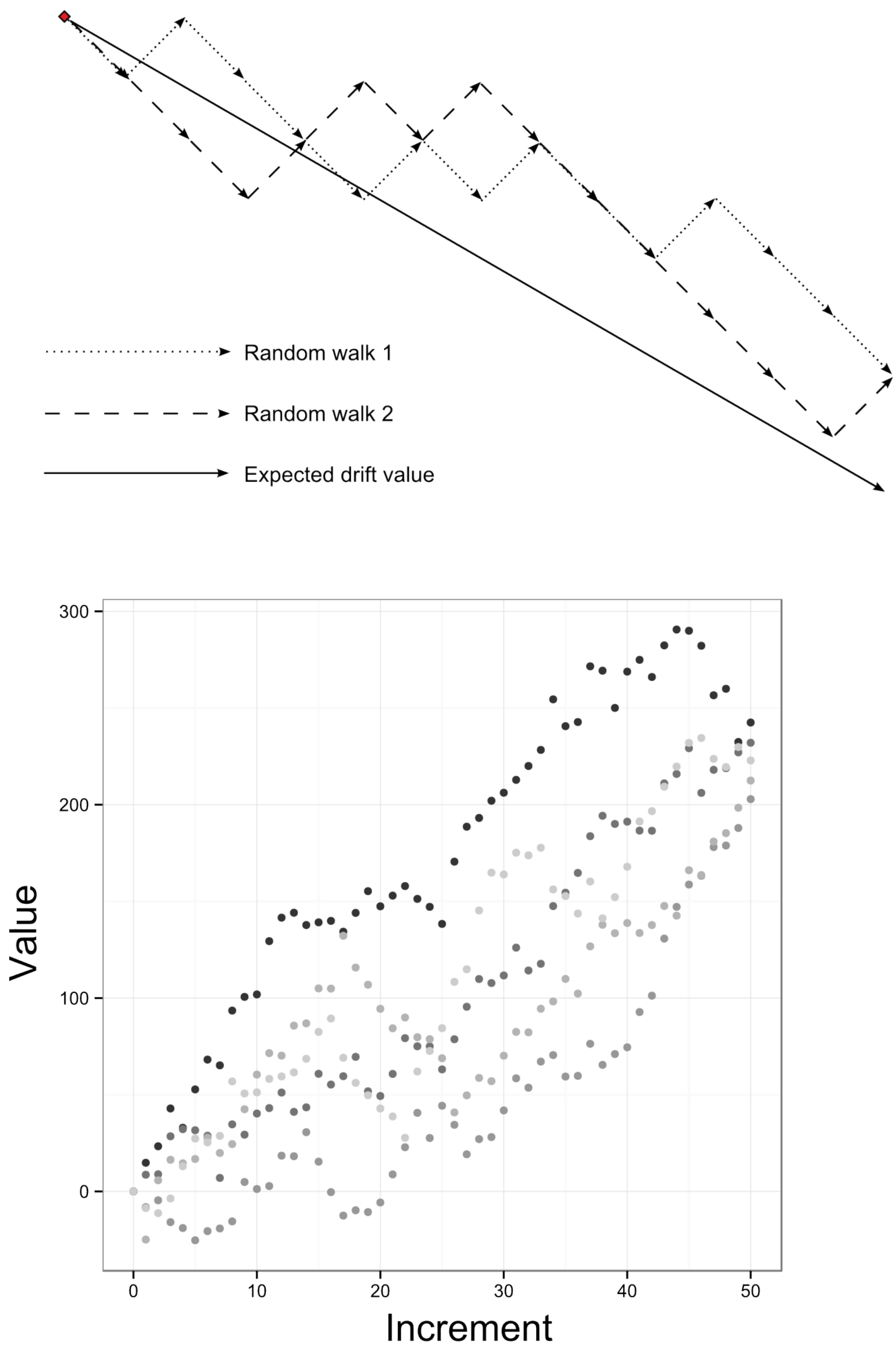



Figure 3.10: Top: the basics of a random walk. The drift parameter ensures that the values change over time in a general direction, but the individual paths depend on independent draws. Here each draw had a 2:1 chance of going one step down at each step. Bottom: Five iterations of a random walk with a distribution N(4,12).

2012, 205-10). Seasonality is another possible cause for differences in radiocarbon levels between different locations, as mixing rates between different reservoirs are controlled by temperature and so injections of $^{14}$C-enriched carbon dioxide from the stratosphere to the troposphere are not uniform throughout the year. Therefore, plants which begin photosynthesis sooner or later than the oaks of the calibration data sets may be offset relative to the calibration curve (Dellinger et al. 2004, 977-8; Kromer et al. 2001, 2531). These theoretical concerns point to a number of possible offset mechanisms, but because the quantification of the radiocarbon cycle is still limited, any propositions of regional offsets need to be evaluated with reference to empirical data.

For most of the theoretical propositions relating to mixing gradients the only solid evidence refers to the offset between the northern and Southern Hemispheres, which is controlled by the differences in ocean cover, as well as a number of other drivers (Hogg et al. 2009, 2013). Regional offsets on smaller scales are less certain and more difficult to identify. One of the oldest postulated offsets suggested increased radiocarbon activity in Alpine areas, due to closer proximity to the stratosphere, but recent research has been unable to detect it (Dellinger et al. 2004, 978). Another traditional argument quotes offsets resulting from ocean upwelling (Damon, et al., 1989), but once again the most recent claims (Keenan 2002) have been refuted (Manning et al. 2002). A more systematic study by McCormac et al. (1995, 398) observed a possible systematic offset between Irish and German timbers within the IntCal calibration data sets, with Irish oaks tending towards younger ages in some periods, including parts of the Scottish Iron Age. However, more substantive statistical analysis is required to assess the claims of such offsets within the original IntCal data sets.

The small number of studies in which atmospheric offsets have been determined relate to the Southern Hemisphere influence. One clear case is demonstrated in pines from Thailand, which, despite having grown in the Northern Hemisphere, follow a Southern Hemisphere trend as a result of southern air mass influence (Hua et al. 2000). Such offsets can also be time-dependent, as seen in some of the numerous studies conducted on Japanese cedar (Nakamura et al. 2013, 769). In any case, all the well documented air-mass movements relate to inflow of air from the Southern Hemisphere and while relevant to wiggle-matching in general, they are of less concern in the Scottish context.

Seasonal effects constitute a more plausible mechanism for regional offsets in the Northern Hemisphere. These were first detected in measurements of paired southern German and Anatolian dendro-dated tree rings. Although radiocarbon content was for the most part indistinguishable, discrepancies between the two series are present between 800 and 750 BC. This is interpreted as the result of increased mixing of the tropospheric and stratospheric air masses during the winter months, leading to offsets in the Anatolian timbers because of their earlier growth period (Kromer et al. 2001). More evidence comes from Egypt, where a similar effect has been identified in floating sequences from between 2200 and 1900 BC (Manning et al. 2014) and from the study of short-lived samples from historical archives, which demonstrated that differences in growth season can extend up to 2.5‰$\Delta^{14}$C (Dee et al. 2010, 690). Such seasonal offsets are further evidenced in modern atmospheric observations, albeit these may be affected by fossil fuels (Currie et al. 2011; Levin et al. 2010).

There may also be an increased sensitivity to production amplitude at high latitudes. Some tentative evidence for this comes from the MacKenzie River delta in Canada, where two series parallel to the single-year section of the IntCal data sets derived from west coast US timbers showed a greater year-to-year amplitude. This was interpreted as a latitude effect, which would be in line with expectations of greater sensitivity to production rates (Fan et al. 1983, 1986). However, the study was undertaken in the early 1980s and the apparent excess amplitude may be the result of precision overestimation which was frequent until the development of the Radiocarbon Intercomparison Programme towards the end of that decade (Scott et al. 1990). Hence, this possibility that Arctic air masses may be more variable in radiocarbon than those of tropical regions requires further exploration.

One final point to consider here, even though it does not relate to offsets as such, is that of short-term increases in radiocarbon production. These have been first identified for AD 775 in Japanese single-ring series (Miyake et al. 2012) and then confirmed by analyses of Siberian larch and Bristlecone pine (Jull et al. 2014). The origin of these events is still disputed with propositions ranging from supernovas (Miyake et al. 2012) to solar effect (Usokin et al. 2013). There is also one curious case on a single inexplicable departure towards a lower amount of radiocarbon in Thai pine for the years 1953 and 1954 (Hua et al. 2000). The presence of such events highlights the need to be aware of the scale of the potential for short-term variability of radiocarbon.

### 3.2.5 Section conclusion

The complexities of the carbon cycle and uncertainties regarding radiocarbon production mean that calibration has to rely on known-age samples. For the period of interest these consist of decadal and bi-decadal blocks of wood dated by four different laboratories: Belfast, Seattle, UC Irvine and Heidelberg. The actual curve used is a model based on these data sets. One of the emerging concerns regarding radiocarbon calibration is the potential for small-scale systematic offsets between the curve and past radiocarbon trends, although in the literature to date, the evidence for these events is minimal.

Regardless of data sets, offsets, or how they are constructed, all the radiocarbon calibration curves to date point to the existence of numerous turning points in past radiocarbon concentrations, which in a Cartesian coordinate system manifest themselves as wiggles. These wiggles undermine the applicability of classical statistical measures to calibrated dates (Michczynski 2007) and cause paradoxes in calibration (Dehling and van der Plicht 1993). Already, in 1979 Malcolm Clark suggested using a Bayesian approach to radiocarbon calibration, which removed many of the conceptual pitfalls encountered to date (Clark 1979, 58). This approach was implicitly implemented in the computer calibration programs of the 1980s (Stuiver and Reimer 1986), before a formal exposition in the 1990s (Buck et al. 1992). The key advantage of the Bayesian method is that it, by default, provides the description of the entire probability distribution of the radiocarbon date and it does not rely on classical statistical measures.

## 3.3 Bayesian analysis of radiocarbon dates

Bayesian inference is the process of inductive learning through Bayes rule (Figure 3.11). Within this framework, an unknown value, known as the parameter, is estimated through updating prior knowledge in light of new data (which is formalized as a likelihood function). The updated probability distribution of the parameter is known as the posterior distribution (Hoff 2009, 1-2). Bayes rule is named after the Reverend Thomas Bayes, whose posthumous paper on the subject is the earliest known document in which the rule is present (Bayes 1763). It is improbable that Bayes developed the rule; the only thing certain about its origin is that it happened in the English intellectual circles in years between the publication of de Moivres *Miscellanea Analytica* in 1730 and the publication of Hartleys *Observations on Man* in 1749, where the rule is first mentioned as already developed by someone else (Stiegler 1983, 290-1). In any case, Bayes original publication only included the theorem in its form for continuous probabilities, which is in little use today. The standard form of the rule was only developed by the 18th century French mathematician P.S. Laplace in *Philosophical Essay on Probabilities* (1902). Over the course of the 19th Century it became clear that the mathematics required to apply Bayes rule to the vast majority of real-life problems is too laborious to be practical and hence it was not until the advent of efficient and economic computing in the 1990s that Bayesian analysis became a viable alternative to classical methods (Fienberg 2006, 27).

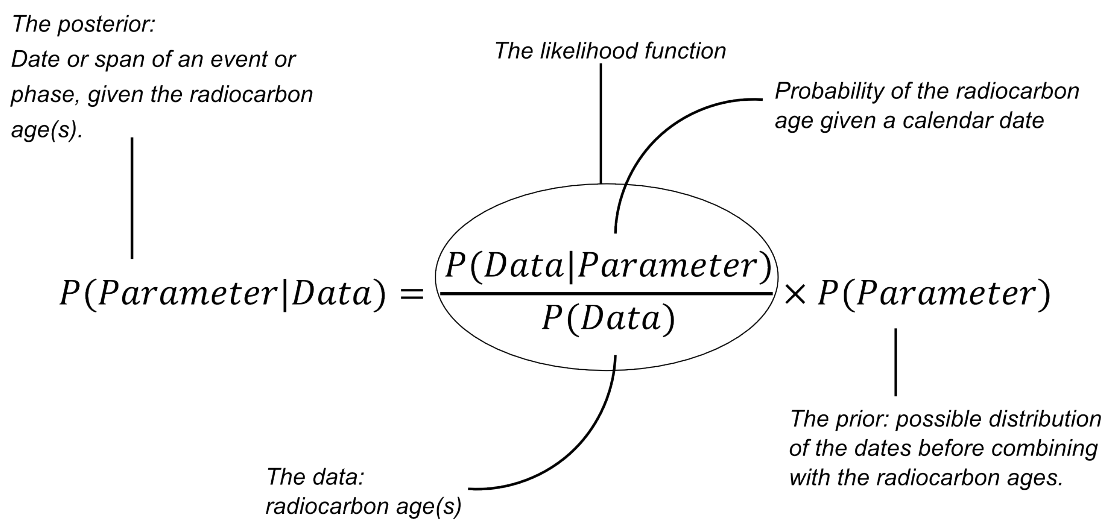



Figure 3.11: Bayes theorem. Based on Bayliss (2007) and Hoff (2009).

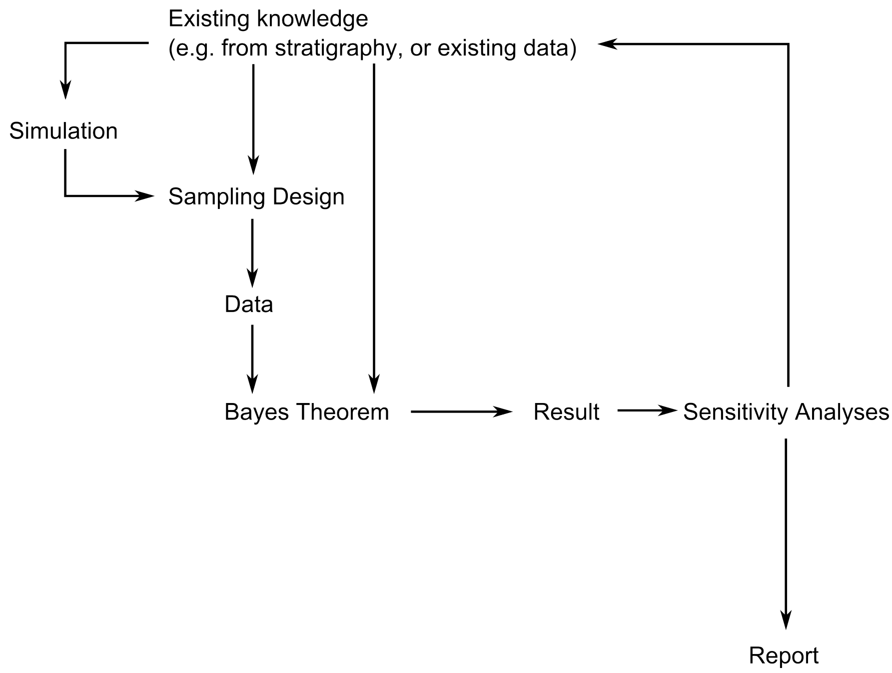



Figure 3.12: Bayes rule in the context of radiocarbon dating. 1: summarize, explicate and formalize the existing knowledge on the problem; 2: develop a sampling design for new data, perhaps with the aid of simulations; 3: apply Bayes theorem; 4: obtain results; 5: conduct sensitivity analyses to ensure the reliability of the results; 6: depending on the outcomes report the results or conduct a new set of analyses.

This section will discuss Bayesian analysis in the context of radiocarbon dating. It begins with the calibration of single determinations, moves onto the discussion of the basic single phase model and from there proceeds to more complex issues, such as sequences, queries and outlier analyses. After that the wiggle-match dating model is introduced. The two final sub-sections deal with Bayesian computation and with the economy of wiggle-match dating.

### 3.3.1 Bayesian calibration of a single date

The wiggles seen in the Suess curve were at first taken to be an artefact of measurement variability and calibrations were carried out by simple geometric means (eg. Ottaway and Ottaway 1972; Renfrew 1973). When, by the late 1970s, the radiocarbon community recognized that these wiggles are real and not just a statistical artefact, it became clear that calibration procedures needed to account for them. The simplest approach to the problem was to find the intercepts of the measurement and the calibration curve. Such an approach fails, however, when it comes to representing uncertainties, as trying to reflect them through the curve can cause paradoxes (Figure 3.13) (Dehling and van der Plicht 1993).

The Bayesian solution to this problem came in 1986 in the calibration program Calib (Stuiver and Reimer 1986). The procedure works because it inverts the question from what is the calibrated date range of this measurement? to what is the probability that a sample of this date would produce this measurement? such change in the direction

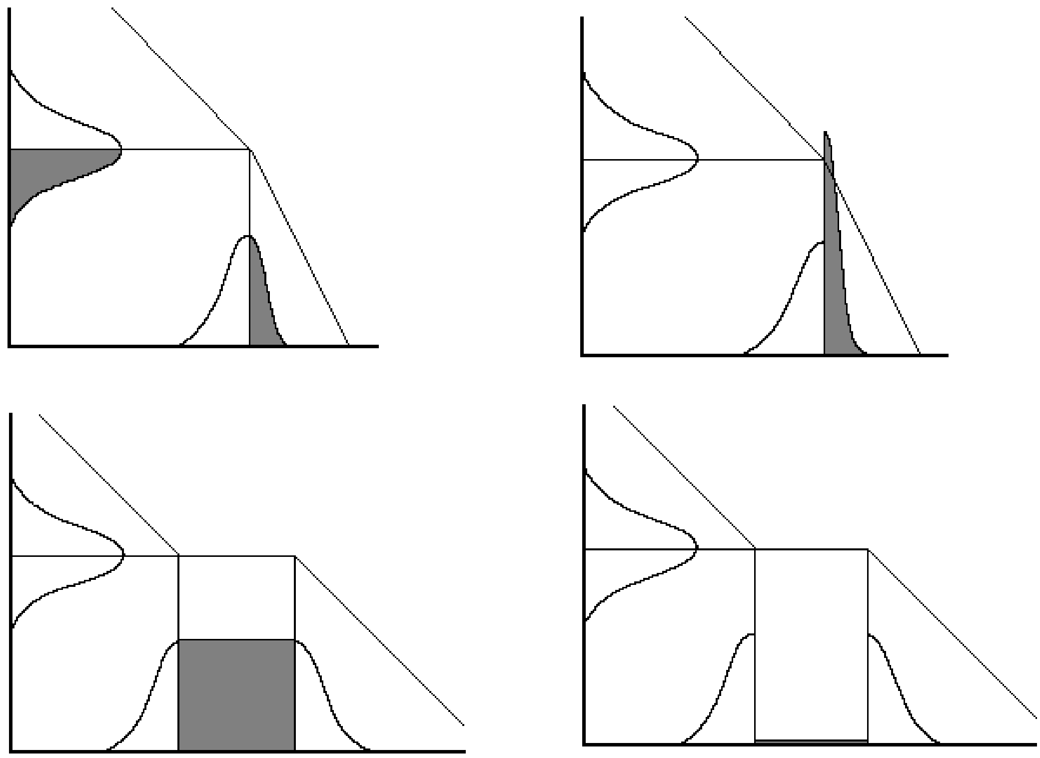


Figure 3.13: The paradoxes in radiocarbon calibration by direct geometric translation. Although the results on the left hand side are intuitively correct, geometric approaches would result in the unrealistic results of the right hand side. In the upper row the case of calibrating against a change in the angle of the curve is pointed out and it is shown that under a geometric approach the calibrated date would have to be discontinuous. Below, the same is shown for a calibration plateau, where, according to geometry alone, the middle portion of the calibrated date range ought to be excluded. Re-drawn from Dehling and van der Plicht 1993, Figure 2-3.

of thought is the reason why until the mid-20th Century Bayesian methodology was referred to as inverse probability (Fienberg 2006, 2). To be more specific, the algorithm begins with selecting a point on the calibrated axis. This axis is covered at that stage by a thin uniform probability distribution summing to unity. The algorithm then multiplies the value of this point by the corresponding products of the calibration curve and the measurement distribution and updates the calibrated date range to the value of this product. Hence, if the value of the measurement was approaching zero for a given point, the resulting value on the calibrated axis will also approach zero. If on the other hand the value on the measurement scale was high, so will be the value on the calibrated axis. Once all the points have been visited and the whole scaled to unity, the calibration is complete (Figure 3.14). In terms of Bayes theorem, the initial list of points on the calibrated time scale is the prior distribution, the measurement is the likelihood and the calibrated date range is the posterior distribution.

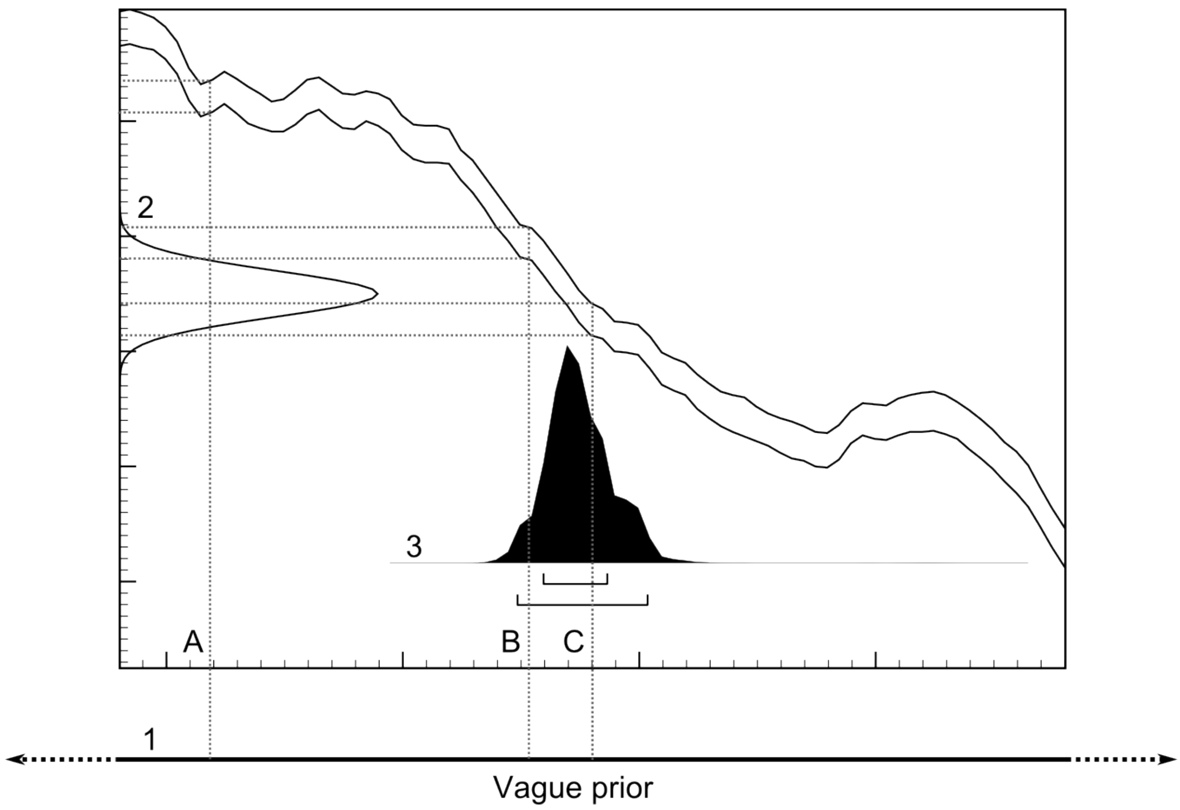



Figure 3.14: Bayesian calibration of a single radiocarbon date. 1) Begin on the low value of the vague prior distribution that covers the length of the calibration curve, 2) update your value by multiplying it through the likelihood function (here the curve and the age determination), 3) the updated posterior distribution is the calibrated date range. Hence, at point A, the posterior is negligible, as the value of the measurement was negligible, in point B it is small because the value of the measurement was small and in point C it is large because the value of the measurement was large.

This procedure affects the interpretation of the calibrated dates. First of all, standard deviations will not always describe the calibrated date well, and instead highest posterior density (HPD) areas are used (Figure 3.15). These areas are the regions under the posterior distribution which contain the greatest amount of probability within the smallest length of the abscissa (most often represented as the horizontal x-axis) (Hoff

2009, 42-3). HPD areas are often referred to in the radiocarbon literature as calibrated date ranges and throughout this thesis both terms will be used. The span and distribution of the HPD areas depends on the calibration curve. This dependency can be abstracted to three different situations (Weninger 1986):

1. The curve shape does not affect the shape of the calibrated date distribution.
2. A wiggle in the curve introduces bimodality in the calibrated date range. In terms of underlying processes this means that the amount of radiocarbon from samples of the two model ages is expected to be the same.
3. The amount of radiocarbon is expected to be similar for samples coming from an extended period, leading to the development of a plateau in the calibration curve stretches out the date range, leading to lower precision (Figure 3.16).

One such calibration plateau is the Halstatt calibration plateau which spans the period 750–400 cal BC and has substantial adverse effects on our ability to interpret archaeological sites from the earliest centuries of the Scottish Iron Age. For example, if two crannogs from that period are located next to one another in a loch, single radiocarbon dates will not be sufficient to determine whether they were built at the same time, within a few generations, or whether they were built several hundred years apart (Figure 3.17). It is the presence of this plateau and the large wiggle that follows that makes the radiocarbon-focussed part of the current project so important.

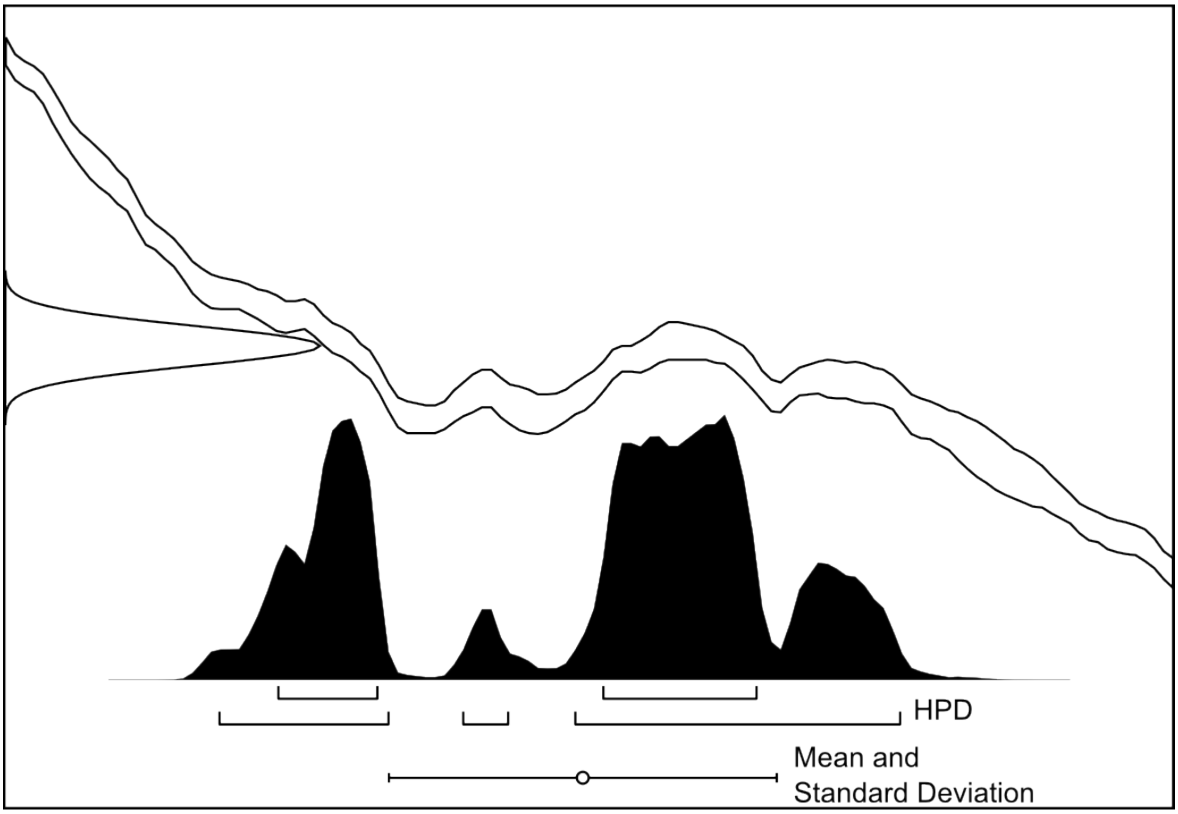



Figure 3.15: Highest posterior density areas. The shape of the calibration curve means that the calibrated date ranges are often asymmetric or multi-modal. Because of this the description of the results in terms of a mean and a standard deviation can be meaningless and hence highest posterior density areas are used instead.

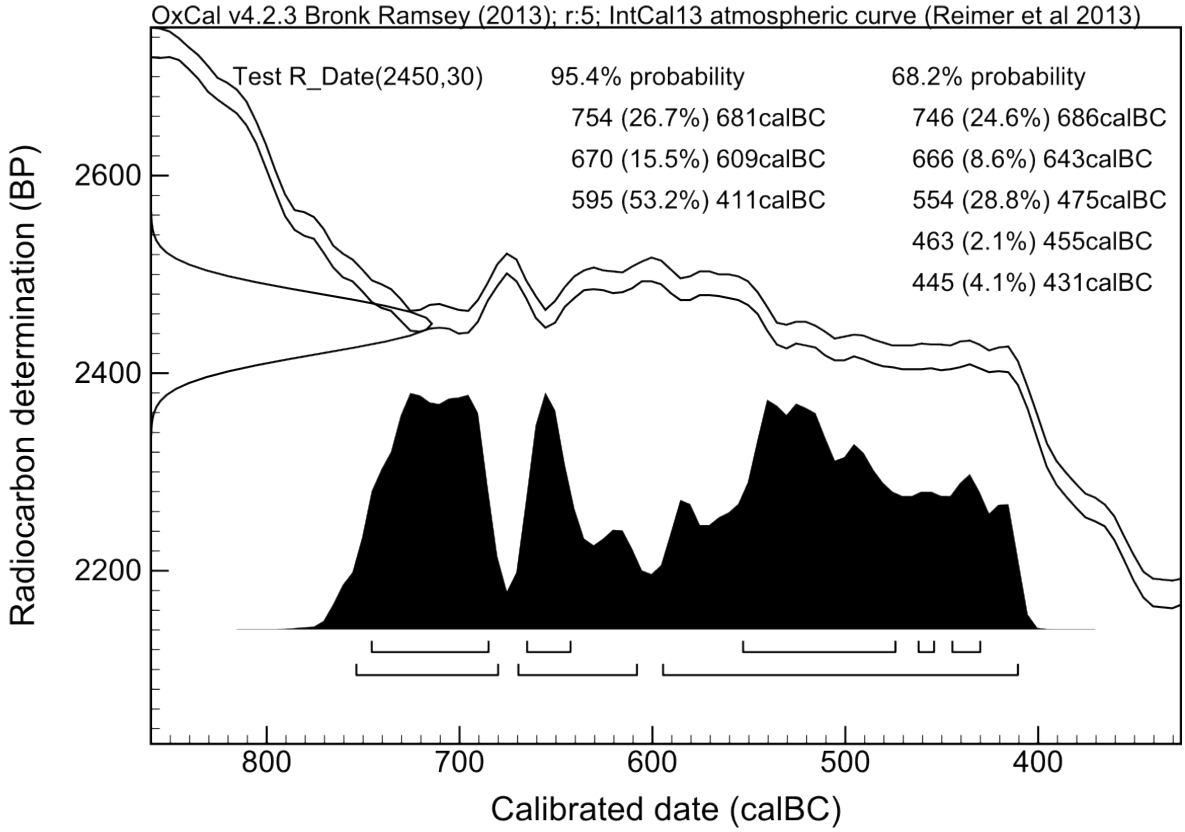
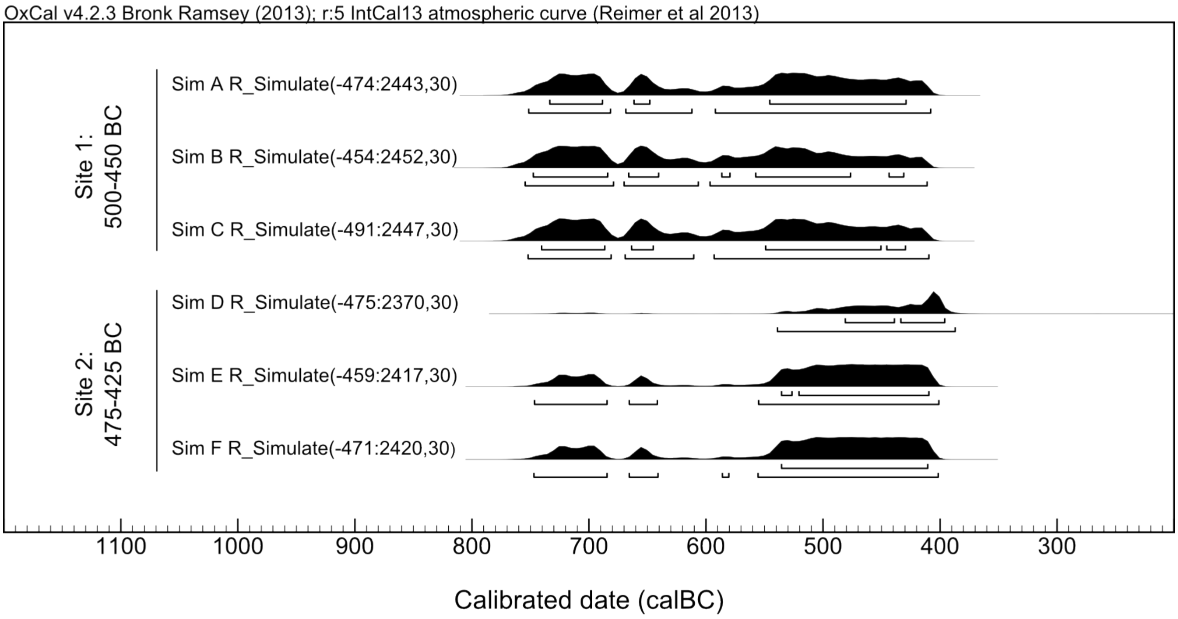



Figure 3.16: A calibrated radiocarbon date from the Hallstatt plateau. Even though the two standard deviations of the age measurement cover only 120 years, the 95.4% HPD region of the calibrated date spans more than 300 years.



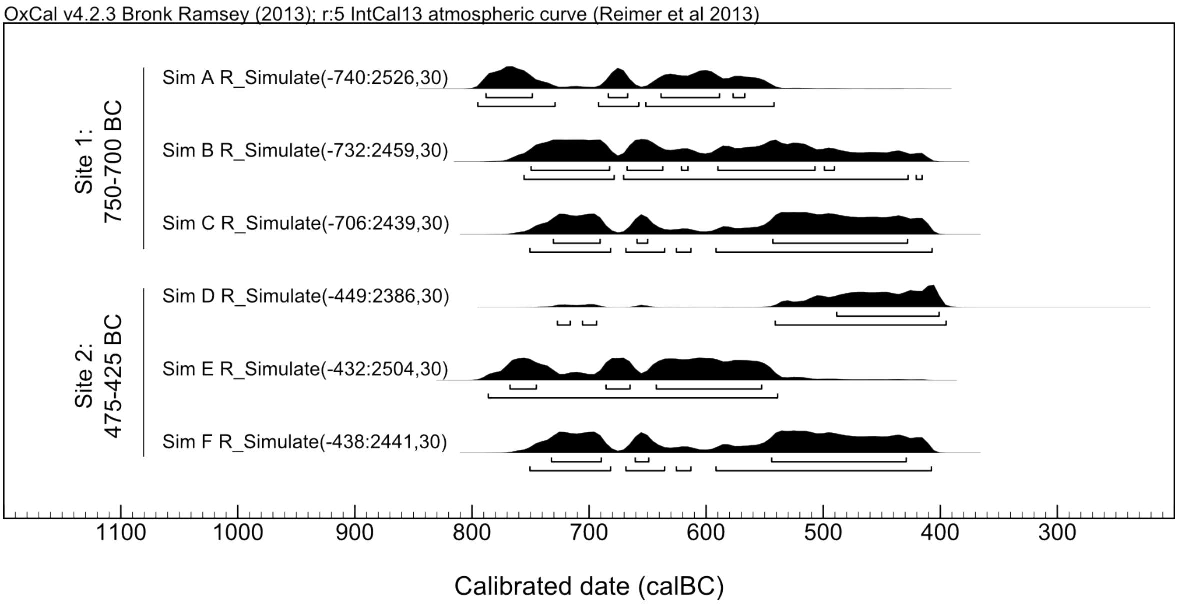




Figure 3.17: Effects of the calibration curve on archaeological interpretation. In the scenario above two groups of simulated dates come from overlapping 50-year spans, whereas in the scenario below they come from 50-year spans set 275 years apart. Nevertheless, the shape of the calibration curve during the Hallstatt plateau means that they cannot be distinguished.

### 3.3.2 Modelling a single phase

It is very rare for radiocarbon determinations to be in a direct relationship with the archaeological questions; it only happens in cases such as the dating of the Turin shroud when the date of the material itself is relevant (Damon et al. 1989). Most situations are more complex. For example, when dating material from an enclosure, the archaeologist will be more interested in when the enclosure was in use, rather than in the dates of death of each individual sample. Hence, besides the need for calibration of radiocarbon age determinations, there is also a need for relating the calibrated date ranges to events of interest.

The basic form of a relationship between archaeological samples and archaeological events is a situation where deposition begns and ends, with no stratigraphic differentiation between the samples. Such a situation can be redefined as a Bayesian unordered uniform phase model (Bronk Ramsey 2009a; Buck et al. 1992, 343-45). In this model there are two parameters of interest (Figure 3.18):

1. The onset of activity.

2. The end of activity.

These are estimated in a similar fashion to the estimation of calibrated date ranges, however there is an added constraint on the prior distribution (onset has to precede the end) and on the likelihood function used (here it is based on the calibrated date ranges). There is also the underlying prior stating that the original deposition of the dated material followed a uniform distribution. All this information allows for the inference of the onset and the end: first, the onset has to be before all the dates and second, the end will follow the dates. At the same time the earliest estimate for the onset of the deposition cannot be much earlier than the dates, as otherwise some material would have been sampled. Likewise, the end cannot be much later. The model algorithm quantifies these assertions and uses them to update the values of the onset and the end from a prior distribution spread across the calibrated timescale axis.

One potential weakness of the single phase model is that it requires an archaeological understanding of the deposition process behind the dates (Bronk Ramsey 1995, 426); in essence the model will treat a group of dates as if it derived from a uniform deposition process. Hence, if a midden was formed only in the final decade of use at a 100 year old site, the Bayesian model for that midden will not be useful for describing the site as a whole. There is also an issue of the intensity of deposition over time. For the most part, the uniform phase model is robust enough to accommodate for a range of deposition rates (Bayliss 2009, 132), but in some cases the deposition rate may be so unusual that the uniform model may no longer apply; for example on a site where successive deposits truncate the earlier material it might happen that the underlying distribution will be closer to exponential due to the loss of older material. In such cases a prior distribution weighted towards the end of the phase may produce more reliable results.

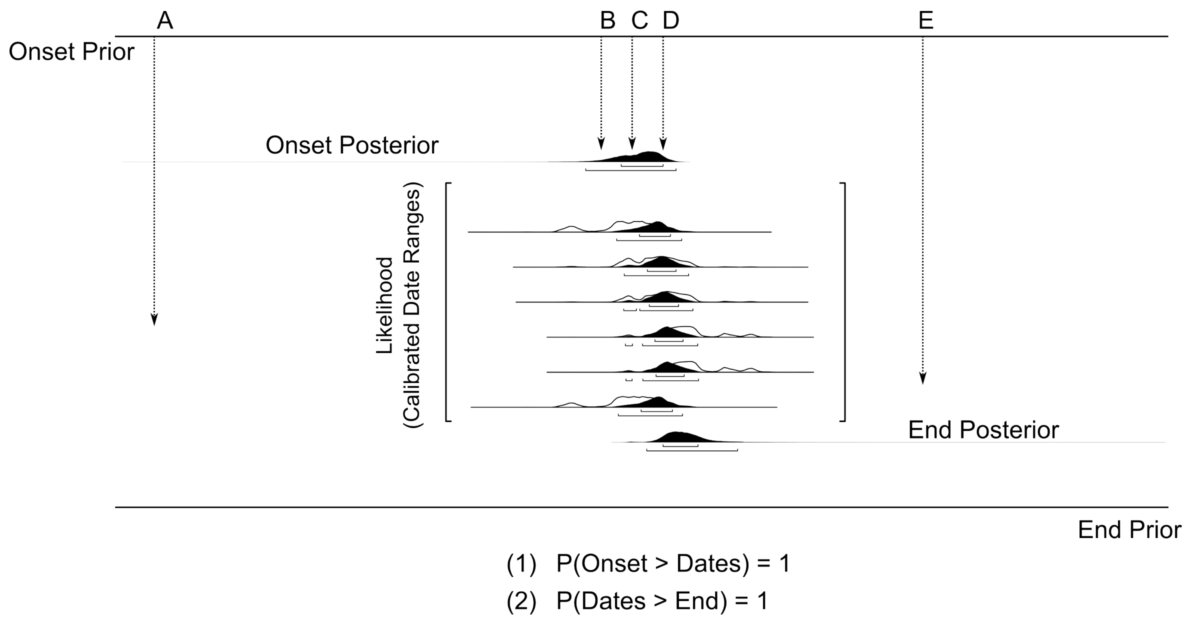



Figure 3.18: Bayesian single phase model. The onset is updated much like the calibrated date range, but this time it is defined by the distribution of the individual calibrated radiocarbon dates. Hence at point A the posterior probability is negligible because the calibrated dates are too far away; at points B-D the posterior probability first increases as the cluster of dates is approached and then decreases as it moves beyond the dates, in light of relation 1 stating that all the dates had to happen after the onset. At point E the onset posterior probability of the onset is negligible again due to the position of the dates. The end posterior is estimated in the same way. For the model to work, an assumption has to be made on the distribution of dates within the phase. As the boundaries are defined, the calibrated date ranges of the individual dates are updated, with the new posteriors in solid black.

### 3.3.3 Extending the model

Bayesian mmethods can be extended to a broader range of situations that include some form of further archaeological information, represented by appropriate prior distributions. They can also be used to deal with a number of related issues, such as the presence of outliers in the data.

Of all the different Bayesian models used, perhaps the ordered sequence is the most popular. It differs from the uniform phase model in that it includes relative relationships between the samples or groups of samples (Buck et al. 1992, 502-4; Bronk Ramsey 1995, 426). For example, we can state that the onset will precede sample 1, sample 1 will precede sample 2 and only after sample 2 the end will take place (Figure 3.19). Adding such information leads to an improvement in the precision of the modelled dates and their related parameters, such as an end or an onset. The ordered sequence can also include unordered phases instead of single dates. For example, if two successive hearth deposits are identified, it is possible to assign charcoal samples from the lower hearth to one phase and the samples from the other hearth to the later phase. Furthermore, it also becomes possible to estimate the interval between the depositions, dates for events based on their terminae ante and post quos, or the time-span over which the process took place. The obvious risk associated with this kind of prior is that, unless the ordering of the sequence is justified, the resulting increase in precision will come at the cost of inaccuracy (Steier and Rom 2000, 197).

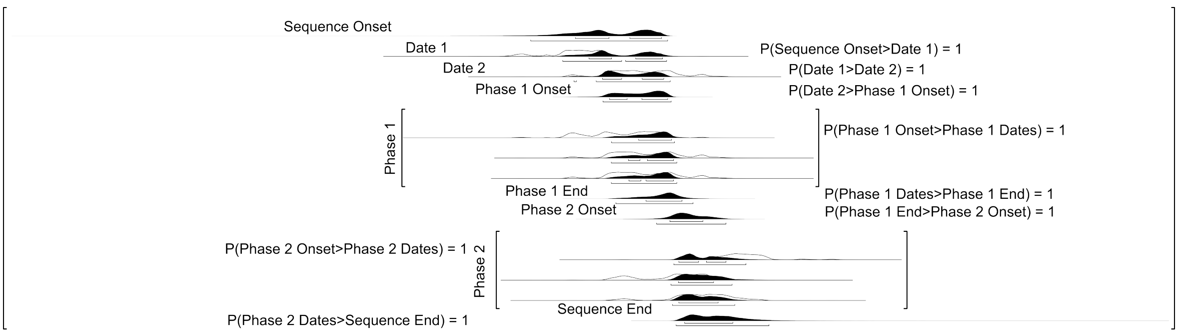



Figure 3.19: A sequence model. Posterior distributions of particular events are estimated in much the same way as in the case of the uniform phase model, but the amount of prior information on relationships between them is greater.

Another useful application of Bayesian methodology in radiocarbon dating is outlier analysis. While the error on a radiocarbon determination covers the uncertainties relating to the measurement process, in some cases there will also be other sources of uncertainty. These include matters such as the presence of old wood, intrusive samples within the site stratigraphy, or systematic offsets from the calibration curve. All such scenarios can be modelled to down-weight the effects of these kinds of outliers on the final model (Bronk Ramsey 2009b).

Note that the priors used in the Bayesian modelling of radiocarbon dates are often very strong, or even absolute, meaning that no number of data can overcome them; if a certain event has a zero prior probability, this cannot change as any likelihood function value multiplied by zero will give zero in the posterior distribution. This means that de Finetti's theorem, which states that sufficient inependent identically distributed data will overcome any prior (Hoff 2009), does not apply. Furthermore, in a number of other cases, where the priors are not absolute, the number of data available when modelling radiocarbon dates, is often low, leading to a situation where the nature of the prior will have a significant effect on the shape of the posterior distributions. What this means in practice is that perhaps the largest proportion of work that goes into Bayesian modelling of radiocarbon dates is not the writing of the model itself, but conducting sensitivity analyses and studying the nature of the archaeological deposits, so as to ensure that the prior chosen is appropriate from both the standpoint of the nature of the deposits and also to ensure that it does not induce analytical artefacts.

### 3.3.4 A wiggle-match date model

The radiocarbon wiggle-match dating model that forms the backbone of the work conducted during the course of this project was executed within a Bayesian framework. The technique itself pre-dates the use of Bayesian methods in radiocarbon and is as old as the notion of calibration itself (Fergusson et al. 1966). Its basic premise is simple: if a series of measurements are taken through a deposition sequence and if we have some estimate of the rate at which the sequence was deposited, we can use this information to limit the uncertainties on the measurements. Most timbers are ideal for wiggle-match dating because they only deposit one growth ring per year. This means that we can collect radiocarbon determinations through the length of a timber and match them to the ratified calibration curve (Figure 3.1). The traditional way of doing this was using the least squares method, in which the match was established at the point where the sum of the squared distances between the calibration curve and the set of unknowns was at its smallest. This approach, however, suffered from an inadequate treatment of uncertainties (Bronk Ramsey et al. 2001, 387-8). Hence, a Bayesian approach is used instead (Christen 1994, 147-53). Within the Bayesian framework, a wiggle-match can be thought of as a sequence with a very strong prior where the felling year constitutes the only parameter of interest. The calculation can be seen as analogous to the procedure for single calibrations, but each point on the calibrated scale needs to fulfil the conditions of a probability distribution dependent on all the measurements and their order and distances in the sequence (Bronk Ramsey 2013).

The wiggle-match dating technique, as applied to timbers, has been used in a wide variety of contexts. Manning et al. (2001) used it to fix the floating Anatolian tree-ring sequences. English Heritage use the wiggle-match technique to date historic buildings (Bayliss 2007; Hamilton et al. 2007). It has also been used for dating a wide range of prehistoric sites where wood survives in sufficient quantities. The Scythian tombs in the Sayan Altai region of Russian (Zaitseva et al. 1998), Iron Age cemeteries of northern Itlay (Quarta et al. 2010), or Latvian lake fortresses (Meadows and Zunde 2014) are just a few examples. Nevertheless, its application to Scottish wetland archaeology so far has been limited to only one experimental match on a foundation timber from Oakbank crannog (Cook et al. 2010). While this wiggle-match has been successful, the exceptional measurement precision meant that the cost was too high for use in routine applications.

### 3.3.5 Bayesian computation

The key challenge of implementing any realistic Bayesian analysis is the computation. A small range of problems has an analytical solution through use of conjugate priors. In these kinds of analyses the parameters feature as variables in well-defined functions (Hoff 2009, Ch.3). In a number of other cases grid approximation and numerical solutions are a possibility. For example, the single parameter problems of calibrating radiocarbon dates, or even basic Bayesian wiggle-matches can be executed in this way (Bronk Ramsey et al. 2010). Most realistic applications, however, are beyond the scope of these low computation methods. This is because for each added parameter a new dimension is added to the problem. Hence, numerical computation of a single radiocarbon calibration on a prior with 1000 possible values requires 1000 calculations. The same computation for this date in a phase requires $1000^3$ computations: for the prior and for each of the boundaries; with each added parameter the number of computations increases by several orders of magnitude and approximating the entire grid of possible solutions becomes unviable (Kruschke 2015a, 235). For this reason Bayesian methods were of little use in applied research until the introduction of the Monte Carlo Markov chain techniques (MCMC) in the 1980s. A clear exposition of the MCMC is provided by Kruschke (2015a, Ch. 7) and the summary below follows his exposition, unless referenced otherwise.

Imagine that we want to describe a discrete probability distribution (Figure 3.20), but for whatever reason we are unable to conduct an exact survey of the values. One way of doing this is to begin at any value of the distribution and flip a coin; if heads, consider a move to the left and if tails, consider a move to the right. This is the proposal distribution. Next, consider the relative probability value of the location of the proposed move to the current location. If it is higher, move there. If it is lower move there with the relative probability of the proposed to current locations: the probability of the move happening is equal to the probability of the proposed parameter value divided by the probability of the current parameter value. Finally, add a counter for whatever location we are at the end of the process. Over a large enough number of iterations, the distribution of counters will be proportional to the target distribution with certainty. Hence the MCMC algorithm is a means of drawing samples representative of the target distribution, without having to calculate approximations of entire grids. Note that any probability distribution can be used as a proposal distribution it does not have to be Bernoulli distribution (the coin flip). Indeed, most real applications use more complex distributions. The MCMC algorithm used throughout this thesis is the Metropolis-Hastings algorithm (Hastings 1970; Metropolis et al. 1953), which differs from the simple example of Figure Figure 3.20 in that it can update any number of parameters in one step and can use any number of proposal distributions.

All MCMC methods are based on samples from the target distribution. Although they will always describe the target distribution given a sufficient number of repetitions, in practice the computation times required mean that analyses stop short of the point of certainty. This in turn means that the MCMC sample may suffer from unrepresentativeness and inaccuracy. The first thing to consider is whether the sample is representative of the posterior distribution; there always exists a probability that the sampler will become trapped in some specific part of the posterior distribution and the outcome will be unrepresentative. The usual approach to preventing this is to run multiple chains and see how well they resemble one another if they are indistinguishable, it is stated that they are well mixed and hence ought to be representative. Note also that each chain will have begun from a different initial value and for a number of iterations will not be mixed with the other chains (Figure 3.21). This period is called the burn in and is discarded from the analyses. The other important question regards the size of the MCMC sample. In general, if the proposal distributions are too narrow or too wide relative to the problem, the chain values might be too dependent on their indirect predecessors and hence provide a poor picture of the variability of the target distribution. For this reason, the number of iterations is not the same as an effective sample size (ESS). A good algorithm will ensure that the dependency is minimal and that the ESS is large compared to the number of iterations. If the ESS is too small, the results of the analyses may be biased.

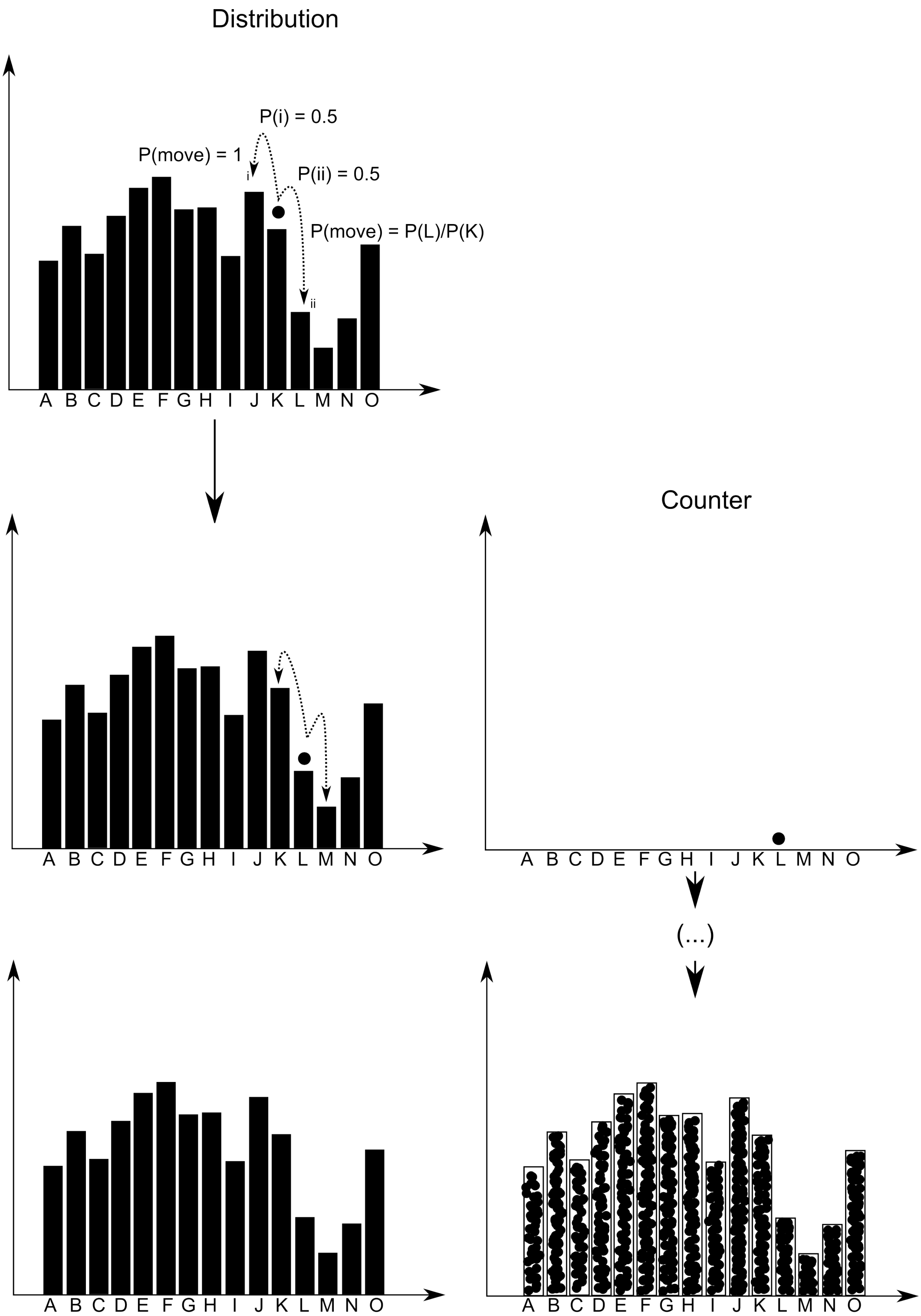



Figure 3.20: Basic Metropolis Monte Carlo Markov chain algorithm. Begin at any arbitrary point of the target distribution here it is K. Select a next candidate location according to a proposal distribution here it is one step left or right with equal 50% probability. If the probability of the candidate location is higher than that of the current location, move. Otherwise, move with a probability equal to that of the candidate location divided by the current location. After the move place a counter in the location of the move and begin anew. After sufficient repetitions the distribution of counters will approximate the target distribution with certainty.

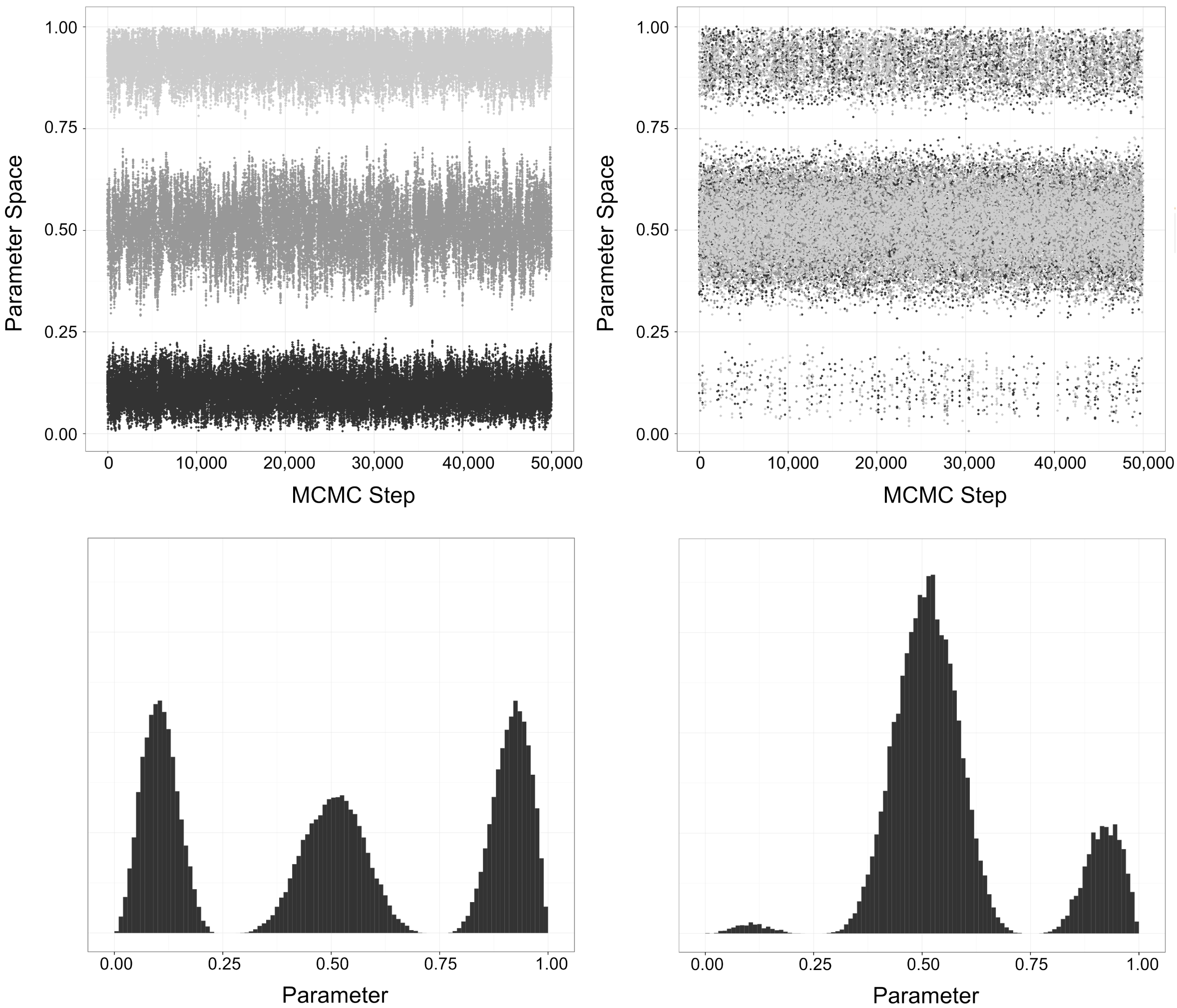



Figure 3.21: MCMC diagnostics. The two MCMC simulations approximate to the same distribution, however, the chains of the left simulations cluster together. In practice they would produce a poor description of the parameter with over-represented low values. Compare to the much better mixed chains on the right.

### 3.3.6 Optimizing wiggle-match dating

One of the key limitations of wiggle-match dating is its expense. Producing each result requires making multiple $^{14}C$ determinations, each one of which will often involve labour-intensive pre-treatment, lab consumables and measurement costs. Furthermore, a single wiggle-match date, regardless of its precision, is still not enough to determine the construction date of a structural element, as the timber in question may have been re-used (see Chapter 6).

To date only one paper asked explicit questions about wiggle-match economy; Galimberti et al. (2004) sought to develop a methodology for estimating the information gain from adding further measurements to a wiggle-match date. This took the form of an efficiency quotient defined as:

$$Eff.Q = \frac{p^2}{rn}$$

Where $p$ stands for precision of the measurements, $r$ is the calibrated date range and $n$ is the number of measurements taken. This definition is based on the use of measurement precision as a measure of effort and the calibrated date range as a measure of quality. In principle, the lower the measurement precision or the smaller the calibrated date range, the better the efficiency quotient. Adding further measurements means that the wiggle-match becomes less efficient.

Galimberti et al. (2004, 917-8) evaluated their approach in multiple simulations, which recognized that there is a point beyond which the increase in efficiency begins deteriorating, leading to a situation where further measurements would no longer make economic sense. Furthermore, their findings confirmed the earlier observations of Goslar and Madry that extending the length of the sequence dated is, in most cases, more beneficial to the precision of wiggle-match dates than increasing the count of measurements (Galimberti et al. 2004, 917; Goslar and Madry 1998, 551). The key weakness of Galimberti et al's approach is that, as discussed in Chapter 5 herein, various small scale offsets within the calibration curve may also affect wiggle-match performance. The other, deeper weakness is that although optimal calibrated date ranges may exist, in reality the value of the range is assessed against the underpinning archaeological question. If this requires a calibrated date range broader than the optimum, providing further measurements is wasteful of limited resources. Likewise, if the required date range is smaller than the optimal date range, uneconomic sampling is necessary. Despite these weaknesses the paper managed to demonstrate the value of simulation studies in wiggle-match research design.

Simulation is also encountered in the broader field of radiocarbon dating design. The core notion behind it is to provide plausible calendar dates of sample death and then run them through a calibration curve with a simulated measurement error to establish a plausible radiocarbon measurement outcome for the given date (Bronk Ramsey 2013). The majority of simulation studies are focussed on research design issues, such as how many determinations are required to date a particular feature (Bayliss 2009, 132).

Simulation is also beneficial in sensitivity analysis; it was thus that Steier and Rom (2000) determined that for samples in a sequence whose date ranges after calibration overlapped, bias can emerge in posterior distributions. Likewise, Griffiths (2014) was able to determine problems associated with using cultural definitions for transition events. The majority of simulations undertaken in the course of this project were of this latter type and their objective was to estimate the effects of minor offsets in the calibration curve on the precision of wiggle-match dates. One of the problems encountered early on was the issue of building sufficient numbers of simulations to attain statistical validity, as well as a lack of determined means of analysing them. One way around this problem is suggested in an automated approach put forward in a set of twin papers by Christen and Buck (Buck and Christen 1998; Christen and Buck 1998).Their approach was to build a program that, provided with the site stratigraphy and some form of chronological constrain, would automate a large number of simulations and provide a summary of their results. The amount of simulation work conducted in the course of the current project did not justify the time that would be needed to rebuild the Christen and Buck simulator.

Yet even without intensive simulations, it is possible to make some basic intuitions about the optimal sampling strategies for wiggle-match dating from geometric principles alone. The wiggle-match dating technique extracts its information from the overall trend of radiocarbon over the duration of the sequence dated and from the shape of individual wiggles (Figure 3.22). The observations by Galimberti et al. (2004) and Goslar and Madry (1998) that wiggle-matches with longer spans produce more precise results stems from longer spans retaining more information about the overall trend of radiocarbon over the period of interest.

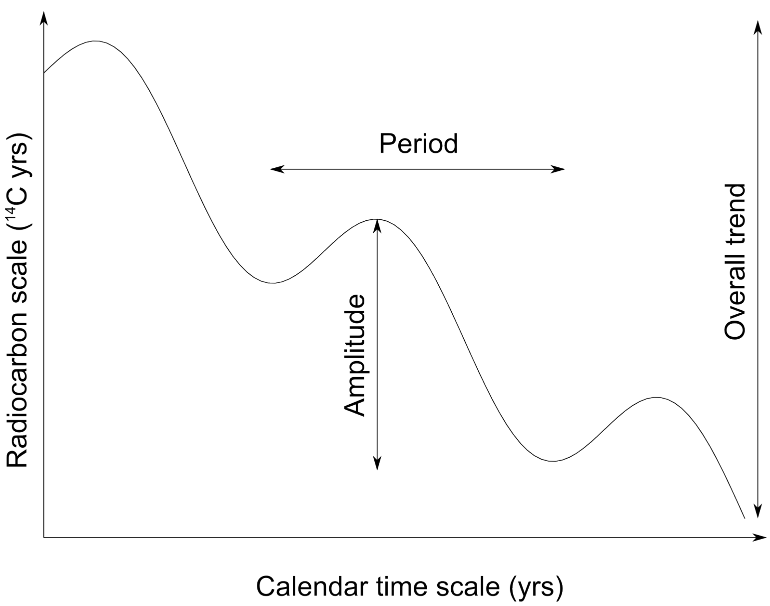



Figure 3.22: Schematic illustration of sources of chronological information in a wiggle-match dating model. Overall trend describes the drift in ages over the entire span of the match, amplitude describes the vertical magnitude of individual wiggles and periodicity describes the duration of the wiggles. Periodicity and amplitude combined describe the shape of the wiggles.

The specific technical challenge to wiggle-match dating in the context of Scottish Iron Age wetland archaeology comes from the fact that the majority of timbers used lived for less than 100 years (see section 3.1, above) and so optimizing a research design through the extension of the length of the sequences dated is not viable. However, it should in principle be possible to mitigate this by improving the description of the short-term changes through more intensive, high-precision measurements (Figure 3.23). As the majority of the short-term variability in past radiocarbon trends can be expected to derive from the Schwabe cycle (section 3.2.2) and as the record of this cycle becomes lost as the number of rings in a wood sample is increased (section 3.2.4), it stands to reason that that single-ring sampling is most advantageous for dating medium and short sequences of tree rings. Tyers et al. (2009) demonstrated that such single-ring sampling is viable for wiggle-match dating in the early modern period, but at that point in time the calibration curve is based upon single-year data. The key question for wiggle-match dating of Scottish Iron Age wetland sites hence becomes one of whether single-ring dating is applicable and, if not, what is the optimal strategy otherwise.

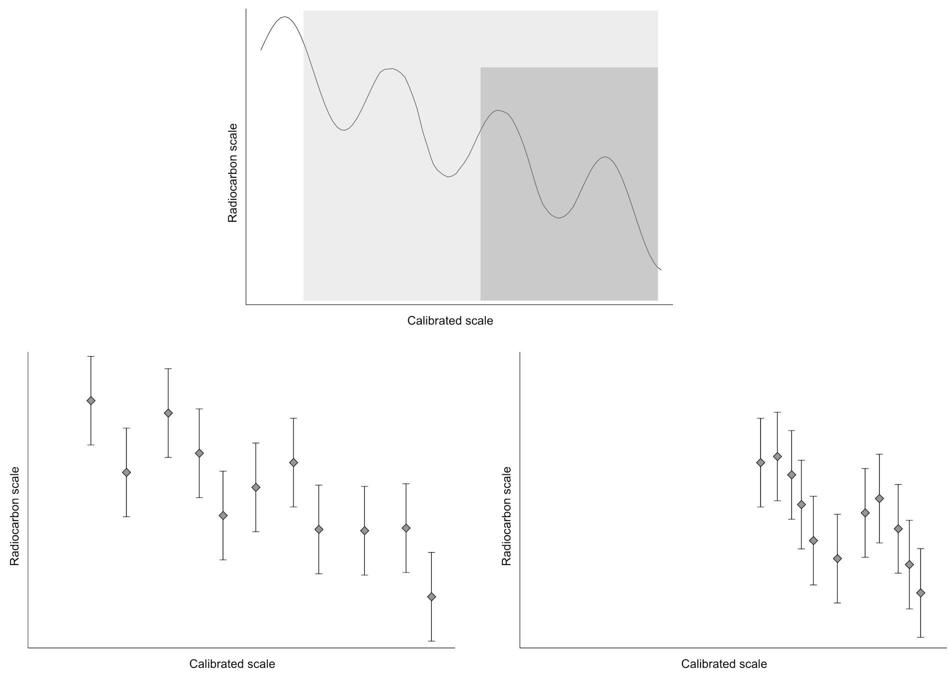



Figure 3.23: Schematic illustration of sources of information in wiggle-match dating sequences of different lengths. While decreasing the span means losing the information from the overall decay trend, this can be mitigated if the individual solar cycles are defined with sufficient precision.

## 3.4 Chapter conclusions

This chapter reviewed the technical underpinnings for attaining the dating precision required for the emergence of linkage. The first section outlined why radiocarbon-based dating is preferred for dating Scottish Iron Age wetland settlement. Next, the basic theory of radiocarbon dating, the need for calibration and the construction of calibration curves were explained. Special attention was given to the issue of offsets from the calibration curves. The third section focussed on the application of Bayesian methods to radiocarbon calibration and modelling of radiocarbon dates. It summarized the reasons for the poor performance of single radiocarbon determinations during the middle of the first millennium BC, when the majority of Scottish wetland sites were built and it also outlined the wiggle-match dating technique, which can serve to overcome these limitations. Nevertheless, the costs of the wide-spread application of wiggle-match dating can become very large very fast and hence it is essential to economize them before this happens. It is the economy of wiggle-match dating that sets up the technical aims of the current thesis: how to sample the timbers from Scottish wetland sites in such a way, as to obtain satisfactory results at a minimal cost.

# 4 Analytical and statistical methods

This chapter summarizes the methodology behind the radiocarbon determinations that underpin the wiggle-matches and single radiocarbon dates discussed throughout the remainder of the thesis, as well as the statistical programs and procedures used in their analysis. The first section of this chapter is concerned with the production of the radiocarbon age measurements, which can be divided into ring sampling, sample pre-treatment, target preparation and isotope measurements. Aspects of the modelling program OxCal are also discussed.

## 4.1 Analytic methods

### 4.1.1 Ring sampling

Ring sampling covers the process from the collection of the timber in the field to cutting specific rings or ring-blocks from the timbers and storing them for analysis.

Field sampling was conducted using hand saws. Once cut, the timbers were stored in polythene bags. To limit decay they were transferred to chilled and/or waterlogged storage within at most a few weeks of retrieval.

The large timber sections were too unwieldy for single-ring and ring-section sampling, so they had to be cut into transverse slices (Figure 4.1). The known age timber T-947 from Cults Loch 3 and the ash from Black Loch of Myrton were cut using a table saw; all other samples were cut using a hand saw. The transverse slices were refrigerated in polythene bags, which in some cases were filled with distilled water to further retard the decay processes. In the case of oak, this secondary waterlogging also ensured that the material was soft and therefore easier to work with. Rings and ring blocks were sampled under a stereoscopic optical microscope using fluorescent and LED lights. Enlargement by a factor of ten was an optimal balance for recognition of fine elements of wood micromorphology, such as the flame patterns in late wood oak, while retaining a field of vision broad enough to trace individual tree rings. A strong LED ring source was preferable when dealing with oak, but the faint nature of alder tree-rings at times required a blend of light sources that could amplify the shadows created by the microstructure of the wood. In the case of the faintest of the alder ring patterns it was also helpful to switch off any lamps other than the ones involved in microscopy, as that ensured greater control over lighting.

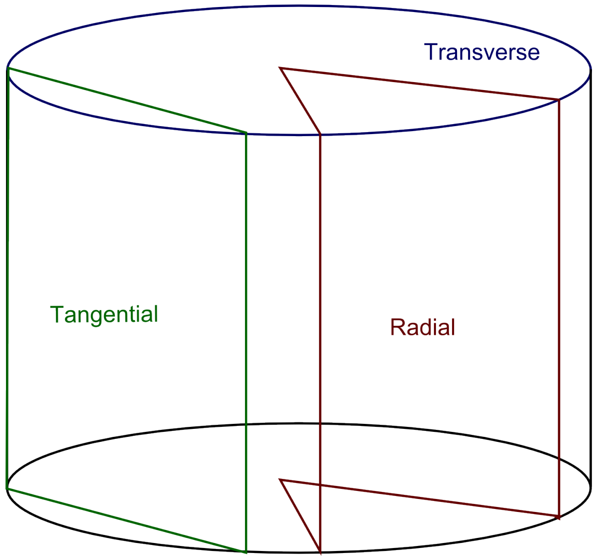



Figure 4.1: Anatomical planes of woody stems.

Wiggle-match dating requires a reliable ring-count of a timber, which in turn requires a clear view of the ring pattern. This can be achieved by using a razor or a scalpel blade to remove the layer of wood on the working surface of the slice. Prior to January 2014 this procedure was applied to the surface of the slice from which the rings were cut. Following January 2014 both sides of the transverse slice were prepared that way, as it ensured that any material exposed to post-fieldwork contamination was removed.

A record of ring-widths was kept throughout the project, with the exception of timbers with a ring pattern too decayed to obtain suitable measurements. Measurements were collected twice, along two different paths in the sector of the slice, using the cross-hairs of the microscope. Double measurement not only validated the reliability of the collected data, but also verified the ring-count.

The samples were cut using scalpels or razor blades, depending on which was easier to use under the circumstances. As a general rule, razor blades performed better for single rings and scalpels for multi-ring blocks. All the scalpel blades were sterile upon delivery and would be replaced between individual transverse slices, if not more often. Razor blades used were commercial stock, obtained from a pharmacy. Whenever spots of packaging glue were identified on the surface of the blades, they would be removed with acetone. Since the razor blades were prone to blunting, they would never be used for more than three tree-rings or a third of a cutting surface preparation. All cutting was done on a steel plate.

Individual samples were assigned unique DSC numbers, standing for *Dating Scottish Crannogs*, an early title of this PhD project. These numbers were assigned as some of the samples were cut as spares in case a more intensive dating pattern was needed and so it was not certain at that point if a given sample would ever be radiocarbon dated. After cutting, the samples were placed in 20ml glass vials, dried in an oven or a fume cupboard and stored. Following January 2014, all the vials used were furnaced overnight at 500°C to reduce the risk of contamination during storage.

### 4.1.2 Sample pre-treatment and graphitization

Radiocarbon determinations are only meaningful if the source of the carbon being measured is known. Hence, it is necessary to pre-treat samples so as to remove any unwanted carbon sources. A tree-ring sample from an archaeological site will contain carbon from its original formation, subsequent metabolic activity, and substances which penetrate it between felling and sampling. Hence, the objective of pre-treating wood is to ensure removal of anything but material from the original formation, which in practice means removing all the material apart from cellulose. In the case of the few non tree-ring samples measured in the course of the project, the focus shifts to only removing the contaminants.

Materials that can penetrate samples after deposition include carbonates, organic acids from the decomposition of plant matter (known as humic and fulvic acids) and remnants of other biological activity such as plant roots. The roots can be removed by hand, while the carbonates and humic and fulvic acids can be removed using the acid-alkali-acid method (AAA), in which a first acid wash reacts with the carbonates and extracts the fulvic acid fraction, an alkali wash dissolves the humic acid and the final acid wash neutralizes the alkali to prevent absorption of atmospheric $CO_2$ (Stenhouse and Baxter 1983). Each one of these steps is undertaken on a hotplate for a period of two hours. For wood samples, this step takes place late in the pre-treatment protocol and has a dual function relating to cellulose extraction.

The substances originating in the living tree which may require removal prior to radiocarbon measurement are lignins and resins. Resins are formed each year and penetrate through the timber, thus introducing a potential shift in the radiocarbon content of the woody stem towards that of a time later than the ring formation. Lignin is responsible for the mechanical strength of wood and, although most of it forms during initial ring growth, further lignification occurs during sapwood to heartwood conversion, as xylem channels[1] collapse. This introduces another source of younger carbon into the sample (Stewart 1966; Taylor et al. 2002). Removal of resins and lignins means that only cellulose is left from the sample and so the protocol is known as cellulose extraction. Although accurate determinations of ring formation can be obtained without it (Staff et al. 2014; Taylor and Southon 2013), experience shows that this should be implemented when possible, as it ensures the removal of any unexpected contaminants that cannot be tackled through the acid, alkali, acid method (Hamilton, pers. comm. 2015).

The SUERC radiocarbon lab uses a cellulose extraction protocol based on that developed by Hoper et al. (1998), which, in turn, was derived from a process developed by Green (1963). The key steps in this protocol are solvent extraction to remove resins, bleaching to remove lignins and an alkali step to remove hemicellulose and any remain-

[1] Xylem is the structure in the woody stem through which nutrients and water are transported within the tree trunk.

ing lignins. In practice, the alkali step is undertaken as a part of the acid-alkali-acid procedure for carbonate and humic/fulvic acid removal.

A Soxhlet extractor is an element of laboratory apparatus in which the solvent is evaporated from a heated glass flask into a condenser. There it condenses and drips into a chamber containing the sample. Once sufficient solvent has accumulated in the chamber, it trips and returns to the flask via a return tube, taking with it whatever material it extracted from the sample. This process repeats until the heat supplied to the flask is removed (Figure 4.2). In the process used for alpha-cellulose extraction, Soxhlet extraction is a three step process. The first step consists of refluxing the sample in a 2:1 (50ml/25ml) mixture of chloroform and ethanol. This is followed by extraction with ethanol only and completed with a water step that removes any remaining ethanol and ensures no carbon has been added to the sample. The single-ring samples from T-947 all underwent the water step in a Soxhlet, but all of the following samples were subjected to multiple washes on a hot plate (at least 10 washes over 24 hours). This was implemented because the water step was a bottle-neck in the pre-treatment process and posed a serious threat to completing the analyses on time. Comparison between T-947 decadal samples, pre-treated with the second method and the decadal estimates from the single rings showed no systematic offset (Figure 4.3). Following the water step, samples are dried to ensure evaporation of any remaining solvent.

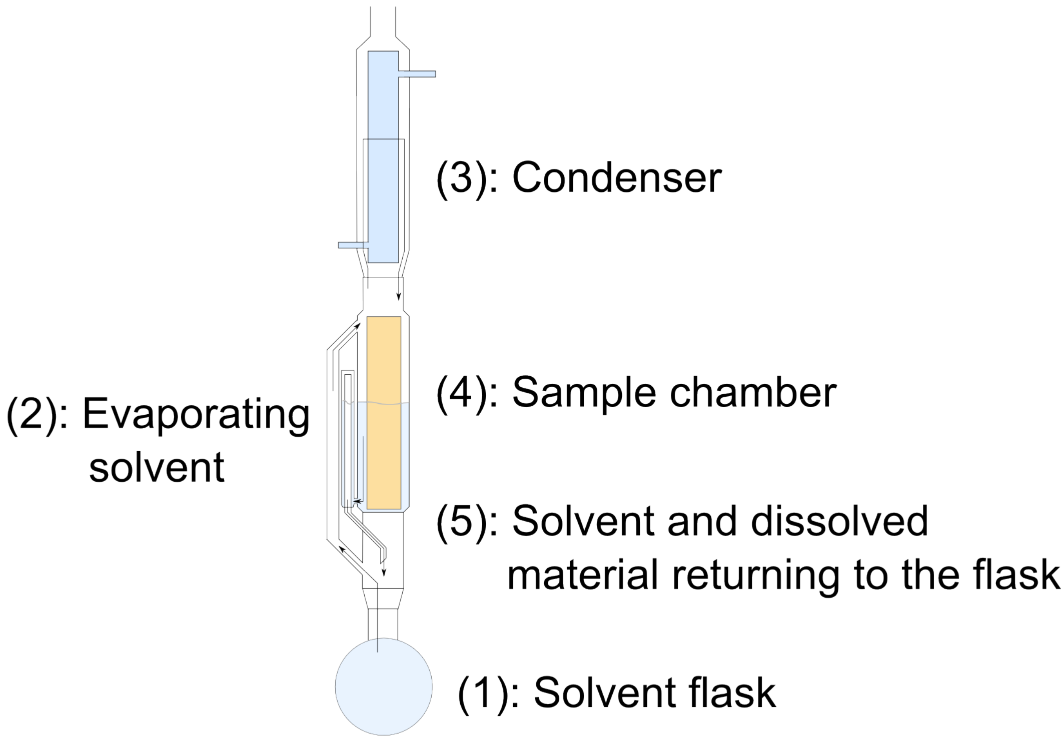



Figure 4.2: Soxhlet apparatus. The solvent is heated in a glass flask (1),evaporates through the side tube (2) and into the condenser (3). There it liquefies and drops into the sample chamber (4). Once the sample chamber is filled up, the solvent trips the side chamber (5) and flows back down into the glass bulb, removing any material it dissolved from the sample chamber.

The subsequent two steps are bleaching and AAA. The samples are first bleached with acidified sodium chlorite (3g $NaCl_2O$ per 1.2ml HCl dissolved in 400ml of water).

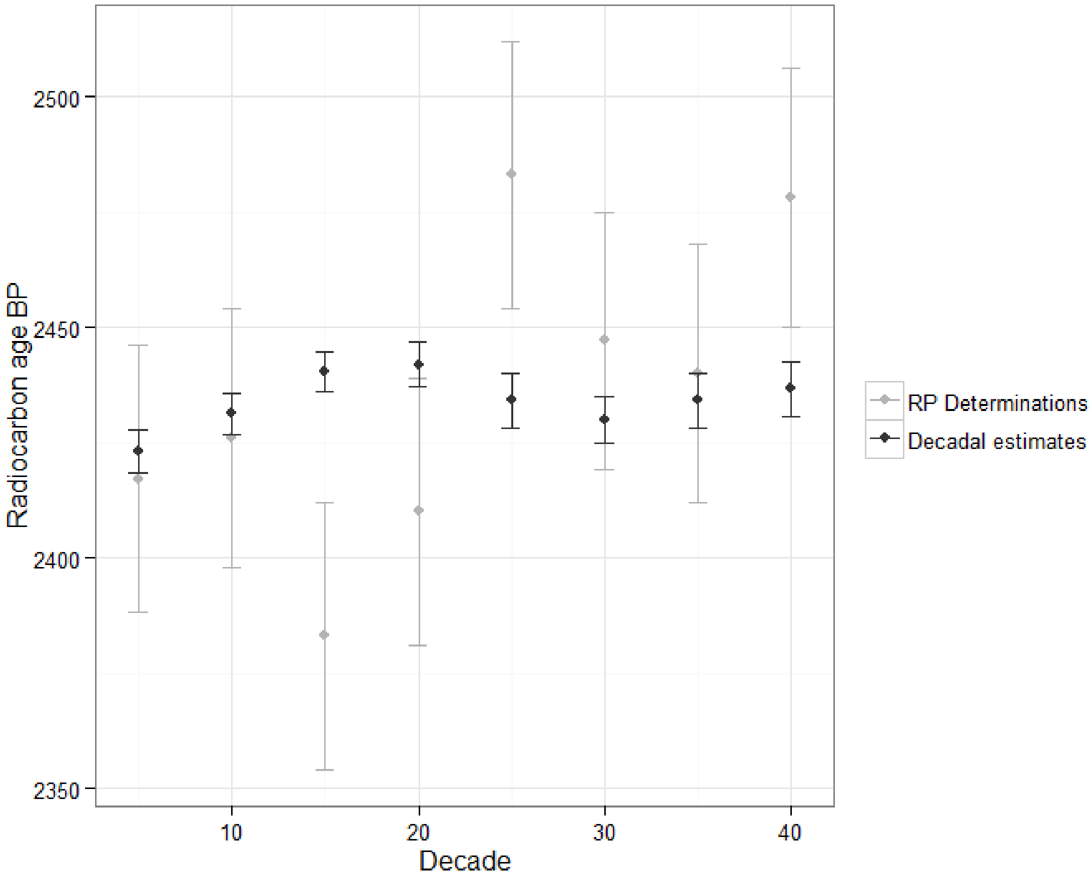



Figure 4.3: Comparison of radiocarbon ages of the width-weighted single-year samples from T-947 combined to provide decadal estimates and T-947 decadal ring blocks. Error bars represent 2-$\sigma$.

Following this, the AAA extraction process is implemented. This utilizes 0.5 molar HCl and 2% NaOH with heating on a hot plate for 2 hours per step. Further alkali steps are included if the NaOH turns to a dark peaty colour. When pre-treating early T-947 samples, none of which would be measured, it was noticed that once dried, the samples still showed black stains indicating incomplete cellulose purification. Hence, the procedure was adjusted so that samples would undergo a secondary bleaching after the acid-alkali acid-step, to ensure cellulose purity. In retrospect, this could be expected. Wood consists of alpha-cellulose the long fibres connected to each other by a web of short hemi-cellulose fibres with lignin filling the spaces in between (Figure 4.4, Wayne 2010). As the alkali step of the AAA treatment dissolves the hemicellulose, it also improves the penetration of any subsequent bleaching into the woody matrix. If the need arises this observation could be used to accelerate the pre-treatment procedure, which may prove essential if large wiggle-match dating projects are to be undertaken under time constraints. The pre-treatment procedure is completed with rinsing in de-ionized water to remove any remaining reagents and drying the sample prior to combustion and graphitization.

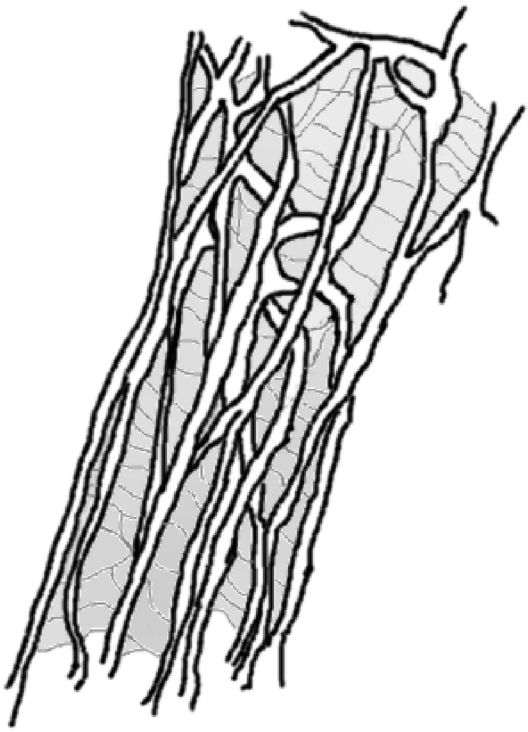


Figure 4.4: Wood microstructure. Thick white lines represent the cellulose, thin diagonal lines represent the hemi-celluloses and the grey matrix represents the lignin (modified from Wayne 2010, Figure 20.5)

At one point during the project a suspicion emerged that some of the outermost and decayed rings of waterlogged timbers may at times produce too old ages (see Chapter 6.2.1). Although the process by which this apparent offset emerged was unclear, a more stringent pre-treatment protocol was experimented with. In the altered cellulose extraction protocol, the following changes were implemented: a) the strength of the alkali was increased from 2% to 10% NaOH; b) the acid step following the alkali used 1 molar (as opposed to 0.5 molar) HCl, and was repeated twice c) the AAA step would be repeated twice, once after primary and once after secondary bleaching. The first alteration was motivated by the possibility that not all of the soluble cellulose fraction would be removed by the weaker alkali (see Zugenmaier 2008). The second alteration was motivated by the need to remove the stronger alkali, in case any residual NaOH absorbed atmospheric carbon dioxide and thus altered the sample age. The third alteration was motivated by the need to ensure that the sample was extracted in full. In practice, two development samples indicated that this more aggressive protocol made no difference to the outcome of the pre-treatment (Figure 4.5; Table 4.1) and was soon abandoned on account of large sample losses.

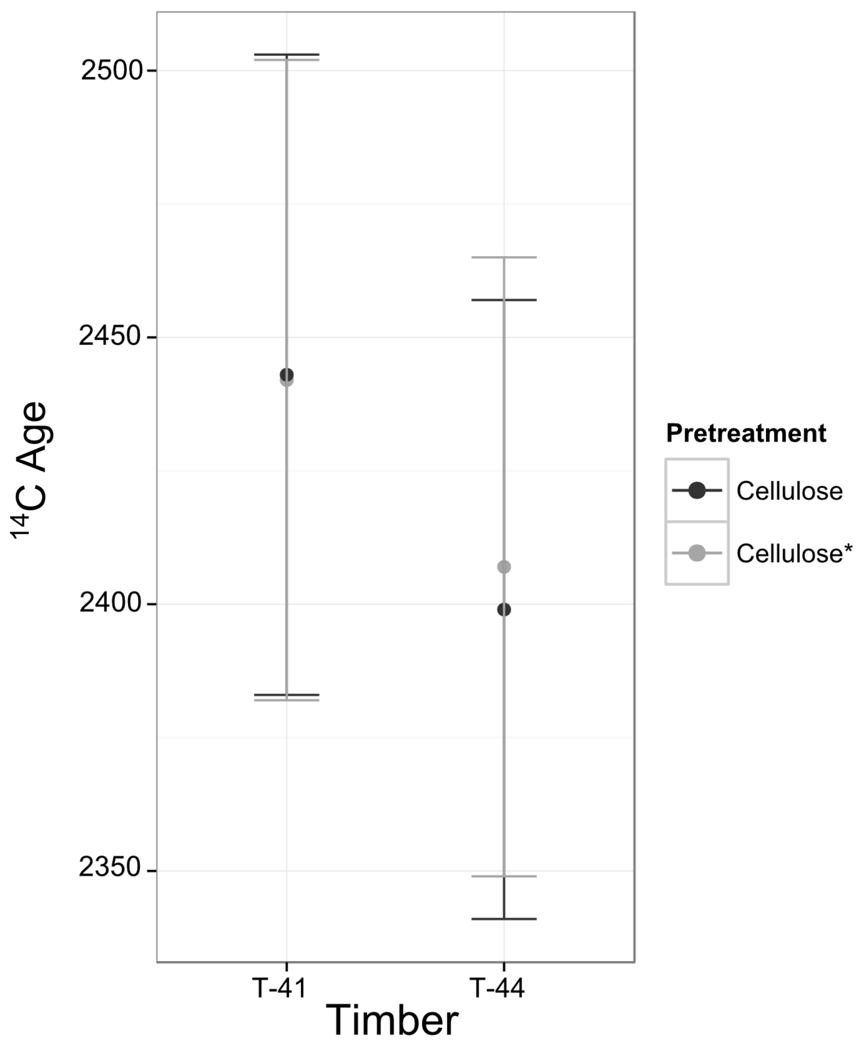



Figure 4.5: Comparison of the ages of the development samples produced following the standard and modified cellulose pre-treatment protocols. Cellulose* refers to the modified protocol. Error bars represent 2-$\sigma$.

Table 4.1: Comparison of the ages from the development samples for the revised alpha cellulose pre-treatment. SUERC-58850 and -58853 were subject to revised pre-treatment. 5% critical value for the $\chi^2$ test statistic is 3.8.

| Timber | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ |
|---|---|---|---|---|
| T - 41 | 58870 | 2443 | 30 | 0 |
| | 58853 | 2442 | 30 | |
| T - 44 | 58869 | 2399 | 29 | 0 |
| | 58850 | 2407 | 29 | |

The wood charcoal samples from the hearths at Black Loch of Myrton and Cults Loch 3 were pre-treated using the AAA method (Stenhouse and Baxter 1983).

The pre-treated cellulose and charcoal contain only the carbon relevant to the dating process, but it still has to be converted into graphite targets before it can be measured. To do so requires sample combustion, carbon dioxide purification, reduction of $CO_2$ to carbon and pressing into target holders. At SUERC, samples are combusted in evacuated quartz tubes using the method of Vandeputte et al. (1996), which uses copper oxide as the source of oxygen and silver to mop up halides and other gaseous contaminants. In order to supply the energy necessary for the reaction to take place, the samples are placed in a furnace at 850°C overnight.

The combustion tube is cracked open under vacuum and the gas is purified by passing it through a slush trap (solid $CO_2$ in ethanol; -80°C) followed by a liquid nitrogen trap (-196°C)(Figure 4.6). The slush trap will freeze down all the water of combustion and some of the contaminants, while the liquid nitrogen will freeze down the carbon dioxide but will allow the more volatile gases to be pumped away. The sample gas is then transferred to a finger, where its volume is measured and from where it is split into aliquots for $^{14}$C and $\delta^{13}$C measurement, and in some cases any excess is transferred into an archive tube. Because of the amount of gas needed in radiocarbon dating, the pressures in the finger always exceed 20mbar, so all the transfers happen in turbulent flow which prevents on-line fractionation (Harris 1989).

Graphitization is the final step of the process. The conversion of carbon dioxide to graphite is achieved in a two-step reduction process described by Slota et al. (1987). The first step entails the reduction of carbon dioxide ($CO_2$) to carbon monoxide (CO) in a reaction with zinc at ca. 450°C. The second step entails the reduction of carbon monoxide to graphite (pure carbon) in a reaction with iron at ca. 550°C. The graphite is then pressed into aluminium holders (referred to as targets or cathodes) on a manual press and sent to the SUERC AMS facility for measurement.

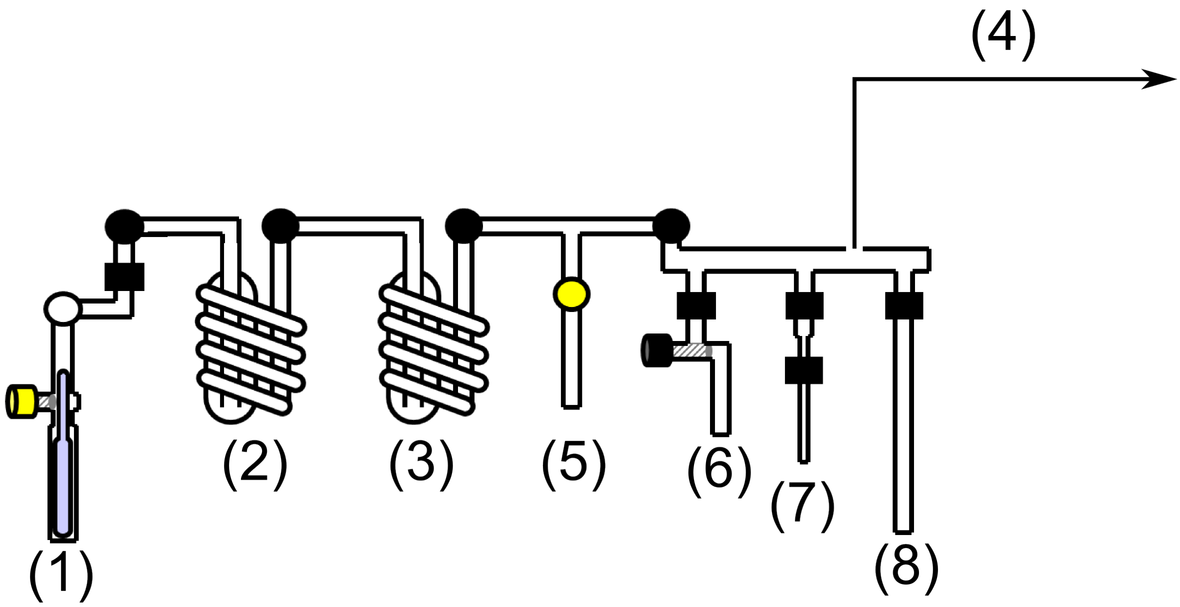



Figure 4.6: Vacuum line diagram. The sealed combustion tube is placed in the cracking unit (1), cracked, the gas then flows through the slush trap, where any remaining water vapour is frozen down (2) the CO2 is held in the liquid nitrogen trap (3) while any more volatile elements are pumped away (4). The gas is then transferred into the finger (5), where its volume is measured and from where it is distributed to the graphite unit (6), mass spectrometry unit (7) and an archive unit (8).

### 4.1.3 AMS and stable isotope measurements

Each radiocarbon determination requires two mass spectrometric measurements. The first measurement is a stable isotope measurement made using an isotope ratio mass spectrometer (IRMS) and is concerned with the proportion of $^{13}C$ relative to $^{12}C$ in the sample. This is necessary to estimate the fractionation correction factor. The second measurement is an accelerator mass spectrometry (AMS) measurement, concerned with estimating the proportion of $^{14}C$ in the sample and thus dating it. At SUERC, the ratio of $^{14}C$ to $^{13}C$ is measured. Samples are assigned their SUERC- numbers during the AMS measurement.

The first of the two measurements, which is concerned with the proportion of $^{13}C$ in the sample, accounts for carbon fractionation between the atmosphere and the formation of the sample. For most plants this occurs in three steps and always discriminates against the heavier isotope. The first step takes place when the $CO_2$ enters the leaves through the leaf pores (stomata), the second when sugars are synthesized by the photosynthetic enzyme RuBisCo (Ribulose 1,5 bisphosphate carboxylase/oxygenase), and the third occurs at wood formation itself (Figure 4.7, McCarroll and Loader 2004). This affects the interpretation of the radiocarbon measurement as it means that tree-ring cellulose will contain a smaller proportion of $^{14}C$ than the atmospheric $CO_2$ of the time, leading to an impression of an older age. This can be compensated for by measuring the proportion of the stable carbon isotope $^{13}C$ in the sample, as $^{13}C$ undergoes half the fractionation of $^{14}C$. Hence, if the scale of fractionation between $^{13}C$ and the atmosphere is known, a correction for $^{14}C$ can be deduced (Aitken 1990). Because stable $^{13}C$ has a high presence in nature about 1% of all carbon atoms on Earth  it can be measured using a conventional mass spectrometer.

All the $^{13}$C determinations undertaken in the course of the current project were conducted off-line, using an isotope ratio mass spectrometer, on gas aliquots taken after the transfer of sample gas. The measurements were made using a VG Optima until August 2014 and on a VG SIRA-11 thereafter. The results are reported as $\delta^{13}$C in the per mil (‰) notation relative to VPDB (Coplen 1995). The instrumental precision is in the range of less than 0.1‰$\delta^{13}$C, however sample processing has the potential to introduce some added variation. This can be estimated from the distribution of measurements on aliquots of homogenous standard samples. For this purpose the sample standard deviation was estimated for the measurements of 155 humic acid measurements conducted between June 2013 and February 2014, which indicated a standard deviation of 0.24‰.

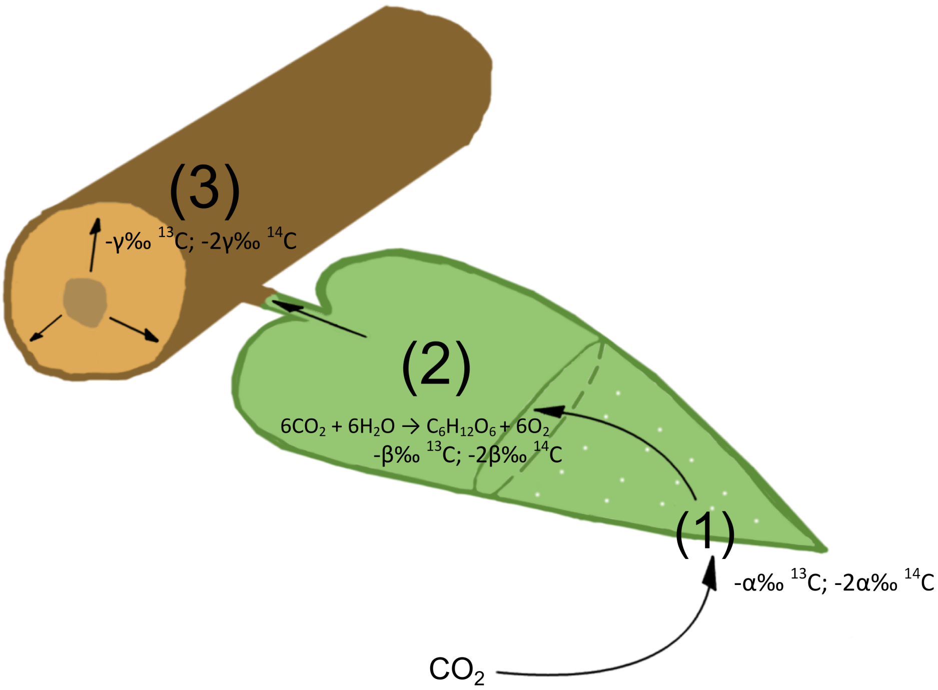



Figure 4.7: Carbon fractionation between the atmosphere and tree-rings. Atmospheric carbon dioxide enters the leaves through leaf pores (stomata; 1), at which point it undergoes the first fractionation stage with the lighter molecules having a greater chance of penetrating into the leaf. The next fractionation stage occurs during photosynthesis (2), where the bonds within the lighter $CO_2$ molecules have a higher chance of being broken down by the photosynthetic enzymes. The final fractionation step takes place with ring-growth (3). Fractionation of $^{14}$C will be twice that of $^{13}$C.

All SUERC $^{14}$C measurements were conducted on one of the two accelerator mass spectrometers available on site. The first machine is the 5MV National Electrostatics Corporation (NEC) Tandem accelerator commissioned in 2003. The second is a 250 kV single-stage AMS (SSAMS), also produced by NEC and commissioned in 2007 (Naysmith et al. 2010). All the measurements conducted as part of this study used the negative ion source and solid target methodology described above.

Samples are submitted to the AMS facility in batches of 130 targets that form a single wheel. Each batch is subdivided into smaller groups of ten graphite targets containing seven unknown and three quality assurance samples. The QA measurements provide a reference for the radiocarbon content, background correction and allow estimation of the analytical precision of the determination on the unknowns. The first of the three QA samples is the primary standard NBS Oxalic Acid II (SRM-4990C), produced from French sugar beet of the 1977 harvest (Stuiver 1983). Once corrected for fractionation, its activity must be multiplied by 0.7459 activity of the 1950 atmosphere as it was estimated based on the measurements of 1890 wood, corrected for radiocarbon decay (Olsson 1974, 38). 19$^{th}$ century wood was dated as reference rather than AD 1950 material to avoid the fossil fuel effect (Suess Effect). The second QA sample is either a wood sample of infinite age with respect to $^{14}$C or Glengoyne distillery barley mash. The former, because of its great age, is a material with no surviving $^{14}$C. It is used to determine the value of the measurement background  the number of false counts on the radiocarbon detector induced by a variety of physical processes. The background material is chosen to match that of the unknown samples; during the course of the current project, for all wood and charcoal samples, Miocene wood (between 5.3 and 20 million years ago), provided by the University of Hochenheim, was used. Glengoyne barley mash constituted sample A of the Third International Radiocarbon Intercomparison (TIRI) and its consensus radiocarbon value is 116.35 pMC (percent of modern carbon) (Scott et al. 1997). The third QA target is Letham Moss humic acid. Collected in 1986, Letham Moss humic acid constituted sample T of the 5$^{th}$ International Radiocarbon Inter-comparison (VIRI), during which a consensus age of 3360 $\pm$ 3 $^{14}$C radiocarbon years BP was determined (Scott et al. 2010). These secondary standards help to ensure measurement accuracy and determine the measurement precision within the target group. Routine precision of SUERC radiocarbon measurements is 35 radiocarbon years or less, depending on the machine performance. This can be improved through allocating more time to counting each sample and increasing the proportion of QA samples within measurement groups. Such high-precision measurements have a target precision of less than 16 radiocarbon years.

## 4.2 OxCal

OxCal was developed in the mid-1990s by Christopher Bronk Ramsey (Bronk Ramsey 1995, 2009a). It is a user-friendly program that allows a broad range of non-statisticians to build the Bayesian models of the kind described in Chapter 2. The description that follows is based on the manual (Bronk Ramsey 2013). In version 4.2, used throughout this thesis, the program consists of three main components: the project manager, the analysis module and the output module. The project manager is used to input data, expressed in Chronological Query Language 2 (CQL 2). The analysis module includes a Metropolis-Hastings MCMC algorithm used for Bayesian estimation. The output module presents the results and enables export of the posterior distributions, either as numeric values, or as graphics.

OxCal results require diagnostics to ensure the reliability of the MCMC sample (see section 3.3.5 herein). OxCal handles this through a convergence integral (often refered to as Convergence) that represents the similarity of distributions between different MCMC trial groups starting from different seed values, with a value of 100% indicating that the distributions are identical. The program defaults to running analyses until convergence greater than 95% is achieved over multiple samples and this default is followed throughout this thesis.

The agreement of the proposed model with the data also has to be assessed; otherwise it might happen that the defined model goes against the data and so gives an inaccurate result. In order to assess whether this is the case, OxCal provides three different diagnostic indices. The individual agreement index (Aindividual) describes the odds of the likelihood within the model, compared to those for the same date treated as a single calibration. This is summarized as a per cent value, with 100% stating that the data are insufficient to choose between the two models and 60% or less indicating that the data is not in agreement with the model. The product of Aindividual values is the overall agreement index (Aoverall). It has now been surpassed by the model agreement index Amodel, but is retained in the model output. The third agreement index, Amodel, describes the fit of the whole model to the data and is used to assess the output of the analyses as a whole.

OxCal also provides subject-specific diagnostics for wiggle-matches. The first of these is the combined agreement, Acomb, which is calculated in the same way as Aoverall, but its pass values are modified based on the length of the matched sequence. The thresholds are estimated so that if the combination was carried out for multiple measurements according to the Chi-squared test as described by (Ward and Wilson 1978), it would pass at the 95% critical value. Besides the Acomb index, OxCal also calculates the Chi-squared test statistic between the calibration curve and the series of measurements at the point of best fit. As a general rule, it is expected that this will pass at the 95% critical value relevant to the given degrees of freedom. A third, alternative approach used on several occasions throughout this thesis is to use the quantile-quantile plots for chi-squared statistics between individual measurements and corresponding values of the calibration curve.

Commands in frequent use throughout the thesis are illustrated in the example model and implement the already-discussed models of Chapter 2.3 (Figures 4.8 to 4.9). Unless stated otherwise, the calibration curve used is IntCal13 (Reimer et al. 2013). Note that estimation of individual Bayesian wiggle-matches in OxCal does not require MCMC methods. Indeed, the process can, in principle, be carried out in a spreadsheet (Blaauw et al. 2003), however OxCal is used for these estimations here as it provides an easy means of integrating wiggle-matches into more complex models.

Whenever OxCal output is presented the following conventions are observed:

- Calibrated dates in regular font (e.g. 400-300 cal BC; 95.4% probability) refer to dates that are calibrated, but not subject to any further statistical modelling.

- Italicized modelled dates (e.g. *400-300 cal BC; 95.4% probability*) refer to dates that have been subject to some form of modelling. This will include component dates of wiggle-matches, but not wiggle-match dates that have not been subject to further modelling.

- All the results in text are rounded up to the nearest five years. The output of the figures is left unaltered so as not to change the appearance of the results, but in practice, due to the nature of the OxCal algorithm, it is not any more precise than the five-year rounding.

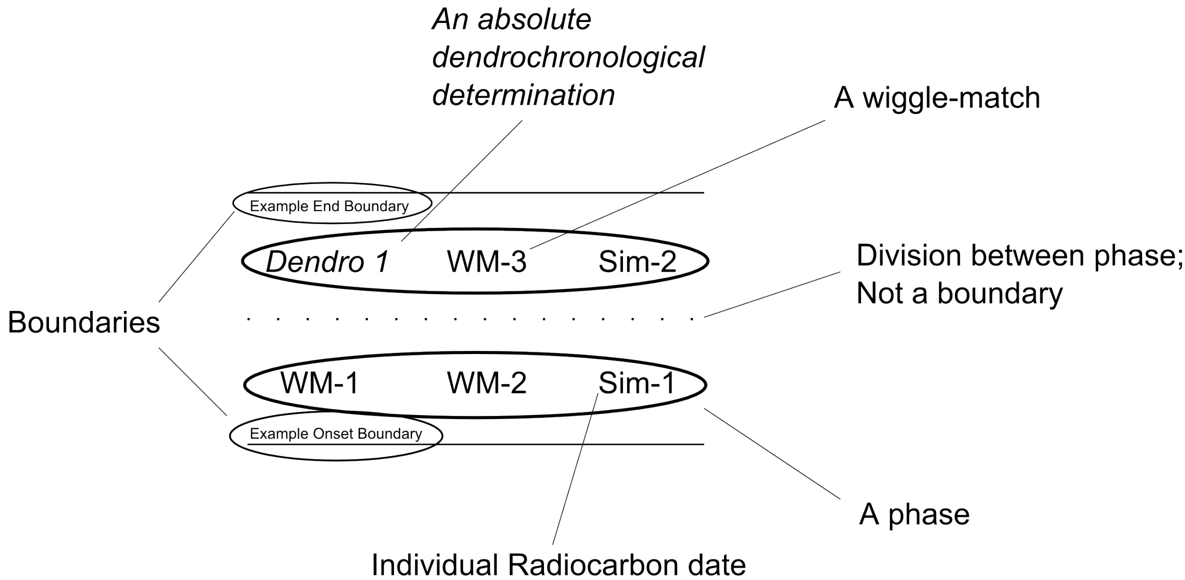



Figure 4.8: An example model schematic. Continuous lines define boundaries as discussed in Chapter 3.3; the dotted lines denote succession of phases without the introduction of boundaries.

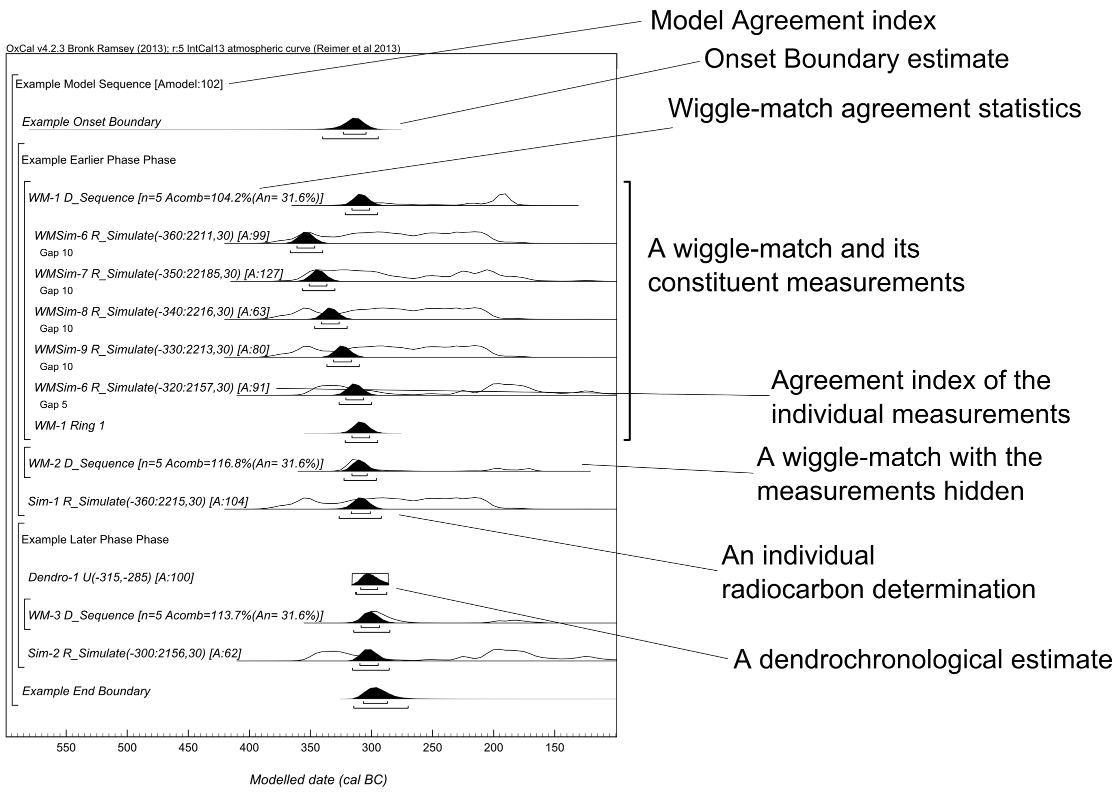



Figure 4.9: OxCal output. Throughout the case studies, details of the wiggle-matches are presented in separate graphics and their component elements hidden within models to save space (like WM-2 and -3 here).

# 5 Technique: from single-ring measurements to decadal sampling strategies

Chapter 3 ended with a suggestion that, based on the principles of past radiocarbon trends and wiggle-match dating, the optimal sampling approach when wiggle-match dating short sequences is to sample single rings, as they retain most information on the short-term radiocarbon fluctuations. Hence they should provide the most specific fits to the calibration curve and thus the most precise wiggle-matches. This deduction, however, is based on theoretical grounds alone and single-ring wiggle-match dating was shown to work only in the early modern period (Tyers et al. 2009). Given that the sections of the calibration curve that cover the duration of the Scottish Iron Age are all built upon decadal and bi-decadal data (Chapter 3.2.4), it was necessary to evaluate whether single-ring wiggle-match dating could work in the period of interest and, if not, what is it that constitutes the optimal approach.

The current chapter addresses these questions. It begins with the summary of the determinations of a known age timber, T-947, from which 50 single rings were sampled and measured to high precision. If these measurements could be wiggle-matched back to their known dates and if the wiggle-matches produced would have good characteristics, then work could have progressed on optimizing the single-ring dating approach (section 5.1). As it happened, the results did not produce a good match due to excess short-term variability that is not represented in the calibration curve due to the decadal and bi-decadal nature of the underpinning calibration data sets (section 5.2). The final section of the chapter discusses alternative approaches to sampling for wiggle-match dating and the challenges involved in implementing them.

## 5.1 T-947 single-ring measurements

The intuition that single rings provide the best samples for wiggle-match dating timbers from the Scottish wetlands was evaluated by dating T-947, an oak stake collected in 2009 from the artificial promontory Cults Loch 3 in Galloway. It belongs to a group of nine dendro-dated oak timbers from the site that form the chronology CLMNx9, which has been correlated to six Irish and one English chronology with t-values ranging between 3.52 and 5.8 (Cavers and Crone, forthcoming). The dendrochronological date for the final ring of T-947 is 450 BC, but the outer rings were too decayed for $^{14}$ dating and so the sampling began at 460 BC. Hence, whenever discussing the results relating to T-947 the target date is always 460 cal BC.

The initial research design envisioned high-precision $^{14}$C measurements of 50 consecutive rings from the T-947 sequence, which would provide sufficient information on agreement with the curve and help in investigating the performance of different sampling patterns. However, the unexpected nature of many of the results meant that altogether 85 determinations were made during this part of the study: 75 on single rings, and 10 on blocks of two to four rings. These were measured between October 2013 and February 2014 in three AMS batches: batch 28/13, batch 38/13 and batch 7/14. The first batch, 28/13 consisted of 50 single-ring samples, measured to high precision in October 2013. The second batch, 37/13, consisted of 16 single rings and one four-ring block, measured to high precision in December 2013. The final batch, 7/14, run in February 2014, consisted of three single-ring samples and three three-year blocks, measured in multiple aliquots to routine precision and combined to achieve the equivalent of a high-precision estimate (Ward and Wilson 1978).

The first batch measured (28/13), covered 50 contiguous rings from 460 to 509 cal BC (Figure 5.1; Table 5.1). Measurements were successful for 47 samples, with two samples lost due to cathode burn-out and one sample displaying an inexplicable $^{14}$C-enriched value. For the 47 successful measurements, the $\delta^{13}$C values were consistent with the ranges for modern English and south-west Scottish oak, corrected to a pre-industrial atmospheric level (Figure 5.2; Loader et al. 2008; Young et al. 2012). The wiggle-match results are at odds with both the dendrochronological date and the radiocarbon calibration curve. The latter is indicated by the very high value of the $\chi^2$ test statistic ($\chi^2$ = 129.239; 5% critical value for 46 degrees of freedom is 62.830), which implies that the probability that these measurements derive from the same distribution as the calibration curve approaches zero as a result of excessive short-term variability. This excess variability had to be verified as real, and not an analytical artefact, before the T-947 data could be used to inform research design strategies.

Table 5.1: Results for Cults Loch 3 timber T-947 single-ring measurements from batch 28/13.

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 1 | 30811 | 48457 | 2463 | 15 | -26.2 |
| 2 | 30812 | 48458 | 2414 | 14 | -24.1 |
| 3 | 30813 | 48459 | 2430 | 16 | -24.3 |
| 4 | 30814 | 48460 | 2439 | 15 | -24.7 |
| 5 | 30815 | 48461 | 2457 | 15 | -23.9 |
| 6 | 30816 | 48462 | 2469 | 17 | -24.8 |
| 7 | 30817 | 48467 | 2504 | 16 | -24.3 |
| 8 | 30818 | 48468 | 2485 | 16 | -25.0 |
| 9 | 30819 | 48469 | 2402 | 15 | -25.2 |
| 10 | 30820 | 48470 | 2429 | 16 | -24.8 |
| 11 | 30821 | 48471 | 2484 | 14 | -23.5 |
| 12 | 30822 | 48472 | 2474 | 14 | -24.6 |
| 13 | 30823 | 48477 | 2520 | 17 | -24.3 |
| 14 | 30824 | 48478 | 2468 | 14 | -23.9 |
| 15 | 30825 | 48479 | 2481 | 16 | -23.7 |
| 16 | 30826 | 48480 | 2458 | 15 | -24.4 |

Continued on next page

Table 5.1 – continued from previous page

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 17 | 30827 | 48481 | 2470 | 13 | -23.1 |
| 18 | 30828 | 48482 | 2463 | 17 | -23.9 |
| 19 | 30829 | 48487 | 2497 | 17 | -24.0 |
| 20 | 30830 | 48488 | 2490 | 16 | -23.6 |
| 21 | 30831 | 48489 | 2473 | 14 | -24.9 |
| 22 | 30832 | 48490 | 2472 | 16 | -24.7 |
| 23 | 30833 | 48491 | 2488 | 16 | -23.8 |
| 24 | 30834 | 48492 | 2553 | 15 | -24.5 |
| 25 | 30835 | 48497 | 2429 | 17 | -24.1 |
| 27 | 30837 | 48499 | 2492 | 17 | -23.7 |
| 28 | 30838 | 48500 | 2449 | 16 | -23.8 |
| 30 | 30840 | 48502 | 2393 | 14 | -25.5 |
| 31 | 30841 | 48507 | 2459 | 13 | -24.5 |
| 32 | 30842 | 48508 | 2455 | 14 | -24.9 |
| 33 | 30843 | 48509 | 2414 | 16 | -24.7 |
| 34 | 30844 | 48510 | 2444 | 17 | -24.0 |
| 35 | 30845 | 48511 | 2426 | 17 | -25.2 |
| 36 | 30846 | 48512 | 2418 | 15 | -24.5 |
| 37 | 30847 | 48517 | 2450 | 17 | -24.4 |
| 38 | 30848 | 48518 | 2490 | 16 | -24.2 |
| 39 | 30849 | 48519 | 2460 | 17 | -24.0 |
| 40 | 30850 | 48520 | 2508 | 16 | -24.2 |
| 41 | 30851 | 48521 | 2471 | 17 | -24.7 |
| 43 | 30853 | 48527 | 2507 | 17 | -24.1 |
| 44 | 30854 | 48528 | 2514 | 17 | -24.3 |
| 45 | 30855 | 48529 | 2485 | 16 | -24.1 |
| 46 | 30856 | 48530 | 2473 | 17 | -25.3 |
| 47 | 30857 | 48531 | 2471 | 15 | -24.1 |
| 48 | 30858 | 48532 | 2463 | 14 | -25.8 |
| 49 | 30859 | 48537 | 2450 | 15 | -26.8 |
| 50 | 30860 | 48538 | 2453 | 15 | -25.8 |

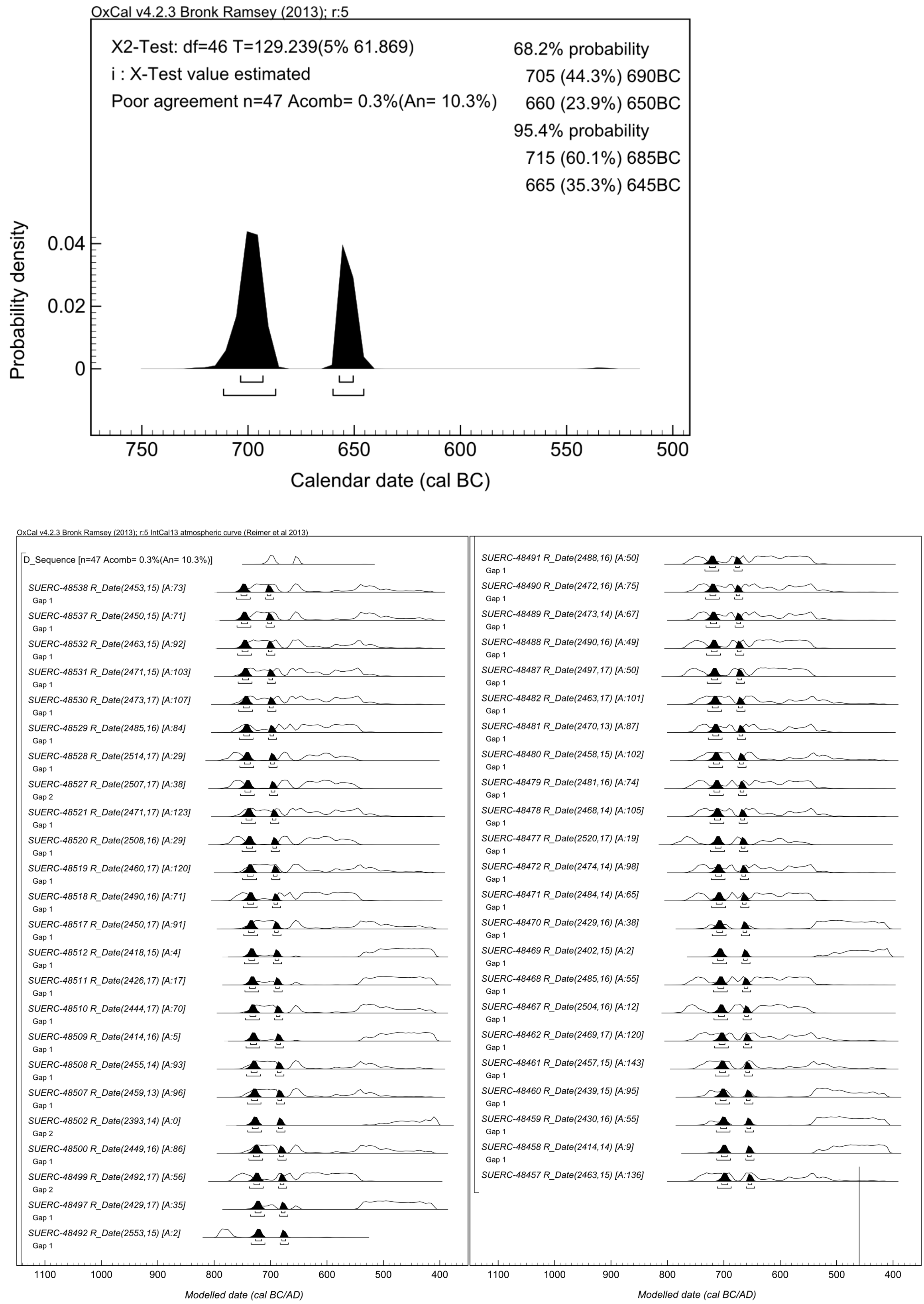



Figure 5.1: The wiggle-match based on the batch 28/13 measurements: summary (above) and individual measurements (below). The vertical line on the detail figure marks the target date.

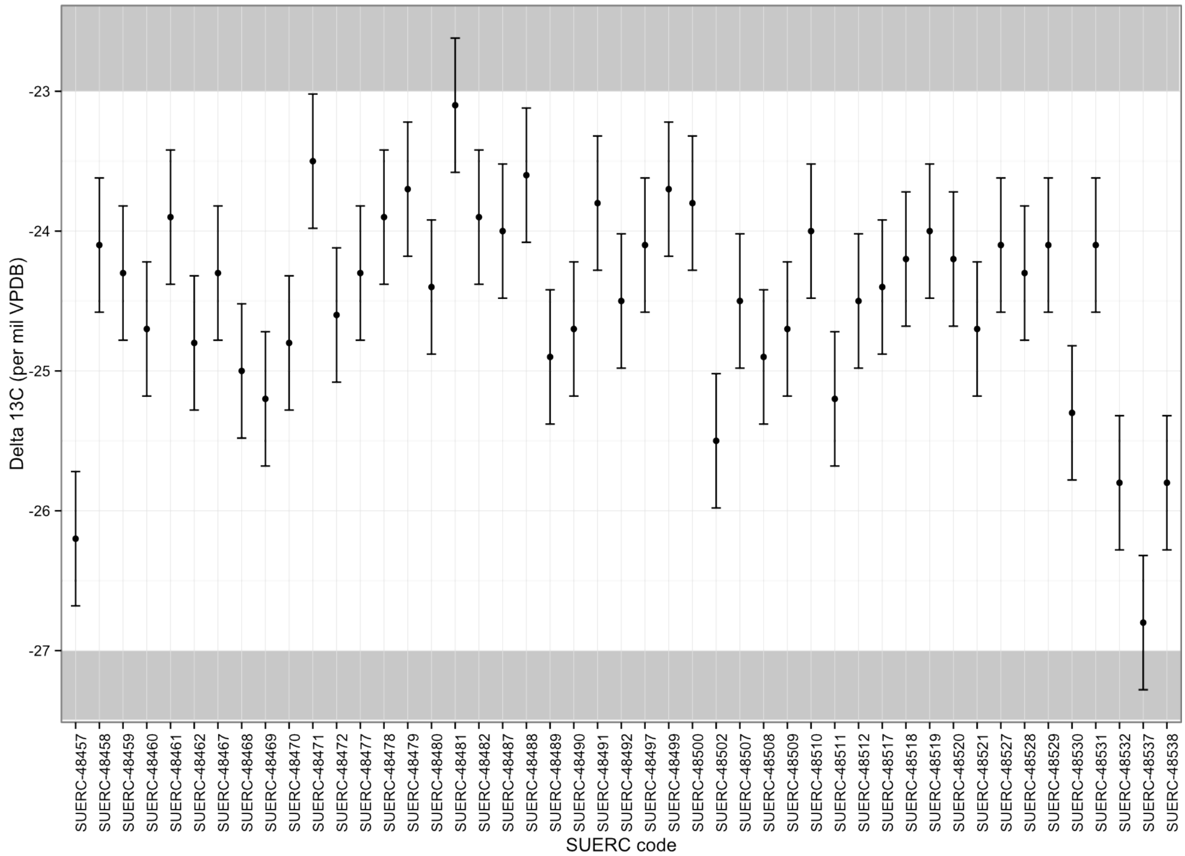



Figure 5.2: $\delta^{13}$C determinations for batch 28/13 T-947 single rings. Area highlighted corresponds to the range of $\delta^{13}$C value in modern English and south-west Scottish oak, corrected for the effects of the industrial revolution. Error bars indicate two standard errors, as calculated from a sample of 64 humic acid measurements.

Batch 28/13 results were validated through dating more T-947 single ring samples. These were chosen to:

1. Replace the three missing values (for rings 26, 29 and 42 corresponding to 485, 488 and 501 cal BC),
2. Provide five further determinations through the series (rings 10, 20, 30, 40, 50),
3. Illuminate the situation of the measurements that deviated from the expectation inherent in the calibration curve to the greatest degree (SUERC-48469, -48477, -48492 for rings 9, 13 and 24),
4. Measure the radiocarbon values of the rings beyond the first 50 (rings 60, 70, 80, 90 and a block of four rings 96–100), so as to better anchor the wiggle-match and hence improve the chances of resolving the chronological discrepancy between the wiggle-match results and the dendrochronological determination.

The main hope for resolving the chronological discrepancy between the wiggle-match and the dendrochronological determination lay with the dating of the inner rings, as at this point the wiggle-match date pointed to T-947 being felled near the beginning of the Hallstatt calibration plateau. Had the inner rings produced an older age than the remainder of the measurements, this positioning would be confirmed. If, on the other hand, the dendrochronological determination was correct, the inner rings would be expected to produce ages not much different from the first fifty as they would lie in the middle of the calibration plateau.

The new data were submitted in batch 38/13 and their results are presented in Table 5.2 and Figure 5.3. All the measurements were successful, but one sample, SUERC-49977, produced stable carbon values inconsistent with the expected range for oak (Figure 5.4). The batch 38/13 results are at odds with the dendrochronological determination, the calibration curve and the 47 measurements from batch 28/13 (Figure 5.5 and Table 5.3). The difference between the 38/13 wiggle-match and the dendrochronological date is easy to explain: once the one measurement with the anomalous $\delta^{13}$C (SUERC-49977) is removed, the 95.4% calibrated date range of the wiggle-match will contain the target date (Figure 5.6). This is because the measurement SUERC-49977 was on the innermost set of rings and its result suggested that it preceded the Hallstatt plateau and in effect drew the whole wiggle-match to earlier dates. Nevertheless, the outlook for the project following batch 38/13 was unfavourable: the new data were in discord with the old data, implying the presence of a technical problem.

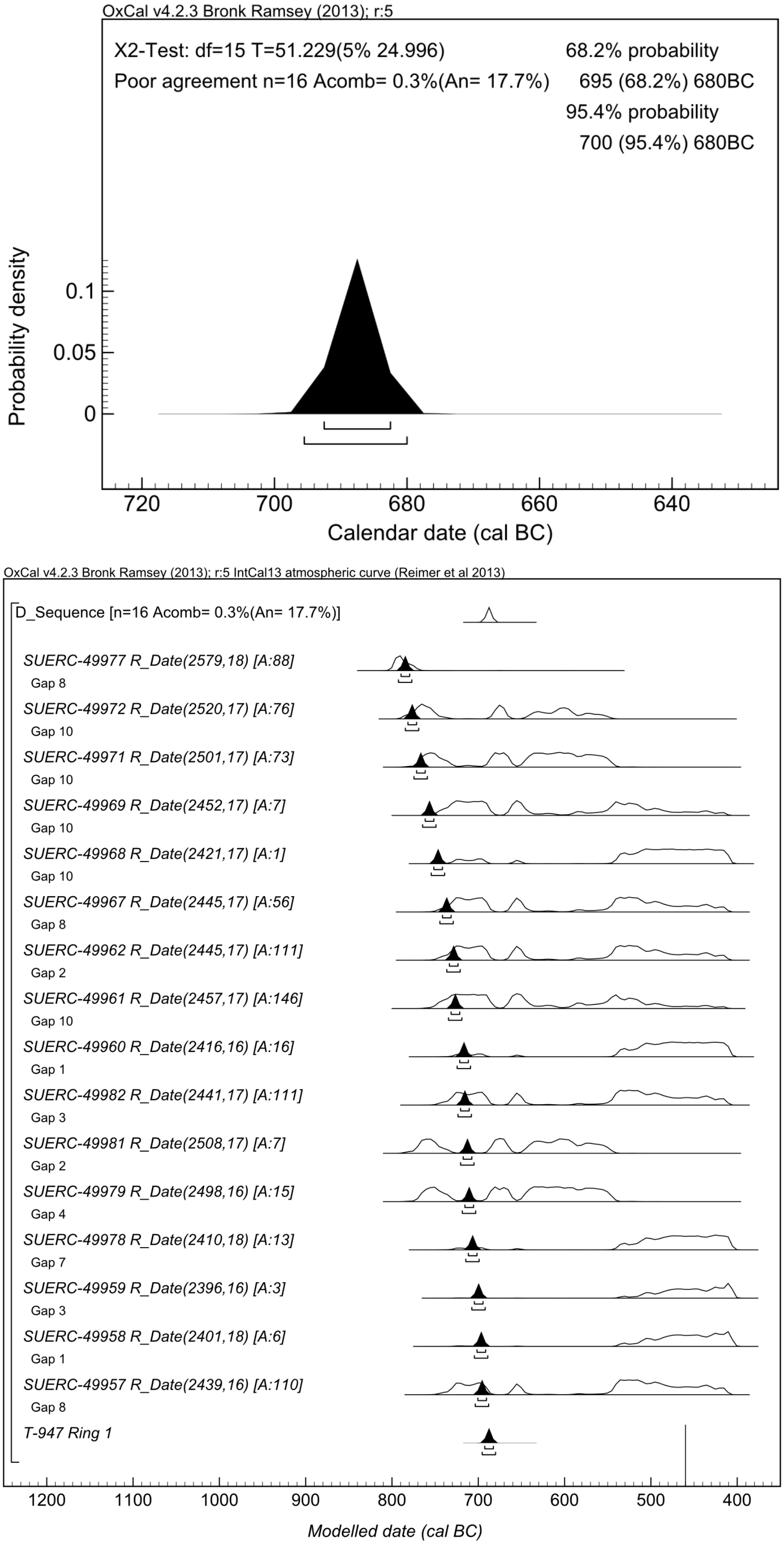



Figure 5.3: The wiggle-match based on the batch 38/13 measurements: summary (above) and individual measurements (below). The vertical line on the detail figure marks the target date.

Table 5.2: Results for Cults Loch 3 timber T-947 single-ring measurements from batch 38/13.

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 9 | 32243 | 49957 | 2439 | 16 | -24.4 |
| 10 | 32244 | 49958 | 2401 | 17 | -24.4 |
| 13 | 32245 | 49959 | 2396 | 16 | -24.2 |
| 20 | 32255 | 49978 | 2410 | 18 | -24.6 |
| 24 | 32256 | 49979 | 2498 | 16 | -24.7 |
| 26 | 32257 | 49981 | 2508 | 17 | -24.7 |
| 29 | 32258 | 49982 | 2441 | 17 | -25.4 |
| 30 | 32246 | 49960 | 2416 | 16 | -25.4 |
| 40 | 32247 | 49961 | 2457 | 17 | -24.2 |
| 42 | 32248 | 49962 | 2445 | 17 | -24.7 |
| 50 | 32249 | 49967 | 2421 | 17 | -25.1 |
| 60 | 32250 | 49968 | 2452 | 17 | -26.2 |
| 70 | 32251 | 49969 | 2450 | 17 | -24.5 |
| 80 | 32252 | 49971 | 2501 | 17 | -27.2 |
| 90 | 32253 | 49972 | 2520 | 17 | -27.0 |
| 96-100 | 32254 | 49977 | 2579 | 18 | -18.2 |

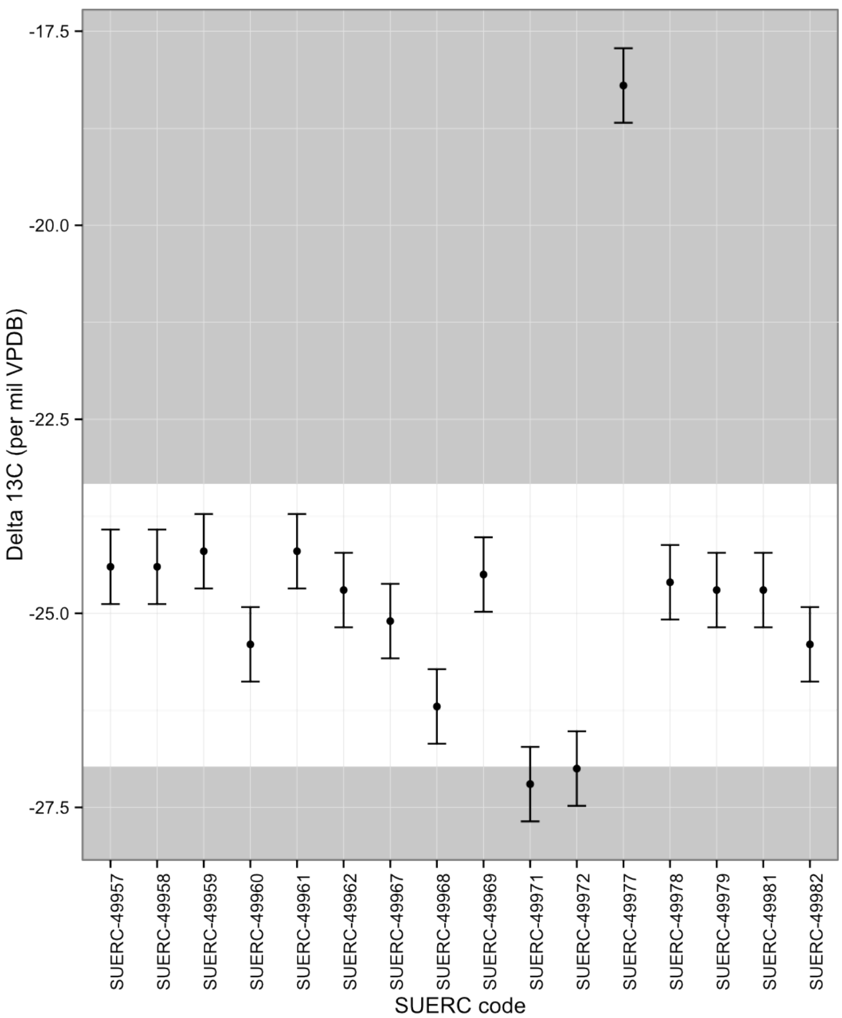



Figure 5.4: $\delta^{13}$C determinations from batch 38/13 T-947 single rings. Area highlighted corresponds to the range of $\delta^{13}$C value in modern English and south-west Scottish oak corrected for the effects of the industrial revolution. Error bars indicate two standard deviations, as calculated from a sample of 64 humic acid measurements. Note the extreme position of SUERC-49977.

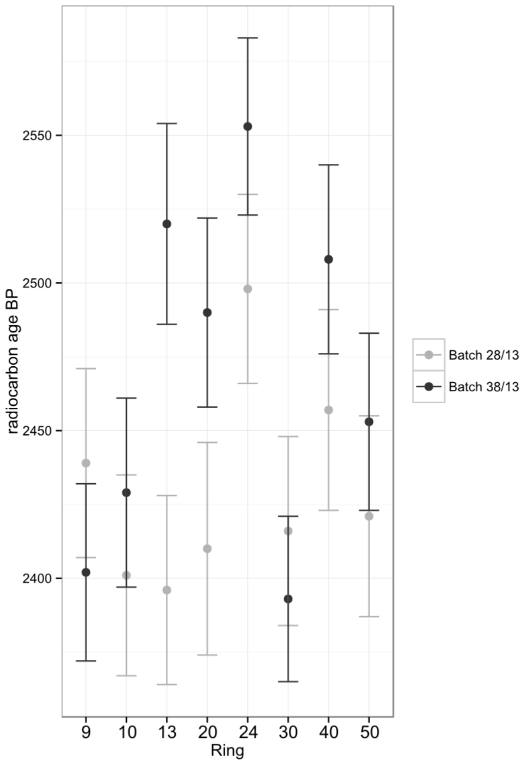



Figure 5.5: Comparison of the radiocarbon ages from the same rings measured in batches 28/13 and 38/13. Error bars indicate two standard deviations.

Table 5.3: Comparison of the ages of overlapping rings from batches 28/13 and 38/13. 5% critical value at two degrees of freedom is 3.8.

| Ring | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ |
|---|---|---|---|---|
| 9 | 48469 | 2402 | 15 | 2.8 |
| | 49957 | 2439 | 16 | |
| 10 | 48470 | 2429 | 16 | 1.4 |
| | 49958 | 2401 | 17 | |
| 13 | 48477 | 2520 | 17 | 28.2 |
| | 49959 | 2396 | 16 | |
| 20 | 48488 | 2490 | 16 | 11.0 |
| | 49978 | 2410 | 18 | |
| 24 | 48492 | 2553 | 15 | 6.3 |
| | 49979 | 2498 | 16 | |
| 30 | 48502 | 2393 | 14 | 1.2 |
| | 49960 | 2416 | 16 | |
| 40 | 48520 | 2508 | 16 | 4.8 |
| | 49961 | 2457 | 17 | |
| 50 | 48538 | 2453 | 15 | 2.0 |
| | -49967 | 2421 | 17 | |

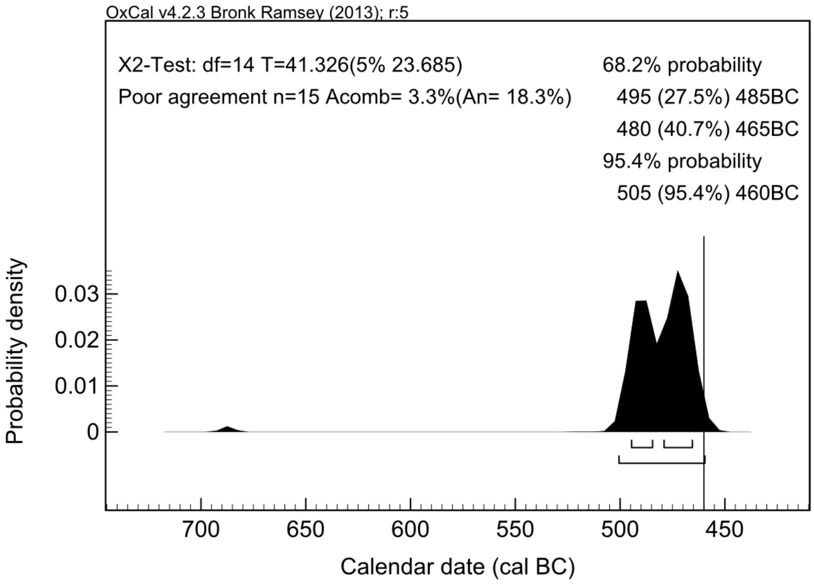



Figure 5.6: Summary result of the wiggle-match on T-947 data from batch 38/13 after the removal of sample SUERC-49977. Vertical bar marks dendrochronological target date of 460 cal BC.

It soon became apparent that some of the discrepancy between the results of the wiggle-match based upon the batch 28/13 $^{14}$C data and the dendrochronological date for the timber T-947 can be traced to a small offset in the measurement results as demonstrated by the TIRI humic acid. At the time these measurements were undertaken, the humic acid in question had a consensus age of 3360 $^{14}$C years BP (see Chapter 4.1.3). However, the measured values of this standard in batch 28/13 and the surrounding batches are older than the consensus value (Figures 5.7 to 5.8). Since 2013, the new inter-comparison program (Sixth Radiocarbon Intercomparison SIRI) has derived a new (preliminary) consensus value of 3374 $^{14}$C years BP (Cook pers. comm. June 2015), yet even had this updated value been accepted instead, the offset within the humic acid standard would have persisted, with all the individual ages remaining older than the consensus. Because these data contribute to estimating the ages of unknown samples within a batch, the results of the 47 single-ring measurements have been skewed towards older ages. Such an offset would have a negligible effect on any routine radiocarbon measurement. However, because the wiggle-match model based upon batch 28/13 determinations used a large number of data measured to high precision under the very strong wiggle-matching prior, the small systematic difference could cause the entire model to drift toward older dates.

The bias towards older ages was mitigated by recalculating the T-947 results from batches 28/13 and 38/13 using the humic acid with values fixed to the TIRI consensus age (3360 $^{14}$C BP) as a primary standard (Xu, pers. comm. 2014). Following this recalculation, the wiggle-match models from both batches contained the target date within their calibrated date ranges, or were within less than a decade of it (Table 5.4, Figures 5.9 to 5.10). Nevertheless, poor agreement with the calibration curve persisted ($\chi^2$= 96.847, 5% critical value = 61.896; Acombine= 1.3%, recommended An= 10.3%) and the discrepancy between the two batches remained (Table 5.5), indicating that

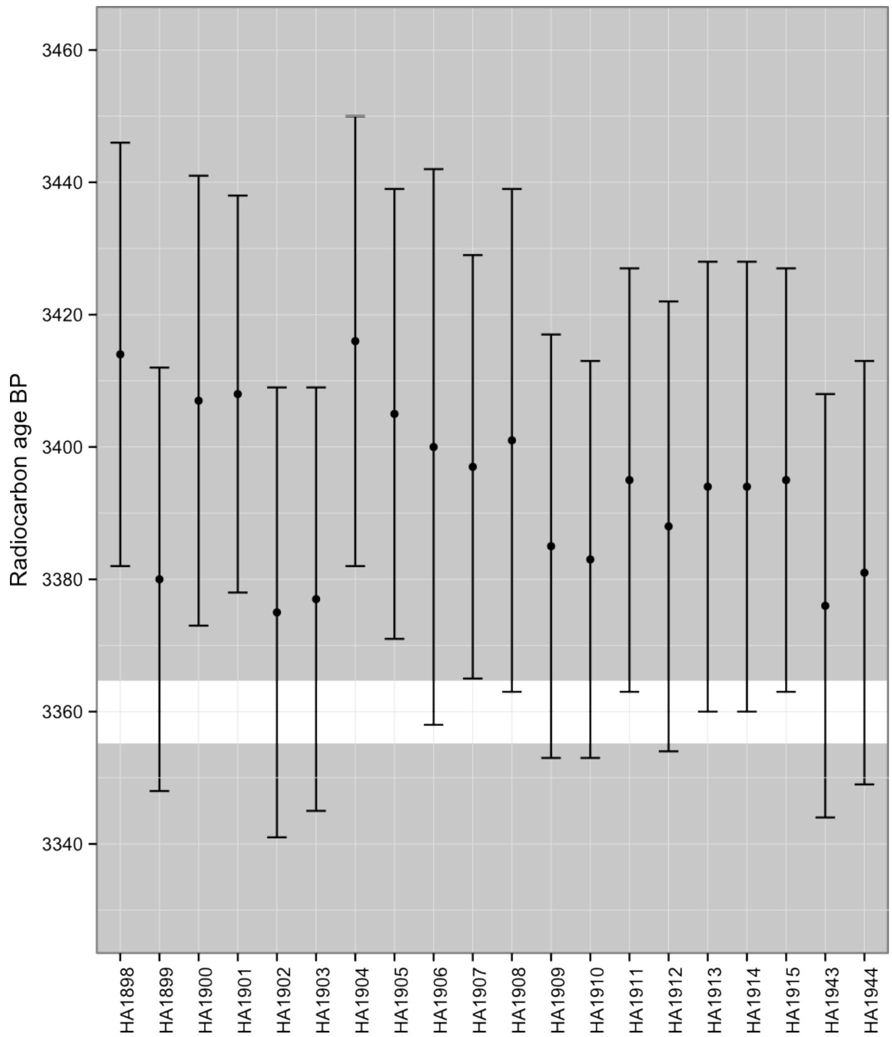



Figure 5.7: Radiocarbon ages of the humic acid secondary standard from batch 28/13 compared to the 95.4% confidence interval of the consensus value (highlighted window). Error bars indicate two standard deviations.

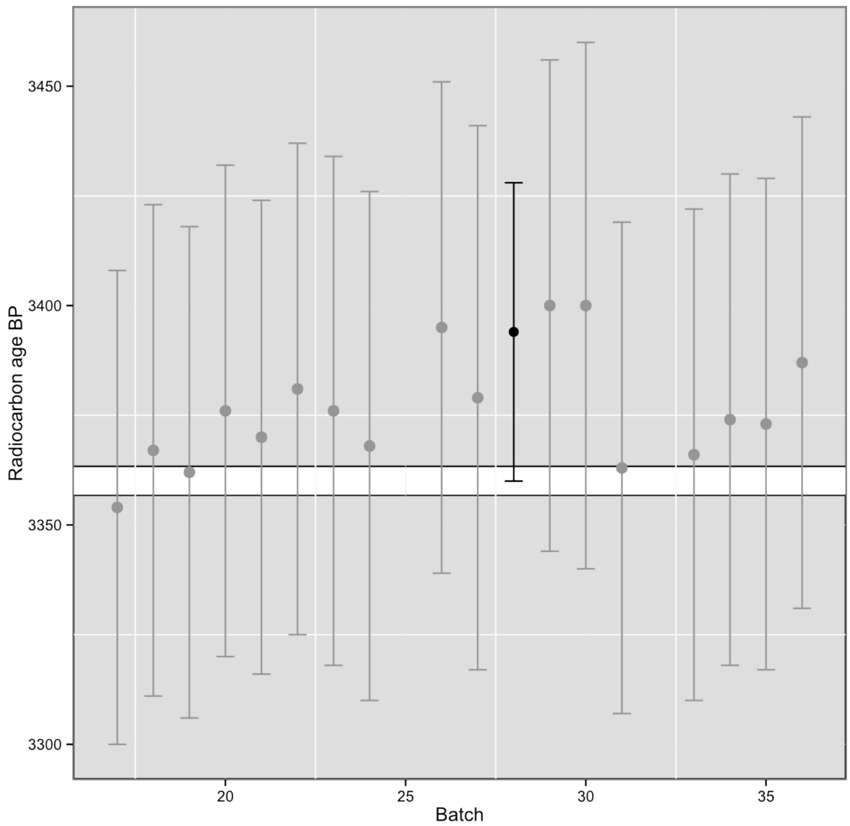



Figure 5.8: Average radiocarbon ages of the humic acid secondary standard from batches 17/13 to 36/13. Note that although the average standard deviations of each group overlap with the consensus values (highlighted window), the means display a consistent bias towards greater ages. Note, however, that they would be more consistent with the preliminary SIRI consensus age. Batch 28/13 highlighted. Error bars indicate two standard deviations.

there was a difference within the data itself that could not be explained through a systematic offset and leaving the issue of excess short-term variability unresolved.

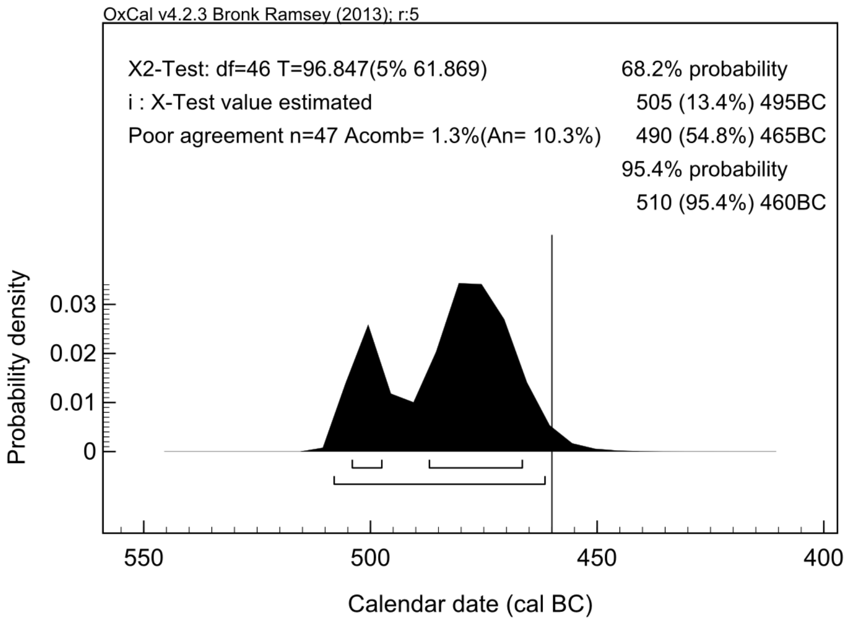



Figure 5.9: Summary result for the wiggle-match based on T-947 measurements from batch 28/13 after humic acid recalculation. Vertical bar marks dendrochronological target date of 460 cal BC.

Table 5.4: Results for Cults Loch 3 timber T-947 single-ring measurements from batch 28/13.

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 1 | 30811 | 48457 | 2424 | 14 | -26.2 |
| 2 | 30812 | 48458 | 2376 | 13 | -24.1 |
| 3 | 30813 | 48459 | 2389 | 15 | -24.3 |
| 4 | 30814 | 48460 | 2396 | 15 | -24.7 |
| 5 | 30815 | 48461 | 2413 | 15 | -23.9 |
| 6 | 30816 | 48462 | 2425 | 17 | -24.8 |
| 7 | 30817 | 48467 | 2457 | 15 | -24.3 |
| 8 | 30818 | 48468 | 2435 | 16 | -25.0 |
| 9 | 30819 | 48469 | 2356 | 15 | -25.2 |
| 9 | 32243 | 49957 | 2419 | 14 | -24.4 |
| 10 | 30820 | 48470 | 2381 | 16 | -24.8 |
| 10 | 32244 | 49958 | 2381 | 16 | -24.4 |
| 11 | 30821 | 48471 | 2445 | 17 | -23.5 |
| 12 | 30822 | 48472 | 2434 | 13 | -24.6 |
| 13 | 30823 | 48477 | 2475 | 16 | -24.3 |
| 13 | 32245 | 49959 | 2401 | 17 | -24.2 |
| 14 | 30824 | 48478 | 2432 | 14 | -23.9 |
| 15 | 30825 | 48479 | 2440 | 15 | -23.7 |
| 16 | 30826 | 48480 | 2420 | 14 | -24.4 |
| 17 | 30827 | 48481 | 2442 | 12 | -23.1 |
| 18 | 30828 | 48482 | 2421 | 16 | -23.9 |
| 19 | 30829 | 48487 | 2450 | 16 | -24.0 |
| 20 | 30830 | 48488 | 2444 | 15 | -23.6 |
| 20 | 32255 | 49978 | 2391 | 17 | -24.6 |
| 21 | 30831 | 48489 | 2433 | 14 | -24.9 |
| 22 | 30832 | 48490 | 2424 | 15 | -24.7 |
| 23 | 30833 | 48491 | 2441 | 15 | -23.8 |

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Table 5.4 – continued from previous page

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 24 | 30834 | 48492 | 2508 | 14 | -24.5 |
| 24 | 32256 | 49979 | 2478 | 14 | -24.7 |
| 25 | 30835 | 48497 | 2402 | 16 | -24.1 |
| 26 | 32257 | 49981 | 2488 | 16 | -24.7 |
| 27 | 30837 | 48499 | 2471 | 16 | -23.7 |
| 28 | 30838 | 48500 | 2449 | 15 | -23.8 |
| 29 | 32258 | 49982 | 2421 | 16 | -25.4 |
| 30 | 30840 | 48502 | 2396 | 13 | -25.5 |
| 30 | 32246 | 49960 | 2395 | 15 | -25.4 |
| 31 | 30841 | 48507 | 2466 | 19 | -24.5 |
| 32 | 30842 | 48508 | 2462 | 14 | -24.9 |
| 33 | 30843 | 48509 | 2426 | 15 | -24.7 |
| 34 | 30844 | 48510 | 2424 | 16 | -24.0 |
| 35 | 30845 | 48511 | 2437 | 16 | -25.2 |
| 36 | 30846 | 48512 | 2431 | 20 | -24.5 |
| 37 | 30847 | 48517 | 2403 | 16 | -24.4 |
| 38 | 30848 | 48518 | 2443 | 15 | -24.2 |
| 39 | 30849 | 48519 | 2416 | 16 | -24.0 |
| 40 | 30850 | 48520 | 2463 | 15 | -24.2 |
| 40 | 32247 | 49961 | 2436 | 16 | -24.2 |
| 41 | 30851 | 48521 | 2422 | 16 | -24.7 |
| 42 | 32248 | 49962 | 2424 | 16 | -24.7 |
| 43 | 30853 | 48527 | 2459 | 16 | -24.1 |
| 44 | 30854 | 48528 | 2466 | 16 | -24.3 |
| 45 | 30855 | 48529 | 2437 | 15 | -24.1 |
| 46 | 30856 | 48530 | 2428 | 16 | -25.3 |
| 47 | 30857 | 48531 | 2424 | 14 | -24.1 |
| 48 | 30858 | 48532 | 2416 | 14 | -25.8 |
| 49 | 30859 | 48537 | 2415 | 14 | -26.8 |
| 50 | 30860 | 48538 | 2416 | 15 | -25.8 |
| 50 | 32249 | 49967 | 2400 | 16 | -25.1 |
| 60 | 32250 | 49968 | 2432 | 15 | -26.2 |
| 70 | 32251 | 49969 | 2429 | 16 | -24.5 |
| 80 | 32252 | 49971 | 2482 | 15 | -27.2 |
| 90 | 32253 | 49972 | 2501 | 16 | -27.0 |
| 96-100 | 32254 | 49977 | 2559 | 17 | -18.2 |

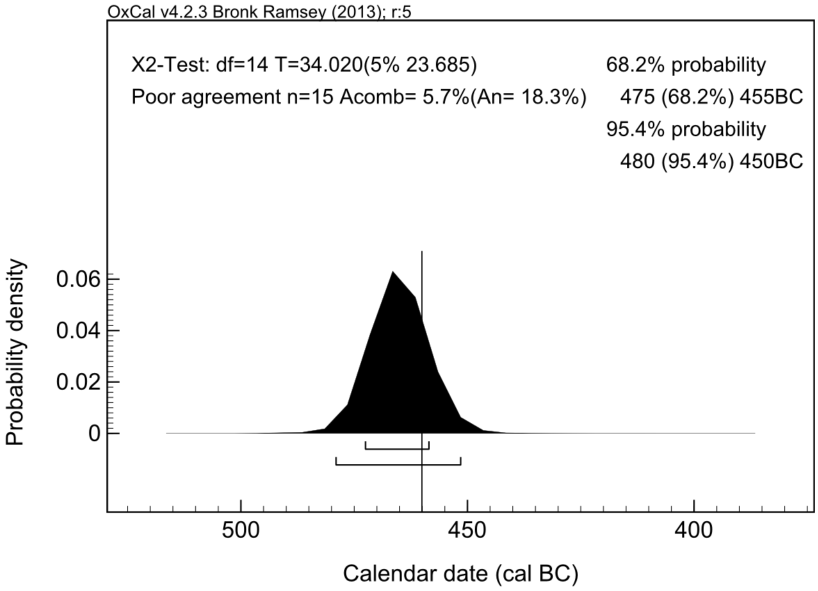


Figure 5.10: Summary result for the wiggle-match based on T-947 measurements from batch 38/13 after humic acid recalculation. Vertical bar marks dendrochronological target date of 460 cal BC.

Table 5.5: Comparison of the ages of overlapping rings from batches 28/13 and 38/13 after age re-calculation with the humic acid secondary standard used as the primary standard used. 5% critical value at two degrees of freedom is 3.8.

| Ring | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ |
|---|---|---|---|---|
| 9 | 48469 | 2356 | 15 | 9.4 |
| | 49957 | 2419 | 14 | |
| 10 | 48470 | 2381 | 16 | 0.0 |
| | 49958 | 2381 | 16 | |
| 13 | 48477 | 2475 | 16 | 10.0 |
| | 49959 | 2401 | 17 | |
| 20 | 48488 | 2444 | 15 | 5.5 |
| | 49978 | 2391 | 17 | |
| 24 | 48492 | 2508 | 14 | 2.3 |
| | 49979 | 2478 | 14 | |
| 30 | 48502 | 2396 | 13 | 0.0 |
| | 49960 | 2395 | 15 | |
| 40 | 48520 | 2463 | 15 | 1.5 |
| | 49961 | 2436 | 16 | |
| 50 | 48538 | 2416 | 15 | 0.5 |
| | 49967 | 2400 | 16 | |

Given the continuing discrepancy between batches 28/13 and 38/13, a new series of measurements was submitted (Table 5.6, Figure 5.11). Its first objective was to resolve which of the original batches was more reliable through re-measuring the three rings with the largest chi-squared statistic, prior to the humic acid correction (rings 13, 20 and 24). Because the difference between the two series was greatest at these three points, the re-measurement had the best chance of producing a definite alignment with one of the series over another and hence providing the clearest resolution of the problem. The second objective was to further explore the inner side of the timber to confirm its chronological position. This objective was addressed by dating three blocks of three rings from near the pith (rings 78–80, 90–92 and 96–98).

Due to the technical problems encountered so far, the approach to obtaining the desired precision was changed. Instead of making a single high-precision measurement on each sample, three separate measurements were made to routine precision and their results combined using the method of Ward and Wilson (1978), as implemented in the R_Combine function of OxCal. All the rings passed the test procedure and the combined values are presented in Table 5.7. The series aligned better with the results from batch 28/13, both in terms of the number of passed individual tests, and in terms of the sum of the $\chi^2$ test statistics (2.5 for batch 28/13 as opposed to 8.9 for batch 38/13, see Table 5.8 and Figure 5.12).

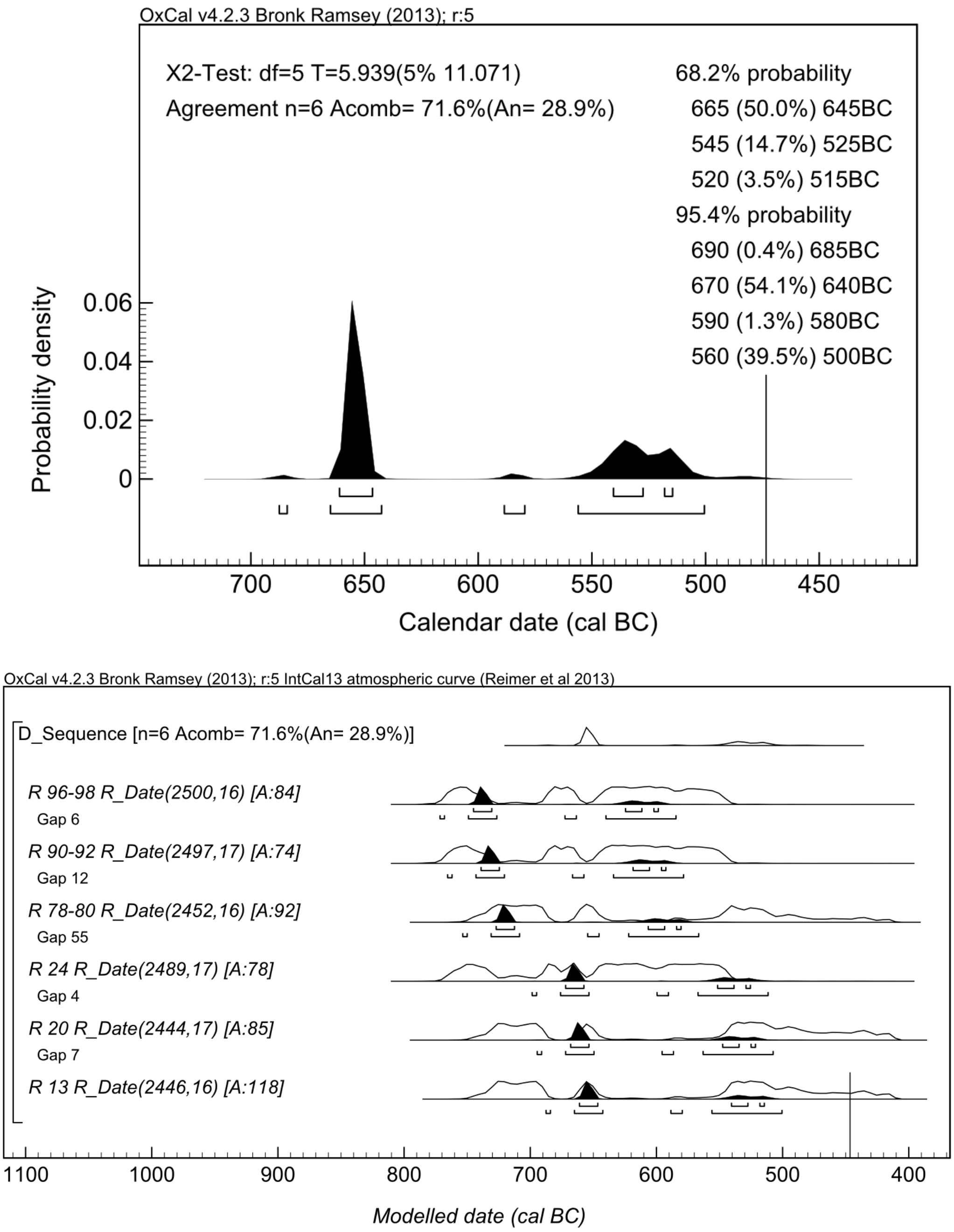


Figure 5.11: The summary result of the wiggle-match on T-947 data from batch 7/14 (above) and the detail of the individual measurements (below). Vertical bar marks dendrochronological target date of 460 cal BC.

Table 5.6: Results for Cults Loch 3 timber T-947 measurements from batch 7/14.

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 13 | 33020 | 50863 | 2447 | 29 | -24.4 |
| | 33021 | 50864 | 2440 | 24 | -24.4 |
| | 33022 | 50865 | 2453 | 29 | -24.3 |
| 20 | 33023 | 50866 | 2481 | 29 | -23.8 |
| | 33024 | 50867 | 2452 | 29 | -23.6 |
| | 33025 | 50868 | 2398 | 29 | -23.6 |
| 24 | 33026 | 50869 | 2481 | 29 | -25.0 |
| | 33027 | 50873 | 2488 | 29 | -25.5 |
| | 33028 | 50874 | 2497 | 29 | -25.4 |
| 78-80 | 33029 | 50875 | 2434 | 29 | -24.7 |
| | 33030 | 50876 | 2422 | 27 | -24.5 |
| | 33031 | 50877 | 2499 | 27 | -24.8 |
| 90-92 | 33032 | 50878 | 2457 | 29 | -24.7 |
| | 33033 | 50879 | 2544 | 29 | -24.9 |
| | 33034 | 50880 | 2490 | 29 | -23.9 |
| 96-98 | 33035 | 50881 | 2512 | 27 | -24 |
| | 33036 | 50882 | 2455 | 29 | -23.8 |
| | 33037 | 50883 | 2531 | 29 | -23.5 |

Table 5.7: The $\chi^2$ tests and combined ages of the rings measured in batch 7/14. 5% critical value at two degrees of freedom is 5.99.

| Rings | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ | Combined Age | Combined 1-$\sigma$ error |
|---|---|---|---|---|---|---|
| 13 | 50863 | 2447 | 29 | 0.1 | 2446 | 16 |
| | 50864 | 2440 | 24 | | | |
| | 50865 | 2453 | 29 | | | |
| 20 | 50866 | 2481 | 29 | 4.2 | 2444 | 17 |
| | 50867 | 2452 | 29 | | | |
| | 50868 | 2398 | 29 | | | |
| 24 | 50869 | 2481 | 29 | 0.2 | 2489 | 17 |
| | 50873 | 2488 | 29 | | | |
| | 50874 | 2497 | 29 | | | |
| 78-80 | 50875 | 2434 | 29 | 4.7 | 2453 | 16 |
| | 50876 | 2422 | 27 | | | |
| | 50877 | 2499 | 27 | | | |
| 90-92 | 50878 | 2457 | 29 | 4.6 | 2497 | 17 |
| | 50879 | 2544 | 29 | | | |
| | 50880 | 2490 | 29 | | | |
| 96-98 | 50881 | 2512 | 27 | 3.8 | 2450 | 16 |
| | 50882 | 2455 | 29 | | | |
| | 50883 | 2531 | 29 | | | |

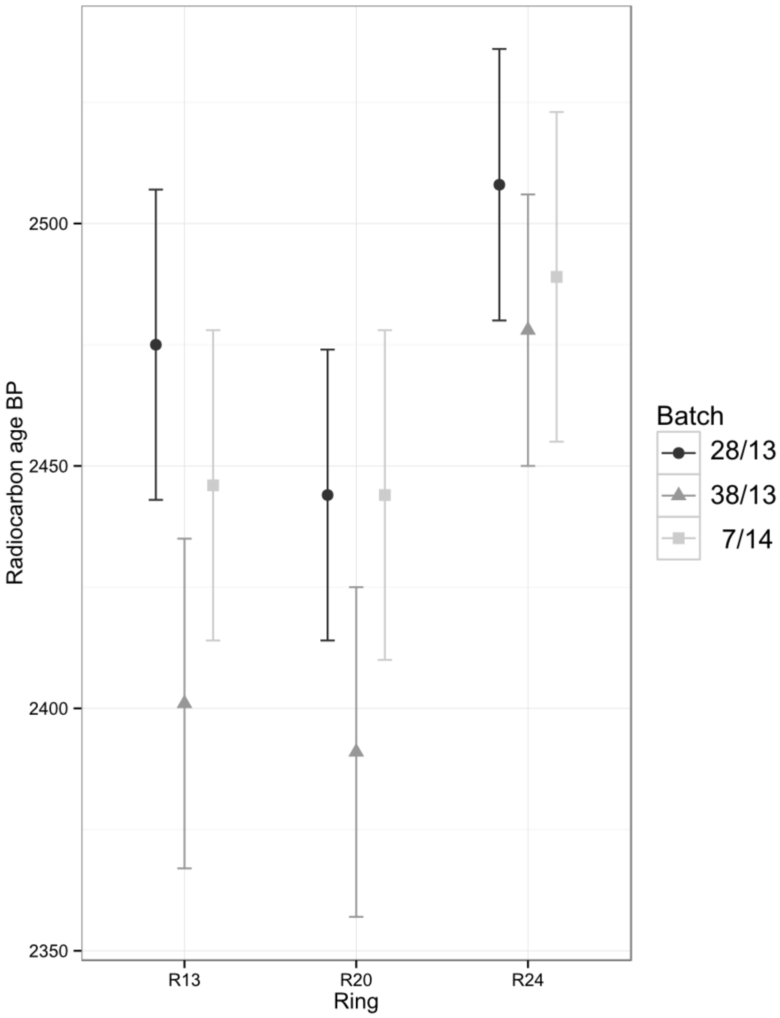


Figure 5.12: Comparison of T-947 single ring measurements from different batches on rings 13, 20 and 24. Error bars indicate two standard deviations.

Table 5.8: Age comparison between the combined values from batch 7/14 and batches 28/13 (SUERC-48477, -48488, -48492) and 38/13 (SUERC-49978, -49979, -49977). Values for batches 28/13 and 38/13 are calculated with the humic acid secondary standard as the primary standard.The 5% critical value is 3.8.

| Ring | Sample | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ |
|---|---|---|---|---|
| 13 | SUERC-48477 | 2475 | 16 | 1.7 |
| | Comb_R13 | 2446 | 16 | |
| 20 | SUERC-48488 | 2444 | 15 | 0.0 |
| | Comb_R20 | 2444 | 17 | |
| 24 | SUERC-48492 | 2508 | 14 | 0.8 |
| | Comb_R24 | 2489 | 17 | |
| 13 | SUERC-49959 | 2401 | 17 | 3.8 |
| | Comb_R13 | 2446 | 16 | |
| 20 | SUERC-49978 | 2391 | 17 | 4.9 |
| | Comb_R20 | 2444 | 17 | |
| 24 | SUERC-49979 | 2478 | 14 | 0.2 |
| | Comb_R24 | 2489 | 17 | |

The results from batch 38/13 were removed from the accepted list of single ring measurements because batch 7/14 agrees better with 28/13. The divergence between batch 38/13 and the other two batches could have been caused by an interruption in the AMS measurement process that took place in December 2013, or through some other unidentified factor; whatever the case, their reliability is in question. Hence the accepted set of T-947 values is based on the results of batches 28/13 and 7/14, combined where appropriate (Table 5.9). Note that although the calibrated date range is now close to the target date of 460 cal BC, the poor agreement with the calibration curve persists (Figure 5.13). This result prompted the question of whether the excessive short-term variability could be real.

Table 5.9: Accepted list of T-947 single ring and short multi-ring block measurements.

| Ring(s) | Sample | Age ($^{14}$C years BP) | 1-$\sigma$ error |
|---|---|---|---|
| 1 | SUERC-48457 | 2424 | 14 |
| 2 | SUERC-48458 | 2376 | 13 |
| 3 | SUERC-48459 | 2389 | 15 |
| 4 | SUERC-48460 | 2396 | 15 |
| 5 | SUERC-48461 | 2413 | 15 |
| 6 | SUERC-48462 | 2425 | 17 |
| 7 | SUERC-48467 | 2457 | 15 |
| 8 | SUERC-48468 | 2435 | 16 |
| 9 | SUERC-48469 | 2356 | 15 |
| 10 | SUERC-48470 | 2381 | 16 |
| 11 | SUERC-48471 | 2445 | 17 |
| 12 | SUERC-48472 | 2434 | 13 |
| 13 | Comb_R13 | 2460 | 12 |
| 14 | SUERC-48478 | 2432 | 14 |
| 15 | SUERC-48479 | 2440 | 15 |
| 16 | SUERC-48480 | 2420 | 14 |
| 17 | SUERC-48481 | 2442 | 12 |
| 18 | SUERC-48482 | 2421 | 16 |
| 19 | SUERC-48487 | 2450 | 16 |
| 20 | Comb_R20 | 2444 | 12 |
| 21 | SUERC-48489 | 2433 | 14 |
| 22 | SUERC-48490 | 2424 | 15 |
| 23 | SUERC-48491 | 2441 | 15 |
| 24 | Comb_R24 | 2500 | 11 |
| 25 | SUERC-48497 | 2402 | 16 |
| 27 | SUERC-48499 | 2471 | 16 |
| 28 | SUERC-48500 | 2449 | 15 |
| 30 | SUERC-48502 | 2396 | 13 |
| 31 | SUERC-48507 | 2466 | 19 |
| 32 | SUERC-48508 | 2462 | 14 |
| 33 | SUERC-48509 | 2426 | 15 |
| 34 | SUERC-48510 | 2424 | 16 |
| 35 | SUERC-48511 | 2437 | 16 |
| 36 | SUERC-48512 | 2431 | 20 |
| 37 | SUERC-48517 | 2403 | 16 |

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Table 5.9 – continued from previous page

| Ring(s) | Sample | Age ($^{14}$C years BP) | 1-$\sigma$ error |
|---|---|---|---|
| 38 | SUERC-48518 | 2443 | 15 |
| 39 | SUERC-48519 | 2416 | 16 |
| 40 | SUERC-48520 | 2463 | 15 |
| 41 | SUERC-48521 | 2422 | 16 |
| 43 | SUERC-48527 | 2459 | 16 |
| 44 | SUERC-48528 | 2466 | 16 |
| 45 | SUERC-48529 | 2437 | 15 |
| 46 | SUERC-48530 | 2428 | 16 |
| 47 | SUERC-48531 | 2424 | 14 |
| 48 | SUERC-48532 | 2416 | 14 |
| 49 | SUERC-48537 | 2415 | 14 |
| 50 | SUERC-48538 | 2416 | 15 |
| 78–80 | Comb_R78-80 | 2453 | 16 |
| 90–92 | Comb_R90-92 | 2497 | 17 |
| 96–98 | Comb_R96-98 | 2450 | 16 |

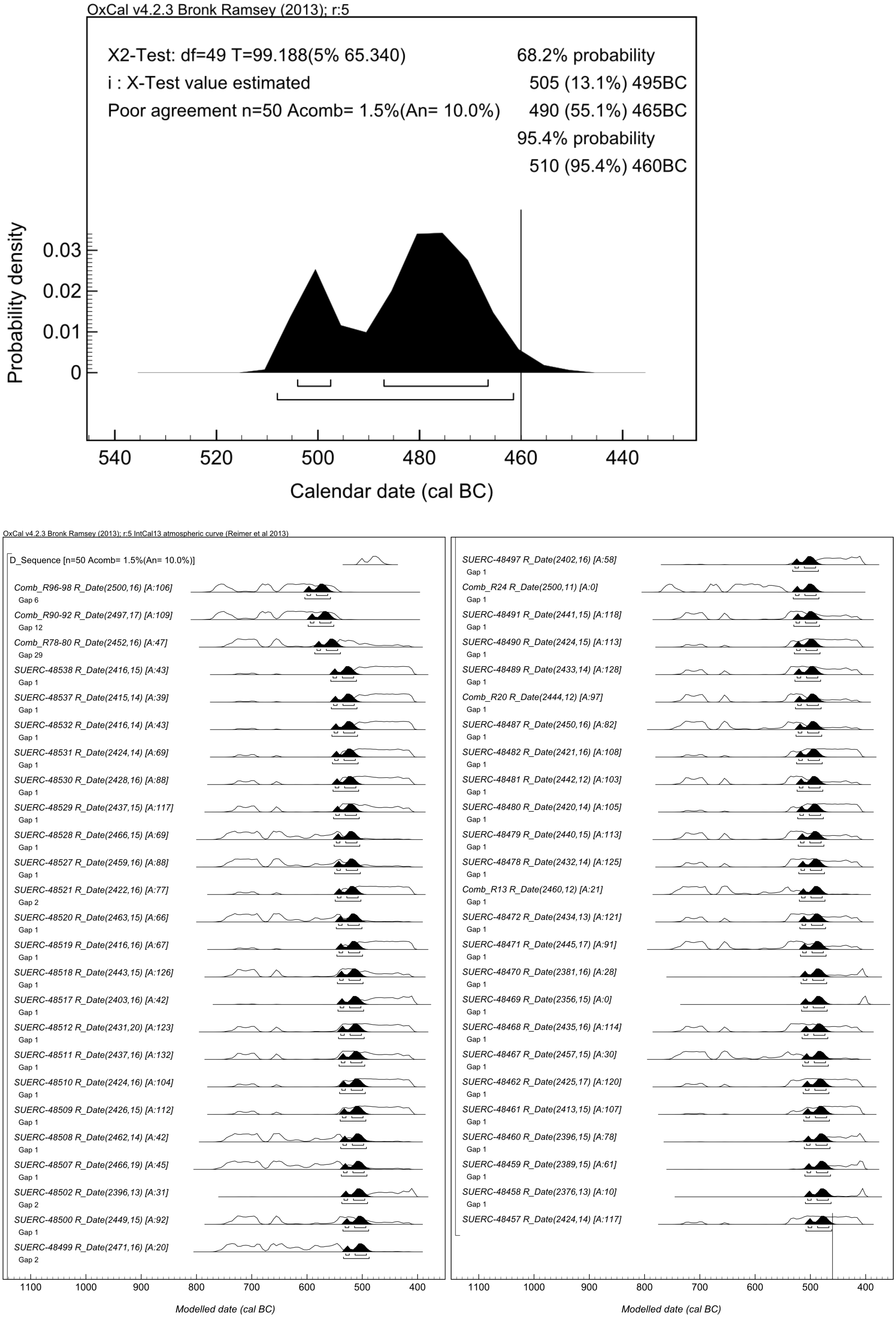



Figure 5.13: The summary result of the wiggle-match on the final set of T-947 data (above) and the detail of the individual measurements (below). Vertical bar marks dendrochronological target date of 460 cal BC.

The very high $\chi^2$ statistic and poor wiggle-match agreement indicate that T-947 measurements do not fit the calibration curve well. This can be traced to excessive scatter of T-947 values relative to the calibration curve (Figure 5.14), which, during the period of interest, shows little variability and values between 2410 and 2420 $^{14}$ years BP with only a slight rise to 2430 BP near the end of the series. On visual inspection the T-947 data are more variable than that (Table 5.9):

1. Beginning at 509 cal BC there is a clear increase in ages from 2416 BP to 2466 BP by 503 BC, followed by a sudden decrease to 2403 BP in 496 BC, making for an amplitude of 60 radiocarbon years in what may be a solar cycle.

2. Next, the trend shifts towards greater ages, perturbed in 489 and 484 BC by sudden age decreases succeeded by an immediate rebound.

3. The trend peaks at 2500 $^{14}$C years in 483 BC, after which point the series drops to a flat section with values oscillating between 2460 and 2420 over a period of 13 years until 470 BC.

4. At 470 BC there is another decrease in the radiocarbon ages, sustained for two years, reaching 2356 $^{14}$C years BP at 468 BC, after which point, ages increase to 2435 BP at 467 BC.

5. From that point, the radiocarbon ages begin to decline until 461 BC when they reach the value of 2376 BP. The final measurement, SUERC-48457, has a greater age than that, standing at 2424 BP, which suggests that it may mark another rise in values.

This pattern can be interpreted as an oscillation with turning points to younger ages spaced at 9, 12 and 14 years, consistent with historic solar cycles (Figure 3.6) Whether the amplitude of the short-term changes is viable can be addressed through comparison with other single-ring, or comparable data sets.

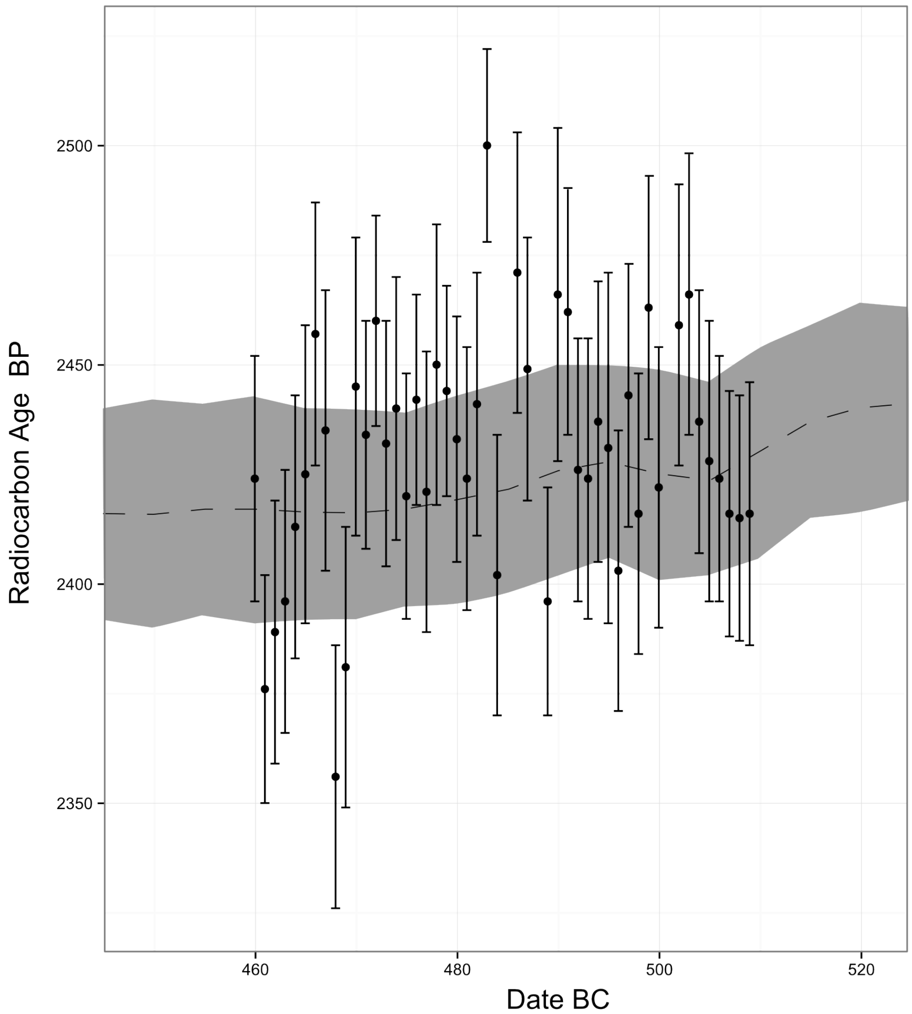



Figure 5.14: T-947 single ring data plotted against the 95.4% confidence interval of the calibration curve. Bars represent 2 standard deviations.

The T-947 data was compared to six single-ring and bi-annual series: 190 years of calibration data from the Quaternary Isotope Laboratory at Seattle (Stuiver 1993), 400 single ring measurements from Korea (Hong et al. 2013), 50 determinations on two-ring samples produced by ETH Zurich (Guttler et al. 2013), and four short series focusing on AD 775 and AD 994 production events (Jull et al. 2014; Miyake et al. 2013, 2012). The latter series were included, as they provide suitable reference for the sudden radiocarbon increased observed in the T-947 series around 482 BC. All comparisons were undertaken in decay-corrected $\Delta^{14}C$ (Eriksson Stenström et al. 2011), as this unit provides the clearest picture of the changes and removes the effects of radioactive decay on variability within the series.

In general, the scatter of year-to-year differences within the T-947 data is comparable, or lesser than, that of five of the six comparative data sets (Figure 5.15). What is noticeable though is the presence of two values in the T-947 data that have a lower annual difference than anything present within the other data sets, save the much-scattered KGM- series. This can be traced to two measurements, SUERC-48497 and -48502, which correspond to the rings 25 and 30 of the series, both of which have younger ages than the surrounding values (Figure 5.16). Given that both are within three standard deviations from the where they could be expected given the position of surrounding data points, it is plausible that they are statistical outliers. Once these two outliers are removed, the scatter of the T-947 results becomes comparable to that of the other data sets, save the ETH- series, where the much tighter distribution can be attributed to the higher average precision of the measurements.

Nevertheless, even after the removal of the two outlying values, the poor fit to the calibration curve persists: the combined agreement index is only 1.2% (10.2% recommended) and the chi-squared test statistic is 93.213, much greater than the 95% critical value of 63.026 at 47 degrees of freedom. Hence, it appears that during the Scottish Iron Age the description of short-term variability in the calibration curve is insufficient for us to benefit from using single-ring data when wiggle-match dating.

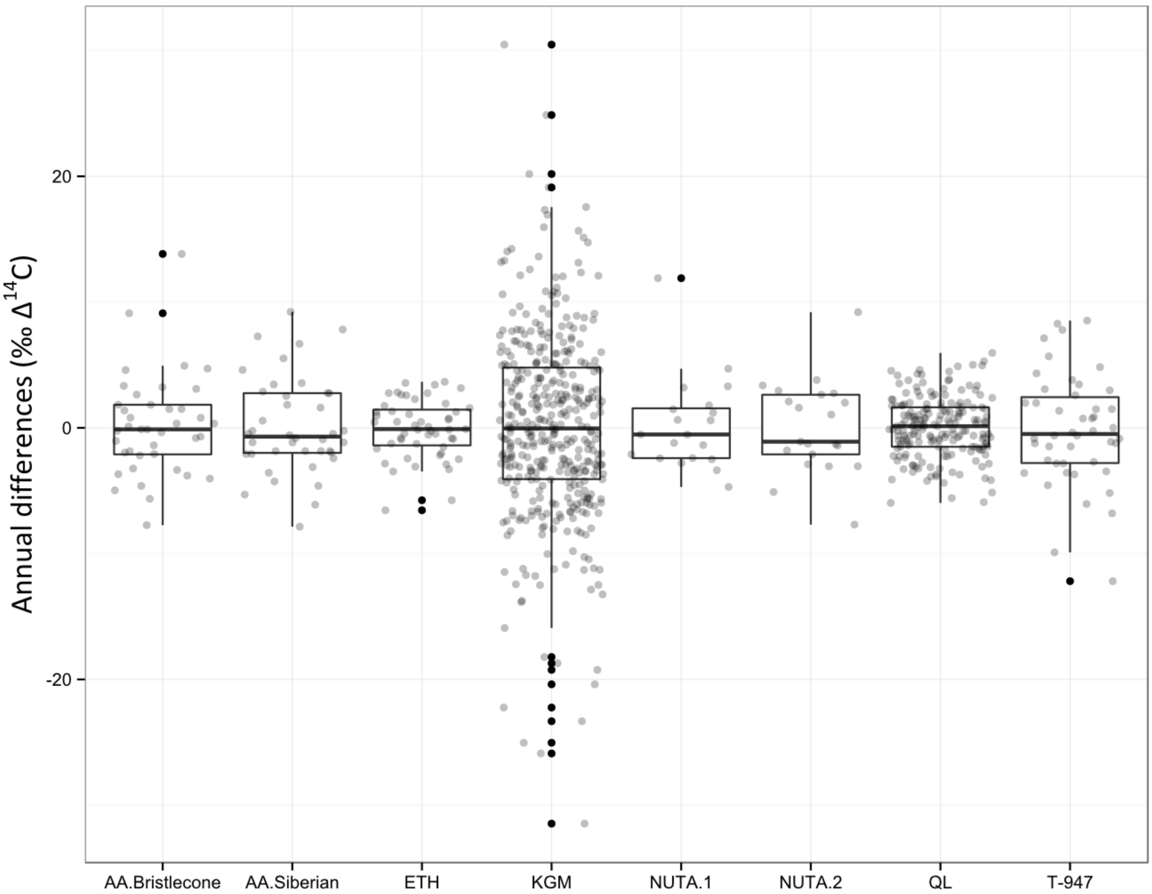



Figure 5.15: Boxplots of the annual differences of the comparison data sets. Note the high degree of scatter in the KGM- data and the low degree of scatter in the QL-data (AA.Bristlecone: single Bristlecone pine rings from AD 760–800 (Jull et al. 2014); AA.Siberian: single Siberian larch rings AD 760–800 (Jull et al. 2014); ETH: German oak biennial series AD 1010–1113 (Guttler et al. 2013); KGM: single Japanese cedar rings AD 1250–1650 (Hong et al. 2013); NUTA.1: single Japanese cedar rings AD 770–800 (Miyake et al. 2012); NUTA.2: single Japanese cedar rings AD 989–1021 (Miyake et al. 2013); QL: single Douglas fir rings AD 1510–1700 (Stuiver 1993); T-947: single oak rings 509–460 BC (this study)).

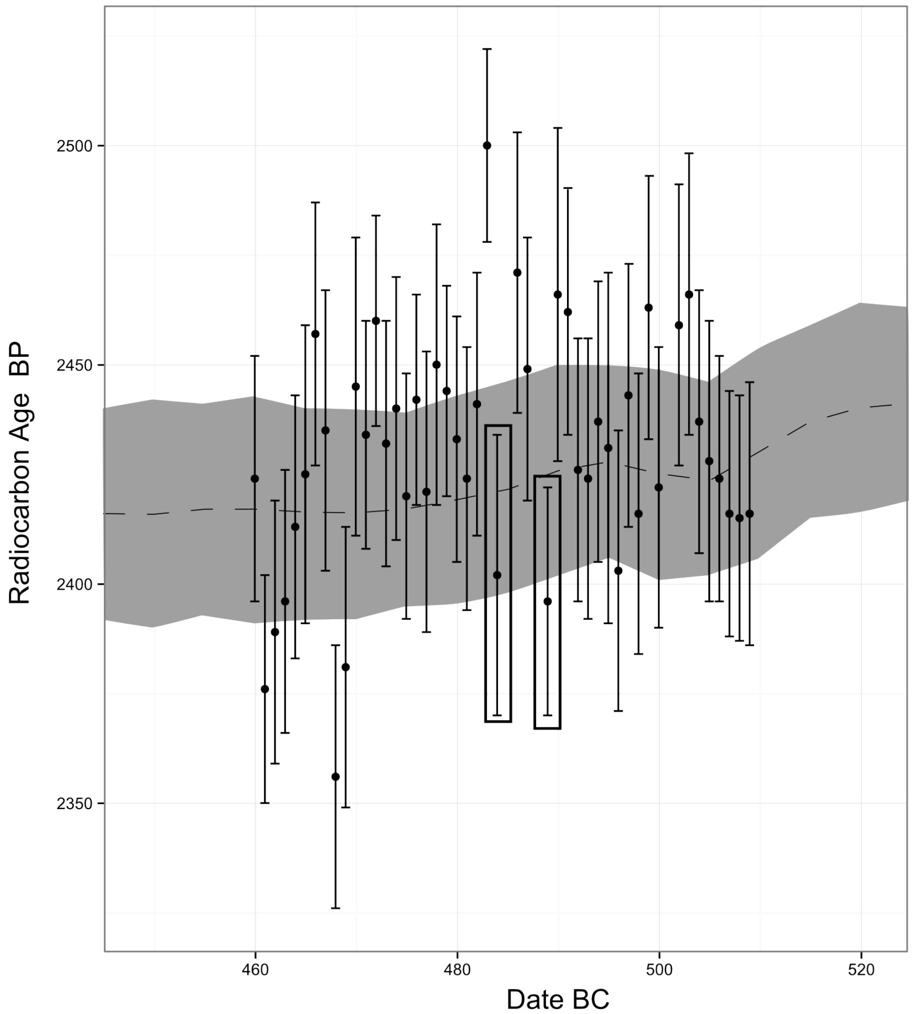



Figure 5.16: T-947 series with the two outliers SUERC-48497 and -48502. Bars represent 2-$\sigma$ error.

## 5.2 Decadal sampling

The results of the T-947 single-ring wiggle-match show that the single-ring approach to wiggle-match dating is impracticable, at least for the time being. The reasons for this become clear when the T-947 data are plotted against the calibration curve (Figure 5.17): although the general location of the match is plausible, the magnitude of the short-term amplitudes exceeds expectation. This section expands on this problem and makes the case for matching the number of rings in each constituent sample of a wiggle-match to the number of rings in the underpinning calibration data. It then evaluates the performance of decadal sample spans through wiggle-matching decadal averages of single-ring data, as well as new decadal measurements of the timber T-947.

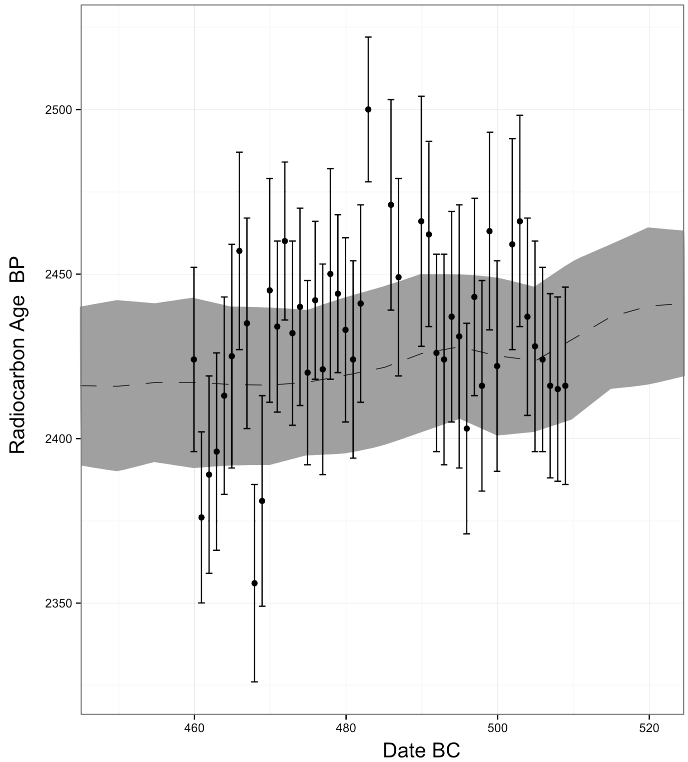



Figure 5.17: T-947 single ring data plotted against the 95.4% confidence interval of the calibration curve after removal of SUERC-48497 and 48502. Bars represent 2-$\sigma$ error.

That the sections of IntCal underpinned by decadal data may underestimate short-term variability of the past radiocarbon record was already recognized by Stuiver et al. (1998), who recommended resolving this issue was to increase the variance of the measurements by 64 $^{14}$C years, which is the square of the average offsets between decadal combinations of QL-single-ring data and the data. Yet, in practice this procedure is insufficient: adding 64 $^{14}$C years to the variances of the T-947 measurements increases the standard deviations of these measurements by only two radiocarbon years. This happens because the method accounts only for the average offset and thus fails to account for the cyclical nature of radiocarbon fluctuations. Nor is T-947 unique in this respect. For example, almost all the single rings from the numerous Japanese studies collecting such data need to be combined into semi-decadal or decadal averages prior to comparisons with IntCal (Sakurai et al. 2006; Suzuki et al. 2010). Likewise, the bi-annual data produced by ETH in Zurich are filtered before comparison with the decadal sections of IntCal (Guttler et al. 2013). Nevertheless, the scale of the excess variability of the T-947 data is still surprising, unless curve construction is taken into account.

Chapter 3.2.4 mentioned how the calibration curve is based on the calibration data and the curve inference algorithm. As far as calibration data are concerned it is important to be aware of their historic context and original purpose. In 1986, when the majority of the calibration data for the mid-first millennium BC was compiled a typical radiocarbon measurement was a bulk charcoal determination with errors oscillating around 1% $^{14}C$, or 80 radiocarbon years. With such uncertainties any offsets in short-lived samples, such as single tree rings, would have been lost in the measurement error. Todays data, however, approach the precision of the calibration data on a routine basis and often surpass it: the measurement errors on the T-947 single-ring series are smaller than those of the UB- and QL- calibration data and comparable to those of UCIAMS-calibration data (see Chapter 3.2.4). As a result, the magnitude of the short-term variability increases relative to the measurement errors and so it becomes a real obstacle to wiggle-match dating.

The nature of the calibration curve algorithm also undermines the efficiency of single ring wiggle-match dating for some periods. As outlined in Chapter 3.2.4, the inference is based on a random walk with a prior drift of one radiocarbon year per calendar year and a standard deviation of eight radiocarbon years. By the very nature of random walks it is impossible to predict its location after a large number of iterations (Isaac 1995), so this prior becomes less informative with passing time. This is a good characteristic as it ensures that all the information about the actual shape of the curve comes from the data, but at the same time it means that the magnitude of the amplitudes in the curve will be conditioned by the data. Decadal tree-ring blocks will have lost between 65 and 100% of the short-term variability introduced by cycles of between nine and fourteen years (Figure 3.8), so this information will be underrepresented in the calibration curve wherever the underpinning data are decadal. Hence, the information on variability in IntCal will match that of the calibration data and so increasing the resolution of wiggle-match samples beyond that level cannot improve the performance of the model. Thus, in the period of interest, decadal samples constitute the optimal sample span.

The performance of decadal sample blocks has been evaluated through radiocarbon measurements of decadal blocks from T-947 and through combining the single-year data into decadal averages. The decadal averages were weighted for analytical uncertainty and ring widths, using a modified approach of Ward and Wilson (1978):

$$A_p = (\sum_{i=1}^{n} A_i \times \frac{W_i}{E_i^2})/(\sum_{i=1}^{n} \frac{W_i}{E_i^2})$$

Wherein $A_p$ is the age pooled from multiple measurements, $A_i$ is the age of an individual measurement $i$, $E$ is the standard error of a measurement and $W$ is the width of the associated ring. The ring-width weighting was implemented as a proxy for variability in the amount of material contributed by each of the rings. The errors for these averages were combined from across the measurements contributing to a given decade and for ring-width, as the larger rings were making a greater contribution to the final result. The irreducible error of eight years suggested in some sources has not been introduced, as it is only applicable as a means of addressing the effects of short-term variability in calibrating short-lived samples (Bronk Ramsey 2013). This is not the case here, as the combinations refer to decadal averages.

The combined data fit the calibration curve well. The agreement index for the entire set is 184.1% (Figure 5.18) and the agreements of the five wiggle-matches constructed to simulate a sampling pattern of decades overlapping every five years are also sufficient (Figure 5.19). However, the match is located between 510 and 475 cal BC (95.4% HPD), 15 years too early to match the target date. This issue will be discussed in depth in the next section.

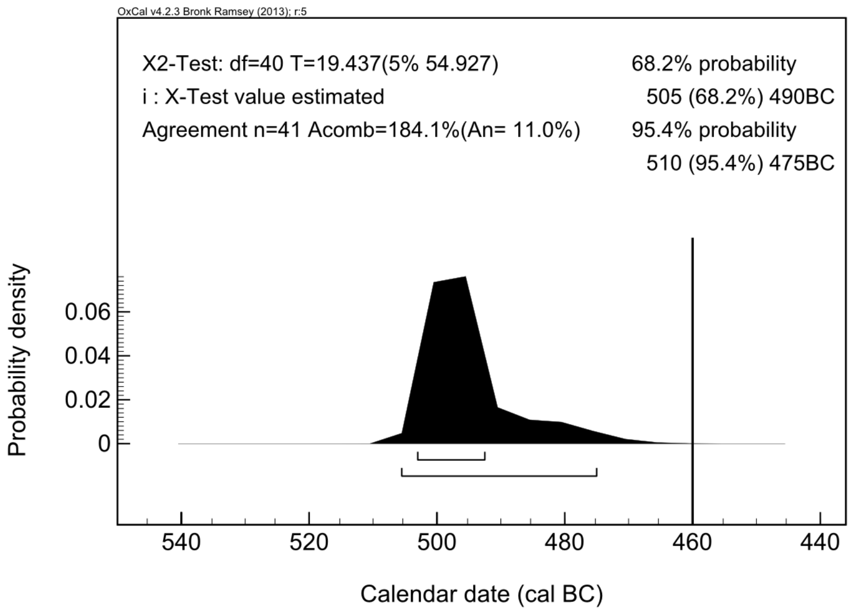



Figure 5.18: Summary results of the wiggle-match on decadal averages of T-947 single ring determinations. Vertical bar highlights the target date of 460 BC.

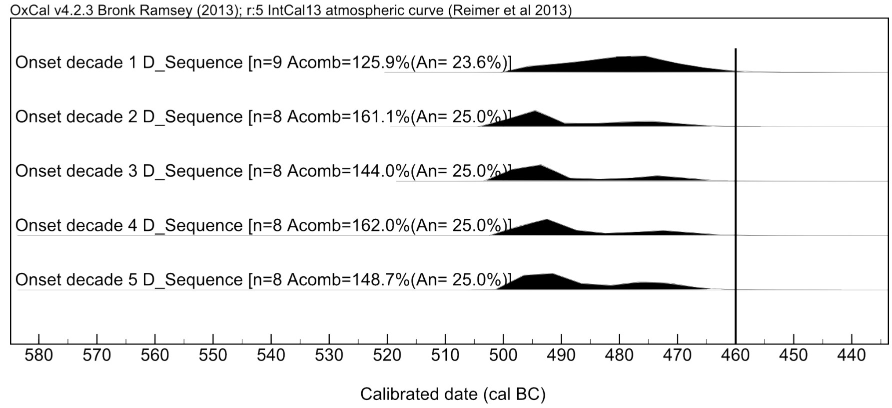



Figure 5.19: Wiggle-matches built from T-947 combined decadal data with five year intervals.

Besides combining the single-year data, the performance of decadal sampling was also explored through a new series of T-947 determinations (Table 5.10). These were intended to validate the performance of the decadal averages of single-ring data and provide information on the usefulness of routine precision measurements in wiggle-match dating on the Hallstatt plateau. The series consists of 17 determinations on ten-ring blocks running from years five through to 94, spaced five years apart giving a five-year overlap between individual blocks and measured in batch 17/14. All of the measurements had acceptable $\delta^{13}$C values, except SUERC-52785 which was lighter than expected for unknown reasons (Figure 5.20). Nevertheless, the result of this measurement is consistent with the group, as indicated by the sensitivity analyses below.

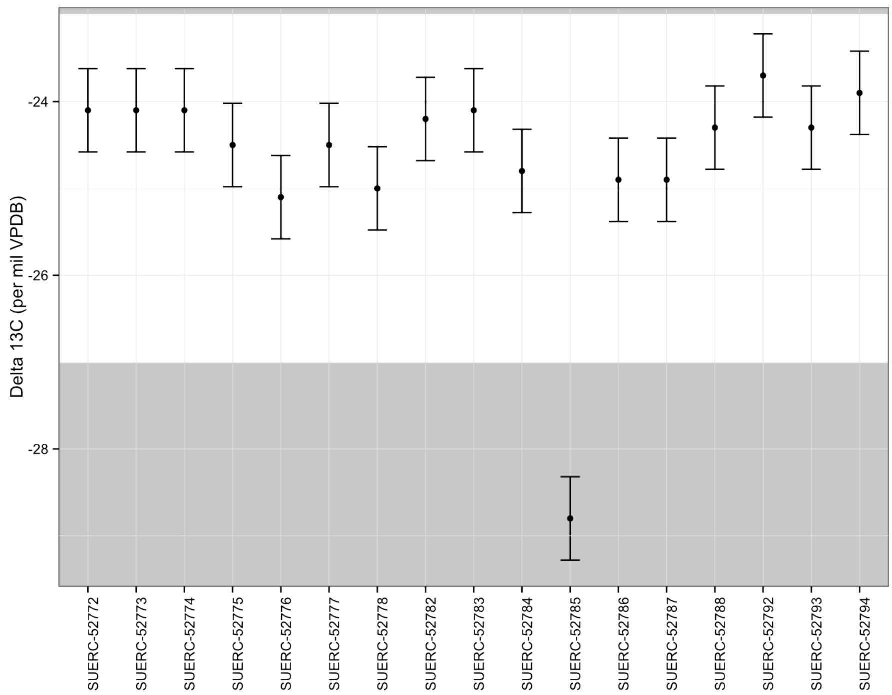



Figure 5.20: $\delta^{13}$C determinations from T-947 decadal ring blocks. Area highlighted corresponds to the range of $\delta^{13}$C value in modern English and south-west Scottish oak corrected for the effects of the industrial revolution.

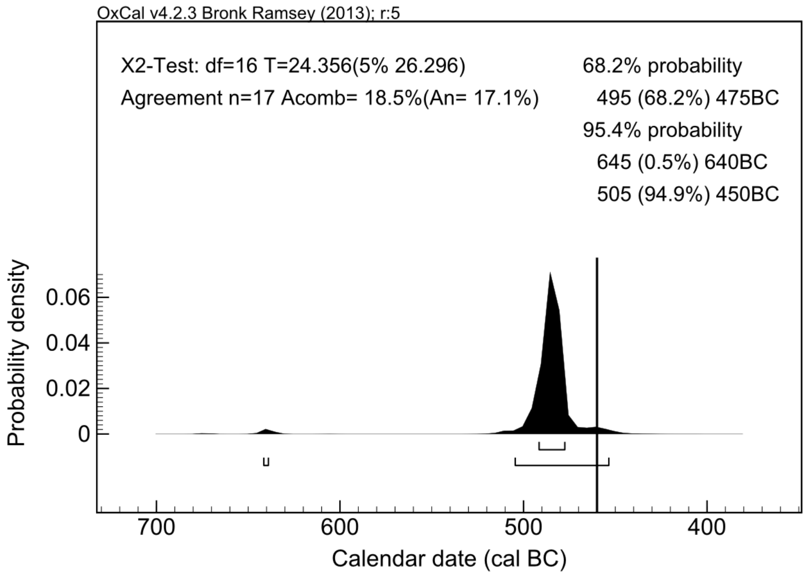
The resulting wiggle-match is similar to that of the combined decadal data (Figure 5.20). The 95.4% HPD area is split into two modes: a minor one between 645 and 640 cal BC (0.5%) and a major mode between 505 and 450 cal BC (92.8%), with

Table 5.10: Results for Cults Loch 3 timber T-947 measurements from batch 17/14.

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 5-14 | 33624 | 52772 | 2431 | 29 | -24.1 |
| 10-19 | 33633 | 52784 | 2440 | 28 | -24.8 |
| 15-24 | 33625 | 52773 | 2397 | 29 | -24.1 |
| 20-29 | 33634 | 52785 | 2424 | 29 | -28.8 |
| 25-34 | 33626 | 52774 | 2497 | 29 | -24.1 |
| 30-39 | 33635 | 52786 | 2461 | 28 | -24.9 |
| 35-44 | 33627 | 52775 | 2454 | 28 | -24.5 |
| 40-49 | 33636 | 52787 | 2492 | 28 | -24.9 |
| 45-54 | 33628 | 52776 | 2395 | 29 | -25.1 |
| 50-59 | 33637 | 52788 | 2435 | 28 | -24.3 |
| 55-64 | 33629 | 52777 | 2486 | 28 | -24.5 |
| 60-69 | 33638 | 52792 | 2486 | 28 | -23.7 |
| 65-74 | 33630 | 52778 | 2489 | 29 | -25.0 |
| 70-79 | 33639 | 52793 | 2418 | 28 | -24.3 |
| 75-84 | 33631 | 52782 | 2508 | 29 | -24.2 |
| 80-89 | 33640 | 52794 | 2463 | 28 | -23.9 |
| 85-94 | 33632 | 52783 | 2414 | 29 | -24.1 |

all of the 68.2% HPD area concentrated between 495 and 475 cal BC. The index Acombine is of 18.5%, above the recommended level of 17.1% and the wiggle-match passes the chi-squared test ($\chi^2 = 24.356$, with the 5% critical value of 26.296 at 16 degrees of freedom).

Given the large amount of measurements included in this wiggle-match, two different sensitivity analyses were applied to it. The first procedure removed single determinations from the model, thus identifying any values which alone control the behaviour of the series as a whole. The aim of these analyses was to assess how sensitive the posterior distribution has been to the removal of particular radiocarbon determinations and hence whether the modelled date range of the wiggle-match can be considered reliable given the possible presence of outliers among the measurements. In the course of this analysis the posterior density of the wiggle-match date developed a substantial subsidiary mode once and suffered from poor agreement with the calibration curve four times. The one significant alteration to the posterior distribution took place after the removal of SUERC-52773, and manifested itself with an emergence of a subsidiary mode within the 68.2% HPD area. This mode spans the period between 650 and 635 cal BC and contains 16.1% of the probability density. Nevertheless 66.1% of the density remains in the period between 520 and 460 cal BC, which is consistent with the original extent of the wiggle-match. The four determinations, whose absence causes failure in the chi-squared test and/or too low agreement, are SUERC-52788, -52787, -52785 and -52772. They have little in common in terms of their relationships with the surrounding dates and best serve to highlight the high dispersal of radiocarbon dates around the calibration curve (Figure 5.22). Yet despite these shortcomings, the wiggle-match date can be considered valid on account of the overall stability of the posterior distribution.



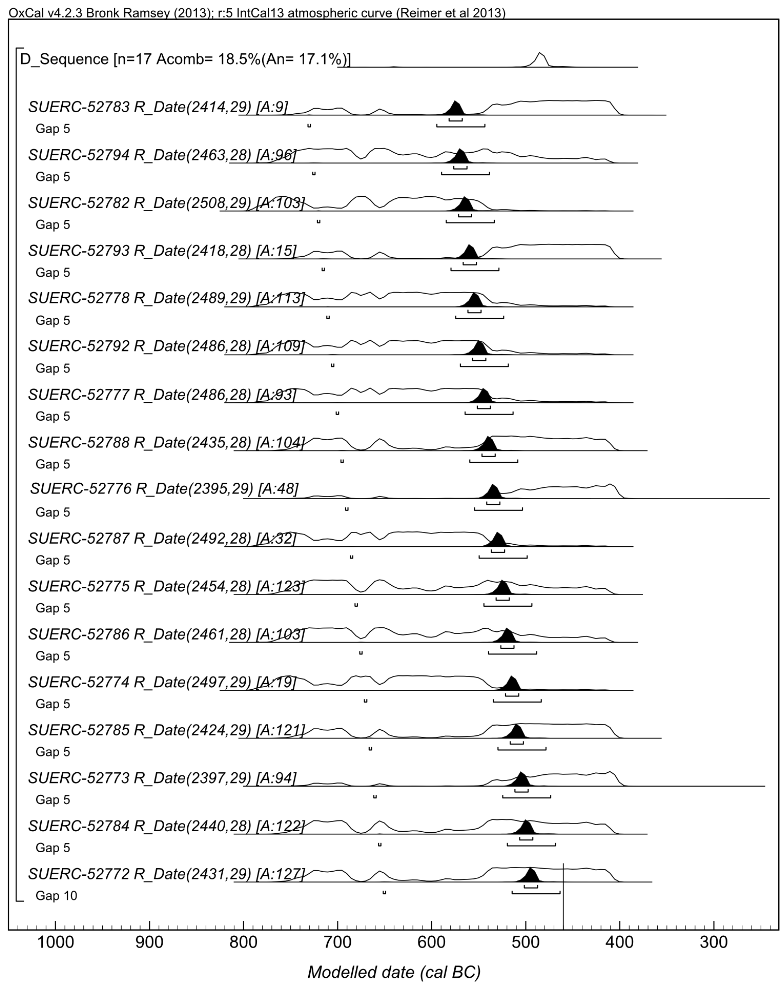




Figure 5.21: The summary result of the wiggle-match on the decadal data of the T-947 rings (above) and the detail of the individual measurements (below). Vertical bar marks the dendrochronological target date of 460 cal BC.

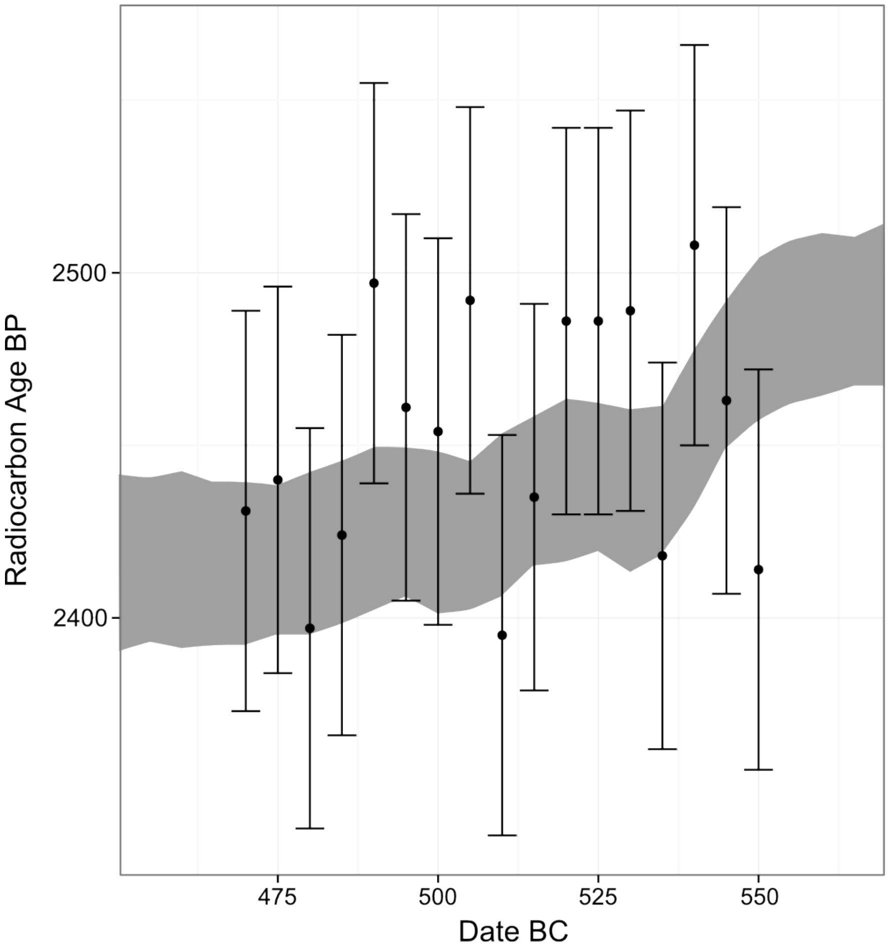



Figure 5.22: Routine precision determinations on T-947 decadal blocks plotted against the 95.4% confidence interval of the calibration curve. Bars represent two standard deviations.

The second procedure divided the match into two separate models, one based on determinations from decades beginning with rings 5, 15, 25 etc., and the second for decades beginning with the rings 10, 20, 30 etc.. The results of this second sensitivity analysis were less satisfactory, with one of the matches suffering from poor wiggle-match model agreement and the other witnessing a substantial change to the shape of the posterior distribution (Figure 5.23). Nevertheless, the areas covered by the calibrated date ranges of the complete wiggle-match are preserved. The combination beginning with the block covering years 5 through 14 suffers a re-distribution of the calibrated date range across multiple modes. The 95.4% HPD area is split into three modes:

1. 680–660 cal BC (5.6%)
2. 655–615 cal BC (30.1%)
3. 520–425 cal BC (59.8%)

The 68.2% HPD area is divided into four distinct modes:

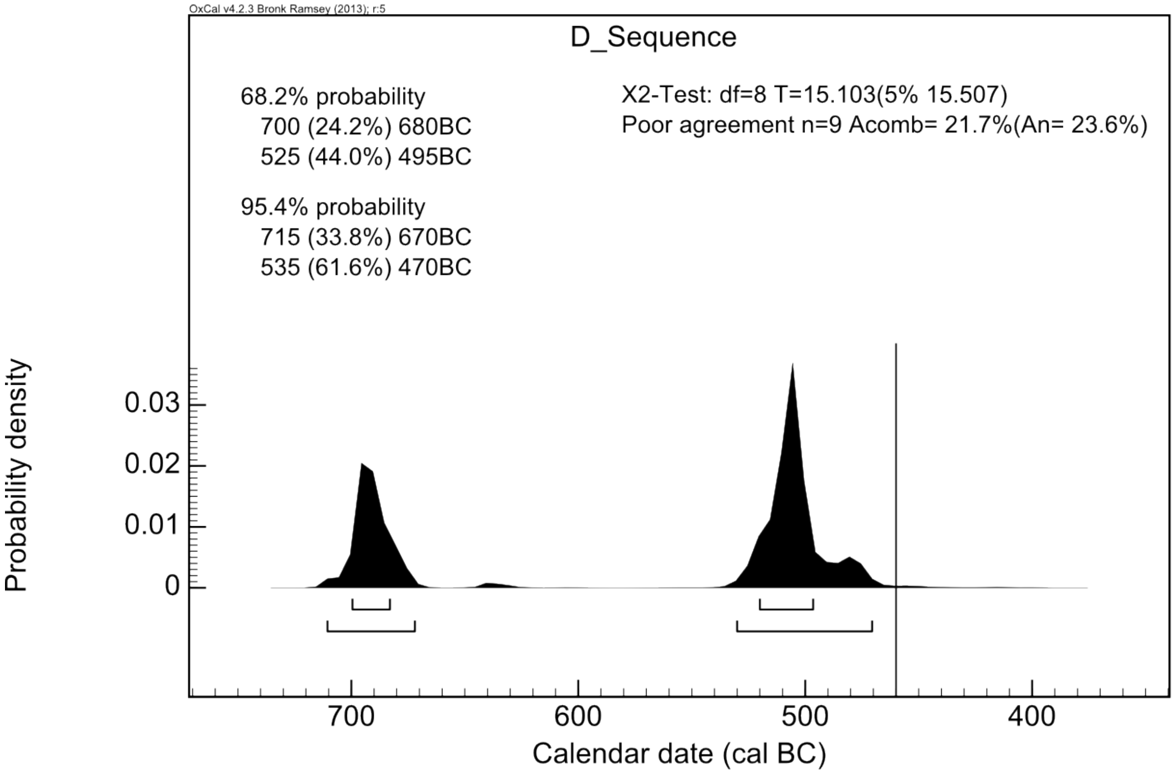
1. 645–625 cal BC (26.5%)
2. 515–495 cal BC (14.5%)
3. 490–470 cal BC (12.1%)
4. 470–450 cal BC (15.1%)

The diagnostic indices are good: the Acomb value stands at 56.4%, thus exceeding the recommended 25% threshold, and the $\chi^2$ statistic stands at 8.591, well under the 5% critical value of 14.067 at seven degrees of freedom. The second combination, beginning with the block covering rings 10 through 19, is more consistent with the original wiggle-match. The 95.4% HPD area is split into three modes, two of which are negligible:

1. 650–635 cal BC (0.8%)
2. 610–600 cal BC (1.0%)
3. 525–445 cal BC (93.6%)

The 68.2% HPD area is continuous and spans the period from 495 to 480 cal BC. The diagnostic indices are good, with an Acomb index of 25.2% (passing value 23.6%) and a $\chi^2$ statistic of 13.513 (5% critical value at eight degrees of freedom is 15.507). In general, these results show that the match is liable to suffer changes to its probability distribution, but at the same time it also demonstrates the persistence of the calibrated date range covering the area in the decades just prior to 460 cal BC.

Both the routine precision decadal data and the combined single-year T-947 data display sufficient agreement with the calibration curve, despite some instability in the former wiggle-match. Comparison of these results to single-year data shows that decadal blocks of tree rings constitute a viable sampling choice for wiggle-matching, at least in the mid-first millennium cal BC, which can be traced to the decadal calibration



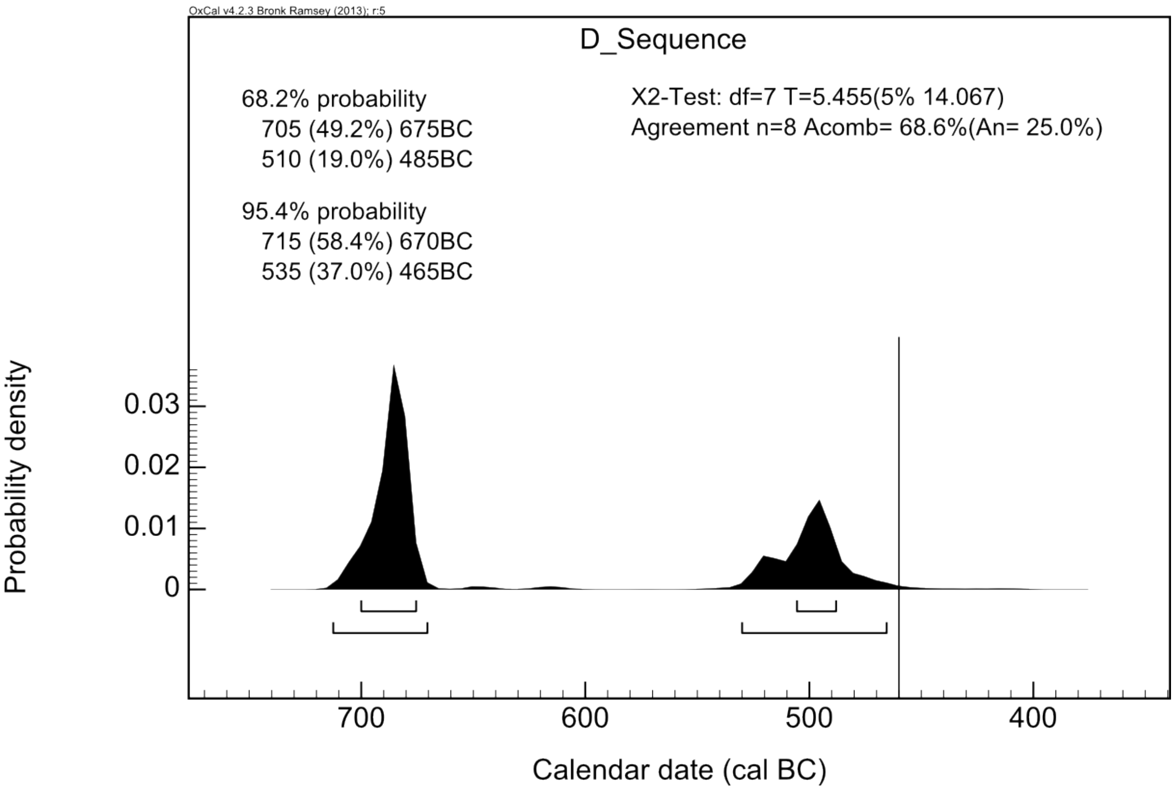




Figure 5.23: Second sensitivity analyses for the T-947. Wiggle-match based on consecutive decades beginning with ring 5 (above) and the match beginning with ring 10 (below). Vertical bar highlights the target date of 460 BC.

data that underpin the calibration curve. Nevertheless, the alignment of the T-947 results with the target date of 460 BC requires further consideration, as the wiggle-match based on decadal averages does not contain the target date and the wiggle-match based on routine precision decadal measurements has a distribution similar to that of the one based on decadal averages and only contains the target date within the tail of the 95.4% HPD area.

## 5.3 Small-scale offsets in wiggle-match dating

Both the decadal radiocarbon measurements and the decadal combination of single-ring dates from the previous section were biased away from the target date of 460 BC. This bias can be traced to small offsets between the actual past trend of radiocarbon and the mean of the calibration curve. These offsets are within the 2-$\sigma$ range of the calibration curve mean, but because they clustered above the mean for several decades, the results of the short-span wiggle-match dates over this period became affected. This would not cause problems for most radiocarbon dating applications and, indeed, they only came to light because of the very high precision of the T-947 results. Nevertheless, for such situations to never emerge the calibration curve would have to be at all times much more precise than the empirical data fitted to it, but this leads us to a situation akin to Dodgson's Red Queen thought experiment (Carroll 1871): because the world moves so fast, the Red Queen has to run just as fast to stay in place. Likewise, the quality of calibration improves on the back of technical improvements in measurement, but these improvements are also applicable to unknown-date samples and so the quality of calibration has to be improved again. This is further complicated by other offset sources that have to be resolved as the precision of calibration improves. As a result, wiggle-match dating research design has to take into account the possibility that the nominal accuracy of wiggle-matches (the 68.2% and 95.4% HPD areas) might become invalid as model precision goes beyond a certain level, at which point small scale offsets start to play a significant part in determining the modelled date range. While some of these concerns may not be of direct relevance to the archaeological problems that will be discussed throughout the remainder of the current thesis, they ought to be kept in mind for future wiggle-match dating research.

### 5.3.1 Autocorrelation and its effects

The offset observed in the weighted decadal averages of T-947 data can be traced to the existence of a difference between the actual path of past radiocarbon variability and the model that is the calibration curve. In general, the fit over the target date is good with the $\chi^2$ test statistics between the curve and the decadal estimates following for the most part the expected distribution (Figure 5.24), but when plotted against the curve it becomes clear that although the decadal averages overlap with the 95.4% confidence interval, they are placed for the most part above the mean of the calibration curve, with a decreasing trend (Figure 5.25). Yet this decrease is misidentified by the wiggle-matching algorithm as the minor break in the calibration plateau around 500 cal BC and therefore drawn to it, leading to the observed discrepancy between the wiggle-match results and the target date.

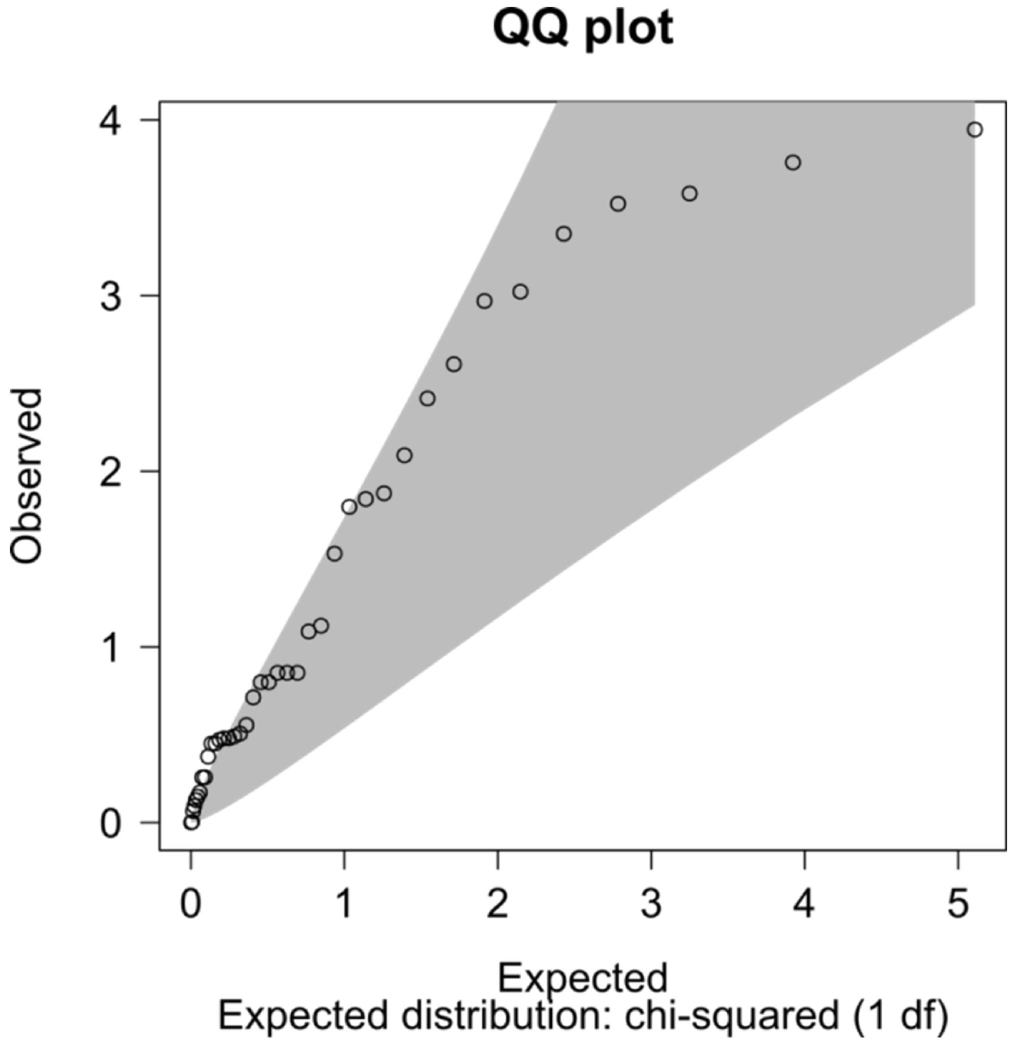



Figure 5.24: Quantile-quantile plot of the $\chi^2$ test statistics between decadal averages of the T-947 data and interpolated IntCal13 values at the dendrochronological point of fit. Despite minor deviations from this distribution for the low values of the test statistics, the overall fit of the data to the curve is within expectation, indicating that there is no significant difference between the decadal averages of T-947 single ring data and IntCal13 at the dendrochronological point of fit.

This discrepancy can be explained through autocorrelation of the calibration curve errors. Autocorrelation is a process whereby a value of a time series at a given instance is dependent on preceding values (Shumway and Stoffer 2011). Such behaviour can be expected in a radiocarbon time series because of the cyclical nature of $^{14}C$ production, and because of the impact of previous years concentrations on succeeding years $^{14}C$ concentration. At the same time the calibration data sets are subject to measurement error. Even if this error is symmetrical, there is a chance that over a group of measurements a number of consecutive determinations will underestimate or overestimate the true values. Once these measurements are built into the calibration curve, the mean of the curve over that period will diverge from the past trend of radiocarbon. The

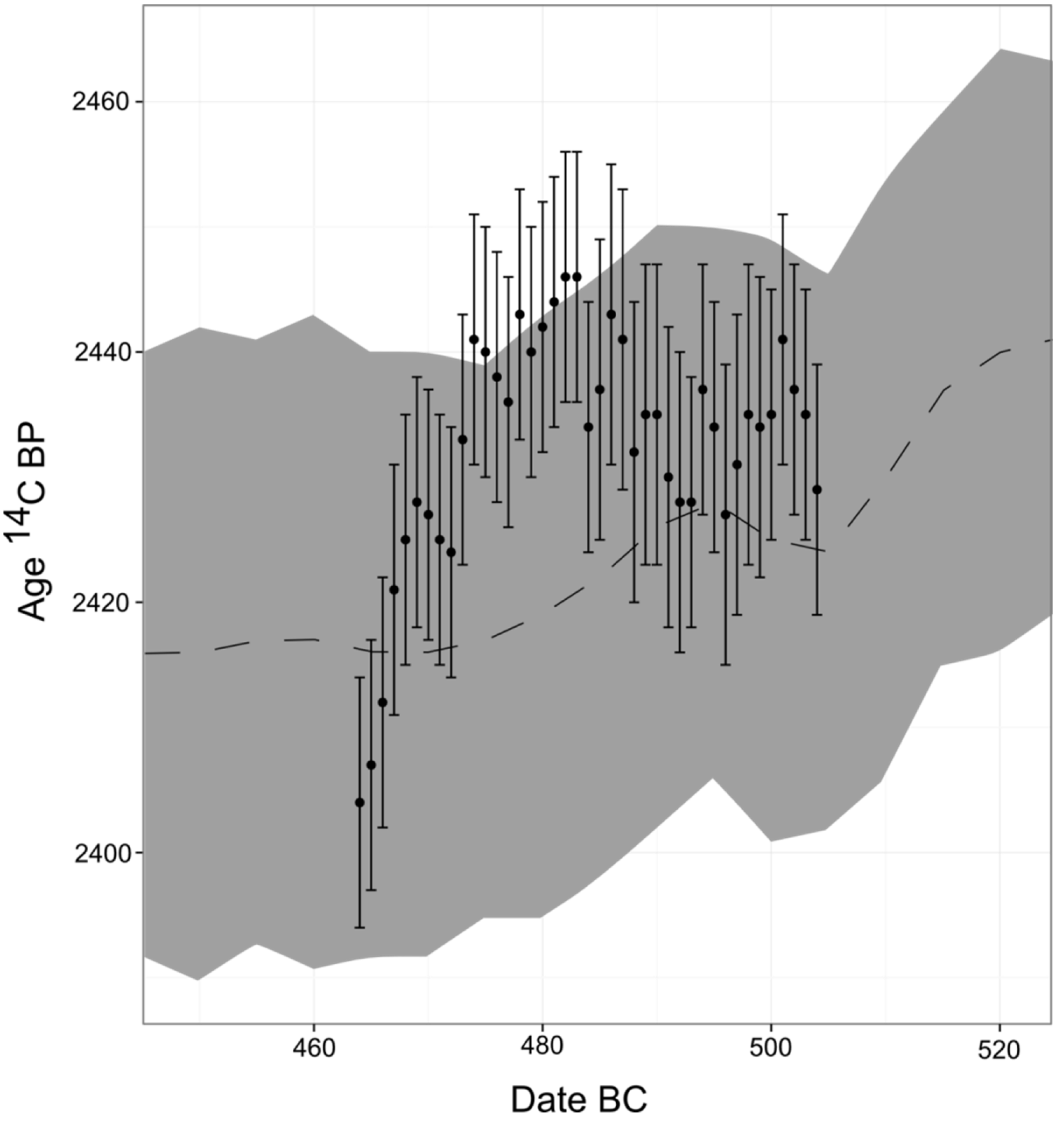



Figure 5.25: Decadal averages of the T-947 single-ring data plotted against the 95.4% confidence interval of the calibration curve. Bars represent two standard deviations.

errors on the calibration curve, understood as the differences between the curve mean and the actual past trend, will then auto-correlate, leading to a temporary asymmetry in the distribution of errors around the mean of the curve. As the wiggle-matching algorithm assumes that no such process is taking place, it will attempt to find a point in time where the measurements will have a symmetric distribution around the curve. Hence, in short-span wiggle-matches there is a potential risk of an offset emerging on the basis of statistical uncertainties inherent in calibration.

This risk of an autocorrelation offset depends on the precision and frequency of measurement on the unknown sample and the calibration data. Decreasing the calibration measurement frequency and the precision should increase the duration and the magnitude of potential autocorrelation based offsets (Figure 5.26). For the unknown sample the converse is true: because the wiggle-match is conditioned by the actual past trend, it will converge toward it as analytical uncertainty decreases and as the number of constituent measurements increases. As long as the uncertainty on the radiocarbon measurements is large enough relative to the uncertainty on the calibration curve, this is not a problem: the amount of information about the actual trend of radiocarbon will be insufficient to induce a significant bias in the model fit. However, as the measurement precision and sampling frequency increase, the description of the actual path improves and the measurements begin to cluster to one side of the curve. This can be observed through simulating wiggle-matches from T-947 decadal estimates, where increasing the precision leads to a clearer distribution to one side of the curve, drawing the wiggle-matches towards 480 BC (Figure 5.27), leading to a paradoxical situation where a greater number of measurements conducted to better precision produce a less accurate and therefore poorer end result. Of course, the results from the measurements on T-947 only indicate that autocorrelation-based offsets are a risk in wiggle-match dating and need not necessarily happen in all cases where short-lived samples are dated – indeed, it would be surprising if such offsets were common enough to affect results on a regular basis. Nevertheless, the presence of the small-scale offset in the T-947 data does mean that it might be prudent to somehow mitigate for the risk of small-scale offsets whenever wiggle-match dating short-lived sequences, in case the particular sample grew on an affected part of the calibration curve.

The interpretation presented here begs the question of why the autocorrelation effect has not been recognized earlier. This can be attributed to measurement precision, statistical models used and explanations alternative to autocorrelation. T-947 decadal estimates provide a much more precise determination of the actual path of the past radiocarbon variability than any published data set for their period. Furthermore, because of the short span of the series, the offset is much easier to recognize than it would have been in a long sequence where the effects of the intermittent biases would cancel each other out and the distribution of the measurements around the calibration curve would become more symmetrical. Most other series are either longer, have their measurements more spread out, or have lower precision and so identifying autocorrelation becomes difficult. For example, the data of Tyers et al. (2009) might be derived from a trend with alternating offsets from the calibration curve mean, but the

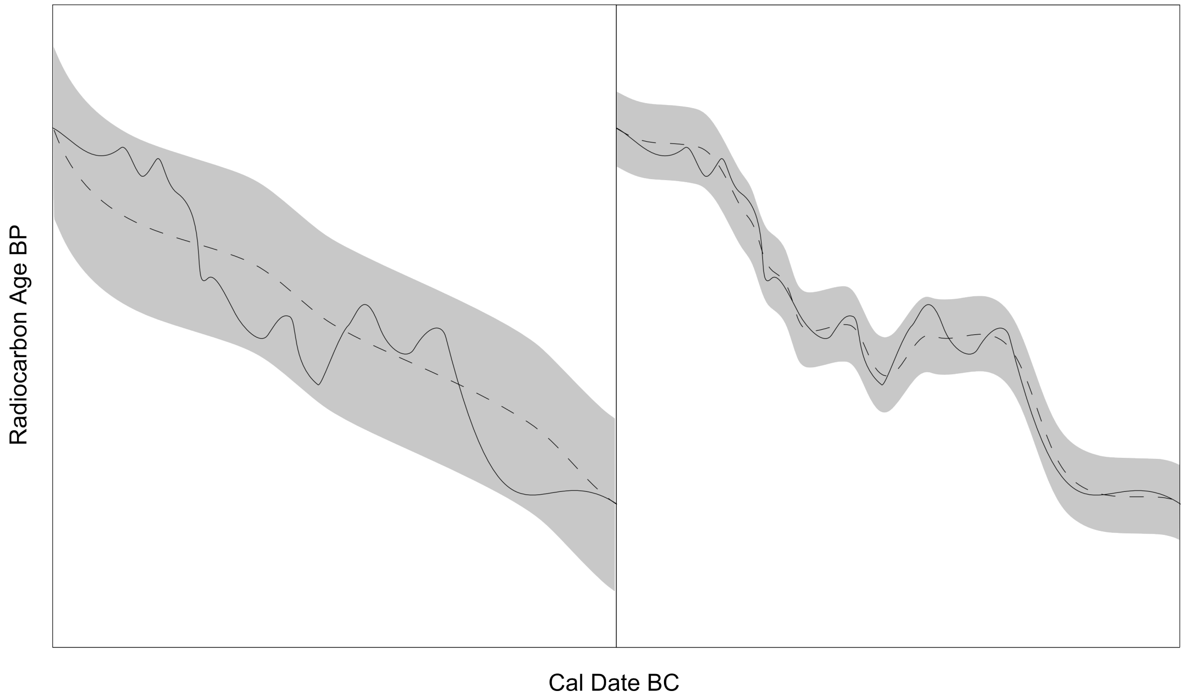



Figure 5.26: Curve precision and autocorrelation. As the precision of the curve is improved, its detail becomes more apparent and hence the probability of the actual trend of past radiocarbon persisting above or below the mean of the curve decreases.

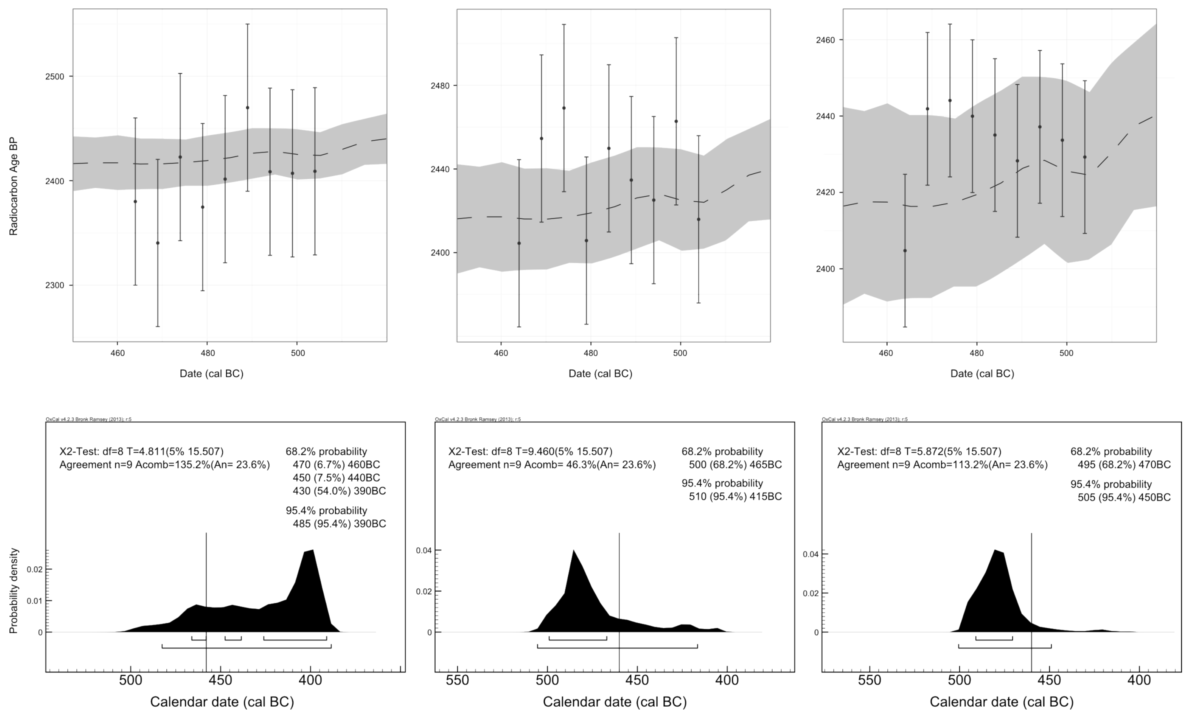



Figure 5.27: Simulates of wiggle-matches from 50 year spans sampled into decadal blocks at overlapping five year intervals at analytical precision of 40, 20 and 10 radiocarbon years at one standard deviation (left, middle and right, respectively). As the precision of individual measurements increases, so does their concentration above the mean of the calibration curve and although the target date might be contained within the 95.4% HPD area, the 68.2% HPD area now has a consistent position towards older dates, indicating bias. Simulations are based on T-947 combined decades. Vertical bar marks the target date. Error bars are at two standard deviations.

analytical precision of the data and their frequency is insufficient to choose between the two models (Figure 5.28). Furthermore, there are also other forms of offsets and because they are subject to more active pursuit, autocorrelations may have been confused with them. In the case of T-947 the confidence that autocorrelation is the causal factor hinges on geographic proximity to Ireland and comparable growth seasons to both Irish and German series, which precludes most offset based on climatic or physical factors (see Chapter 3.2). Nevertheless, these alternative sources of bias need attention whenever wiggle-match dating outwith areas close to the sources of the calibration data.

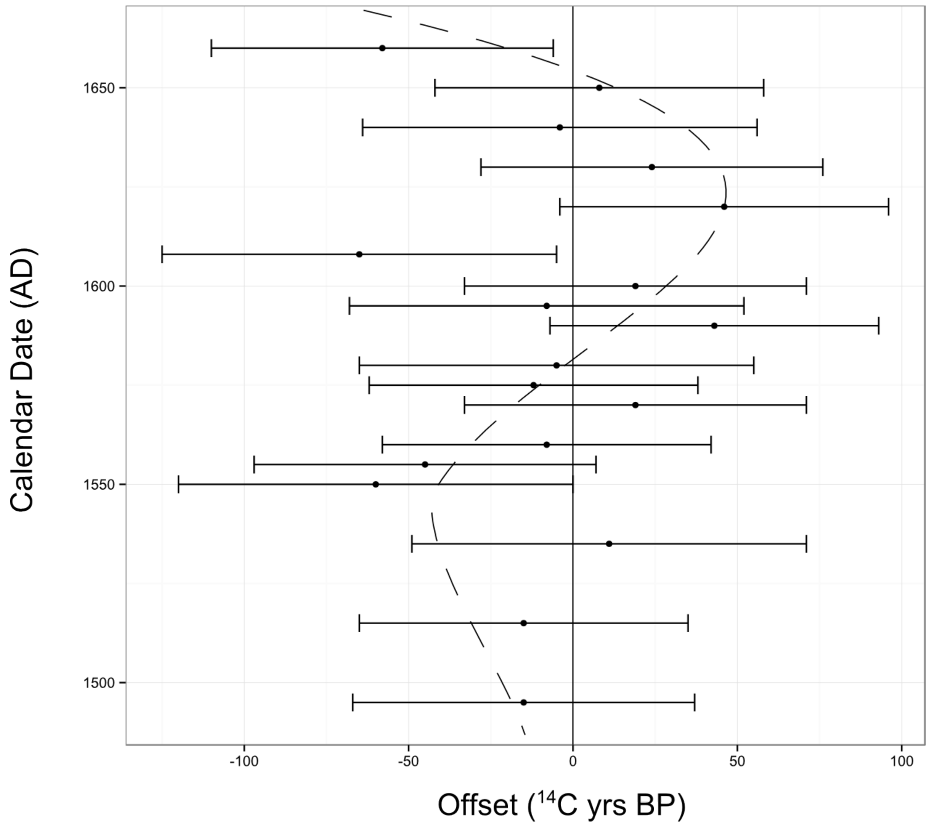



Figure 5.28: Radiocarbon offsets between early modern pine from Jermyn Street (London) and the mean of IntCal13. While for the most part the empirical data overlap with the calibration curve, they are insufficient to reject alternative models (e.g. the one implied by the dashed line). The error bars represent two standard deviations. Data from Tyers et al. (2009).

### 5.3.2 Persistence of biases in wiggle-match dating short sequences

The previous sub-section argued that there is a relationship between measurement precision, calibration curve precision and magnitude of offset to be expected in a dating model. However, there are different kinds of offsets, each of which requires a different management strategy. While not pertinent to the problem at hand, they are relevant to the application of wiggle-match dating in places with different seasonal growth patterns and geographic separation from the origin of the calibration data.

Three provisional kinds of offsets can be defined: analytical, geographic and archive-dependent.

1. Analytical offsets are introduced by measurement errors and statistical effects of the calibration curve construction algorithms, such as the autocorrelation in the T-947 decadal averages. They can be resolved through increasing curve precision. Another form of analytical offset would come from oversmoothing the data by the calibration curve algorithm. As the IntCal algorithm makes its estimates of the calibration curve based on a large number of data surrounding any point of interest (see Chapter 3), there does exist the possibility that, in points of sudden increases in short-term variability, oversmoothing will take place. Indeed, one of the archaeological case studies discussed in Chapter 6 herein may be affected by such offset (see section 6.5.1).

2. Geographic offsets emerge due to a persistent presence of a radiocarbon source or sink pulling the atmospheric concentration at the sampling location away from the global average. In this category inter-hemispheric offsets are of widest importance (Hogg et al. 2009, 2013), albeit in some cases localized offsets can emerge, for example through proximity of vents emitting geologic $CO_2$ (Capano et al. 2013). Geographic offsets will also include transient offsets, such as the intermittent shifts of atmospheric radiocarbon to the southern hemisphere trend in Japan (Imamura et al. 2007; Nakamura et al. 2013), given that they persist over the time-scale of the analysis. They can be resolved either through calibration against local archives, or through modelling the causal processes and updating the curve. Both these strategies have been applied in developing the SHCal curve for the southern hemisphere (Hogg et al. 2013).

3. Archive dependent offsets stem from the nature of the samples themselves. They emerge because different archives develop through different mechanisms, drawing upon different carbon reservoirs and being subject to different mixing rates. The resolution of these offsets can be achieved either through understanding and modelling the effects of their underpinning mechanisms (this procedure was applied in the development of the Holocene marine calibration curve; Reimer et al. 2013), or through taking paired measurements of samples whose carbon derives from different reservoirs (e.g. dating terrestrial animal bone points embedded in remains of humans who had a significant aquatic diet component to difference between atmospheric and aquatic reservoirs in a given location (Cook et al. 2001).

The key difference between analytical, geographic and archive-dependent offsets is that analytical offsets are a function of our technical capacity to produce accurate and precise data and develop appropriate statistical models for it. In other words, with a greater number of more precise calibration measurements and algorithms that limit the artefacts (such as oversmoothing) in the calibration curve, the number of instances in which analytical offsets would have a noticeable effect on the interpretation of data will diminish. Geographic and archive-dependent offsets are objective: they are inherent in the objects studied and their effects become greater as the precision of the calibration curve improves.

Of the two objective offsets, the archive-dependent ones pose the greatest challenge to calibration and force a limit on how far we can improve a wiggle-match or any dating model for that matter. A simple example of an archive dependent offset is dating animal tissues. We know from the human body regenerative map that different tissues have different carbon turnover times (Salephour et al. 2013): blood will be equilibrated with the diet, bone collagen will have several years of delay relative to the diet and neurones, with the exception of a small proportion of cells in the hippocampus, will date the birth of an individual. Hence, the animal organism will consist of a set of different archives with different carbon turnover rates, some of which will no longer equilibrate with the atmosphere. Besides some of the more speculative implications, such as the potential to wiggle-match human remains if sufficient tissue diversity has been preserved, this is important in understanding the resultant models. For example, when building a site model using animal bones, it can be expected that the parameters will be offset by several years. As long as parameter HPD areas are wide, this does little to affect interpretation. However, as the HPD areas are reduced to several decades or less, the offset introduced by the different cycling rates, will have an increasing effect on interpretation.

As the precision of the calibration curve improves, archive specific offsets may become the greatest challenge to wiggle-match dating due to variability in growth seasons. From observation we know that the radiocarbon content of the atmosphere may be subject to seasonal fluctuations, with amplitudes of up to 7‰$\Delta^{14}$C (Currie et al. 2011; Graven et al. 2012a,b; Levin et al. 2013, 2010). This is driven by a number of factors including, but not exclusive to, the oceanic carbon exchange rates (Siegenthaler and Sarmieto 1993), circulation of air from the tropics into the extratropical lower stratosphere and towards the poles (Andrews et al. 2001), or the down-welling of high-altitude air from the stratospheric overworld (Boering et al. 1996; Holton et al. 1995), all of which are coupled with climate in different ways. Hence, the inter-annual changes of radiocarbon discussed so far are supplemented by an intra-annual variability (Figure 5.29). As different tree species will have different growth rates and seasons, and are subject to different environmental stressors (Vaganov et al. 2006), the section of intra-annual variability recorded in tree rings will be dependent on all of the factors mentioned above (Figure 5.30). Until now this has not been a challenge as variability even as high as 0.5‰$^{14}$C (4$^{14}$C years BP) would have been lost in the uncertainties of measurements and the calibration curve. However, the recent results from the eastern Mediterranean demonstrate that we are already capable of detecting archive-specific offsets in plants (see Chapter 3.2.4). Given that some laboratories now consider analytical uncertainty of less than 20 $^{14}$C years to be routine (Szidat et al. 2014), we can expect the effects of these archive specific offsets to become more visible in the coming years.

All of these offsets create a Red Queen-like paradox for wiggle-match dating. As the analytical offsets caused by curve uncertainties are resolved with improvements in the calibration programme, the part played by objective offsets will increase; on a calibration curve with a standard deviation of 12 $^{14}$C years, an archive-specific offset of 3 $^{14}$C years will be a lesser issue than on a curve with a standard deviation of 6 $^{14}$C years. Hence, as the technical capacity to identify the individual Schwabe cycles develops, wiggle-matches will be at risk of producing more biased results due to increasing input of divergences between different archives. So, to take full advantage of the increases in analytical capacity (understood as sample throughput and measurement precision), the calibration curve will need to be intensified and sourced from more diverse locations. But, if the increase in analytical capacity required for calibration improvement is reached, it can also be used for measurements on unknown samples. However, as these will match the precision of the underlying curve, they will become sensitive to any of the underpinning offsets, both objective and analytical. Therefore, taking full advantage of the analytical capacity would then require another extension of the calibration programme that would be possible only through increasing analytical capacity to tackle the greater demands on calibration. But once this increase is achieved, the situation resumes. Hence, wiggle-match dating research design has to make a conscious effort to maintain the accuracy of the results, which can be lost if measurement frequency and precision are increased beyond what is feasible under a given calibration curve. In other words, it is risky to conduct wiggle-matches to the highest possible precision and measurement frequency, as the resulting modelled date ranges may be inaccurate.

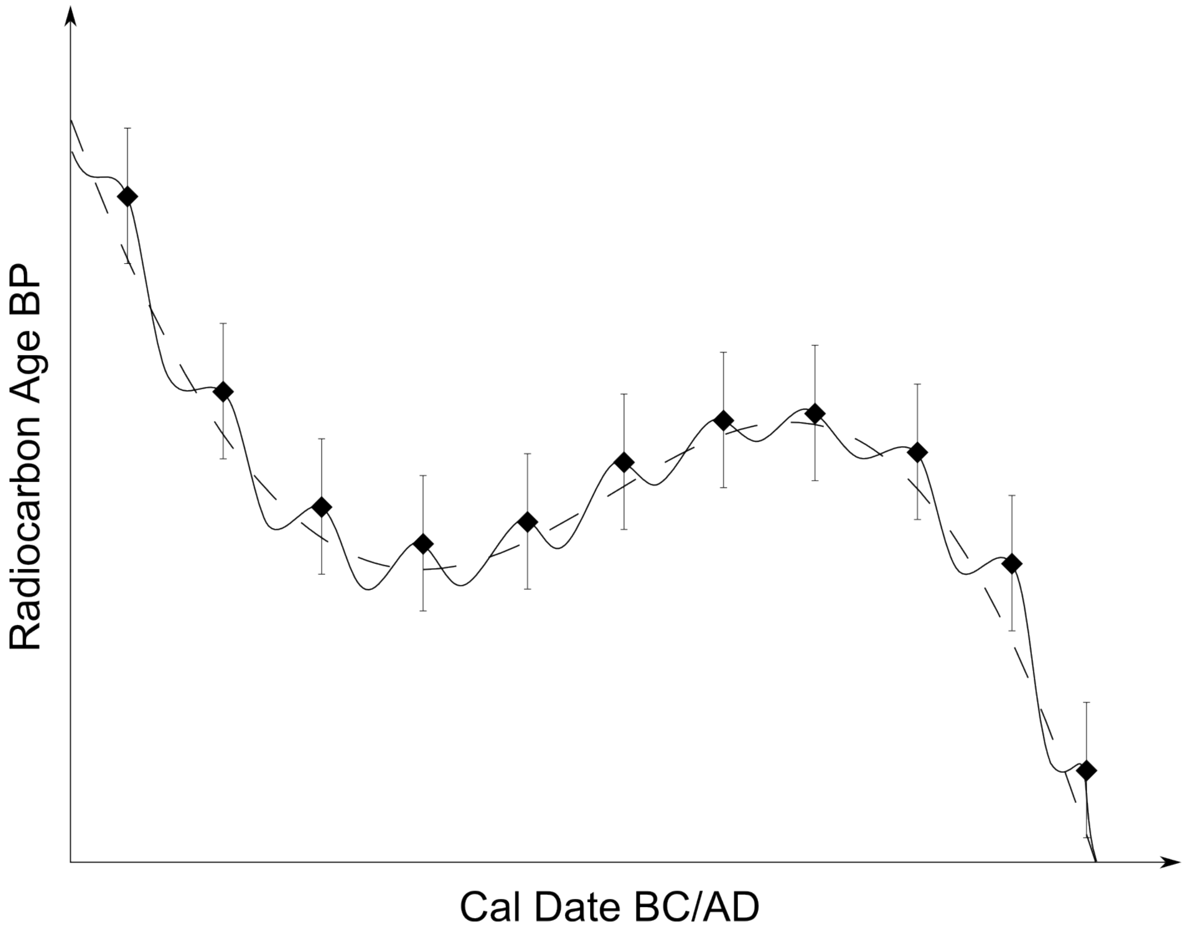



Figure 5.29: Schematic representation of the intra-annual radiocarbon variability (continuous line) over an 11-year solar cycle (dashed line). If an archive is deposited on a seasonal basis, as is the case for tree-ring growth in the temperate zone, there exists a chance that it will overestimate or underestimate the decadal average of a given year on a persistent basis.

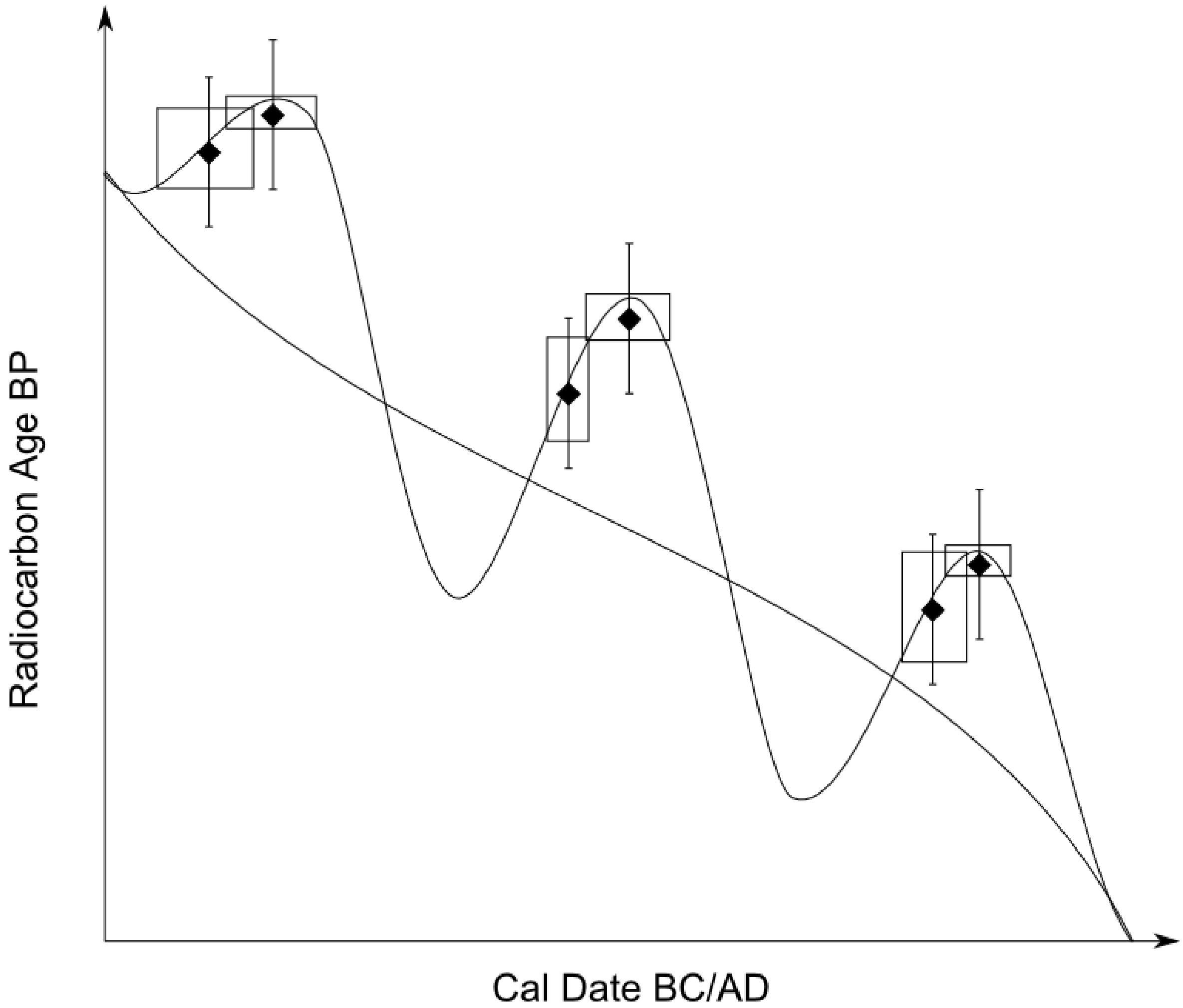



Figure 5.30: Schematic representation of the effects of Intra-annual radiocarbon variability on comparing radiocarbon determinations. Samples collected from archives with different deposition seasons, for example because of differences between tree species, will contain records of different atmospheric radiocarbon concentrations. If the difference between these concentrations is large enough relative to the measurement uncertainties, a systematic offset may develop.

## 5.4 Chapter conclusions

The analyses presented in the current chapter had their origin in the geometric intuition that single-ring data are best suited to wiggle-match dating short tree ring sequences. Hence, 50 consecutive rings of a known-age timber T-947 were dated to evaluate whether this is true for the Scottish Iron Age. After resolving the technical difficulties relating to the measurements themselves, it became clear that the single-ring data contains more short-term variability than what is included in the calibration curve based upon decadal and bi-decadal blocks of wood. These results demonstrated that, as far as archaeological applications of wiggle-match dating are concerned, there is no clear gain in increasing the sampling resolution to more than that of the underlying calibration data (hence decadal sampling is optimal for the Scottish Iron Age). What also became clear, however, is that for several decades in the early fifth century cal BC the mean of the calibration curve is lower than the past trend of radiocarbon, leading to the risk of small-scale offsets in the results. These biases do not, however, preclude improving the performance of wiggle-match dating: they only point out that there is a point beyond which precision will be gained at the cost of accuracy. Therefore, there ought to exist a sample space of measurement frequencies and analytical precisions within which offset magnitude is negligible. This was illustrated in Figure 5.27 where wiggle-matches constructed from simulations of routine precision measurements have covered the target date within their calibrated date ranges, even though some of the bias is retained, much the way it has been present in the decadal measurement series. However, because the number of measurements involved is smaller, and because their precision is much lower, the measurements on the hypothetical unknowns should no longer "float" within the calibration curve, and so the extent to which they are pulled onto the mean of the calibration curve should also be lower. The resulting wiggle-matches will have lower precision, however they also ought to be more reliable. A further benefit is that these less precise wiggle-matches will also be less expensive and hence it becomes possible to date a larger number of timbers within the same budget. This larger number of more reliable (but less precise) wiggle-match dates can then be included within Bayesian models to obtain a more holistic description of archaeological sites and, in some instances, to regain some of the lost precision. Such an approach is, of course, nothing more than a practical mitigation of a deeper problem of offsets from the calibration curve, a problem which, in the long run, ought to be addressed by improved methods of statistical analysis, better data sets, and the improvements in the understanding of production and cycling of radiocarbon, so as to develop a systematic way of dealing with archive-dependant and geographic offsets. Nevertheless, such comprehensive solutions are far beyond the sccope of this project and the research capacity of any single archaeological funding agency and hence, at this point in time, research into the chronologies of Scottish wetland sites needs to accept that there are limits to how precise short-span wiggle-matches can be before they begin losing accuracy.

# 6 Practice: Application of wiggle-match dating to Scottish wetland sites

Chapter 5 argued that wiggle-match dating can produce reliable results, even if small-scale offsets from the calibration curve are present. Nevertheless, this notion alone cannot provide suitable guidelines for the implementation of wiggle-match dating to a specific group of sites  this can only be achieved through the discussion of actual case studies. The current chapter discusses six such case-studies: the analyses of legacy dates from loch Arthur and Dormans Island and the new wiggle-match dating projects at Black loch of Myrton, Cults Loch 3, Dumbuck and Erskine Crannog (Figure 6.1). From these analyses three main conclusions emerged: 1) for most cases (but not all), wiggle-match sampling ought to take place within a feature-oriented framework; 2) research design ought to assume that complications related to timber re-use and other site-formation factors will appear and hence it should retain flexibility to allow for this fact; and 3) the relationship between site formation processes and archaeological questions is paramount and has to be reconsidered at every step of project design.


Figure 6.1: Locations of sites discussed throughout this chapter. Modified from: https://commons.wikimedia.org/wiki/File:Scotland_location_map.svg.

Feature-oriented sampling is concerned first and foremost with establishing a set of modelled date ranges for an associated group of material to a precision sufficient for the archaeological question at hand. An example of such an approach would be distributing the available measurements across two timbers from a single structural feature, rather than focussing them on a single log, or dispersing them to two timbers from different parts of the site. Without this procedure, timbers with unusual dates may skew interpretations of sites and create the illusion of multiple phasing.

Complexities of wetland site formation processes trigger the need for flexibility in research design. During the dating of both Black Loch and Cults Loch 3, the original simulation-based designs had to undergo significant alterations, either through the need to better understand the relationships between specific timbers, or through the emergence of new subsidiary objectives that had to be achieved before the project aims could be fulfilled. In practice this calls for iterative sampling, whereby only a part of the available dating resources is spent at any one time, as the key characteristics of the site are being explored.

Both of these concerns, feature-oriented dating and design flexibility, stem from the relationship between archaeological questions and the formation process of a given site. In essence, it is impossible to answer a question that requires information rendered unavailable by the sampling pattern applied, the excavation methods used, or the loss of contexts through erosion and other processes. This relationship, however, also takes subtler forms; for example, there always exists a possibility that some of the timbers comprising a part of a structure have been sourced from an older building and not felled for the purpose of new construction. It is because of such instances that feature-oriented sampling is so important to a comprehensive understanding of the dating of wetland sites. At the same time, there are situations where the relevant information can be obtained without such sampling designs, or when a particular question does not require feature-level information. Hence, utmost attention needs to be given to the relationship between the postulated questions and the site formation processes to avoid the risk of falling into a routine sampling pattern that may not be optimal for resolving the archaeological problem at hand. It is also the archaeological questions that constitute what classes as good precision; for some questions date ranges of several centuries may be sufficient, while for others annual precision might prove essential.

The chapter consists of six main sections. The first section introduces the concepts outlined above in more detail through exploring them in the legacy data from Dormans Island in Galloway and Loch Arthur in Dumfriesshire. The limited extent afforded by the legacy data permits a clearer exposition and also stresses the need for adjusting the questions asked to the data available and achievable model precision. The second section introduces aspects of wiggle-match stability and systematic bias in decayed wood, as well as shrinkage; these are the main technical issues that recurred in the wiggle-match based case studies. The third section reports on Block Loch of Myrton in Wigtonshire, Galloway, where the archaeological aims were to derive a date for the construction of the site and hence place it within the regional sequence. The case study highlights the advantages of iterative sampling and demonstrates the need to be ready to go beyond original research design in the number of samples commissioned, as the sampling designs that work in simulation might not be sufficient to resolve ambiguities of applied research. The fourth section summarizes the wiggle-match dating project conducted at Cults Loch 3, also in Galloway. Here more ambitious aims were pursued, with the focus on establishing relative chronologies in a context with instances of possible timber re-use during the Hallstatt plateau. The fifth section reports on the results of the wiggle-match dating of Dumbuck and Erskine Crannog, the two exposed intertidal platforms in the firth of Clyde. These case studies demonstrate that off the Hallstatt plateau it becomes possible to use wiggle-match dating to not only address overall dating, but also site formation processes. The final section concludes the chapter.

## 6.1 Legacy dates from Loch Arthur and Dormans island

The introductory section of this chapter outlined the notions of feature-oriented sampling, design flexibility and the relationship between the data and the archaeological questions. The analysis of legacy dates from Loch Arthur and Dormans Island puts feature-oriented sampling and the question-data relationship into context. At Loch Arthur, the limited dating evidence, consisting of single un-stratified radiocarbon dates from a period of calibration ambiguity, as well as the lack of feature-oriented dating, meant that specific questions regarding the site formation process could not be answered. However, the distributed nature of the sampling justifies an assertion that the crannog mound had accreted sometime in the second half of the first millennium cal BC. At Dormans Island, where almost all of the dating effort focussed on a single structural element with several precise dendrochronological sapwood estimates, the opposite is true: a very clear picture of the chronology within this structural grouping was possible, alongside the identification of a timber that may have been re-used. At the same time, the focussed nature of the dating precluded providing answers as to the history of the site as a whole.

### 6.1.1 Loch Arthur

The Loch Arthur crannog (NGR NX 9028 6898) is located in the Loch of the same name in the parish of New Abbey, Dumfries and Galloway. The site, first recorded in the 1870s by Gillespie (1876) and then re-excavated by Williams in 1966-7 (Williams 1971), consists of both submerged deposits, as well as a section located on a small island. The location was inspected several times during the South-West Crannog Survey (SWCS) and, when ongoing erosion became evident, a small-scale excavation was undertaken (Henderson and Cavers 2011).

The work took place in 2003 over the eroding submerged sections of the site (Trenches 1 and 2) and above the water line (Trench 3; Figure 6.2). Trench 1 lay in depths of between 2.5 and 3.5m of water. The excavated area consisted of possible midden deposits within a matrix of over 50 alder timbers laid down at angles of about 60°. No vertical piles were identified. Trench 2 (Figure 6.3), lay in about 0.75 m of water. The timbers, once again, displayed similar 60°angles. The natural loch bed was reached after 0.95m of excavation. The third trench was placed on the island above the crannog mound. After breaking the topsoil, a significant amount of stone was encountered, as well as a glazed pottery sherd, securing the late medieval dating of these remains. Underneath, inorganic loch silts were encountered and below them a set of parallel waterlogged alder logs, interpreted as a floor.

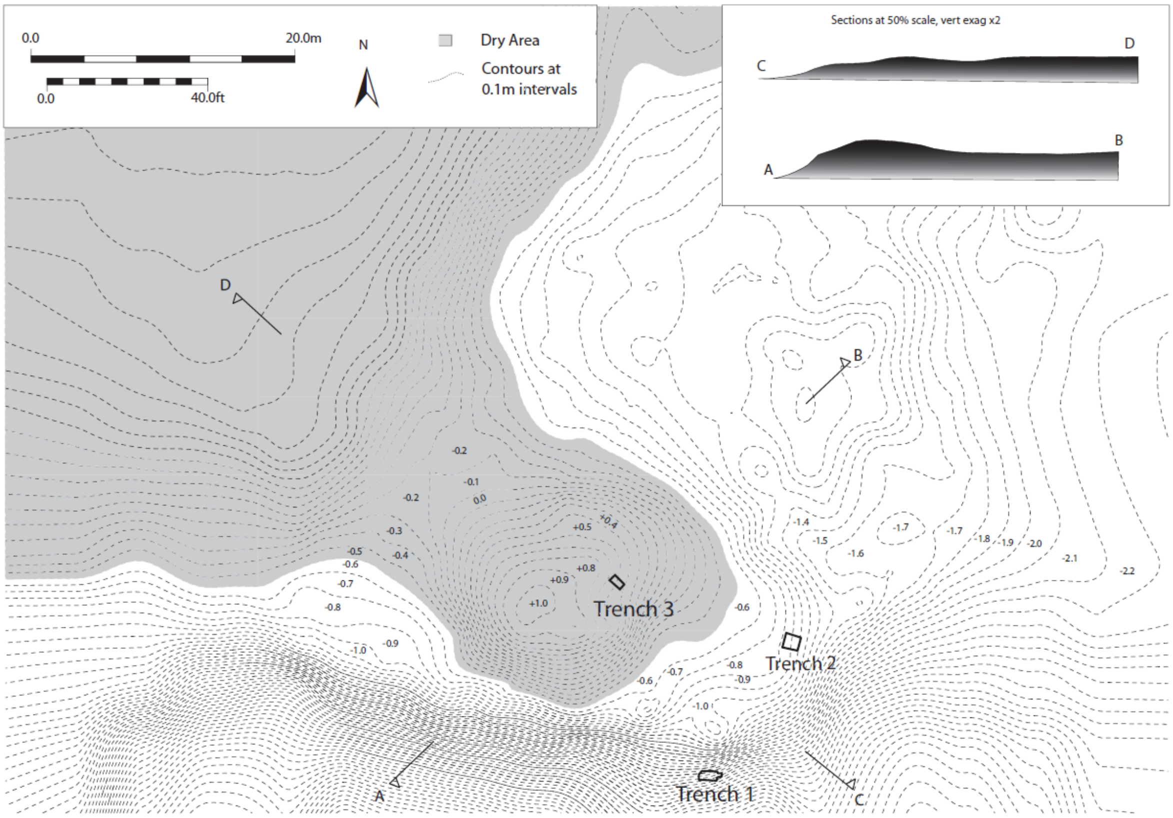



Figure 6.2: Plan of the crannog at Loch Arthur with trench locations indicated. From: Henderson and Cavers 2011, Illustration 2

The excavators collected three samples for radiocarbon dating, one from each trench, which supplemented the earlier dates from an early 1990s survey Table 6.1. The samples were collected from the outermost rings and pre-treated with a hot acid wash, two alkali washes and concluded with a second acid wash. The early 1990s samples were converted to benzene and measured by liquid scintillation (Noakes et al. 1965). The more recent samples were measured by accelerator mass spectrometry (AMS) using the same procedures as the measurements collected for the current thesis (see Chapter 3).

The two questions asked of this data set are:

1. When was the mound constructed?
2. Are the timbers forming the mound contemporaneous, hence providing support for the notion that the mound was constructed in a single event?

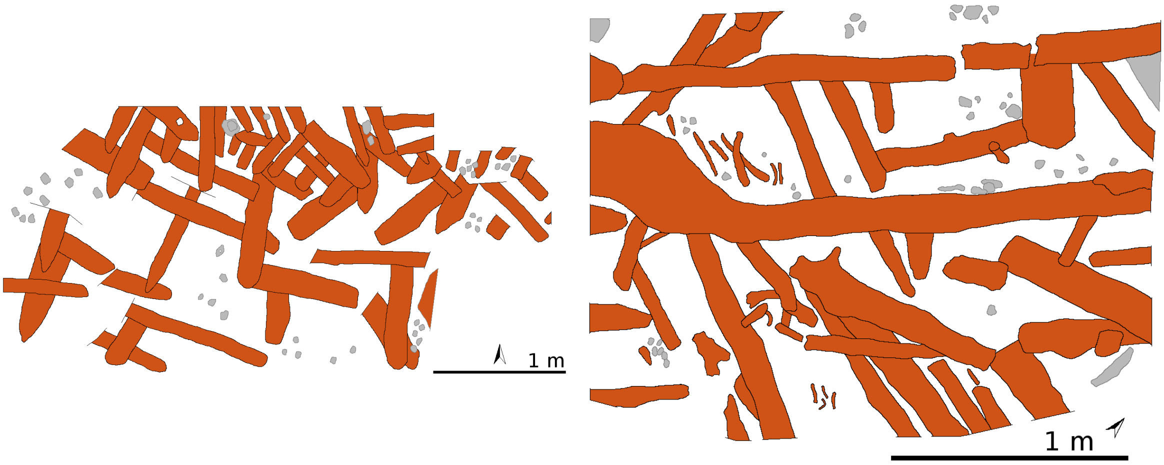



Figure 6.3: Plans of Trenches 1 (left) and 2 (right) from Loch Arthur, re-drawn from Henderson and Cavers 2011, Illustrations 3 and 6

Table 6.1: Legacy radiocarbon dates from Loch Arthur. From Henderson and Cavers 2011, Table 1

| Context | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| Survey | *Betula sp.* | 2643 | N/A | 2260 | 50 | -28.0 |
| Survey | *Betula sp.* | 4644 | N/A | 2240 | 60 | -28.5 |
| Trench 1 | *Alnus sp.* | 12173 | 2989 | 2240 | 35 | -29.2 |
| Trench 2 | *Alnus sp.* | 12174 | 2990 | 2275 | 35 | -28.7 |
| Trench 3 | *Alnus sp.* | 12175 | 2991 | 2215 | 35 | -28.2 |

The resolution of these questions was sought through a bounded uniform phase model that only sought to estimate the onset and termination of the depositional activity (to answer the first question), as well as its duration (to answer the second question)(Figure 6.4).

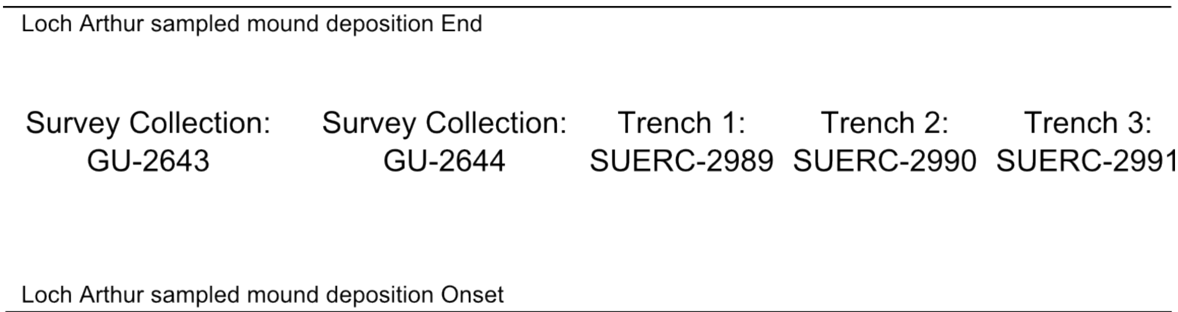



Figure 6.4: Schematic representation of the model estimating the formation of the mound of Loch Arthur crannog.

The Bayesian model succeeded in identifying the overall chronological placement of the Loch Arthur crannog mound, but failed to resolve the question of how long it took for these timbers to be felled (Figure 6.5):

- The results of the model estimate the onset to *460–225 cal BC (95.4%)*, with the 68.2% range distributed into two modes: *405–360 cal BC (23.4%)* and *320–250 cal BC (43.9%)*.

- The deposition of timbers would have ended in *380–140 cal BC (95.4%)*, with the 68.2% range once again broken into two modes, *365–350 cal BC (4.8%)* and *280–190 cal BC (63.4%)*(Figure 6.5).
- The span is estimated to *0–150 years (95.4%)*, with the greatest probability in the range *0-65 years (68.2%)*. The median is *35 years* (Figure 6.6).
- The model agreement is good (Amodel = 109.6%).

The boundaries for the deposition of the timbers are unequivocal in that they place the site in the second half of the first millennium cal BC, thus making it possible to link the mound formation to Iron Age activity in the region, but making it separate from the medieval deposits on top. The span of the deposition lacks precision necessary to aid the resolution of the archaeological question of wheter the mound was deposited in a single event. The position of the median indicates that there is about a 50% chance that the deposition would have happened in the course of just over a generation, but this is too indecisive.

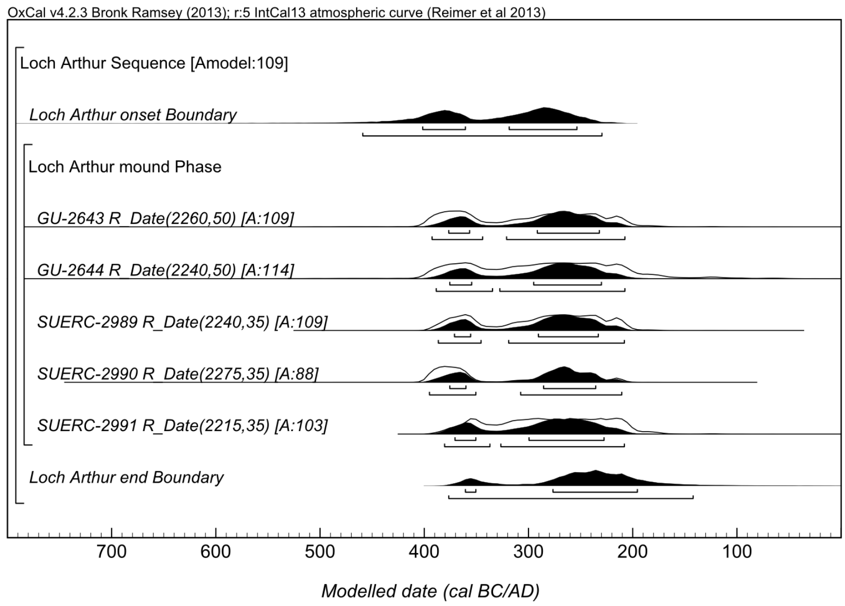



Figure 6.5: Results of the Bayesian analysis of the timbers forming the mound of the Loch Arthur crannog.

The cause of the ambiguity regarding the deposition span is clear from the perspective of the calibration curve (Figure 6.7). The tight cluster of ages cuts through the drop from the calibration plateau and across the major wiggle around 250 cal BC. Hence, each one of these dates has two possible interpretations and, given the archaeological evidence, there is no means of distinguishing between them. In other words, the precision required to state whether the mound was built in a single event, has not been achieved because the calibration curve at this point in time makes it unattainable with such a small research investment.

This leads on to the more general issue whether the question of the deposition span in this situation can be resolved by modelling single radiocarbon dates using an uninformative prior. Simulation evidence shows that on some parts of the wiggle between

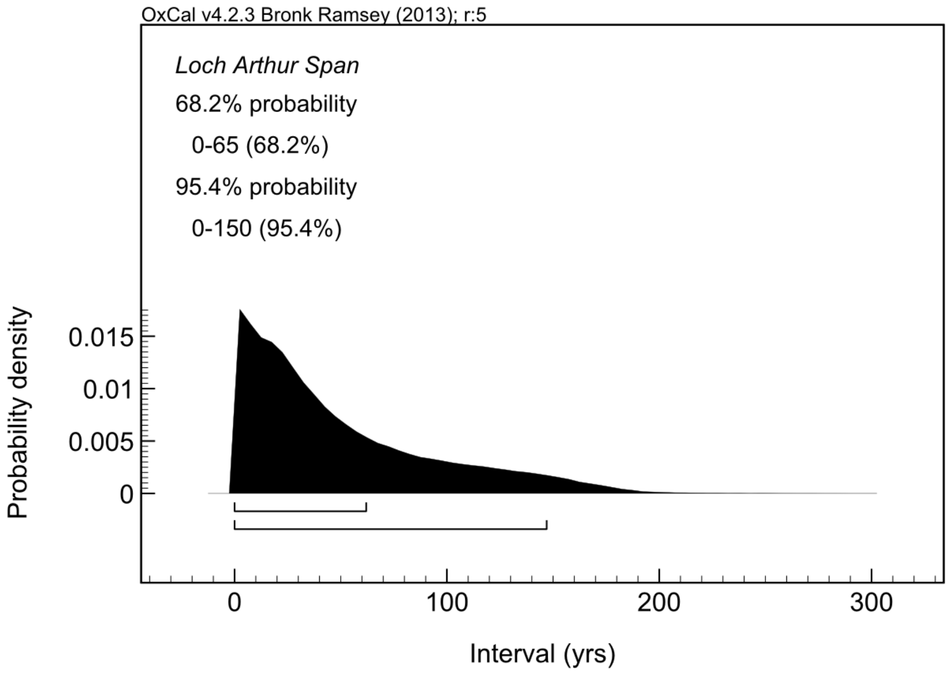



Figure 6.6: Estimated felling span for the timbers from the mound at Loch Arthur crannog.

400 and 200 cal BC increasing the number of measurements cannot resolve this issue (Figures 6.8 to 6.9) and while this might not be the case for all of this period, it still means that pursuing this model carries with it an inherent risk of failure regardless of investment. However, if wiggle-matches are used instead of increasing the number of individual determinations, it becomes possible to resolve these uncertainties, as the shape of the calibration curve between 400 and 200 cal BC is conductive to wiggle-match dating (Figures 6.10 to 6.11). Thus, there exists a possibility that the question about the length of time over which the timbers from Loch Arthur have been felled may only be answered if an appropriate dating and modelling techniques are involved, regardless of the amount of the data collected.

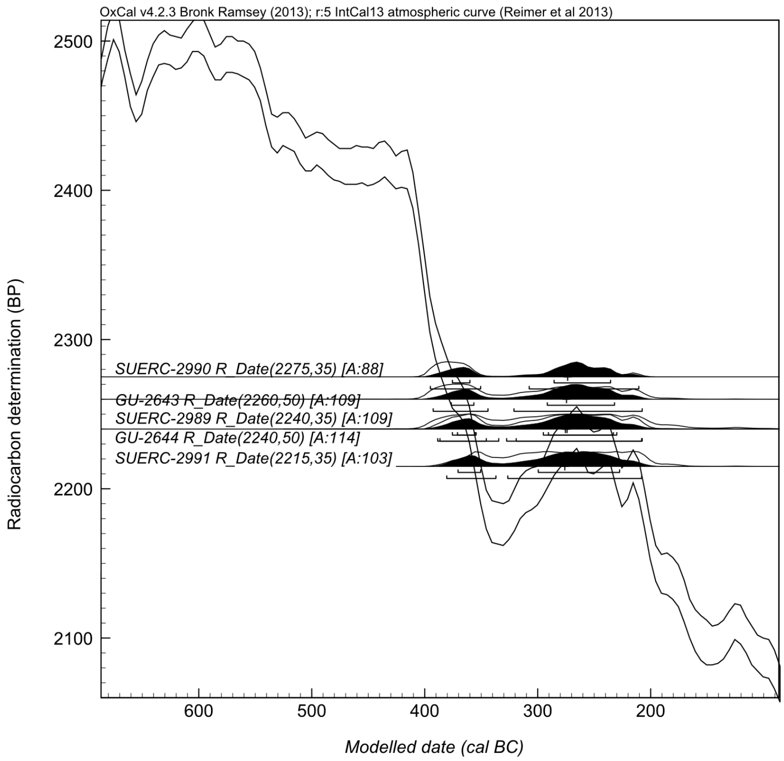



Figure 6.7: Modelled date ranges from Loch Arthur plotted against the calibration curve. Note the effect of the large wiggle between 400 and 200 cal BC.

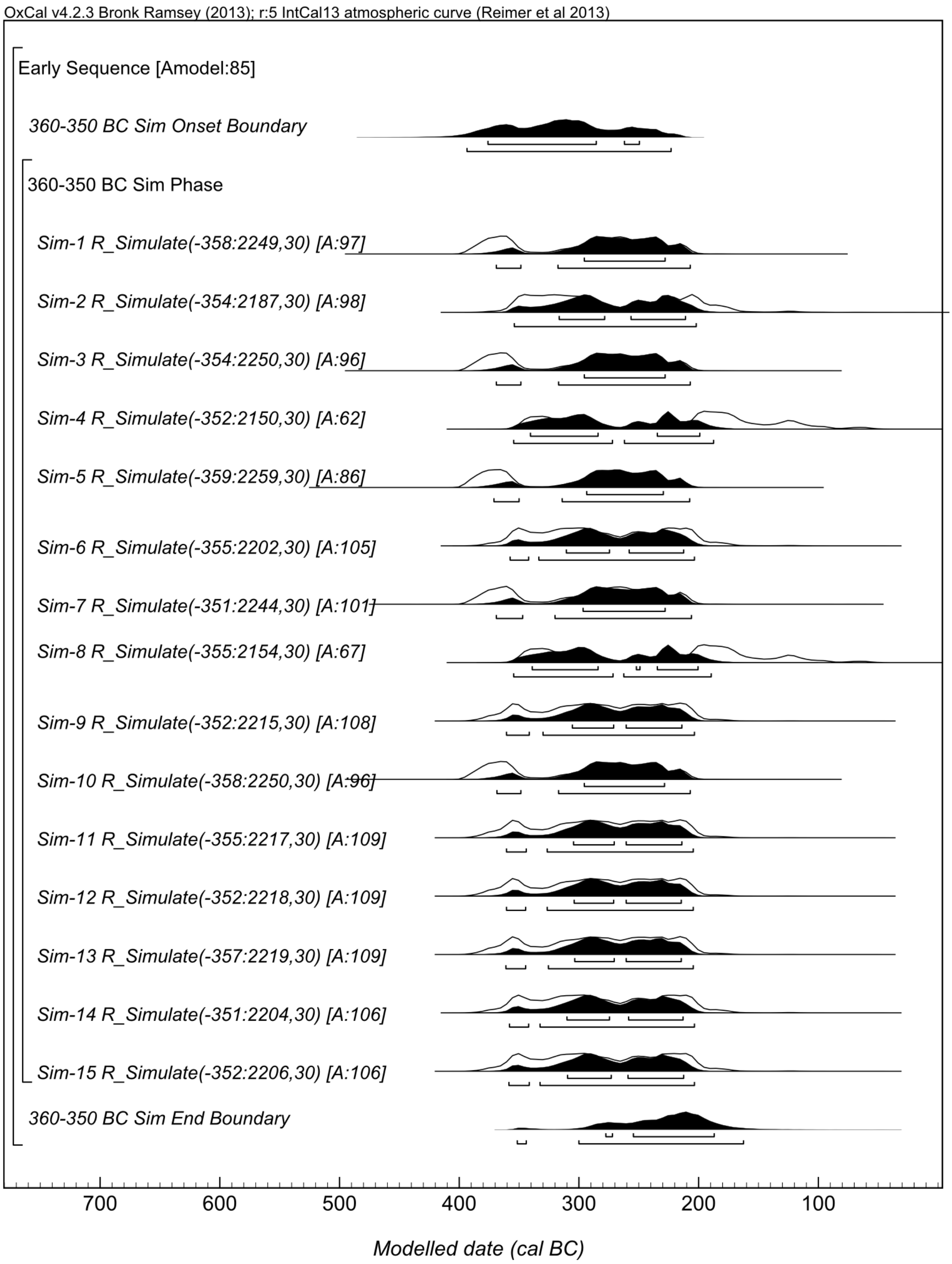



Figure 6.8: Results of the simulation exploring the effects of the large wiggle in the calibration curve on a bounded uniform phase with 15 determinations from between 360 and 350 BC.

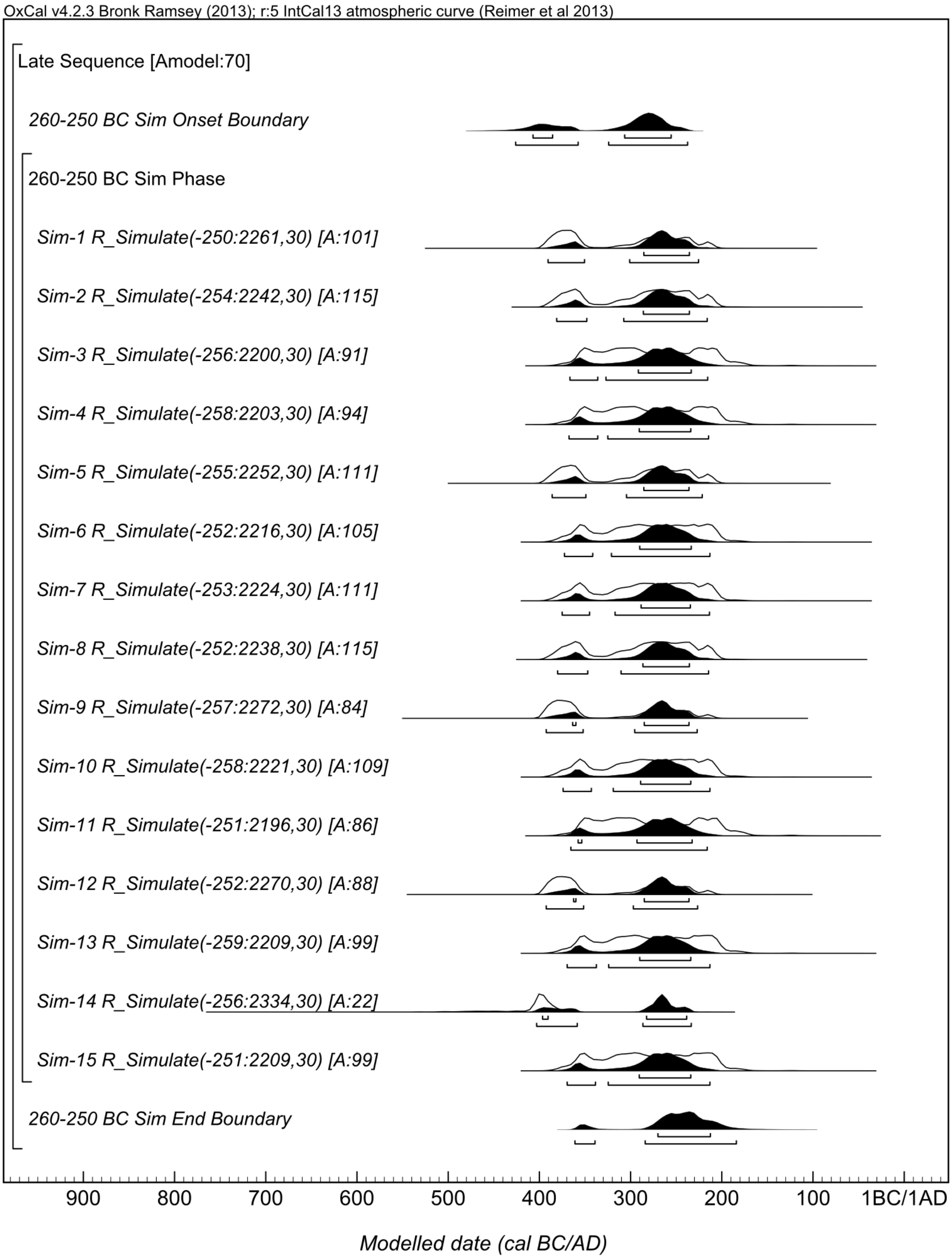



Figure 6.9: Results of the simulation exploring the effects of the large wiggle in the calibration curve on a bounded uniform phase with 15 determinations from between 260 and 250 BC.

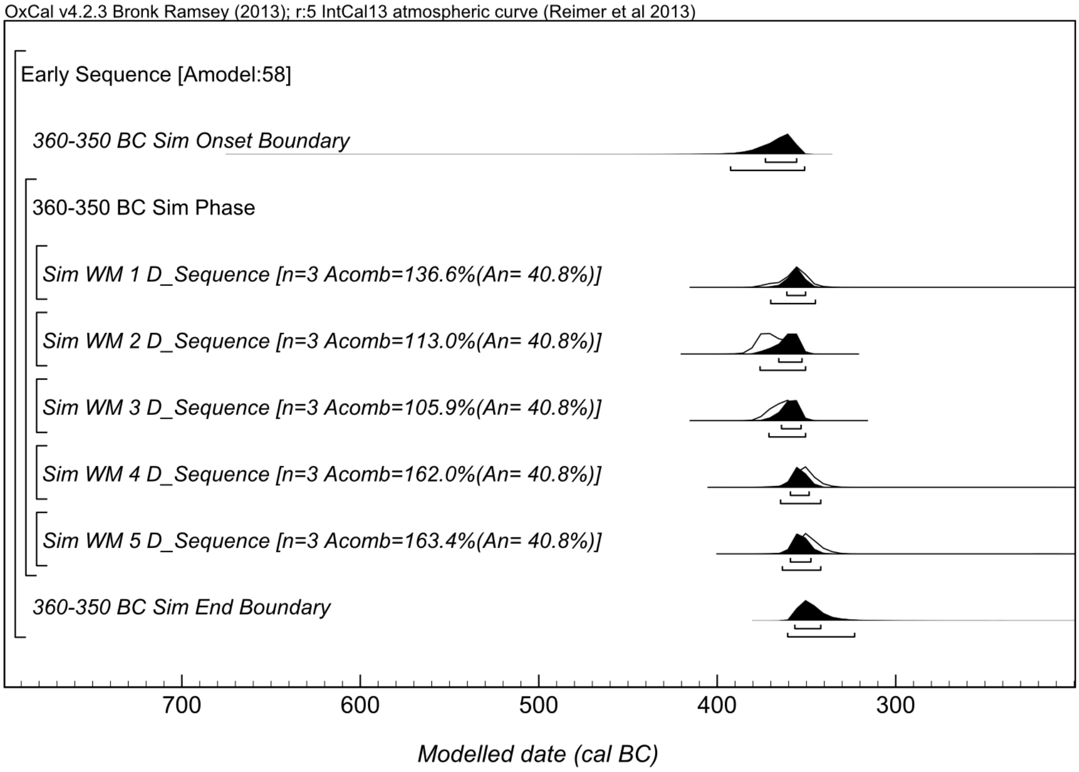



Figure 6.10: Results of the simulation exploring the effects of the large wiggle in the calibration curve on a bounded uniform phase with five wiggle-match dates, based on three determinations each with target dates between 360 and 350 BC.

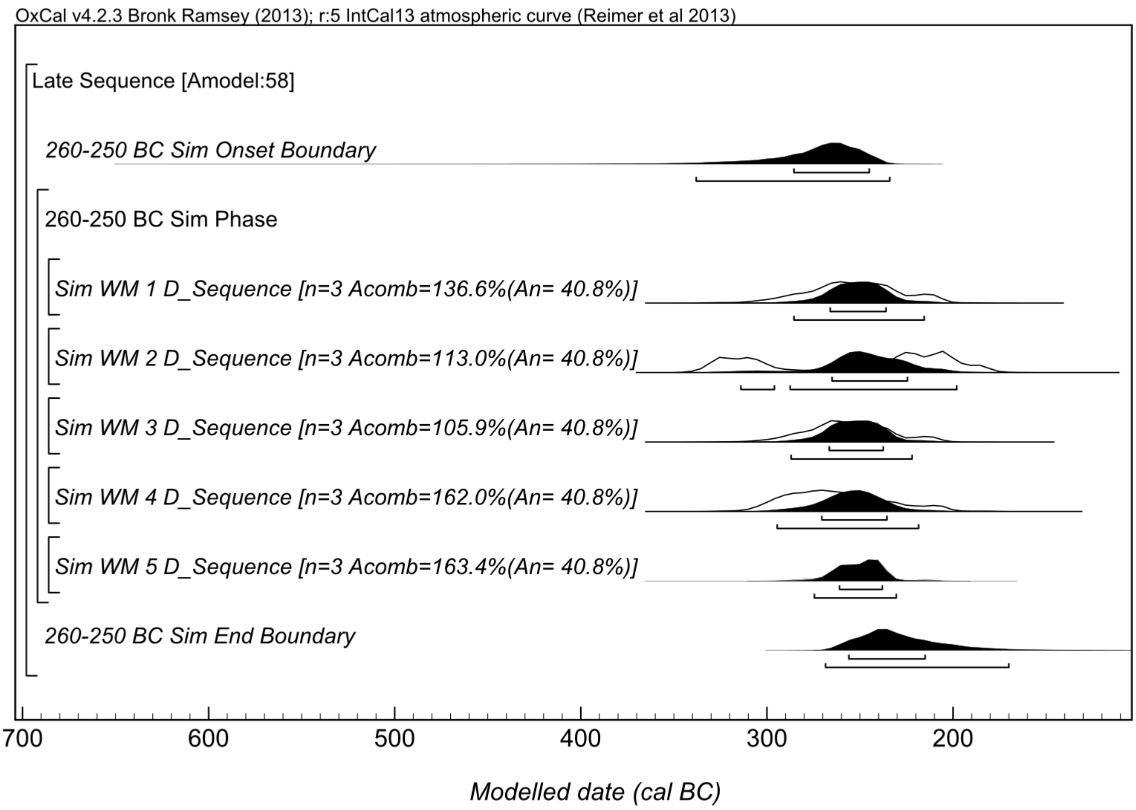



Figure 6.11: Results of the simulation exploring the effects of the large wiggle in the calibration curve on a bounded uniform phase with five wiggle-match dates, based on three determinations each with target dates between 260 and 250 BC.

There is also the relation between the sampling strategy and interpreting the results of the dating programmes. If, at Loch Arthur, the five timbers were wiggle-match dated and their results were identical, then a short felling span and hence a single construction event would be plausible. But if the wiggle-match dates produced different results for each of the timbers and if the results spanned the length of time between 400 and 200 cal BC, the interpretation would be more difficult. On the one hand it would be possible to assert that the mound accreted over a series of successive depositions, but on the other hand the argument could be made that the mound was still built in a single event, but using a significant proportion of re-used timbers. Hence, if we wanted to shift our question from asking about the time over which the timbers were felled, to whether the mound was constructed in a single event, the sampling of the timbers would have to be altered to identify any re-used specimens. The most straightforward way to resolve such uncertainties would be to apply feature-oriented sampling focussing on timbers with structural associations to one another within the mound itself.

### 6.1.2 Dorman's Island

Dormans Island is a crannog located in Whitefield loch, to the north-west of the Machars peninsula in Galloway. It was first reported as a crannog by the Reverend Wilson (1874), who recorded the site without excavation and, when the location was revisited during the course of the Scottish Wetland Archaeology Programme, organic deposits were identified within an eroding section (Cavers et al. 2011). Their overall good preservation suggested that the remainder of the mound would be in a likewise good condition, and this in turn led to a limited excavation over two seasons. During the first season, in 2006, a series of three test pits was placed over the surface of the mound and re-confirmed good levels of organic preservation within. Then, in 2008, a 6 by 4 m trench (Trench 4) was sunk between the test pits (Figure 6.12). In the upper layers of this trench, little was found except un-stratified objects including chipped stone and a Roman Iron Age glass bracelet, but further down, well-preserved features were encountered. Of special interest here are contexts [409], [407] and [406]. [409] consisted of large oak structural timbers nested within the dark orange compressed silts of [407], which are interpreted as a product of activity on the site. Context [406] consists of blue-grey clay that, in portions, supersedes [407]. Throughout the remainder of this subsection the term structural feature refers to the [409] timbers. The excavation was limited only to the extent of trench 4 and had to be halted 0.75 m below the water table due to excessive flooding.

At Dormans Island (NGR NX 2375 5502), both dendrochronological and radiocarbon dates are available. The absolute dendrochronology is based on seven oak timbers from feature [409] fitted together in the site master chronology DIMNx7, with results pointing towards felling dates in the 2nd century BC (Table 6.2). Furthermore, eight radiocarbon dates are available from the site: seven from Trench 4 and one collected underwater during an earlier survey from the piles surrounding the island (Table 6.3). Of the seven radiocarbon determinations from trench 4, four have been conducted on


Figure 6.12: Trench 4 at Dormans Island. The feature of interest, context [409] consists of the major timbers protruding from the southern section of the trench.

Table 6.2: Absolute dendrochronological determinations from Dormans Island.From Cavers et al. 2011, Table 2.

| Context | Species | Sample | Number of rings | Outer rings | Final Ring date | Felling estimate |
|---|---|---|---|---|---|---|
| 409 | *Quercus sp.* | T-1 | 83 | Unknown | 154 | N/A |
| 409 | *Quercus sp.* | T-7a | 117 | Unknown | 159 | N/A |
| 409 | *Quercus sp.* | T-7b | 140 | 14 sapwood | 153 | 153–121 |
| 409 | *Quercus sp.* | T-8 | 74 | Unknown | 197 | N/A |
| 409 | *Quercus sp.* | T-9 | 139 | h/s boundary | 185 | 175–139 |
| 409 | *Quercus sp.* | T-12 | 97 | h/s boundary | 184 | 174–138 |
| 409 | *Quercus sp.* | T-14 | 124 | Unknown | 154 | N/A |

structural timbers from [409], two on samples from [407] and one on a sample from [406]. The seven samples from Trench 4 were measured by AMS, while the remaining determination, GU-10917 was conducted at an earlier date using liquid scintillation technology. The calibrated radiocarbon dates overlap in ranges with the felling estimates derived from the absolute dendrochronology, with two exceptions. The first, SUERC-22918, is much too young and in all probability derives from some later activity on the island. The second, SUERC-22917, is too old and, as will be discussed further on, indicates possible timber re-use.

Table 6.3: Radiocarbon determinations from Dormans Island. From Cavers et al. 2011, Table 1.

| Context | Sample type | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|---|
| 409 | Vertical post | *Quercus sp.* | 18415 | 22919 | 2210 | 30 | -25.3 |
| 409 | Vertical stake | *Betula sp.* | 18414 | 22918 | 255 | 30 | -26.2 |
| 409 | Horizontal plank | *Quercus sp.* | 18413 | 22917 | 2515 | 30 | -28.9 |
| 409 | Horizontal plank | *Quercus sp.* | 18412 | 22916 | 2125 | 30 | -26.8 |
| 407/6 | Wood fragment | *Corylus avellana* | 18411 | 22915 | 2070 | 30 | -24.3 |
| 407/4 | Charred grain | *Triticum spelta* | 18410 | 22914 | 2125 | 30 | -21.8 |
| 407/7 | Charcoal fragment | *Betula sp.* | 19006 | 24644 | 2175 | 35 | -25.8 |
| Survey | Pile | *Quercus sp.* | 10917 | N/A | 2250 | 50 | -24.2 |

There are two questions to be asked of the Dormans Island chronological data:

1. When was the structural feature represented by the context [409] constructed?
2. What is its place in the history of the site?

The first question can be answered by a Bayesian model that takes advantage of the good recording of the excavation and the presence of a short stratigraphic chain that begins with the context [409], moves onto [407] and concludes with [406]. The answer to the second question relies on the comparison between the construction date for the structural feature represented by the context [409] and the felling date for the pile that was sampled for the measurement GU-10917.

To answer the first question, regarding the construction date for the context [409], we need to make several model choices. First of these is deciding on the most suitable proxy for the construction date. One approach would be to assume that all the timbers in question have been felled in the same year, in which case the average of their modelled dates would constitute the best estimate. However, the dendrochronological determinations for the timber T-1, T-14 and T-7b show that this might not have been the case: the outermost ring of T-7b grew in 153 BC and is the 14$^{\text{th}}$ sapwood ring, while the outermost rings of T-1 and T-14 both grew in 154 BC, but there is no evidence that they even approach sapwood. Hence, it is plausible that the two latter timbers may have been felled after T-7b. Therefore, it becomes more realistic to consider the date of the most recent felling within the group as a more suitable proxy for the actual construction event, as this takes into account the possibility that some of the timbers within the group may have been stored before incorporation into the structure. The proxy itself is established as a parameter in OxCal by using the command Last();, which estimates the date range for the most recent plausible sample in a grouping. This approach is used in all the remaining case studies. The next thing to consider is how to deal with the timber T-10 (dated by the determination

SUERC-22917), which has an apparent too old age. One way to approach this would be to build this timber into the model as a *terminus post quem* (*TPQ*), indicating a date after which the successive activity has happened. An alternative is to treat it as an old outlier using the outlier model that was intended for charcoal (Bronk Ramsey, 2009); although T-10 is not a charcoal fragment the outlier model is designed to deal with analogous situations and hence is suitable here. Its additional value is that it not only allows T-10 to contribute to date estimation, thus being less wasteful of information, but it also estimates by how many years T-10 is too old and hence helps to understand the process behind the offset. The final model will thus include a charcoal outlier model for the measurement SUERC-22917 associated with T-10 and a Last(); parameter to estimate the construction date. The radiocarbon results from contexts [407] and [406] are further included as successive elements of the sequence; while they are not of interest, they help to constrain the construction parameter (Figure 6.13).

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End Recorded Deposition Dorman's

[406] SUERC-24644

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

[407] SUERC-22914 SUERC-22915

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

[409] *T-7b* *T-9* *T-12* SUERC-22916 SUERC-22919 SUERC-22917

Dorman's Felling Phase Onset

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Figure 6.13: Schematic of the model estimating the construction of the structural feature marked by context [409] at Dormans Island. The pile sampled as GU-10917 is not included as it was not located in Trench 4. Sapwood estimates are modelled by uniform distributions to ensure consistency with the site report. The charcoal model is only applied to the timber T-10 (SUERC-22917). Dendrochronological determinations in italics.

The results of the initial model were not satisfactory on account of poor agreement (Amodel= 48.2%) caused by the early age of the sample SUERC-24644, a piece of birch charcoal from context [406]. While it has little effect on the construction estimate, which is the main parameter of interest, it does affect the T-10 outlier model. Given that it is a single charcoal fragment, and the only sample from its context, it is plausible that it is residual and hence its rejection is justified. Once this is taken into account the model provides the following results (Figure 6.14):

- The construction date is estimated to *160–115 cal BC (95.4%)*, with the greatest probability in *155–130 cal BC (68.2%)* (fig. 6.15
- The outlier model indicates that T-10 is *645–310 years* older than the remainder of the context [409] (*95.4%*), with the highest probability at *540–365 years (68.2%)* (Figure 6.16).
- The model has good agreement with the data (Amodel= 88.1%).

The lower edge of the construction date estimate is earlier than one of the dendrochronological estimates, T-7b; this is the result of rounding errors. Other than that the construction date is feasible and puts context [409] in the mid-2nd century cal BC. The outlier model indicates that T-10 is several hundred years older than the remainder of the [409] material, which is too long to be justified in terms of how the timber plank was split from the timber and hence it is best explained as an example of a re-used timber. This makes a strong case for implementing feature-oriented design; had T-10 not been associated with the remainder of the context [409], its date would be liable for interpretation as a sign of much earlier activity on the site. Furthermore, if we do accept the re-use interpretation for the oak T-10, it becomes important to consider the possibility that not only other structures elsewhere may contain such timbers, but also it may be the case that abandonned crannogs could have been mined as a source of construction material, adding yet another layer of difficulty to understanding site formation processes on Scottish wetland sites.

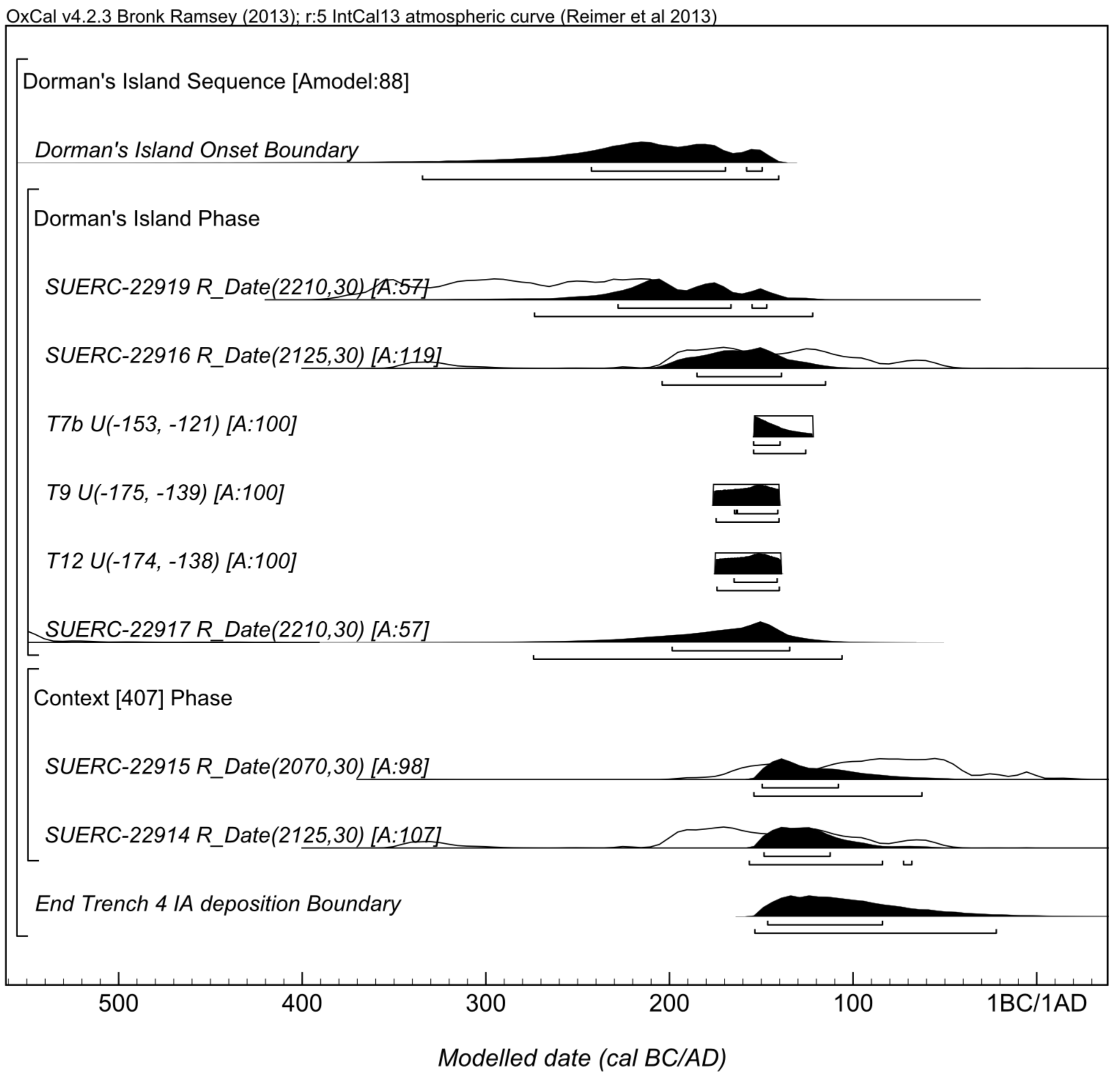



Figure 6.14: Results of the model estimating the construction of context [409] at Dormans Island, after the removal of the measurement SUERC-24644.

The question regarding the relationship between the structural feature within Trench 4 and the remainder of the crannog is not as clear. Comparison of the construction date to the calibrated date range of the measurement GU-10917 indicates that the piles surrounding the island may have been felled at an earlier date than the construction of

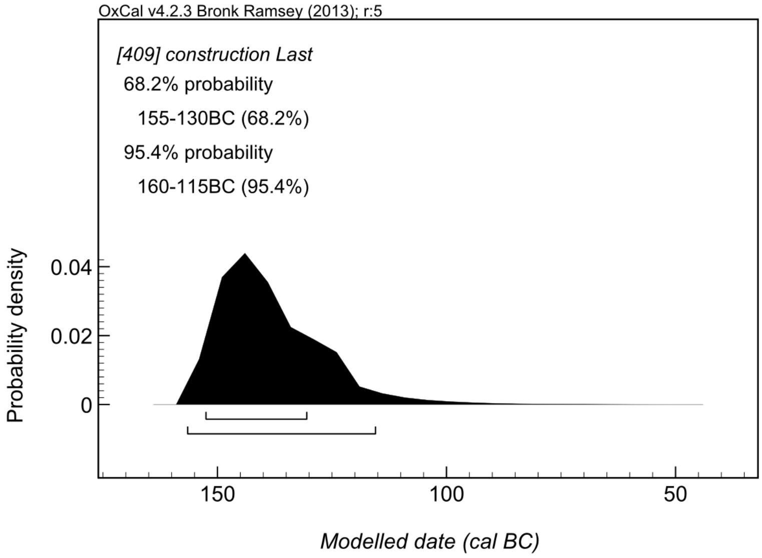



Figure 6.15: The construction date estimate for context [409] at Dormans Island.

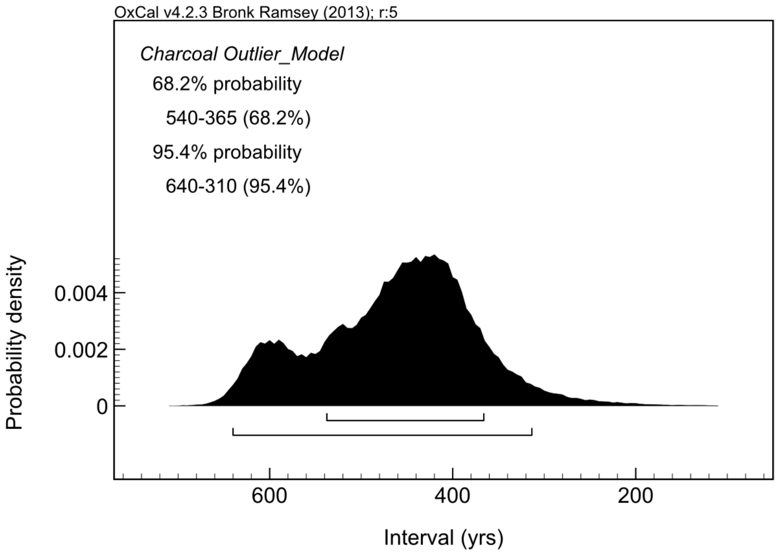



Figure 6.16: The results of the outlier model applied to the timber T-10 from Dormans Island.

context [409] (Figure 6.17). At the same time, GU-10917 is only a single measurement, which may be a statistical outlier, or in some other way biased with regard to the development of the halo of timbers surrounding the crannog. Thus, we cannot know the relationship between the structural feature and the timbers in the loch without more extensive dating of the former. Yet even if we had the latter information, we would still need a more extensive excavation of the deposits to estimate whether the deposits encountered belong to the original activity on the site, or are the result of more recent re-use. Hence, the samples available are insufficient to relate the material from Trench 4 to the overall site history.

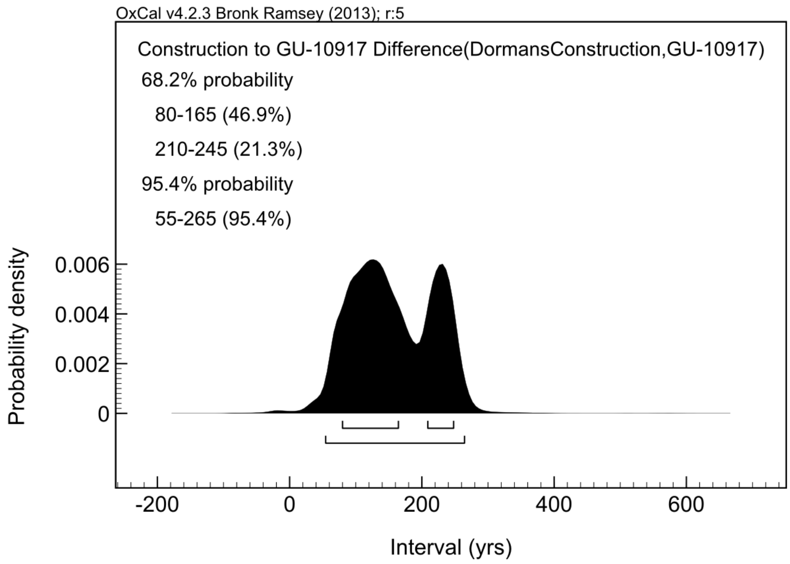



Figure 6.17: The difference between the calibrated date range of the sample GU-10917 and the estimated construction date for feature [409].

The key notion behind this section was the importance of the relationship between the viability of archaeological questions, field sampling, and technical capacity. In case of both Loch Arthur and Dormans Island different sampling approaches, dictated to a large extent by different excavation aims and objectives, meant that not all the questions that could be asked of the chronology of the sites can be answered. The wide coverage of the mound at Loch Arthur permitted statements about when it formed, accurate to several centuries, but the lack of feature-oriented dating would make working with questions about site formation difficult even if technical resolution made such questions feasible. At Dormans Island the situation is different: with most of the dating evidence focussed on a single structural feature, context [409], it becomes possible to not only date it well, but also identify an outlier timber and put forward an informed guess as to why it is older than the remainder of the assembly. At the same time, the much more focussed nature of sampling precludes making any generalized statements on the relationship between the feature in question and the remainder of the mound. The two sites also differ in terms of the technical aspects of dating. At Dormans Island a suite of absolute dendrochronological determinations means that the construction estimate can be precise to particular decades, while at Loch Arthur, the presence of only individual radiocarbon determinations from a challenging part of the calibration curve means that the dating evidence is insufccient to address questions on the nature of the deposition process.

The case studies discussed within this section only covered legacy dates from sites with no wiggle-matches and their main purpose was to demonstrate the importance of the question-sampling-technique relationship when dealing with the practice of dating individual wetland sites. The succeeding sections focus on the relationship between questions and techniques and explore what kinds of results can be achieved using wiggle-match dating on different parts of the calibration curve. In doing so, the discussion of the relationship between the field sampling and questions asked becomes more implicit, as the designs are geared towards the available material and hence the questions do not become unanswerable due to lack of suitable samples. Nevertheless, it has to be re-iterated here that whenever dealing with a project of this kind the ultimate goals of any prospective dating project have to be kept in mind already during fieldwork, as, in absence of suitable samples, no dating technique will enable the resolution of what may be a burning archaeological question.

## 6.2 Recurrent technical issues

There are two technical issues that affect each one of the wiggle-match dating case studies presented in the succeeding sections: wiggle-match date stability and potential for excessive shrinkage. Concerns over wiggle-match date stability are most pertinent during calibration plateaux, when a single outlying measurement can cause a major shift in the wiggle-match date range. Shrinkage is a process in which the hierarchy of a statistical model causes the contraction of parameters to a particular value; in general this is a welcome effect as it reduces the effect of noise in the data, but in some cases can lead to biased results. The following section explains these two issues in more detail to provide the necessary background for when they arise in the case studies.

### 6.2.1 Wiggle-match dating stability and systematic bias in outermost and decayed rings

Radiocarbon wiggle-match dates are conditional upon the relationship between the samples measured (in Bayesian wiggle-match dating this takes the form of a prior) and on the data in the form of calibrated ranges of the individual determinations. However, different determinations will have different impact on the distribution of the wiggle-matched date range; for example, if the wiggle-match contains a major feature of the calibration curve, such as the onset of the Hallstatt plateau. or the large wiggle around 675 cal BC, the measurements that represent these features will have a much greater impact on the final position of the wiggle-match than the measurements describing the surrounding flat parts of the curve. Hence, if a single measurement mimics one of these features either through a systematic bias in the underlying material, or due to measurement uncertainty, the wiggle-match result as a whole can become biased. To ensure that this does not happen it becomes important to assess wiggle-match stability. The easiest way of doing this is the removal of individual constituent determinations from the wiggle-match model and taking note on the effect this has on the posterior probability of the results. If these include the range of the unmodified results then the match is stable. If, on the other hand, the removal has a significant effect on the posterior distribution of the wiggle-match, further action has to be taken to ensure that the results are valid. In general, if such situations arise, the ideal course of action is to repeat the measurement in question. Given that this is often impossible, the more viable alternative is to run two alternatives of the site model, one with the key measurement included, and the other without it, so that the effects on the overall picture of the site can be assessed. With a sufficient number of measurements available to the project, this approach should be sufficient to identify any instability caused by measurement scatter, as the problematic determination ought to have poor agreement with the site model. There will be cases, however, where this approach is not enough due to systematic offsets.

One such case became clear in the archaeological case studies discussed below, as some timbers displayed a consistent shift towards older radiocarbon ages in decayed wood and outermost rings (Figure 6.18). This has been encountered in some form on all of the sites discussed and appears to be independent of the period in which the timbers were felled, thus excluding the possibility that a minor offset in the calibration curve is the underpinning cause. Common to all the cases was the species affected (alder) and exposure of the wood to the water saturating the site, either due to position on the outermost rings, or due to porosity caused by decay. This in turn allows an increased movement of sediments, as well as fulvic and humic substances that can have an adverse effect on the results of the radiocarbon dates unless the pre-treatment protocol is strict enough. The problem is only compounded by the possibility that in some cases dissolved cellulose might dissolve and then reconstitute (Zugenmaier 2008, 101-103), perhaps incorporating molecules of intrusive carbon into the new strands. Such soluble cellulose can be removed with a strict enough pre-treatment protocol, but an experiment conducted on implementing such a stringent protocol showed that the sample loss rates would be unsustainable on a routine basis (see Chapter 4.1).

This excess variability has an adverse effect on both the quality assurance indices and the date ranges of the wiggle-matches. The problem with the quality indices emerge as the drift of some samples towards greater ages means that the wiggle-match resembles the underlying calibration curve to a lesser extent leading to an apparent mismatch between the model and the data. The bias in the date ranges has been observed most often with regard to the outermost rings from the timbers that have been felled in the 5th century BC. In these timbers a bias to older ages on the outermost rings of a short or medium span sequence will make the wiggle-match resemble the beginning of the large wiggle around 675 cal BC, or the rise to the middle part of the calibration plateau around 640 BC and hence a drift of results towards that part of the calibration curve.

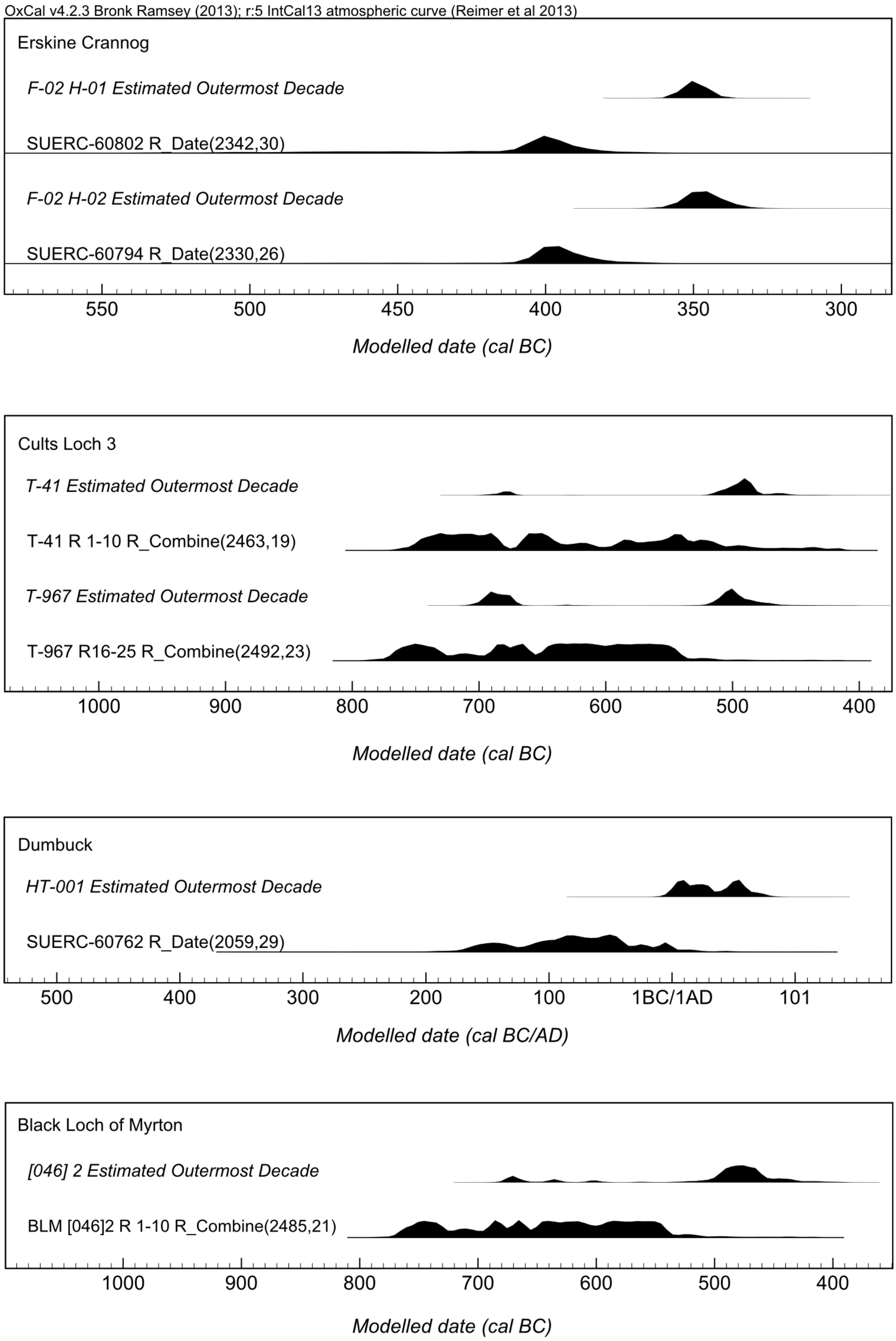



Figure 6.18: The calibrated date ranges for the actual determinations on the affected outermost rings and their estimates based on the remainder of the constituent wiggle-matches, by site. Note the systematic shift towards older dates in the actual measurements.

In all the case studies presented here, these biases could have been resolved through comparison of the results to other timbers within a particular feature, or through the emergence of stratigraphic incongruences. In situations where this kind of additional information is unavailable, the recommendation is to avoid decayed or outermost rings, at least in alder timbers. If this proves impossible either due to overall state of the site, or because a particular feature of interest did not preserve well, the recommendation is to check if the removal of the outermost rings affects the site models and, if so, publish both results, as long as they do not conflict with other archaeological information.

### 6.2.2 Shrinkage

Shrinkage is a process where individual parameters converge towards one another under the influence of an overarching distribution (Kruschke 2015b). In the context of the Bayesian analysis of radiocarbon determinations the simplest example of shrinkage is the narrowing of the modelled date ranges under the influence of the uniform phase prior (see chapter 3.3.2). In most cases shrinkage is a welcome phenomenon, as it means the reduction of statistical scatter and improved precision of model results. However, if the overarching distribution does not describe the model well, shrinkage may lead to the emergence of a systematic bias.

In the context of the current chapter, adverse instances of shrinkage arose during the Hallstatt calibration plateau when date ranges of different precision were placed under the same distribution based on the uniform prior. When this happens the distributions of the less precise determinations will shrink towards the more precise ones. This is not an issue if the model in question is a good description of the underpinning site formation process and in the vast majority of cases is welcome as a means of negotiating the effect of the calibration plateau. There does exist, however, a small number of possible situations where the dates from a specific part of the phase have a greater precision than those from the remainder of the dated activity. In these instances, the less precise dates will shrink towards the more precise ones even if their updated distributions do not provide a good description of the actual date (Figure 6.19). This applies for the most part to models which include both wiggle-match dates and single radiocarbon determinations, but can also affect some wiggle-match based models; for example, wiggle-matches that catch the break in the calibration plateau around 550 BC have the potential to bias wiggle-match dates from a later period that have lower precision as they failed to catch that particular feature of the calibration curve. It is important to stress that instances where such adverse shrinkage affects the 95.4% HPD areas are rare and often require conscious effort to develop. These issues are a part of the broader set of concerns regarding the effects of the calibration curve on the robustness of Bayesian modelling (Steier and Rom 2000).

For the most part instances of adverse shrinkage will become apparent in review of model results. The first sign is the presence of groups of skewed modelled date ranges of the data-based parameters (skewed distributions are expected for a number of inferred

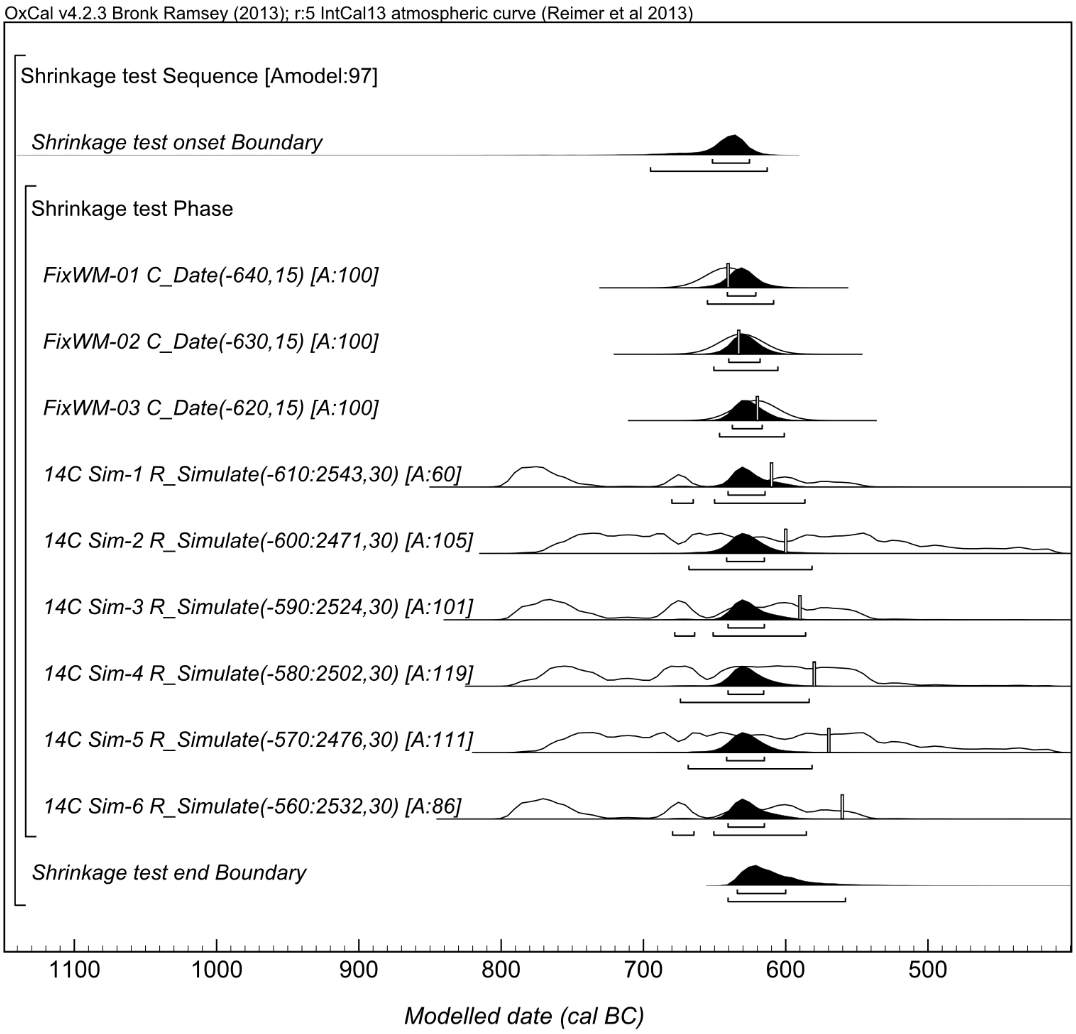



Figure 6.19: Induction of adverse shrinkage in a uniform bound phase model through the concentration of high-precision determinations on one edge of the modelled phase. In this simulation a group of fixed high-precision distributions near the onset of a bound uniform phase draws in the posterior distributions on the simulated radiocarbon dates. Because of this, the modelled simulated radiocarbon dates display a systematic offset from their target dates (vertical bars), even though all the measurements follow a uniform distribution. While it is improbable that this magnitude of the adverse effect is to emerge in practice, wiggle-match dating research design ought to avoid clustering of very precise wiggle-matches to one side of a bound model that also contains dates of a lower precision.

parameters such as boundary events). If such groups display very narrow modelled date ranges (*¡50 cal yrs* within the *95.4%* HPD area during the plateau) and if they display systematic divergence from their non-updated distribution, adverse shrinkage may have taken place. The easiest way to identify whether this is indeed the case is to assess if the model makes sense in archaeological terms; compression of 20 refurbishment events into a 10-year window indicates a high probability of adverse shrinkage. The best way to avoid such situations is to ensure that the site stratigraphy is well-understood and that this understanding is mirrored in the site model implemented.

## 6.3 Dating Structures on the Hallstatt plateau: Black Loch of Myrton

The wiggle-match dating study at Black Loch of Myrton sought to evaluate whether the basic archaeological questions, such as "when was this structure built?" can be dealt with during the Hallstatt calibration plateau. The site was chosen on account of its importance to contemporary wetland archaeology in Scotland (see Chapter 2.2) and because a legacy radiocarbon date from one of the test pits indicated that some of it may have been constructed during the Hallstatt plateau, thus giving an opportunity to explore the performance of wiggle-matching under the demanding plateau conditions. The results of the wiggle-match dating study show that it is possible to obtain an 80-year window for a feature construction under plateau conditions, thus demonstrating that the technique and the approach taken herein are capable of delivering the much-needed improvement in chronological precision of the earlier Iron Age. Furthermore, the study demonstrated the importance of feature-oriented sampling and it also became clear that wiggle-match dating research design needs flexibility in case of unexpected results.

### 6.3.1 Background to Black Loch of Myrton

The Black of Loch of Myrton (NGR NX 3612 4280) lies on the Monreith estate in the Machars peninsula of Galloway (Figure 6.1). It was first excavated by Herbert Maxwell in 1884 and, despite the hurried nature of this early project, Maxwell managed to summarize the general picture of the site: a group of stone mounds on a drier patch of ground in an area where 80 years earlier drainage operations were carried out. This result was then reported by Munro (1885), but with time the site faded into obscurity and its exact location was forgotten by the end of the 20th century. It was only during renewed drainage operations in 2010 that the tenant farmer discovered worked oak timbers. The discovery was reported and the location investigated by AOC Archaeology, who dug two test pits, which uncovered wooden structures not unlike those that could be expected at a crannog (Cavers 2010a). In the aftermath, two timbers were radiocarbon dated: one stake from the uncovered structure (SUERC-32597: 768–430 cal BC; 95.4% probability) and one of the oak timbers from the drainage cut (SUERC-32598: 380–198 cal BC; 95.4% probability; Table 6.4). These results confirmed that the remains dated to the Iron Age, while the findings of the test pits were sufficient to assert that the site was indeed what Maxwell reported as Black Loch of Myrton.

Table 6.4: 2010 radiocarbon determinations from Black Loch of Myrton (Crone and Cavers 2015, 15)

| Context | Sample type | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|---|
| 021/B | Vertical stake | *Alnus sp.* | 22943 | 32597 | 2470 | 35 | -28.3 |
| Drainage Ditch | Possible palisade | *Quercus sp.* | 22944 | 32598 | 2215 | 30 | -27.3 |

More extensive operations were carried out in 2013, when the area around the original test pits was excavated, the adjoining mound sectioned, the remaining mounds surveyed and transects running through the site were cored for palaeo-environmental data (Crone and Cavers 2013, 2015). The main finding of the environmental studies is that the stone mounds cover an area that has not been a lake in recent geological history and hence the site was a lakeshore, or perhaps a marshland settlement and not a lake dwelling. Meanwhile, the excavations uncovered a section of a preserved roundhouse with a radius of about 5 m (Structure 1; Figure 6.20), consisting of radial timbers forming a floor and a stone hearth within a timber frame. Besides the original construction, the hearth also had the evidence of two successive refurbishments (Figure 6.21). In both cases the previous hearth deposits were sealed by a layer of clay and a stone capping. The radial timbers of the floor were placed on the underlying peat, with no evidence for a crannog mound, thus further supporting the conclusions of the environmental survey. The topographic survey recorded a further seven or eight mounds, suggesting the presence of further roundhouses on the site. This is supported by the chance discovery of another floor during the excavation of a trench intended to collect a monolith sample for environmental analyses.

Feature-oriented dating was possible only for Structure 1. As can be seen in Figure 6.20, this structure can be divided into two main parts for sampling purposes: the alder floor and the hearth structure with the hearth sequence itself. Samples from the alder floor were collected and moved to SUERC, but upon investigation they proved a poor choice for wiggle-match dating, as they often lacked the bark edge and also because the tree-ring patterns failed to preserve well. The second group of material was the hearth structure (context [046]) alongside structural features in its direct proximity. Here the preservation was much better, with clear ring patterns and frequent survival of the bark edge. As the archaeological evidence indicated that both the hearth structure and the floor were laid down in a single construction event, the better-preserved timbers from the hearth structure could be used to date the floor. Hence, the wiggle-match dating samples discussed below will have come from two of the hearth structure contexts: [022] and [046] (see Figure 6.21). Context [022] has been interpreted as the remnants of an internal partition and consists of ash stakes, while [046] contains the stone hearth


Figure 6.20: Plan of Structure 1 at Black Loch of Myrton. The stone hearth complex is located in the middle of the structure and is surrounded by the retaining timbers and associated features. Beyond them are the radial timbers and gravel spread. Re-drawn from Crone and Cavers 2013, Figure 3.

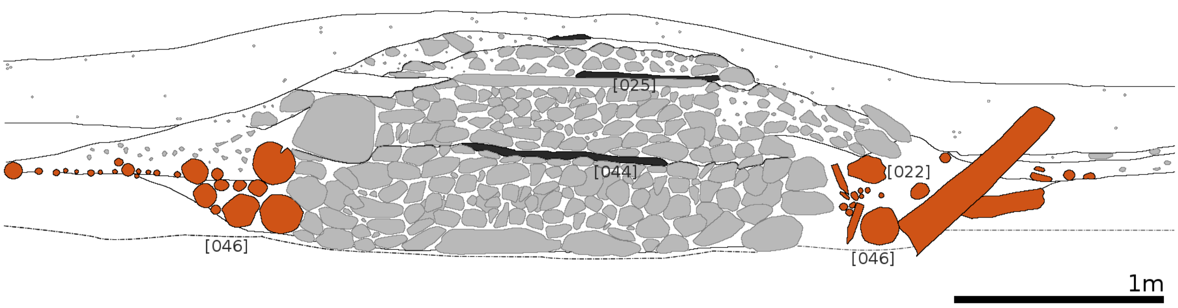



Figure 6.21: Section through the hearth structure at Black Loch of Myrton. Sampled contexts [022], [025], [044] and [046] are indicated. Re-drawn from Crone and Cavers 2013, Figure 5.

and was built with massive alder logs. The third element suitable for dating was the hearth sequence itself. The hearth had been refurbished twice and good dating samples of short-lived charcoal survived in the first two deposits (contexts [025] and [046]).

The post-excavation of the Black Loch of Myrton Structure 1 included a suite of dendrochronological analyses which yielded four chronologies, one of which has a tentative absolute date (Crone and Cavers 2015, 15). The one absolute chronology is F40oakx3, based on three oak planks that may have been cleft from the same trunk. They displayed correlations to the site master from Cults Loch 3 (CULTSx9) and have surviving sapwood, permitting a felling estimate between 461 and 429 BC. The second chronology is PALx2, based on two oak samples from the 2010 drainage trench. It did not correlate to the chronology F40oakx3, or to any other chronologies and hence remains undated. The third chronology, ASHx3 is based on three ash stakes from contexts [022] and [046]. These were felled in the same year. The fourth and final chronology is the alder-alder ALDERx11, which includes 11 timbers from various locations across the structure.

The main archaeological question for Black Loch of Myrton is: when was Structure 1 built. As Black Loch belongs to the period of the Hallstatt plateau, the successful resolution of this question would demonstrate that wiggle-match dating can be used to overcome the effects of a radiocarbon calibration plateau. Note that because of the limited exposure inferences can only be drawn about Structure 1 and cannot be extrapolated to the site as a whole. Furthermore, the timber elements from the area surrounding the hearth sequence in all probability relate to the original construction of the structure, but provide little information about its life-span. This is mediated to a degree by the presence of the hearth material, but the youngest hearth has no secure material surviving and so asking questions regarding the span of the activity over the entire structure is impossible.

### 6.3.2 Wiggle-match and new radiocarbon dates from Black Loch of Myrton Structure 1

Four Structure 1 timbers were wiggle-match dated: [022]-1, [022]-2, [046]-2 and [046]-15, all of which retained bark edge (Figure 6.22). [022]-1 is an ash timber of over 50 rings, from which four decadal sample blocks were submitted for AMS measurement, one of which failed during the measurement process. [022]-2 was an ash timber of over 60 rings, from which four decadal sample blocks were collected. The timber [046]-2 had over 100 rings and seven decadal blocks were submitted for measurement, with the outermost decade measured twice. The final timber, [046]-15 contained over 90 rings, from which eight decadal samples were measured, three of them twice.

The wiggle-match dating results are, to an extent, incongruent with one another (Figures 6.23 to 6.26; Tables 6.5 to 6.7). The two timbers from the context [022] date to either the seventh or the fifth century cal BC. Based on all the measurements, timber [046]-2 produces a distribution that is located in the seventh century cal BC, but

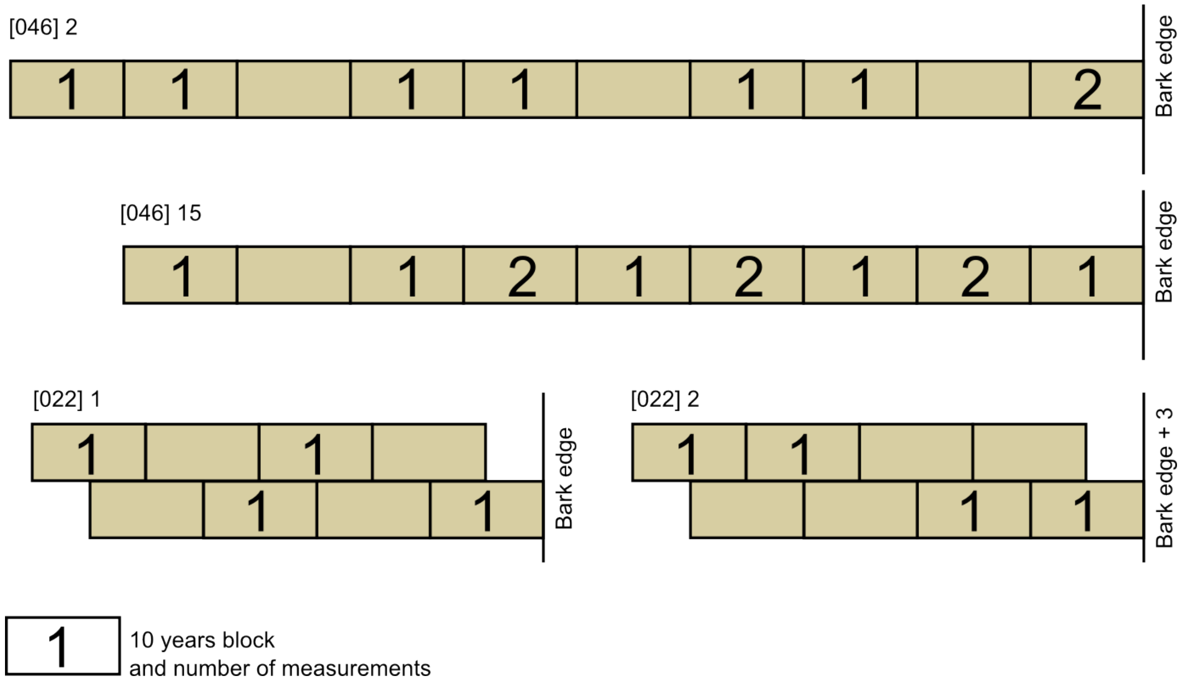



Figure 6.22: Schematic representation of the sampling pattern for the four Black Loch of Myrton wiggle-match dates.

fails the $\chi^2$ test with the [022] timbers ($\chi^2$= 7.622, 5% critical value at 2 df is 6.998). This issue resolves itself once the outermost decade of the timber [046]-2 is removed: the result is a wiggle-match that produces a stable distribution concentrated in the fifth century cal BC and that passes the $\chi^2$ test with the [022] timbers ($\chi^2$= 4.106, 5% critical value at 2 df is 5.991). Given that the issue with outermost and decayed rings is recurrent (see section 6.2.1), it is plausible that this is what has happened in this case as well and the results presented and used in subsequent analyses use the [046]-2 wiggle-match date with the excluded outermost rings. [046]-15 presents a more complex situation, as most of its modelled date range falls into the sixth century cal BC and hence is at odds with all the other timbers. The wiggle-match is also stable and its position does not hinge on the presence or absence of any single measurement. Hence, the recommended wiggle-match date for the timber [046]-15 is based on all the available measurements and points to a felling in the sixth century cal BC.

The two hearth contexts, [025] and [044] have been dated with seven radiocarbon determinations. All the samples submitted were either roundwood charcoal with ten or fewer growth-rings, or cereal grains, which would only contain the carbon from the year of growth. The scatter in the dates suggests that even though the hearths were sealed by clay layers, some residual material may have found its way in, or some old material may have been burnt (for example old hurdles)(Table 6.8).

One thing to consider at this point is how to reconcile the discrepancy between the wiggle-match [046]-15 and the dates for the remaining timbers, including [046]-2, which is derived from the same feature. There are four conceivable reasons for what may have happened: measurement scatter, laboratory contamination, a reservoir related offset and timber re-use. Of these four possibilities, given the current evidence, timber reuse

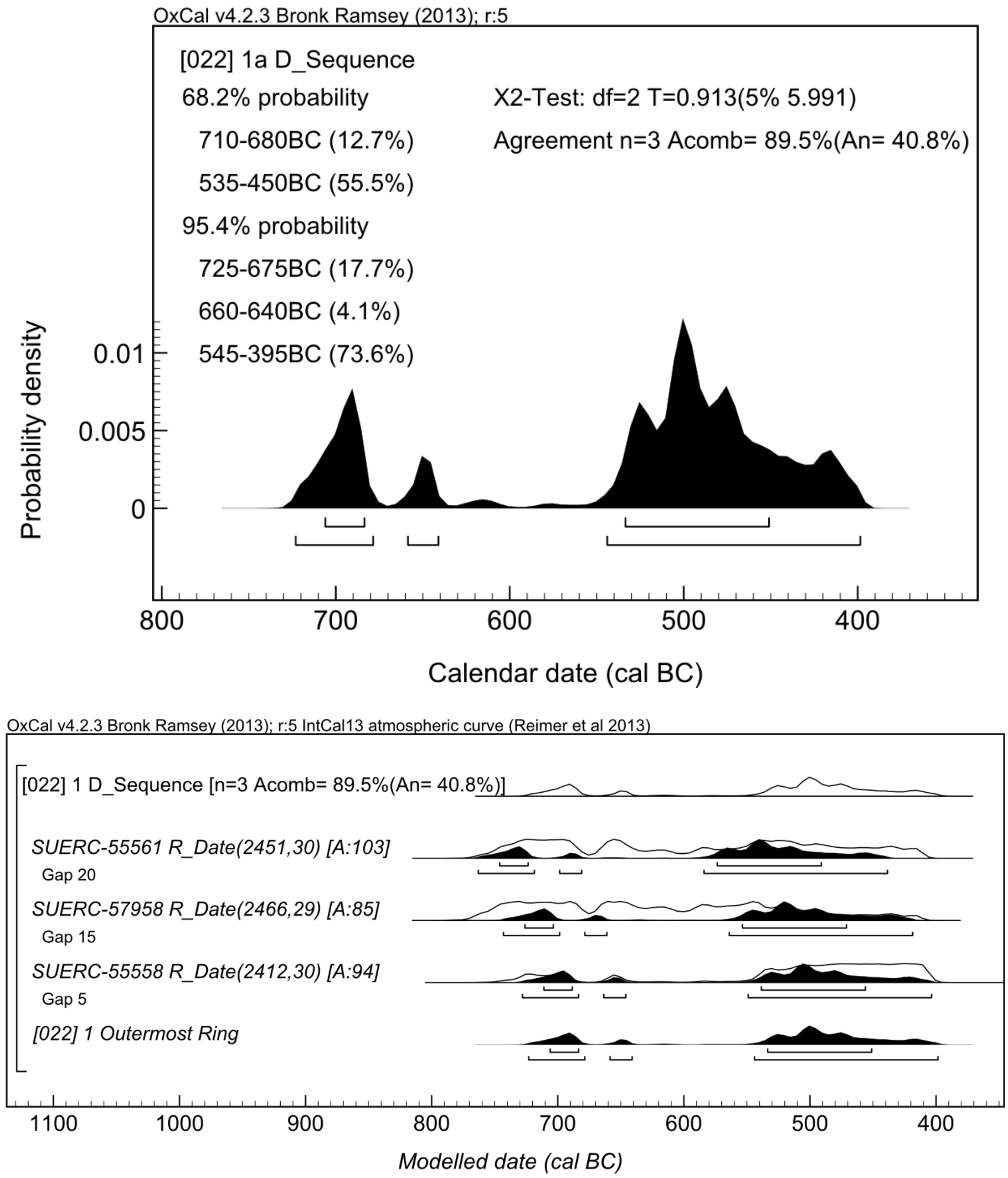



Figure 6.23: Wiggle-match date results for the timber [022]-1: summary (top) and individual determinations (bottom).

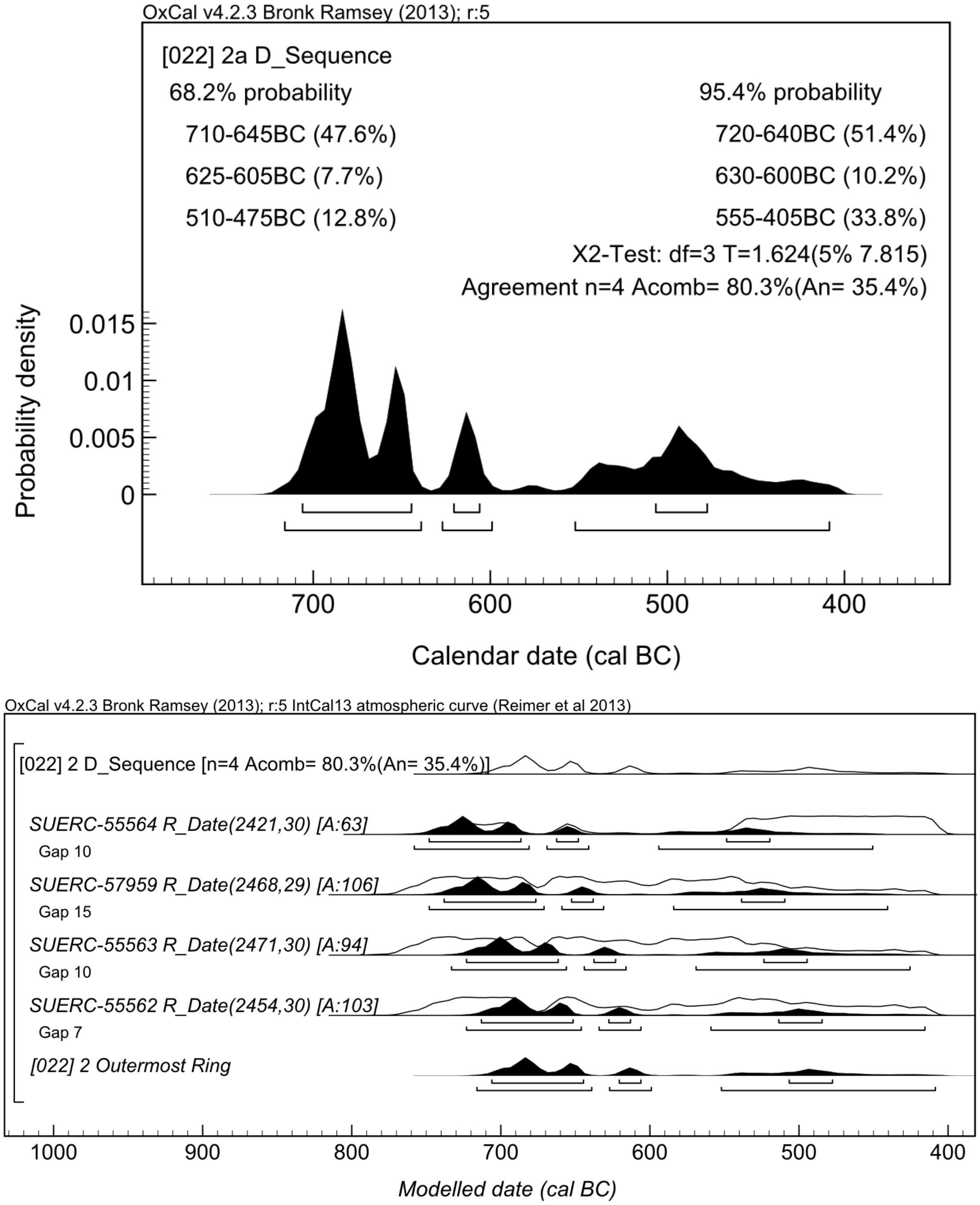
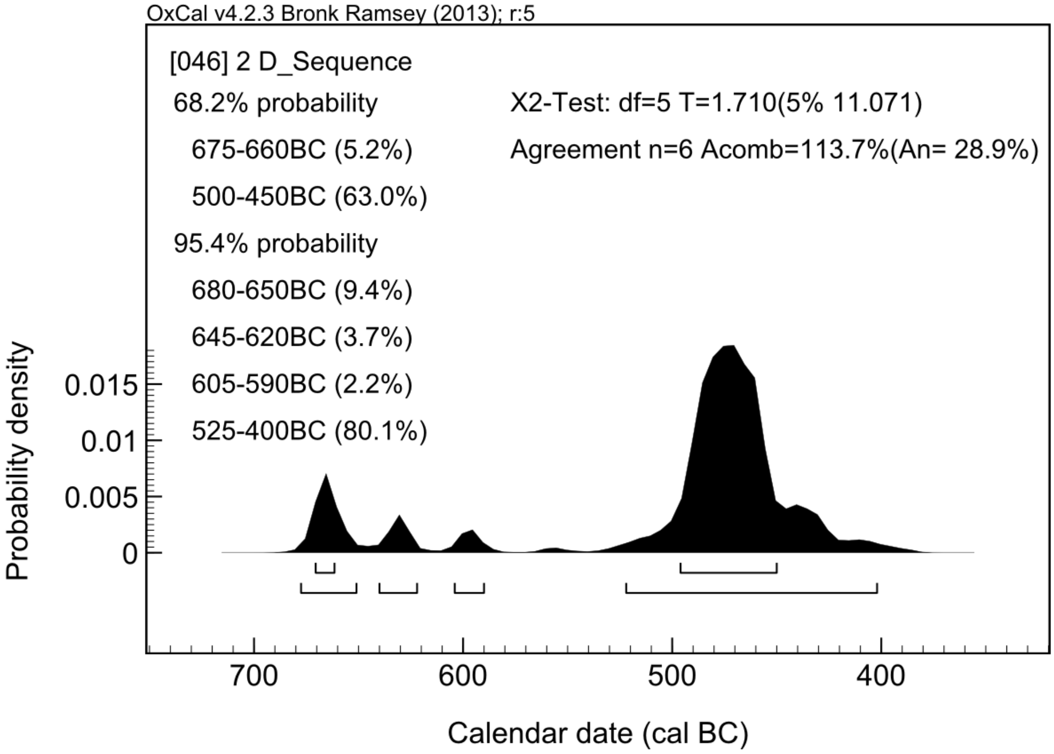



Figure 6.24: Wiggle-match date results for the timber [022]-2: summary (top) and individual determinations (bottom).



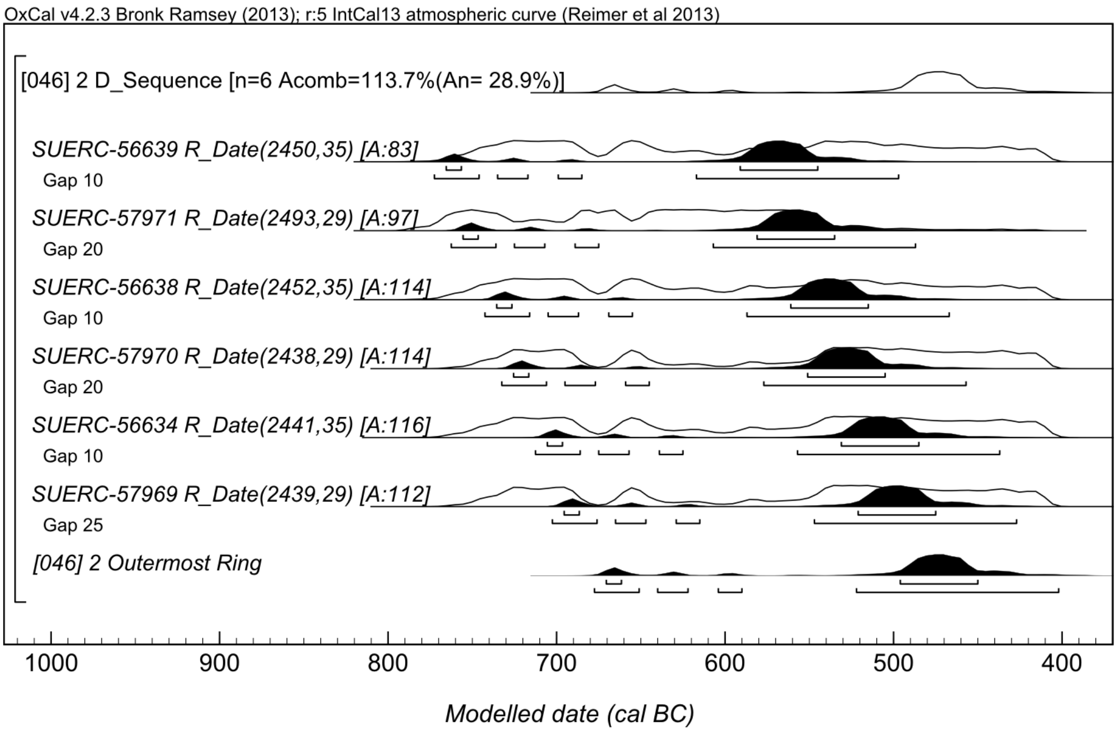
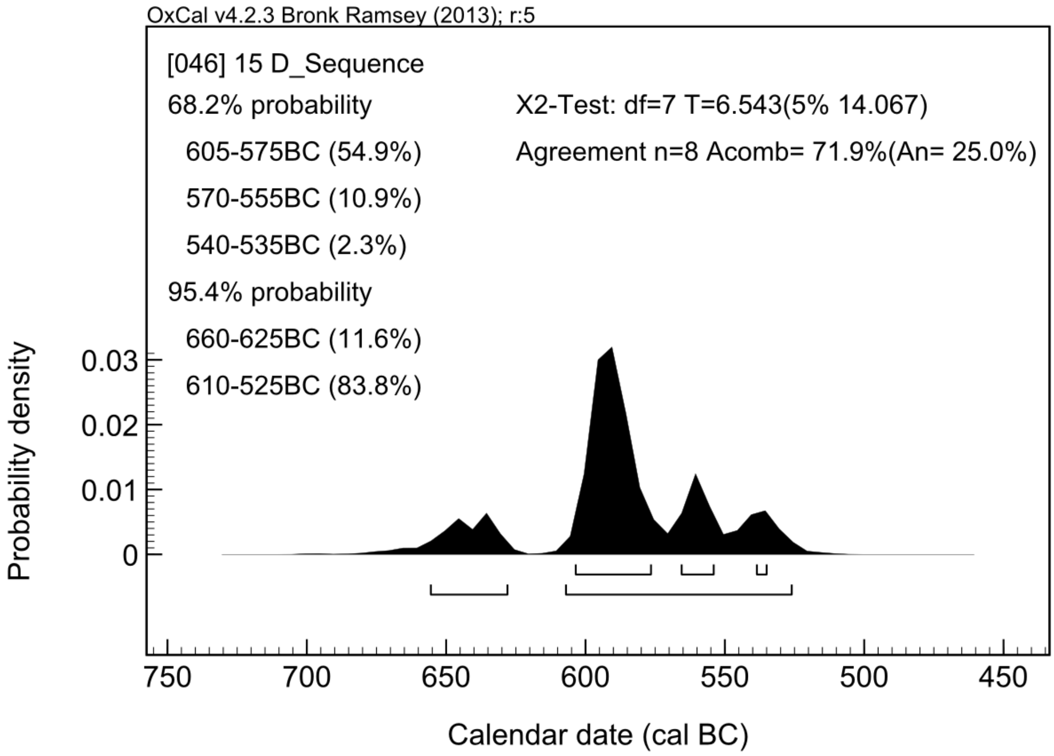




Figure 6.25: Wiggle-match date results for the timber [046]-2: summary (top) and individual determinations (bottom).



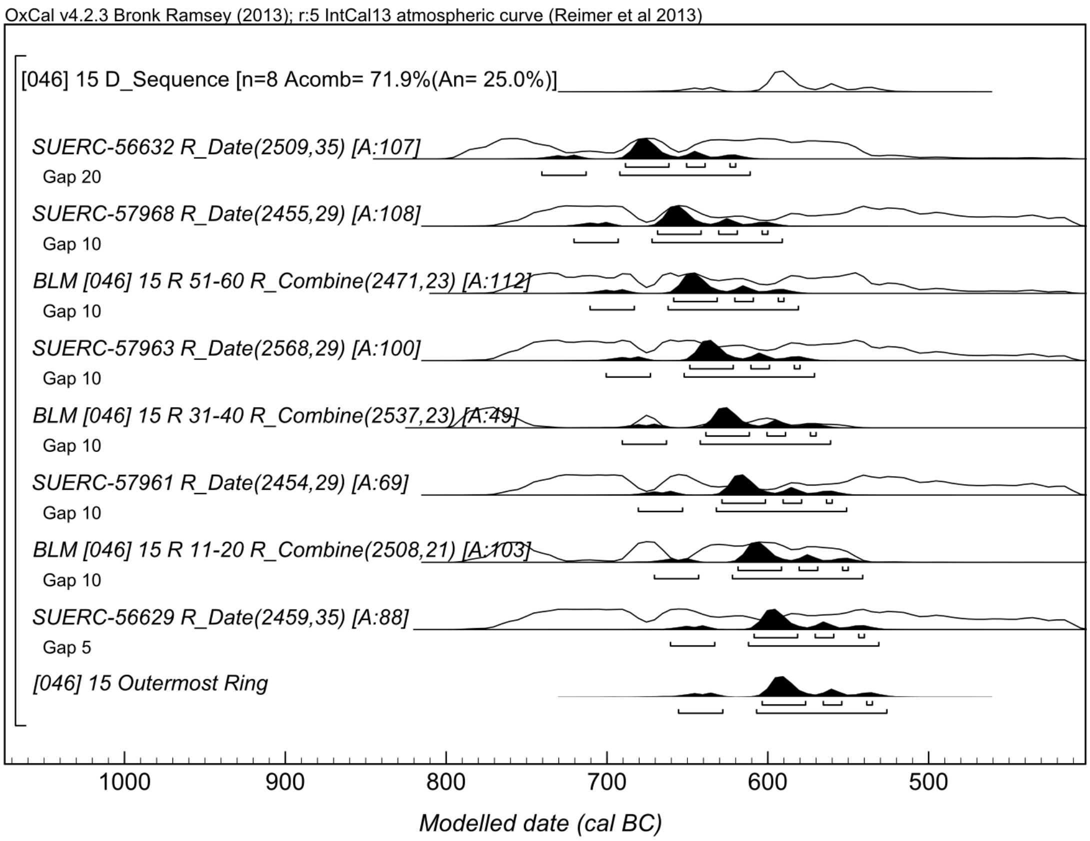




Figure 6.26: Wiggle-match date results for the timber [046]-15: summary (top) and individual determinations (bottom).

Table 6.5: The radiocarbon determinations underpinning the Black Loch of Myrton Structure 1 wiggle-match dates. The timbers from the context [022] are ash (*Fraxinus sp.*) and the timbers from the context [046] are alder (*Alnus sp.*).

| Timber | Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| 022-1 | 1–10 | 34895 | 55558 | 2412 | 30 | -24.6 |
| 022-1 | 16–25 | 36216 | 57958 | 2466 | 29 | -25.5 |
| 022-1 | 36–45 | 34897 | 55561 | 2451 | 30 | -24.8 |
| 022-2 | 3–12 | 34898 | 55562 | 2454 | 30 | -24.8 |
| 022-2 | 13–22 | 43899 | 55563 | 2471 | 30 | -25.1 |
| 022-2 | 28–37 | 36217 | 57959 | 2468 | 29 | -25.7 |
| 022-2 | 38–47 | 34900 | 55564 | 2421 | 30 | -25.2 |
| 046-2 | 1–10 | 35789 | 56633 | 2480 | 35 | -25.2 |
| 046-2 | 1–10 | 37204 | 59615 | 2488 | 26 | -25.9 |
| 046-2 | 21–30 | 36224 | 57969 | 2439 | 29 | -26.1 |
| 046-2 | 31–40 | 35790 | 56634 | 2441 | 35 | -26.4 |
| 046-2 | 51–60 | 36225 | 57970 | 2438 | 30 | -26.2 |
| 046-2 | 61–70 | 35791 | 56638 | 2452 | 35 | -26.6 |
| 046-2 | 81–90 | 36226 | 57971 | 2493 | 29 | -25.5 |
| 046-2 | 91–100 | 35792 | 56639 | 2450 | 35 | -28.7 |
| 046-15 | 1–10 | 35785 | 56629 | 2459 | 35 | -24.6 |
| 046-15 | 11–20 | 36218 | 57960 | 2544 | 27 | -25.4 |
| 046-15 | 11–20 | 37203 | 59614 | 2472 | 29 | -25.5 |
| 046-15 | 21–30 | 36219 | 57961 | 2454 | 29 | -25.1 |
| 046-15 | 31–40 | 36220 | 57962 | 2527 | 29 | -25.4 |
| 046-15 | 31–40 | 35786 | 56630 | 2552 | 35 | -25.1 |
| 046-15 | 41–50 | 36221 | 57963 | 2468 | 25 | -25.3 |
| 046-15 | 51–60 | 36222 | 57967 | 2454 | 27 | -25.4 |
| 046-15 | 51–60 | 35787 | 56631 | 2496 | 35 | -25.4 |
| 046-15 | 61–70 | 36223 | 57968 | 2455 | 29 | -25.7 |
| 046-15 | 81–90 | 35788 | 56632 | 2509 | 35 | -25.5 |

Table 6.6: The results of the $\chi^2$ test statistics and combinations between the repeat measurements of the same decades within the Black Loch of Myrton Structure 1 timbers [04]6-2 and [046]-15. The 5% critical value at 1 df is 3.8.

| Timber | Rings | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ | Combined Age | Combined 1-$\sigma$ error |
|---|---|---|---|---|---|---|---|
| 022-2 | 1–10 | 56633 | 2480 | 35 | 0.0 | 2485 | 21 |
| | | 59615 | 2488 | 26 | | | |
| 022-15 | 11–20 | 57960 | 2544 | 29 | 3.1 | 2508 | 21 |
| | | 59614 | 2472 | 29 | | | |
| 022-15 | 31–40 | 56630 | 2552 | 35 | 0.3 | 2537 | 23 |
| | | 57962 | 2527 | 29 | | | |
| 022-15 | 51–60 | 56631 | 2496 | 35 | 0.9 | 2471 | 23 |
| | | 57967 | 2454 | 29 | | | |

Table 6.7: The summary results of the Black Loch of Myrton Structure 1 wiggle-match dates. The results for the timber [046]-2 are based on the model excluding the outermost decade due to the high probability of a systematic offset producing a spurious result (see text). Posterior probabilities are displayed in Figures 6.23 to 6.26.

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine \An (%) | $\chi^2$ \5% crit |
|---|---|---|---|---|
| 022-1 | *710–680 cal BC (12.7%)*<br>*535–450 cal BC (55.5%)* | *725–675 cal BC (17.7%)*<br>*660–640 cal BC (4.1%)*<br>*545–395 cal BC (73.6%)* | 89.50%<br>\40.80% | 0.913<br>\5.991 |
| 022-2 | *710–645 cal BC (47.6%)*<br>*625–605 cal BC (7.7%)*<br>*510–475 cal BC (12.8%)* | *720–640 cal BC (51.4%)*<br>*630–600 cal BC (10.2%)*<br>*555–405 cal BC (33.8%)* | 80.30%<br>\35.40% | 1.624<br>\7.815 |
| 046-2 | *675–660 cal BC (5.2%)*<br>*500–450 cal BC (63.0%)* | *680–650 cal BC (9.4%)*<br>*645–620 cal BC (3.7%)*<br>*605–590 cal BC (2.2%)*<br>*525–400 cal BC (80.1%)* | 113.70%<br>\28.90% | 1.71<br>\11.071 |
| 046-15 | *605–575 cal BC (54.9%)*<br>*570–555 cal BC (10.9%)*<br>*540–535 cal BC (2.3%)* | *660–625 cal BC (11.6%)*<br>*610–525 cal BC (83.8%)* | 71.90%<br>\25.00% | 6.543<br>\14.067 |

Table 6.8: Results of the radiocarbon measurements on the material from the hearth deposits of Black Loch of Myrton Structure 1

| Context | Sample type | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|---|
| 025 | Roundwood charcoal | *Corylus avellana* | 35955 | 57032 | 2355 | 29 | -26.4 |
| | Cereal grain | *Hordeum sp.* | 35956 | 57033 | 2447 | 26 | -23.0 |
| | Hazelnut shell | *Corylus avellana* | 36821 | 58732 | 2398 | 29 | -25.0 |
| | Cereal grain | *Hordeum sp.* | 36822 | 58733 | 2440 | 29 | -23.4 |
| 044 | Roundwood charcoal | *Alnus sp.* | 35953 | 57030 | 2376 | 29 | -26.5 |
| | Roundwood charcoal | *Corylus avellana* | 35954 | 57031 | 2481 | 29 | -26.1 |
| | Roundwood charcoal | *Corylus avellana* | 36820 | 57831 | 2457 | 29 | -27.8 |

is most credible through the process of eliminating the alternatives. This interpretation might change depending on new evidence.

The first possibility is that the stochastic nature of the radiocarbon measurement process is responsible for the apparent offset in the calibrated date range. Given the overlap between the determinations from both timbers (Figure 6.27), it might be that the [046]-15 measurements are older through chance alone. Nevertheless, this interpretation is very difficult to accept as the results of the [046]-15 wiggle-match do not change subject to removal of any one determination, so the chance effect in question would have had to be the same for all the measurements in question, which is very improbable. Another way to see the issue is by looking at the measurements of decades overlapping between the [046]-2 and [046]-15; once the outermost rings are ignored, the [046]-15 samples all have older ages than the [046]-2 samples. The likelihood of this happening by chance is 3.125%, and this is without taking into account that other

[046]-15 determinations also seem to be older than the neighbouring [046]-2 determinations. Hence it is improbable that the dating discrepancy developed on the back of measurement error.

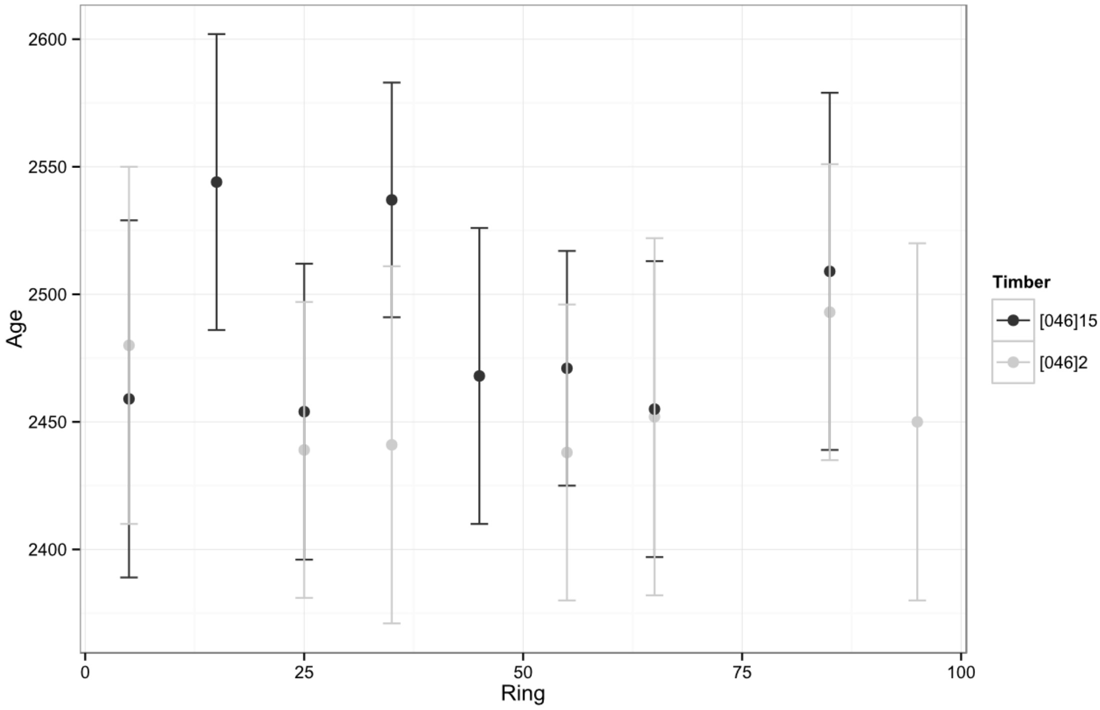



Figure 6.27: The comparison of the age measurements between the corresponding decadal sample blocks from timbers [046]2 and [046]15 age, matching at the bark edge as implied by the relative dendrochronology ALDERx11. Error bars indicate 2-. Note that even though the errors overlap, for all the decades except the outermost rings, the [046]-15 measurements have older $^{14}$C ages.

The second possibility is based on the introduction of a systematic offset through contamination at some stage of the pre-treatment and measurement process. While this may have happened, it is very improbable as samples from both timbers were pre-treated alongside one another and measured in the same batch using the same Oxalic acid primary standards, as well as the same background and secondary standard samples. Furthermore, the measurements have been conducted in three separate batches, as was the pre-treatment, so that any contaminating effect would have had to have targeted the [046]-15 samples on three different occasions, months apart. This is very improbable.

The third possibility assumes that some kind of reservoir dependent offset is in action. The simplest explanation here is that during its life [046]-15 grew over an area off gassing a significant amount of old carbon. Such processes have been encountered elsewhere, for example at Ansanto Valley in Italy (Capano et al. 2013). However, in that case it was the presence of significant amounts of geological carbon dioxide from an active vent that caused the offset to greater ages in the surrounding vegetation. Given the lack of limestone systems, volcanoes or other major sources of geological carbon dioxide in Galloway, this scenario is very improbable.

Hence, timber re-use constitutes the most plausible explanation for the age discrepancy between [046]-15 and the remainder of the hearth structure timbers. Given the good preservation of the context [046] timbers it is plausible that similar quality of survival would have been present within other structures of the settlement and so it is not inconceivable that the timber could have been obtained from an abandoned structure within Black Loch of Myrton. Such an action would allow for a more efficient use of available resources and, if the roundhouses indeed had some special forms of significance (see Chapter 2.1.3), then it stands to reason that remnants of older structures would have been brought in to add some form of symbolic capital to the new building.

The main challenge to this interpretation emerges from the existence of the alder-alder chronology ALDERx11, according to which the two timbers [046]-2 and [046]-15 were felled in the same year. Given that the development of alder-alder chronologies is still an experimental phase (Crone 2014), it is possible that the re-use interpretation presented above is valid, with the proviso that if further evidence emerges supporting the validity of ALDERx11, the interpretation of the wiggle-matching differences will have to change. For the time being, however, the re-use scenario is held to be valid and followed in developing site models for Black Loch of Myrton Structure 1.

### 6.3.3 Black Loch of Myrton Structure 1 site model

The site model for Structure 1 at Black Loch of Myrton includes all of the wiggle-match data, single radiocarbon determinations from the hearth, as well as stratigraphic information; the construction of the hearth structure would have happened before the final uses of the first hearth, dated by the material from the context [025], which in turn would have happened before the final uses of the subsequent hearth, dated by the material from the context [044]. Furthermore, the evidence of the relative dendrochronology ASHx3, according to which timbers [022]-1 and [022]-2 were felled in the same year, was also included (Figure 6.28). The additional parameters introduced into the model are the boundary for the onset of the activity, the boundary for the end of activity and the *Last*(); estimate within the phase for the felling of the timbers from the foundation of the hearth, which provides an estimate of the most recent plausible felling and, by proxy, an estimate for the construction of Structure 1.

End: BLM Structure 1 dated deposition

| | | | | |
|---|---|---|---|---|
| Structure 1 Hearth 2 | SUERC-57032 | SUERC-57033 | SUERC-58732 | SUERC-58733 |
| Structure 1 Hearth 1 | SUERC-57030 | SUERC-57031 | SUERC-58731 | |
| Structure 1 felling | [046] 2 | TPQ: [046] 15 | [022] 1 [022] 2 Span(U(0,1)) | |

Onset BLM Structure 1 dated deposition

Figure 6.28: Schematic of the Bayesian model for Structure 1 at Black Loch of Myrton.

The model results demonstrate that wiggle-match dating combined with Bayesian analysis can produce estimates of construction events with 95.4% HPD areas as good as 70 years even under plateau conditions (Figure 6.29):

- The onset of activity at Structure 1 is estimated to *530–450 cal BC (95.4%)*, with the greatest probability in the range *505–470 cal BC (68.2%)*.
- The end of the dated activity at Structure 1 is estimated to *500–390 cal BC (95.4%)*, with the greatest probability in the range *490–430 cal BC (68.2%)*. Note that this does not include the final refurbishment of the hearth, as no good samples were available from that deposit.
- The construction estimate dates to *515–445 cal BC (95.4%)*, with the greatest probability in the range *505–470 cal BC (68.2%)* (Figure 6.30).
- Model agreement is low at Amodel = 40.6%.

The poor model agreement can be traced to the two hazelnut roundwood charcoal determinations SUERC-57031 and -57032. SUERC-57031 is older than the remainder of the samples within context [044] (the remains of the first hearth in the sequence), from which it derives. The cause behind this effect is uncertain; with this age the sample may have derived from a wattle fence, or some other hazel feature or artefact that has been burnt after the branch from which the sample derived has been cut. It is also possible that the sample is a statistical outlier, as it lies within three standard deviations of the average of the other two samples within the same context. SUERC-57032 is younger in radiocarbon terms from the remainder of its context [025] (the use of the second hearth) and as such is more difficult to explain; it may either have been introduced into the context during some later disturbance, which is difficult to conceive given that the hearth deposits were sealed by a layer of stone and clay, or it is a statistical outlier, which is easier to conceive as it is within three standard deviations of the average of the remainder of measurements from that context. Removal of these samples improves the model agreement to 64.7%, but the actual changes to the estimates are negligible (for the construction estimate these are less than 5 cal years) and hence the determinations are not removed from the model.

The 95.4% modelled date range of the construction parameter (*515–445 cal BC*) overlaps with the sapwood felling estimate for the planks from the absolute dendrochronology F40oakx3 that constitute part of a structural feature [040], which is also located within the footprint of Structure 1. This is an important result, as it shows congruence between the wiggle-match dating and the provisional absolute dendrochronology of the site. It also indicates that it might be possible that the planks in question were felled at the same time as the timbers constituting contexts [022] and [046] and hence they can be integrated into the felling phase of the site model. The resulting model moves the construction date to *465–435 BC* (Figure 6.31), but the model agreement index is low at 33.7%. This indicates that under the ratified calibration curve IntCal13 it is improbable that the planks from F40oakx3 were felled at the same time as the timbers

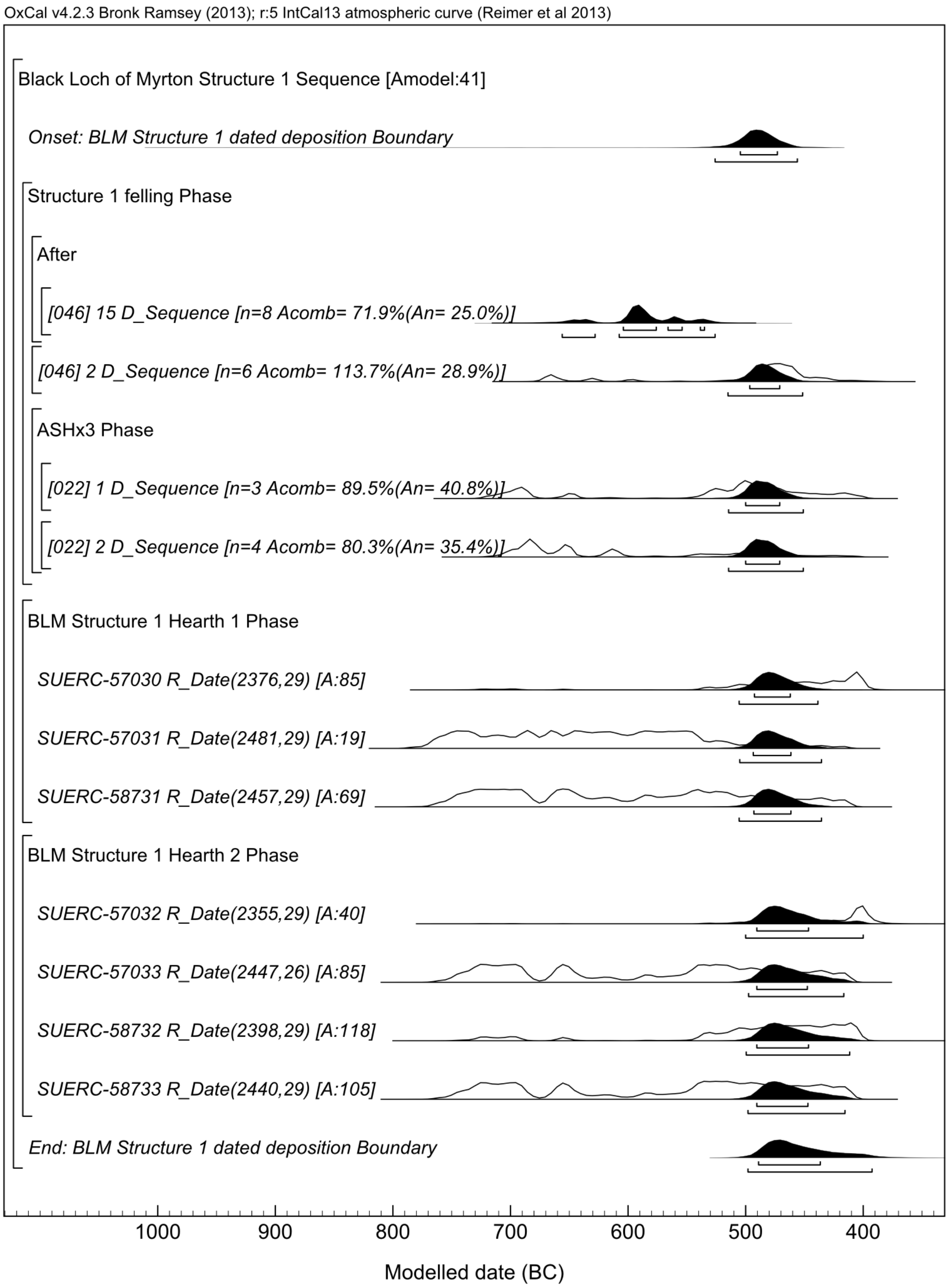



Figure 6.29: The results of the model for the construction of the Black Loch of Myrton Structure 1.

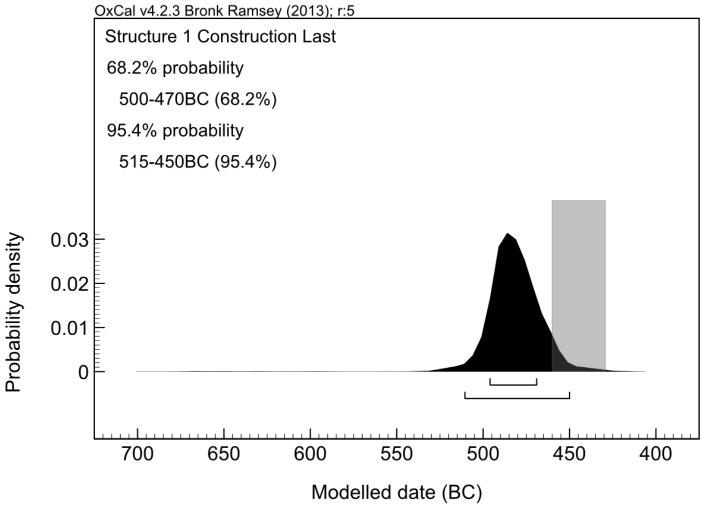



Figure 6.30: The estimate of the construction of the Black Loch of Myrton Structure 1.The grey band indicates the felling range of the oak planks F40oakx3 from feature [040] within the same building.

forming the hearth frame and associated features. Rather, the recommended interpretation from this perspective would be that the planks in question were added during one of the refurbishment events testified to by the presence of successive hearth layers. Hence, the recommended model excludes F40oakx3 from the initial felling phase, leaving a construction date of *515–445 cal BC (95.4% probability)*.

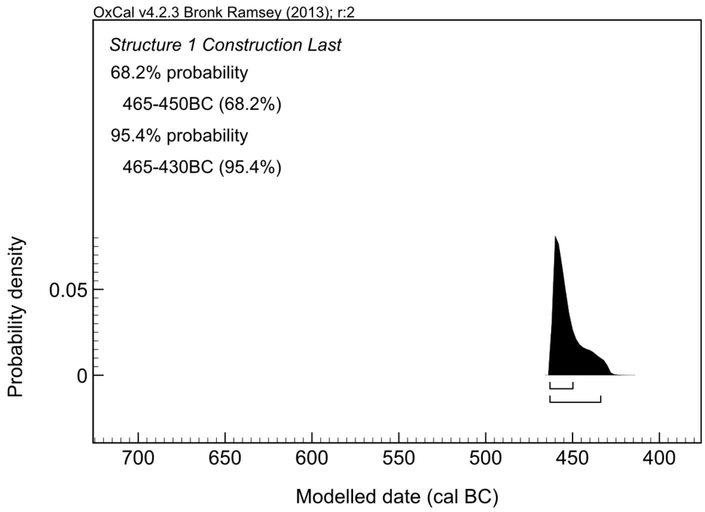



Figure 6.31: The construction estimate for Structure 1 at the Black Loch of Myrton after including the F40oakx3 determinations within the felling phase for the hearth structure. In this particular case the truncated shape of the distribution implies that the absolute dendrochronological data is at odds with the wiggle-match determinations.

### 6.3.4 Black Loch of Myrton: alternative interpretations and lessons learned

In the course of the dating of the Structure 1 at Black Loch of Myrton a number of issues came to the fore. The four most important of these are the need for flexibility in research design, approaches to resolving ambiguities in the data, potential for adverse shrinkage in similar models and the slight changes to the interpretation of the results if calibrating against a curve augmented with the T-947 data (see Chapter 5.1).

#### Flexibility in implementing research design

The original design for the wiggle-match dating of Structure 1 at Black Loch of Myrton called for half the number of measurements that were committed in reality. This estimate was derived by first making two wiggle-matches based on allocating three measurements to each of the two Context [022] timbers and then using the results to guide a simulation study. As the results of these pilot wiggle-match dates pointed to a felling in either the first or the final third of the Hallstatt plateau (Figure 6.32), the research design for the structure could be focused on choosing between these two alternatives. The simulation work revealed that, if all the timbers have been felled at the same time, or within a very constrained time period, it ought to be possible to make a confident decision between these two alternatives by allocating as little as 12 new measurements: four each to two timbers that lived in excess of 80 years, and two each to the hearth deposits. In actuality both long span sequences failed to fit in with these expectations, as [046]-2 suffered from the issue with the outermost rings and [046]-15 appears to have been derived from the middle part of the calibration plateau, hence not conforming to the two alternatives suggested by the preliminary wiggle-matches (Figure 6.33). Furthermore, because at this early stage each of these wiggle-matches has been based on only four determinations, it was impossible to resolve whether they are contemporaneous or not and hence substantial further dating resources had to be committed to resolving this issue, as well as the somewhat large scatter of the hearth determinations. It was only after the conclusion of this follow-up round of measurements that the wiggle-match dating study could be led to its successful conclusion.

This failure of the original research design carries with it implication for future work, most so if it includes the sites from the Hallstatt calibration plateau. Had the nature of the overarching project not allowed the additional dating resources, then the project would be inconclusive and the initial investment lost for no return better than confirming that Structure 1 was indeed built sometime in the mid-first millennium cal BC. On the other hand, had the number of measurements allocated to the project from the start been large enough to deal with the emergent uncertainties, then, if the original design worked, the remaining measurements would have been better used elsewhere. Therefore, efficient use of the wiggle-match dating technique benefits from management flexibility that allows to first conduct pilot dating to orient the research design, then conduct a dating project with the minimum number of measurements needed for a realistic chance of success and then, if necessary, allocate further measurements to clear up any ambiguities that may emerge on account of timber re-use, or any other complicating factor.

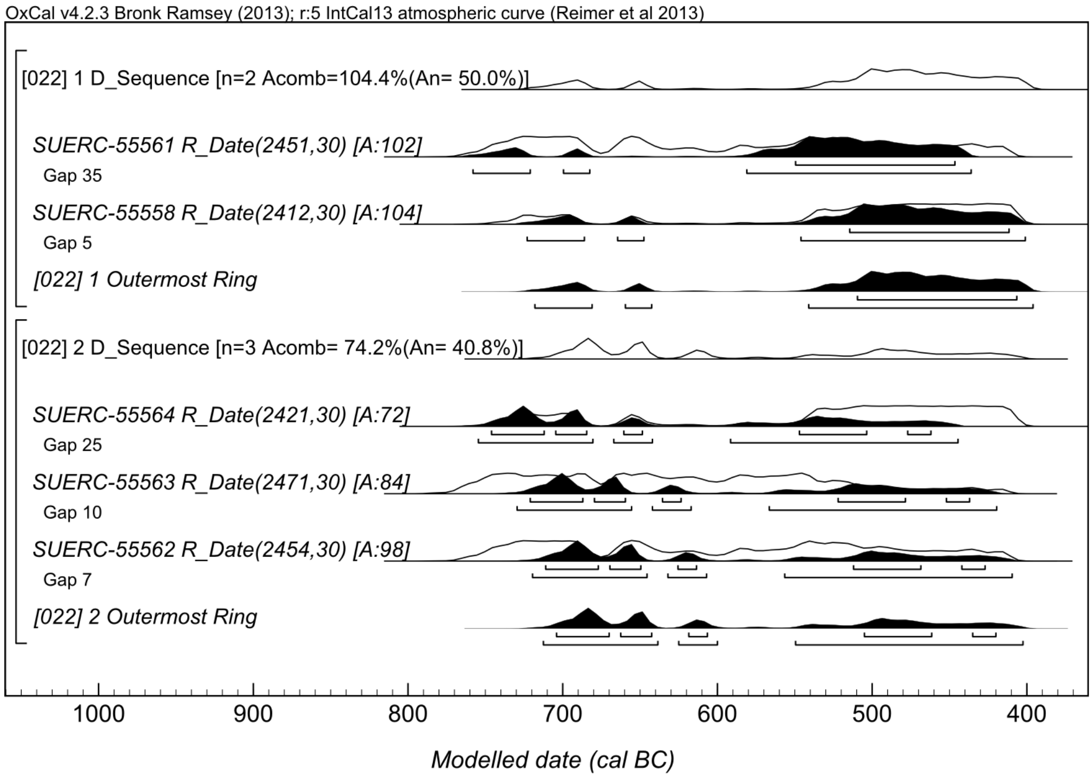



Figure 6.32: The two [022] pilot wiggle-match dates from Black Loch of Myrton Structure 1.

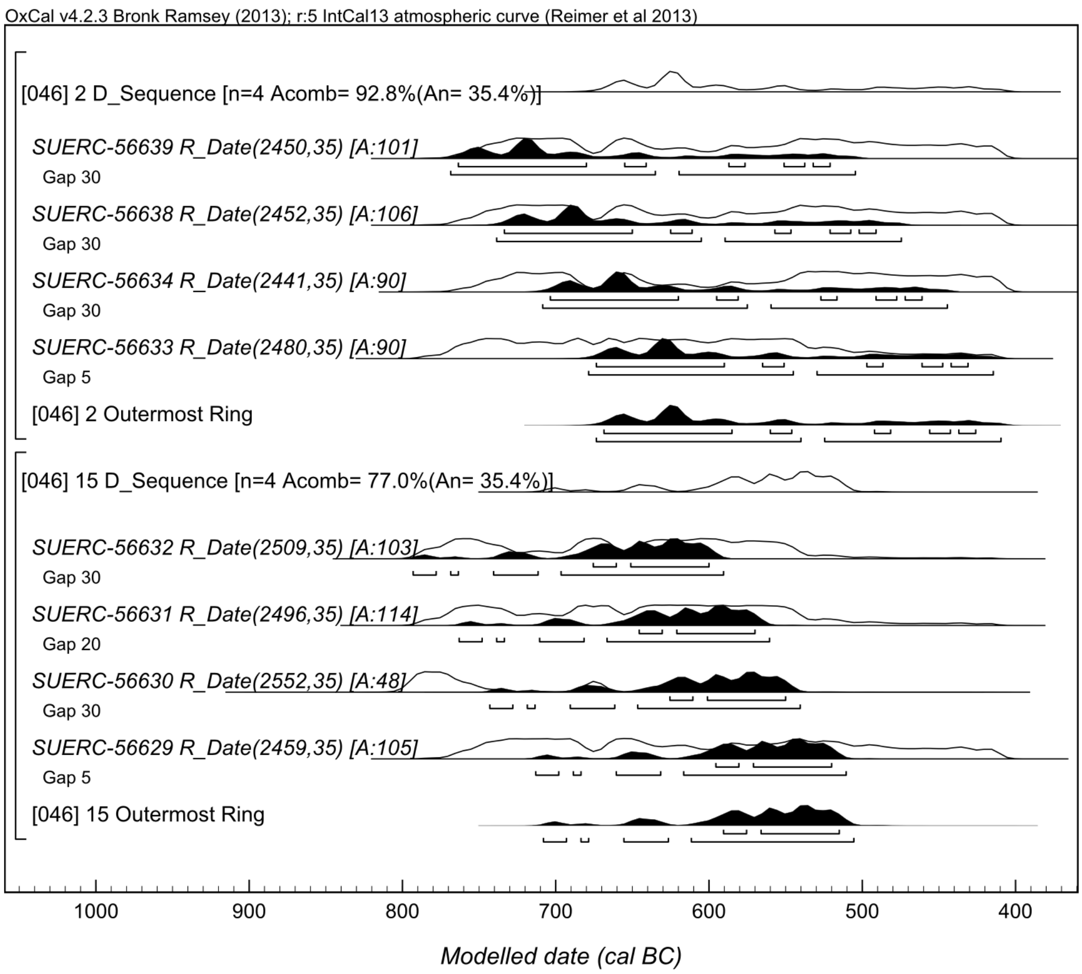



Figure 6.33: The initial results of the two context [046] wiggle-matches from Black loch of Myrton Structure 1.

**Resolving ambiguities within a model**

During the course of the successive stages of measurement described above, the wiggle-match dates appeared to produce an alternative date for the construction of Structure 1 at Black Loch of Myrton. Within this interpretation the measurement SUERC-56630 is removed from the combined radiocarbon age for rings 31–40 of the timber [046]-15. This measurement derived from batch 37/14, which produced a number of other determinations that caused issues with the dating of Cults Loch 3, with the most probable explanation being too gentle pre-treatment. The removal of this measurement makes little change to the calibrated date ranges of the wiggle-match (Figure 6.34), but it means that the agreement index for combinations with the other three wiggle-matches changes to Acombine = 35.1%, which is very close to the passing threshold of 35.4% (the $\chi^2$ test statistic is still too high at 11.085, with the 5% critical value at 3 df being 7.815). Furthermore, the low agreement can be traced to the effects of the outermost rings of the timber [022]-1, whose measurement mean is somewhat younger than that of the preceding decades. While the outer ring issue (see section 6.2) has been seen to only lead to deflection towards greater ages, this might be the effect of the greater effect that such deflections have for wiggle-match dates on the Hallstatt plateau  in other words, it might be that deflection towards younger ages went unnoticed. Once the determination SUERC-55558 from the outermost rings of [022]-1 is also removed, the agreement index of the combination Acombine = 70.7% and the $\chi^2$ test statistic is 7.294, meaning that the posterior distributions of the four wiggle-match dates become indistinguishable. This means that under this interpretation the chronology ALDERx11, according to which [046]-2 and [046]-15 are contemporaneous, becomes viable and hence these two timbers can become constrained to a single year within the model for the felling phase. Implementing this model, without reference to the hearth deposits, leads to a very different construction date of *685–585 cal BC (95.4%)*(Figure 6.35).

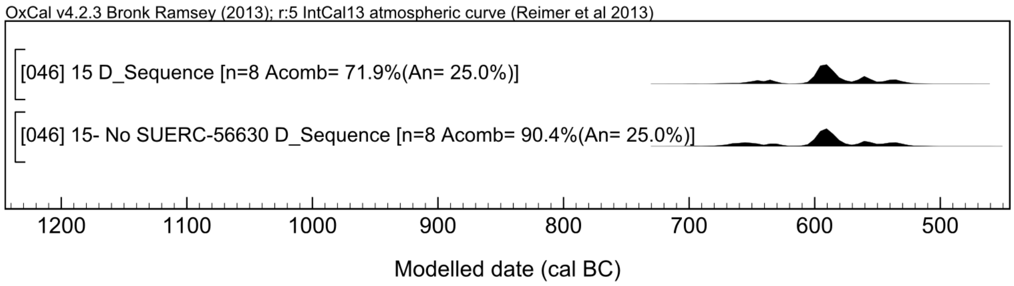



Figure 6.34: The wiggle-match for the timber [046]-15 before and after the removal of the radiocarbon determination SUERC-56630.

The problem with the interpretation and the model above is that, while it appears to agree with the relative chronology ALDERx11, it hinges on two somewhat arbitrary removals and conflicts with the data from the hearth sequence. While there have been issues with batch 37/14, the measurement SUERC-56630 still passes the $\chi^2$ test with the re-run measurement SUERC-57962 ($\chi^2$= 0.3; 5% critical value is 3.8). Furthermore, the deflection towards younger radiocarbon ages on the outermost rings from timber

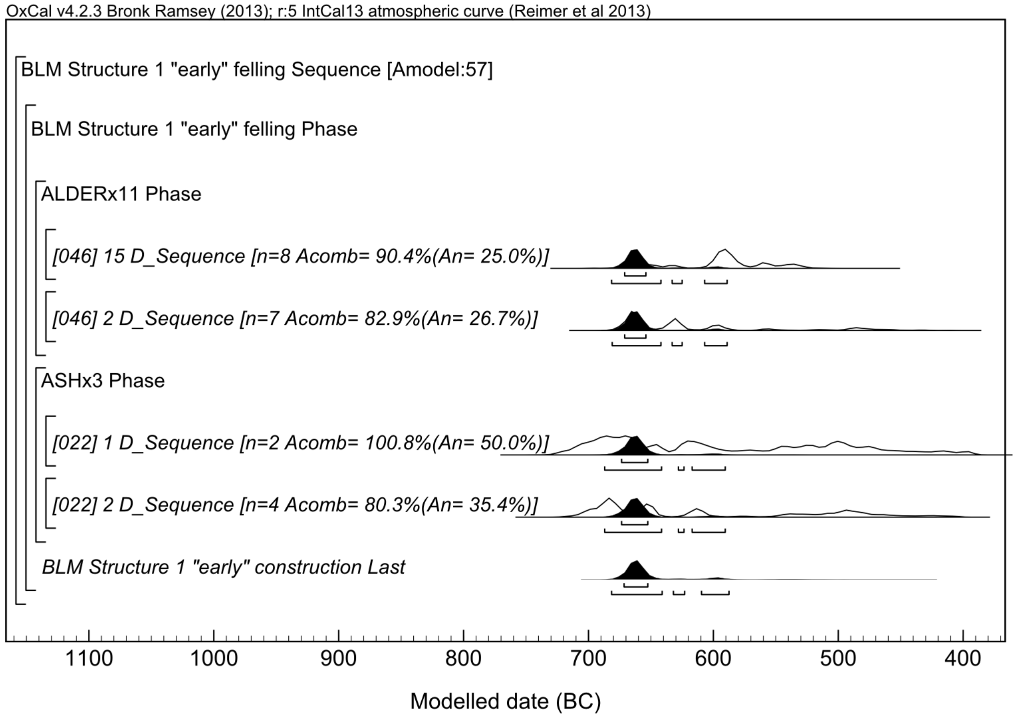



Figure 6.35: Results of the felling phase for the Black Loch of Myrton Structure 1 under the early interpretation.

[022]-1 is the only case where this effect happens in this direction and also the only case where it happens in a non-alder species ([022]-1 is ash). Hence, the grounds for justifying the removals necessary to justify the model in question are weak. The main issue, however, is the lack of agreement with the hearth data; had this early model of the felling phase been implemented, the hearth deposits would still point to the end of activity towards the latter part of the Hallstatt plateau (Figure 6.36), meaning that retaining this model would require postulating an activity duration at Structure 1, which is too long to be realistic.

While it was rejected on account of its incongruence with the data, the early interpretation for Black Loch of Myrton Structure 1 begs the question of how to deal with such uncertainties had the hearth data been unavailable. In general, the procedure that would have been taken in the particular case of Black Loch of Myrton Structure 1 would be to date another of the large alder logs from the context [046], avoiding the outermost rings. The resulting wiggle-match would provide support for one or the other of the possible interpretations. In more general terms, had the issue emerged in a situation where no long-lived timbers have been available, or where the third long-span sequence would have failed to resolve the ambiguities, it would be necessary to close off the report with stating the presence of two possible interpretations and indicating a preference for that which conflicts less with other circumstantial information; in the current case it would be the late interpretation, as it is in better congruence with the current experiences regarding outermost rings. Note that all these discussions hinge on feature-oriented sampling; had this not been implemented, the decision process outlined above would become meaningless, as it would become impossible to recognize whether the differences in wiggle-match dates emerged due to difference in felling dates of the timber, technical issues, or whether they reflect different construction events.

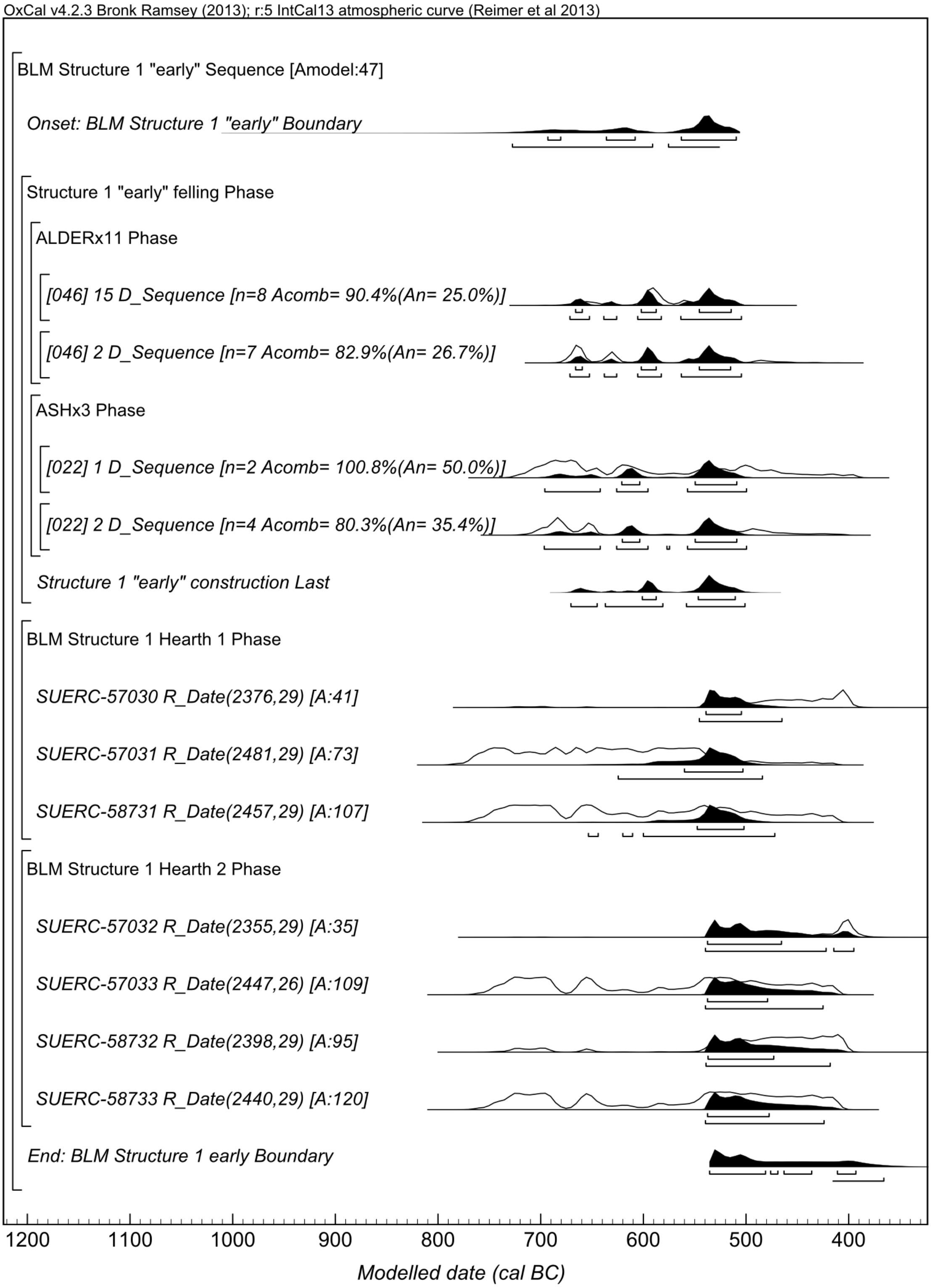



Figure 6.36: The results of the Black Loch of Myrton Structure 1 model using the early felling phase. Note the wide dispersal of the modelled date ranges after the addition of the hearth data, demonstrating the difficulties in reconciling the hearths dates and the wiggle-match dates under this interpretation.

#### Shrinkage and the interpretation of the hearth results

The results of the model for Structure 1 at Black Loch of Myrton also present an opportunity to explore whether, under certain circumstances, adverse effects of shrinkage (see section 6.2.2) could take hold in this kind of model design. To this end a simulation experiment was conducted within which the felling phase remained unchanged from of the model in section 6.3.3, but the hearth measurements were replaced by simulates at 25 year intervals from the mode of the construction estimate and each other (simulated phase 1 is at 457 BC and simulated phase 2 is at 432 BC). The simulation was re-iterated 40 times and the accuracy of the modelled date ranges was noted. This experiment simulates a situation of a site model where a group of wiggle-match dates precedes individual samples from deposits with some stratigraphic relation, but no indication of continuity; an example would be a log floor feature followed by successive layers of occupation debris interspersed with abandonment layers.

The results of the simulation experiment are unambiguous with 39 of the 40 68.2% modelled HPD areas being inaccurate and displaying a bias towards older dates. This indicates that in this kind of situation adverse effects of shrinkage can take hold and will affect the validity of the nominal modelled ranges. As a result, when there is no indication of continuity in these kinds of situation on sites coming from flat parts of the calibration curve, it becomes important to conduct further sensitivity analyses on the model, focussing on the effects of different prior distributions and adding further boundary parameters to account for the interruption of activity. These considerations do not affect the construction date for Black Loch of Myrton Structure 1, as the adverse effects of shrinkage appear not to affect the construction estimate, and also because half a century interval between the construction of the building and the final use of the first re-furbished hearth is unrealistic in this particular case.

#### The Black Loch of Myrton and potential effect of small scale calibration offsets

One other possible analysis of the Black Loch of Myrton Structure 1 data is to re-run the model including all the available information and the absolute dendrochronology F40oakx3, but do all the radiocarbon calibrations against a curve that includes the decadal averages of the Cults Loch 3 T-947 high-precision data (see Chapter 5). This analysis is for exploratory purposes only and, while its results are more favourable than those conducted against the ratified IntCal13, they cannot be recommended for site interpretation. This is because the T-947 data has been measured by a single laboratory only and also because its inclusion results in mixing of time scales, as changing the calibration curves leads to dates that are incongruent with one another. To highlight these objections all the date ranges are reported as *T-947 BC* rather than *cal BC*.

Use of the T-947 data for calibration allows a better reconciliation between the absolute dendrochronological data and the radiocarbon model and also improves the agreement of the model itself, relative to that constructed based on IntCal13. The construction estimate is now placed at *465–435 T-947 BC (95.4%)*, with the greatest probability at *465-445 T-947 BC (68.2%)*(Figure 6.37). The model agreement is still poor (43.2%), however, the distribution is no longer truncated as it was under the IntCal13 calibration, suggesting a better degree of agreement between the two sources of data under this model.

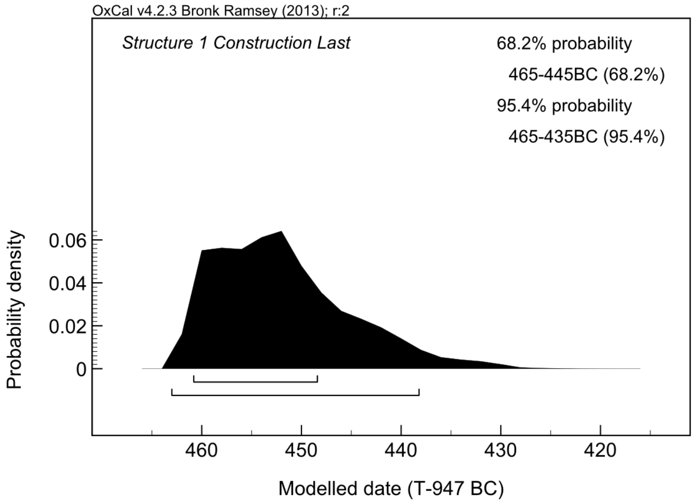



Figure 6.37: Construction estimate for Black loch of Myrton Structure 1 based on all the available chronological information and a calibration curve that includes the T-947 data. Notice that this distribution no longer has the truncated appearance seen in Figure 6.31, suggesting that under the modified calibration curve it is more plausible that F40oakx3 planks constituted a part of the construction event.

The T-947 curve can also be used to assess the impact that the small-scale offsets could have on the preferred model for the site, without the F40oakx3 data within the construction phase. Calibrating against the augmented curve results in some minor changes, with a minor shift towards younger dates: the construction is now estimated to *505–435 T-947 BC (95.4%)*, with the greatest probability concentration in *480–450 T-947 BC (68.2%)*(Figure 6.38). These changes are all between 5 and 20 years and the two distribution are indistinguishable ($\chi^2$= 1.231, 5% crit = 3.841). In practice this means that while the small offsets may have some effect on models where radiocarbon is the only source of dating information pertaining to calendar dates, these effects are small as far as most realistic questions are concerned.

Evaluating the effects of calibration against the curve augmented with the T-947 data has two important implications. First of all, it shows that in some cases, like when dealing with F40oakx3 dendrochronological determination, the fine shape of the curve can affect interpretation and hence further progress in calibration might prove beneficial for situations where wiggle-match and dendrochronological dates are employed side by side. What is more important however, is the second implication, that the effect of the curve change on the construction date is minimal. This shows that, despite some of the issues that might be had with the calibration curve, it is possible to obtain reliable feature dates during the Hallstatt calibration plateau on a routine basis.

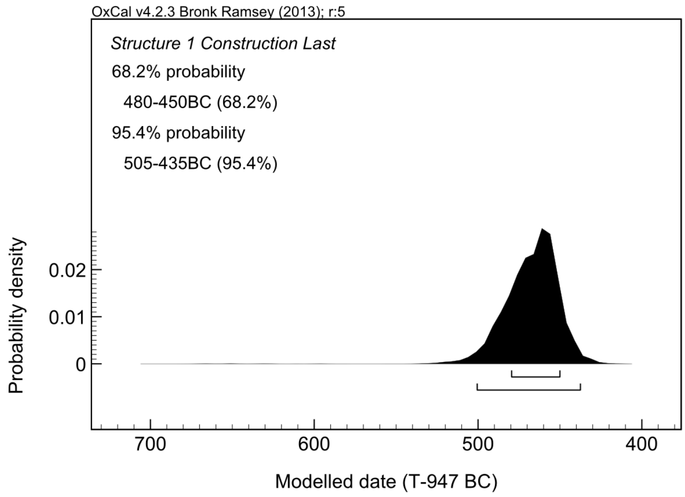



Figure 6.38: Construction estimate for Black Loch of Myrton Structure 1 based on wiggle-match dates, stratigraphic information, relative dendrochronology ASHx3 and a calibration curve that includes the T-947 data.

### 6.3.5 Section conclusions

This section presented the wiggle-match dating of Structure 1 from the wetland settlement at Black Loch of Myrton. It both outlined the wiggle-match dating results and discussed some of the emergent issues pertaining to the site. As far the date for the construction of Structure 1 is concerned, the best estimate from the wiggle-match dating point of view is *515–450 cal BC (95.4%)*, as presented in section 6.3.3. This demonstrates that is possible to wiggle-match date construction events on the Hallstatt plateau to less than a century. The wiggle-match dating study at Black Loch of Myrton can also be used to provide some basic guidelines for future research design for projects intended to determine construction dates for features from the Hallstatt calibration plateau through wiggle-match dating:

1. Use of pilot dates to guide final design (2–3 measurements on two timbers from each feature of interest). While these guides may not always be successful, they limit the range of possible answers, thus allowing for more targeted and therefore more economic dating.

2. Unless special circumstances arise, employ feature-oriented sampling. In most cases this will be the simplest way to highlight the presence of discordant wiggle-matches and take suitable action to deal with the issue.

3. Aim for the collection of longest-lived timbers available in the feature of interest. The short sequences from context [022] were included in the present study only as a check of their utility and not for pragmatic reasons.

4. When choosing samples for wiggle-match dating select two longest possible sequences per feature dated and, if possible, have a third timber set aside to aid in resolving any uncertainties that may emerge.

Note that these recommendations assume flexible research design that allows for separate pilot and main dating studies, as well as a follow-up round to clear ambiguities if they emerge.

## 6.4 Site formation on the Hallstatt plateau: Cults Loch 3

The Black Loch of Myrton case study demonstrated that it is possible to obtain construction date estimates precise to under a century during the Hallstatt calibration plateau. The next logical question is whether it is possible to use the wiggle-match dating technique to explore site formation processes during the calibration plateau; to this end the Cults Loch 3 dating study was conducted. The aim of the study was to establish the chronological relationship between two roundhouses, Structure 1 and Structure 2, at the crannog Cults Loch 3.

### 6.4.1 Site stratigraphy, the archaeological question and research design

An artificial promontory, Cults Loch 3 (NGR NX 1203 6058) lies about 3km east of Stranraer in Galloway and is one of three sites within and around Cults Loch excavated as a part of the Cults Loch Landscape Project between 2009 and 2010. All the information on dendrochronology and site stratigraphy given here comes from the forthcoming site report by Graeme Cavers and Anne Crone.

Cults Loch 3 consists of a mound bearing the remnants of three roundhouses, associated features and very probable remnants of later activity (Figures 6.39 to 6.40). The excavators interpreted the site to have six distinct stratigraphic phases:

1. The construction of the crannog mound
2. Construction and activity at Structure 1
3. Construction and activity at Structure 2, as well as deposits and structures in the N quadrant
4. Construction and activity at Structure 3
5. A decay horizon, with possible later activity phases
6. Renovation of the causeway

The main ambiguity regarding the stratigraphy of the site has to do with the relationship between Structures 1 and 2. They overlap in plan and hence are assigned to different phases. However, it was impossible to determine their relationship in the field and the current phasing is based on circumstantial evidence. The aim of the Cults Loch 3 wiggle-match dating study was to resolve this question of relative chronology.

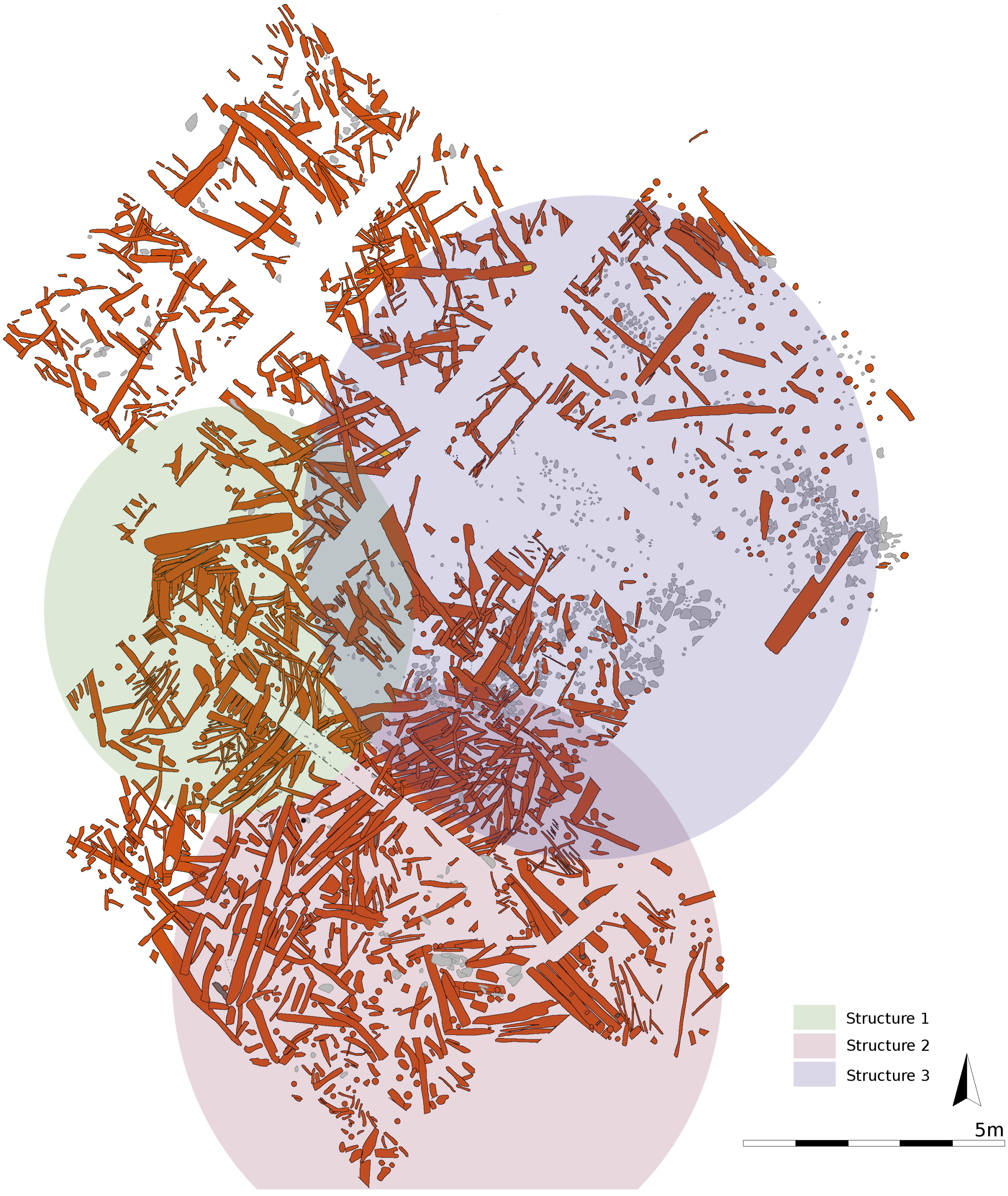



Figure 6.39: Plan of Cults Loch 3 with the roundhouses indicated (re-drawn from Cavers and Crone, forthcoming).

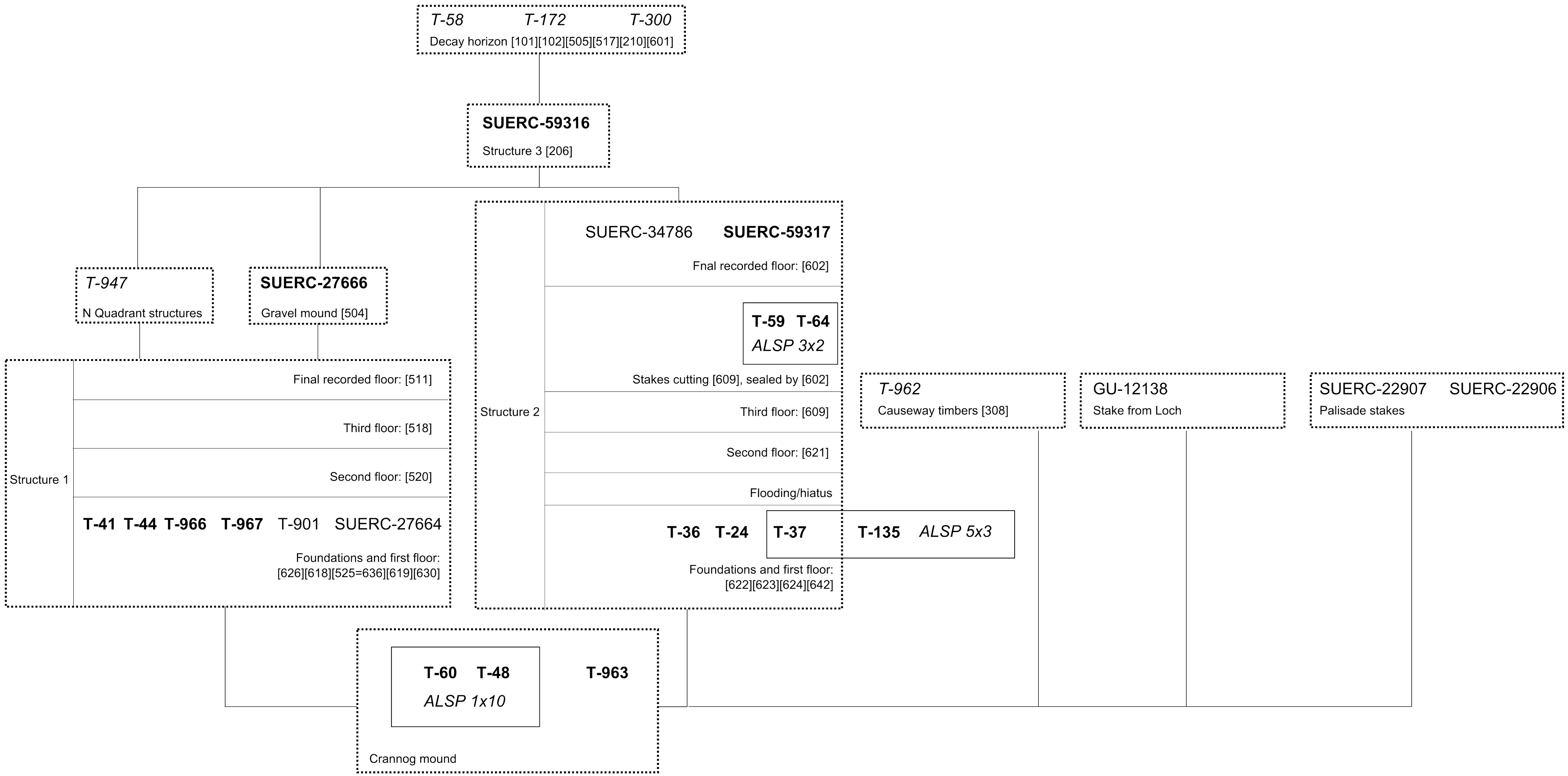



Figure 6.40: Relevant elements of site stratigraphy with dated timbers and contexts. New radiocarbon dates and wiggle-matches in bold. Dendrochronological determinations and relative chronologies are in italics.

Besides this main subdivision, each of the structures also contained several floor layers and, in the case of Structure 2, a flooding or hiatus deposit. Furthermore, a walkway to the crannog was discovered and various strands of evidence suggest that the site began as an artificial island and only after abandonment became a promontory.

Cults Loch 3 has had the most detailed chronology of any earlier Iron Age crannog in Scotland, even before the wiggle-match dating study. Based on a suite of ten absolute dendrochronological determinations, including three timbers with sapwood, it was almost certain that the site dated to the 5th century BC (Table 6.9). This was further augmented by the availability of a legacy wiggle-match (Table 6.10) and a group of nine individual radiocarbon determinations from across the site (Table 6.11), all of which are congruent with the 5th century BC dating of the site, as exemplified in Hamilton's (forthcoming) Bayesian model for the site. Furthermore, a number of alder-alder and alder-oak chronologies have been developed, which, despite their restriction in terms of timber counts, can provide useful information when modelling wiggle-matches (Table 6.12).

Table 6.9: Absolute dendrochronological determinations from Cults Loch 3 (data fromCavers and Crone, forthcoming).

| Context | Species | Timber | Number of rings | Outer rings | Final Ring date | Felling estimate |
|---|---|---|---|---|---|---|
| 601 | *Quercus sp.* | T-58 | 143 | 23 sapwood | 438 BC | 435-412 BC |
| N/A | *Quercus sp.* | T-131 | 54 | N/A | 494 BC | N/A |
| 218 | *Quercus sp.* | T-172 | 186 | N/A | 511 BC | N/A |
| 300 | *Quercus sp.* | T-300 | 177 | N/A | 478 BC | N/A |
| 508 | *Quercus sp.* | T-945 | 82 | N/A | 479 BC | N/A |
| 644 | *Quercus sp.* | T-947 | 109 | 11 sapwood | 450 BC | 450-415 BC |
| 308 | *Quercus sp.* | T-962 | 232 | h/s boundary | 462 BC | 452-416 BC |
| 519 | *Quercus sp.* | T-964 | 213 | N/A | 558 BC | N/A |
| 308 | *Quercus sp.* | T-968 | 239 | N/A | 471 BC | N/A |
| 308 | *Quercus sp.* | T-972 | 102 | Bark edge | 194 BC | 193 BC |

Table 6.10: Component radiocarbon determinations of the legacy wiggle-match date on the oak (*Quercus*) timber T-901 from context [630] Cults Loch 3 (data from Cavers and Crone, forthcoming).

| Rings | GU- number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 56–60 | 23576 | 34787 | 2505 | 30 | -24.9 |
| 51–55 | 23577 | 34788 | 2450 | 30 | -26.5 |
| 46–50 | 23578 | 34789 | 2455 | 30 | -25.7 |
| 41–45 | 23579 | 34794 | 2425 | 30 | -25.6 |
| 36–40 | 23580 | 34795 | 2465 | 30 | -25.9 |
| 31–35 | 23581 | 34796 | 2470 | 30 | -25.6 |
| 26–30 | 23582 | 34797 | 2445 | 30 | -25.9 |
| 21–25 | 23583 | 34798 | 2450 | 30 | -26.0 |
| 16–20 | 23584 | 34799 | 2440 | 30 | -26.1 |
| 11–15 | 23585 | 34804 | 2465 | 30 | -26.7 |
| 6–10 | 23586 | 34805 | 2420 | 30 | -25.8 |
| 1–5 | 23587 | 34806 | 2445 | 30 | -26.2 |

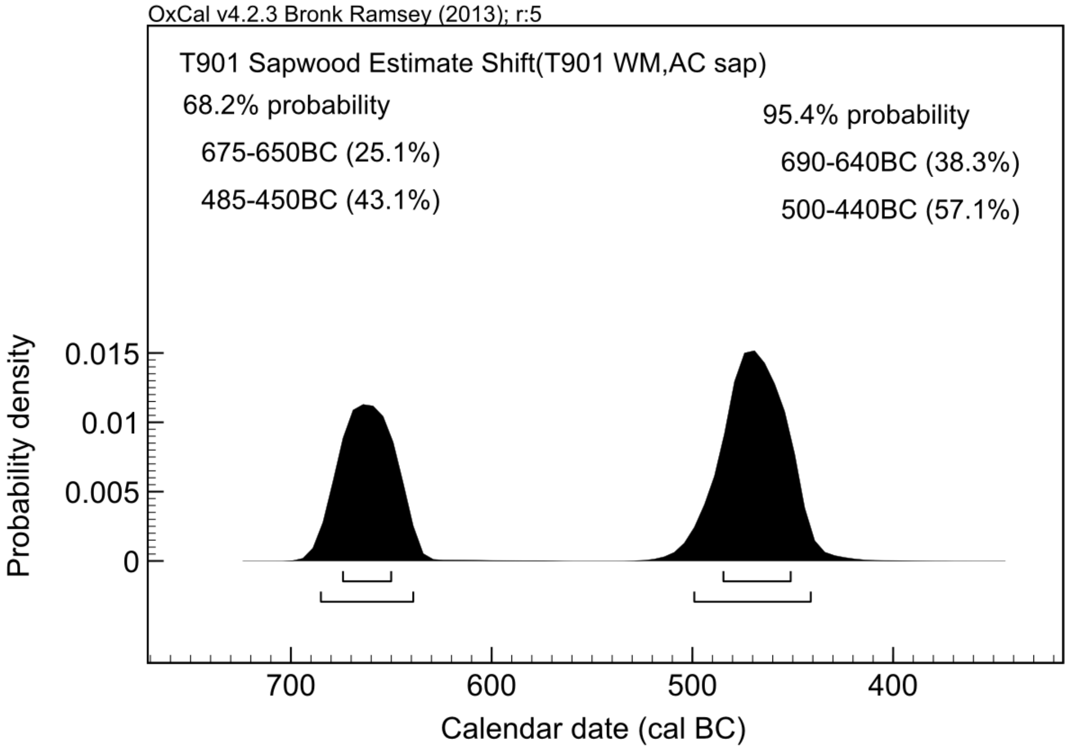
Table 6.11: Legacy radiocarbon dates from Cults Loch 3 (data from Cavers and Crone, forthcoming).

| Context | Sample type | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|---|
| Survey | Pile | Quercus | 12138 | N/A | 2340 | 50 | -26.4 |
| Palisade | Stake T-207 | Quercus | 18317 | 22906 | 2440 | 25 | -24.9 |
| Palisade | Stake T-294 | Alnus | 18318 | 22907 | 2375 | 30 | -27.0 |
| Lowest levels | T-963 | Alnus | 20882 | 27660 | 2420 | 35 | -28.4 |
| 521 | Plant litter flooring | Pteridium | 20883 | 27664 | 2405 | 35 | -25.7 |
| 504 | Charcoal from gravel mound | Corylus | 20885 | 27666 | 2330 | 40 | -25.3 |
| 602 | Gravel spread from structure 2 | Corylus | 23575 | 34786 | 2355 | 30 | -24.6 |
| Structure 2 | Horizontal log | alnus | 23574 | 34785 | 2435 | 30 | -24.3 |
| Structure 1 | Timber | Alnus | 20884 | 27665 | 2355 | 35 | -28.0 |

Table 6.12: Alder-alder and alder-oak relative chronologies. Timbers wiggle-match dated during the course of this study are in boldface (data from Cavers and Crone, forthcoming)

| Chronology | Species | Timbers |
|---|---|---|
| ALSP 1x10 | *Alnus* | T-129, **T-48**, **T-60**, T-137, T-62, T-113, T-117, T-146, T-53, T-138 |
| ALSP 2x2 | *Alnus* | T-933, T-28 |
| ALSP 3x2 | *Alnus* | **T-59**, **T-64** |
| ALSP 4x3 | *Alnus* | T-37, T-135, T-320 |
| ALSp 5x2 | *Alnus* | T-33, T-144 |
| ALSP 6x3 | *Alnus* | T-34, T-35, **T-36** |
| QSP 1x2 | *Quercus* | T-935, T-937 |
| QSP 2x2 | *Quercus* | T-942, T-959 |
| QSP 3x2 | *Quercus* | T-327, T-231 |
| QSP 4x2 | *Quercus* | T-214, T-101 |
| | *Alnus-Quercus* | T-971, T-52 |
| | *Alnus-Quercus* | T-936, T-293 |
| | *Alnus-Quercus* | T-67, **ALSP 1x10** |
| | *Alnus-Quercus* | T-961, **T-41** |

The legacy wiggle-match is based on 12 consecutive measurements of semi-decadal blocks from timber T-901 from context [630]. This sequence, spanning a total of 60 years, ends at the heartwood-sapwood boundary and hence an additional uncertainty estimate had to be added. A uniform distribution of between 10 and 45 years was used, in line with the dendrochronological report for the site (Cavers and Crone ming). The results indicate that the timber would have been felled either in *690–640 cal BC* (*38.3%*), or *500–440 cal BC* (*47.1%*), with the 68.2% HPD region spanning the periods *675–650 cal BC* (*25.1%*) and *485–450 cal BC* (*43.1%*) (Figure 6.41).



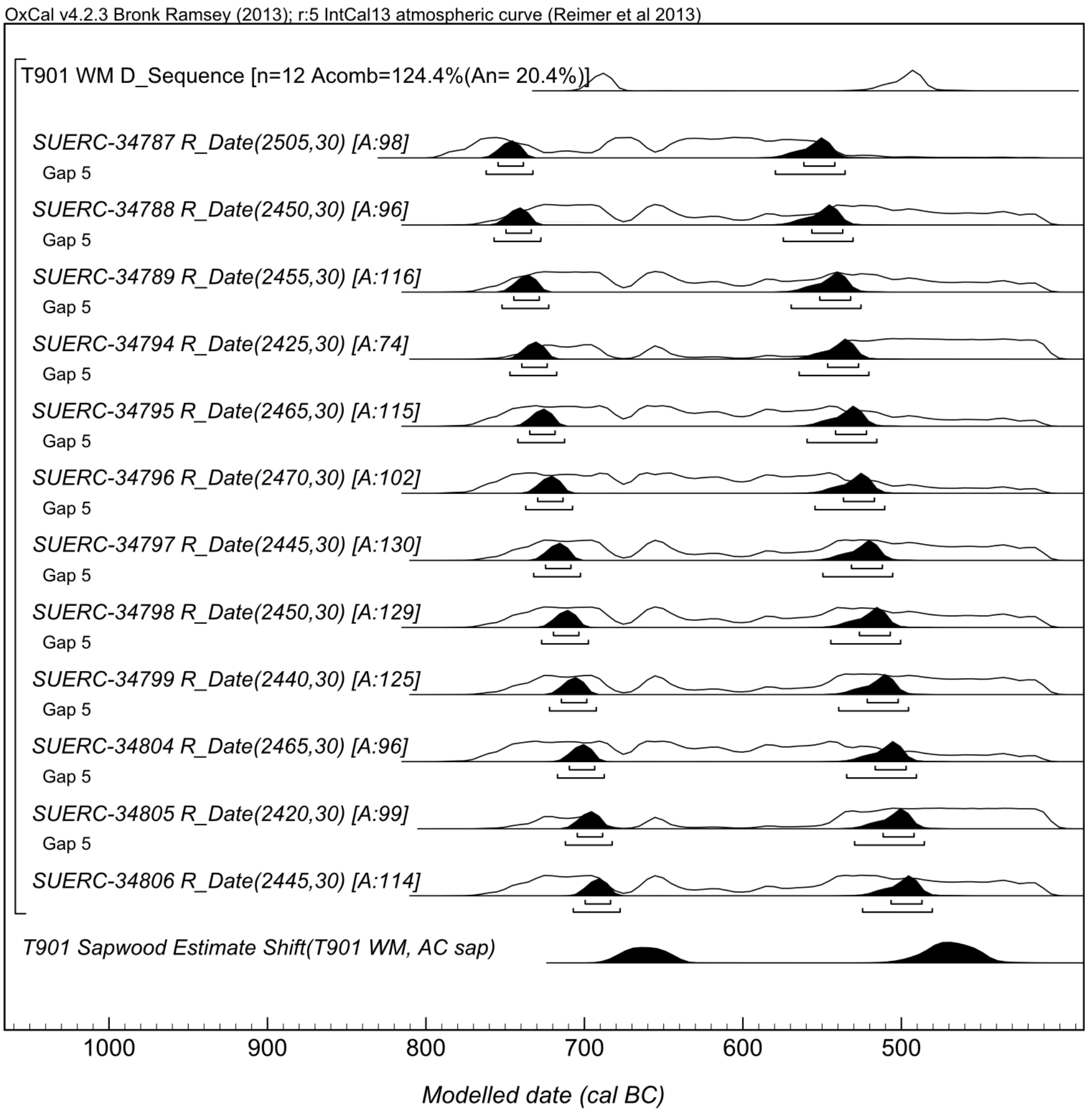




Figure 6.41: Results of the wiggle-match on the Cults Loch 3 timber T-901: summary (top), and the individual determinations (bottom).

### Research design and sample selection

The research design for the project intended to evaluate which of the roundhouses (Structure 1 or Structure 2) came first, proceeded in two steps. First, the available legacy data and the stratigraphic information were integrated to provide an overview of what could be asserted given only the data available prior to any wiggle-match dating. After that, simulated wiggle-match dates were added to assess the kind of investment that would be necessary to answer the question at hand. The legacy data model indicated that the probability of the Structure 1 construction event preceding the same event for Structure 2 was 53%, far too vague for resolving the archaeological question. The model was also very unstable, as removal of specific individual determinations, or of the legacy wiggle-match T-901, could change its results altogether. To resolve these uncertainties, the model had to be improved, both by the addition of further wiggle-matches and also by the inclusion of further stratigraphic information. Wiggle-match dating was to focus on the two structures and also on the packwerk mound itself, so as to obtain a strict *TPQ* for all the subsequent activity. Furthermore, additional tree-rings were dated to assess the alder-alder chronologies and also determinations of short-lived materials were conducted to better understand the overall site chronology.

The timber selection for the Cults Loch 3 wiggle-match dating project was controlled by four criteria:

1. Preference for bark edge,
2. Preference for clear contexts to implement feature-oriented dating,
3. Aim for selection of multiple timbers per construction event,
4. Where possible, preference toward timbers tied into alder-alder chronologies and sequences in excess of 50 tree-rings.

Based on these criteria, 12 timbers were selected. Four came from Structure 1: T-966 and T-967 (from context [525]), and T-41 and T-44 (from context [630]). The two contexts are synchronous and constitute the remains of the original construction of the structure. Although the roundhouse also underwent subsequent refurbishment, only one timber from within these deposits fulfilled the first two criteria: oak T-927. T-927 was not selected for dating for two reasons: first, as it was the only sample from the given construction event, feature-oriented sampling could not be implemented; second, its rings were very compressed, making cutting of reliable decadal blocks nigh on impossible. The dating of Structure 2 was improved by five timbers from three different contexts. The stakes T-59 and T-64 derived from under context [602], but cut through the preceding floor [609]. They also form alder-alder chronology ALSP3x2, according to which they were felled in the same year. Contexts [624] and [642] are represented by timbers T-36, T-37 and T-24. Although T-24 is the only sample from context [642], it is part of a floor surface that was laid down over the sub-floor [624] and the evidence indicates that the two events happened during the same construction event. The crannog mound was dated through three different wiggle-matches: T-963, T-48 and T-60, the latter two of which belong to the alder-alder chronology ALSP1x10. Timber T-963 was deposited within the mound matrix itself, while T-48 and T-60 were pinning the mound; T-60 was discovered underneath Structure 2, while T-48 was discovered underneath Structure 1. T-135 was the final wiggle-match. It is associated with neither the mound, nor the two structures and was included as a check on the relative dendrochronology ALSP5x3, according to which it has been felled 10 years before T-37.

### 6.4.2 Summary of the new data for Cults Loch 3

Altogether 13 new wiggle-matches were commissioned as a part of the Cults Loch 3 project, including three timbers from the crannog mound, four timbers from Structure 1, five timbers from Structure 2 and one timber to assess the relative dendrochronology ALSP4x3. A majority of the results indicate felling towards the end of the 6th century BC, or in the 5th century BC, in line with the expectations from the dendrochronology. The two exceptions are timber T-36 and T-37, both from the context [624], a log floor within the earliest Structure 2 deposits and which produced earlier dates, pointing to possible re-use. Furthermore, two individual radiocarbon determinations were commissioned to confirm the dating of the final deposits from Structure 2 and obtain at least a tentative result for Structure 3.

Three of the wiggle-matched timbers came from the settlement mound to provide a firm terminus post quem for the succeeding material: T-963, T-60 and T-48 (Tables 6.13 to 6.14)(Figures 6.42 to 6.45):

- T-963 was a substantial alder log from the basal deposits, which lived in excess of 85 years, and is the only timber in the wiggle-match dating study without surviving bark-edge. Its dating has been motivated by it being the longest sequence from these deposits and thus offering the best opportunity of a precise date. The wiggle-match was conducted on six measurements and displayed a good degree of stability.

- The second timber dated was T-60, a stake from underneath Structure 2. It had 62 rings, and was wiggle-matched with 5 determinations. One of these determinations, SUERC-57951, which came from a very decayed section of the stake, had much older radiocarbon age than the surrounding decades and, given that this was a recurrent problem, was removed.

- The third timber was T-48, a stake from underneath the Structure 1. It lived for 65 years and five decadal samples were cut from it. One of the measurements, SUERC-60219, was rejected from the wiggle-match, as its presence had an adverse effect on the stability of the wiggle-match; this can be the result of the decayed wood effect, or of SUERC-60219 being a statistical outlier.

Table 6.13: Results of the radiocarbon determinations on the timbers from the crannog mound at Cults Loch 3. All the timbers are alder (*Alnus sp.*).

| Timber | Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| T-963 | 6–15 | 36123 | 57939 | 2428 | 27 | -25.8 |
| | 26–35 | 37205 | 60208 | 2519 | 29 | -26.6 |
| | 36–45 | 36124 | 57940 | 2471 | 26 | -27.2 |
| | 46–55 | 36125 | 57941 | 2447 | 25 | -26.7 |
| | 56–65 | 37206 | 60209 | 2518 | 29 | -26.3 |
| | 76–85 | 36126 | 57942 | 2475 | 27 | -26.9 |
| T-60 | 3–12 | 36131 | 57950 | 2401 | 29 | -24.3 |
| | 13–22 | 36132 | 57951 | 2581 | 29 | -25.6 |
| | 23–32 | 36133 | 57952 | 2419 | 29 | -24.8 |
| | 33–42 | 36134 | 57953 | 2474 | 29 | -24.6 |
| | 43–52 | 36135 | 57957 | 2396 | 25 | -25.2 |
| T-48 | 1–10 | 37212 | 60217 | 2452 | 27 | -25.5 |
| | 11–20 | 37213 | 60218 | 2440 | 29 | -25.2 |
| | 21–30 | 37214 | 60219 | 2513 | 29 | -25.5 |
| | 46–55 | 37215 | 60223 | 2416 | 29 | -25.0 |
| | 56–65 | 37216 | 60224 | 2450 | 27 | -26.3 |

Both T-60 and T-48 belong to the alder-alder relative chronology ALSP1x10, which includes eight other stakes that pinned the crannog mound. As the posterior distributions of their wiggle-matches are statistically identical ($\chi^2$= 0.957; 5% critical value = 3.841), there is nothing in the radiocarbon data to refute this chronology.

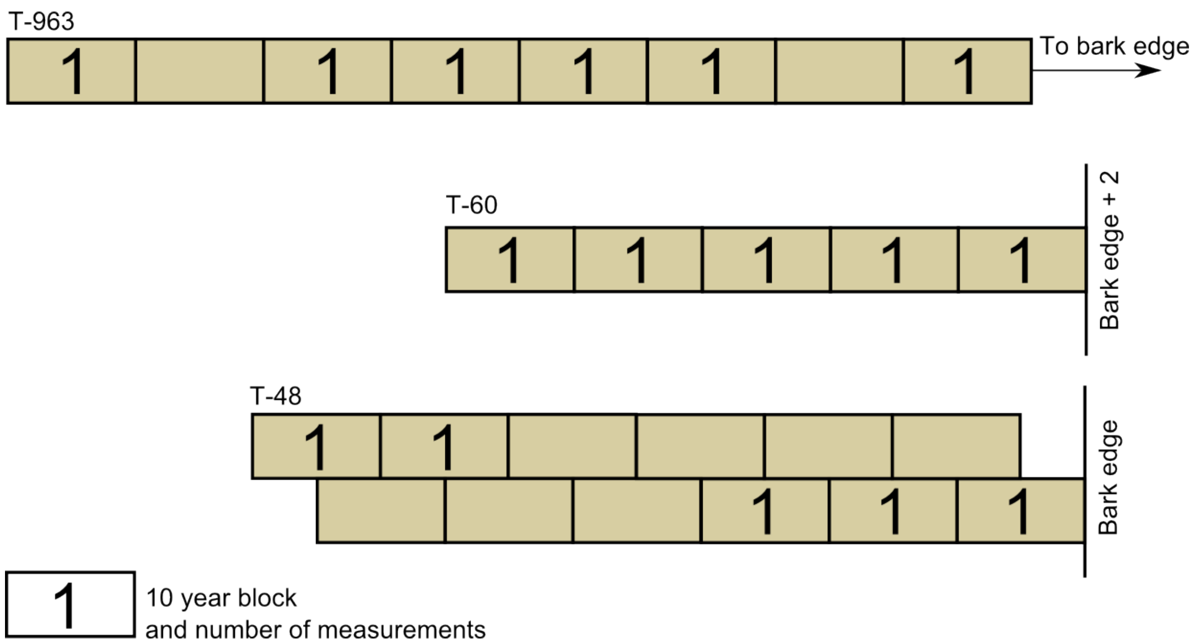
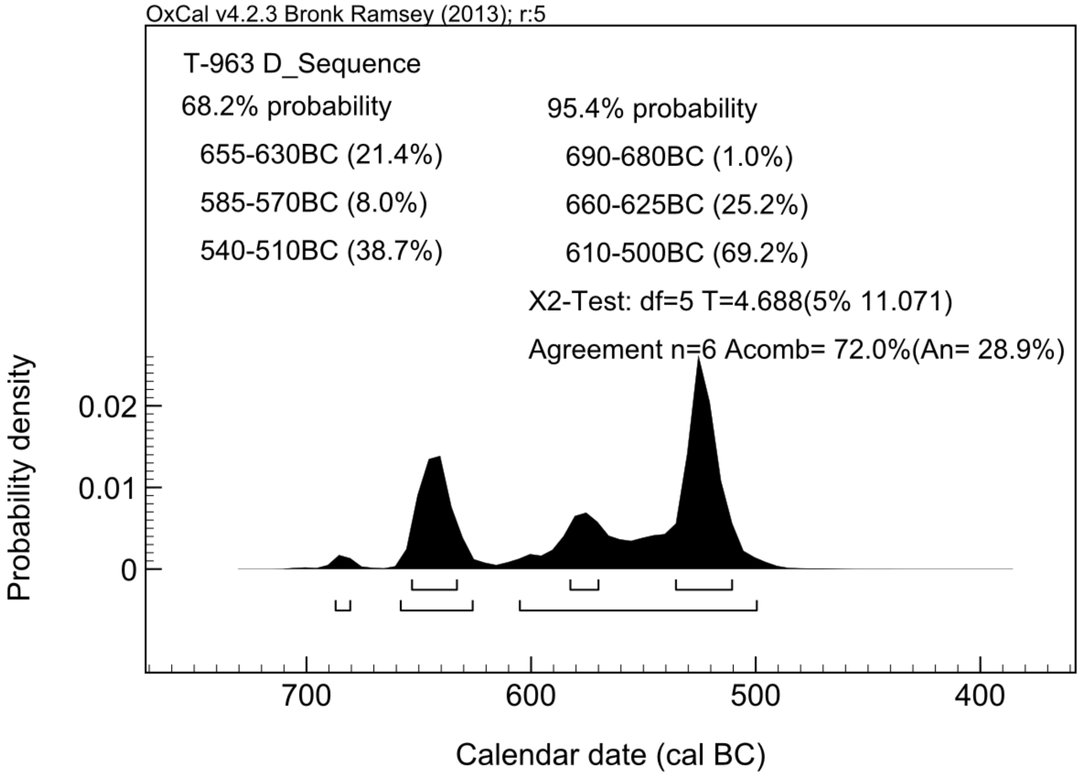



Figure 6.42: Sampling pattern for Cults Loch 3 mound timbers.



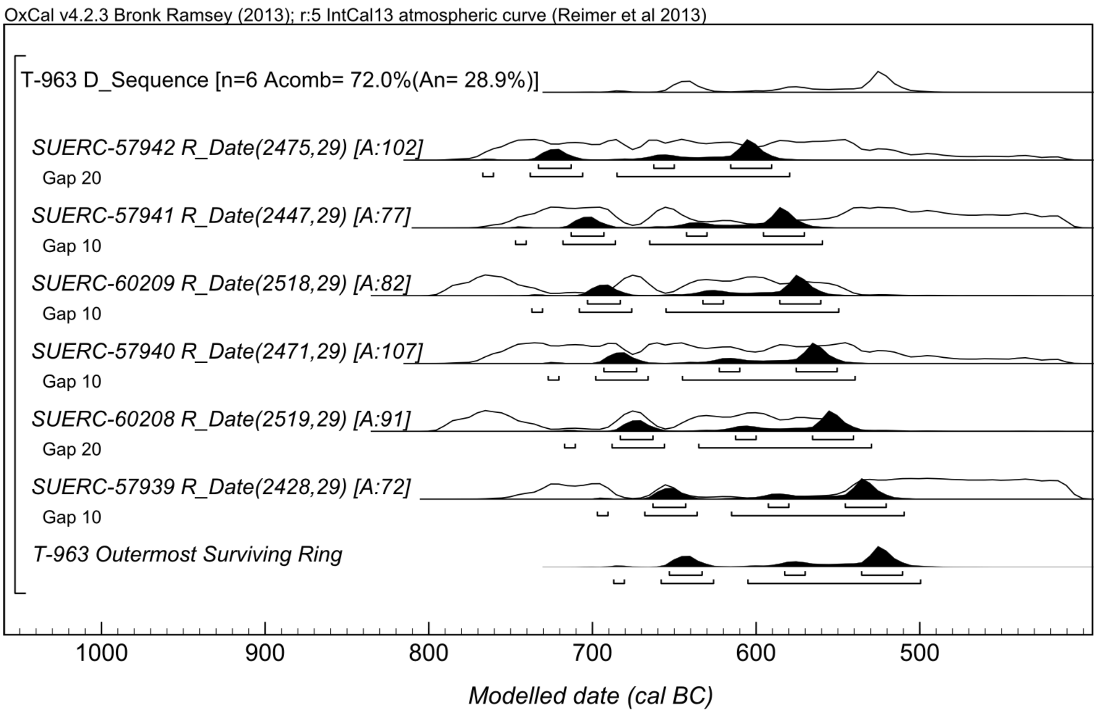




Figure 6.43: Results of the wiggle-match on Cults Loch 3 timber T-963: summary (top), and the individual determinations (bottom).

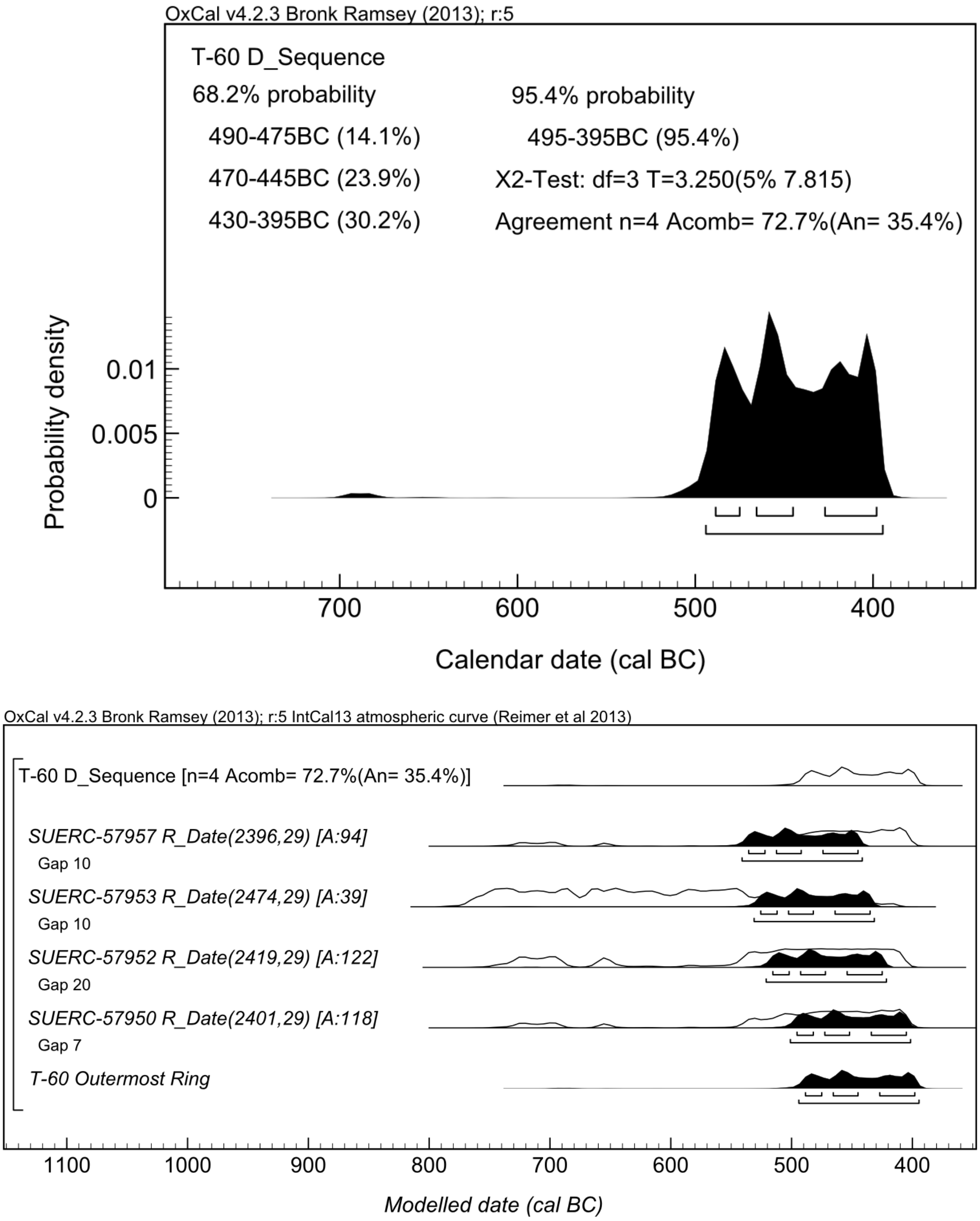



Figure 6.44: Results of the wiggle-match on Cults Loch 3 timber T-60: summary (top), and the individual determinations (bottom).

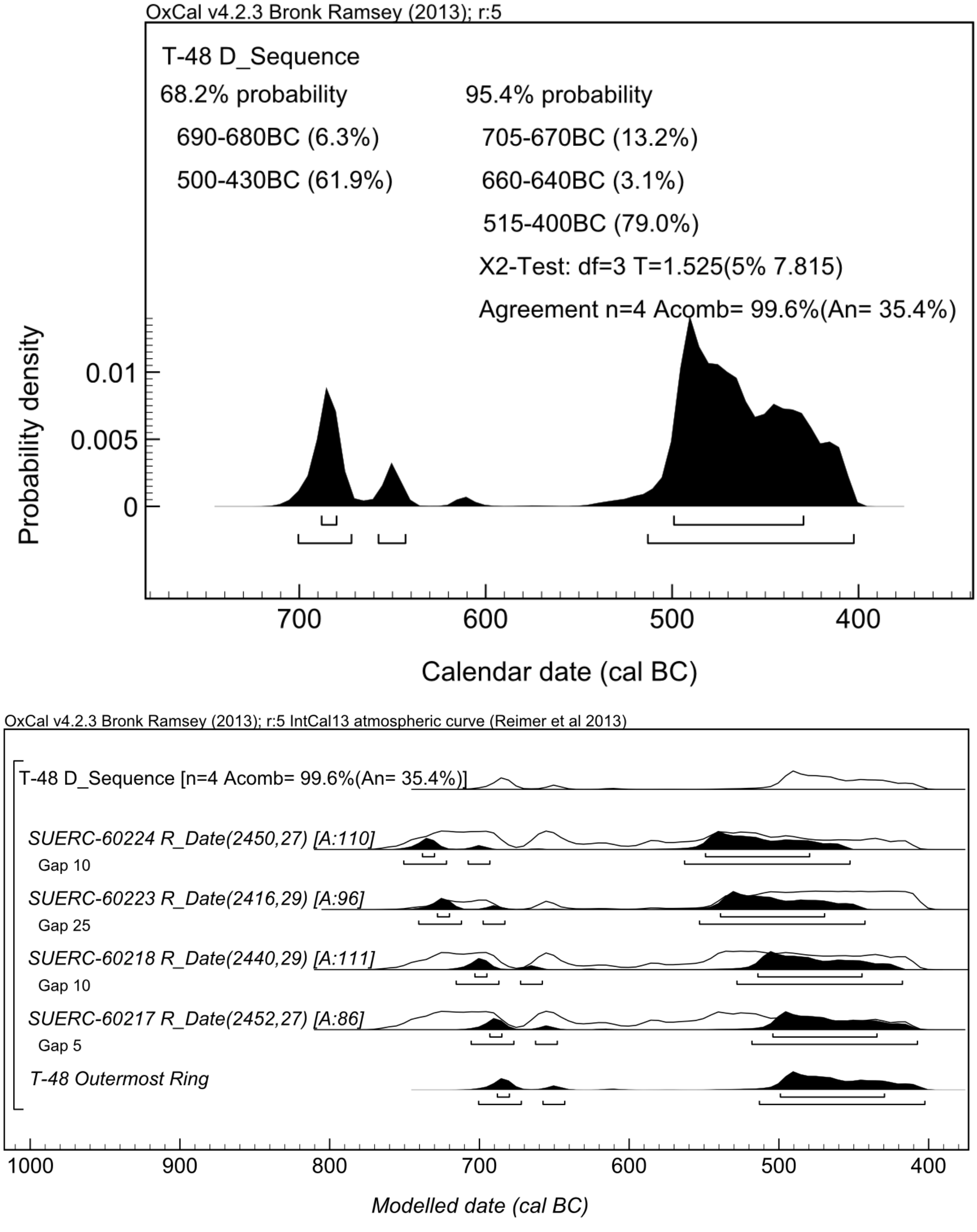



Figure 6.45: Results of the wiggle-match on Cults Loch 3 timber T-48: summary (top), and the individual determinations (bottom).

Table 6.14: The wiggle-match dates of the timbers from the crannog mound at Cults Loch 3. Posterior probabilities are displayed in Figures 6.43 to 6.45.

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine<br>\An (%) | $\chi^2$<br>\5% crit |
|---|---|---|---|---|
| T-963 | *655–630 cal BC (21.4%)*<br>*585–570 cal BC (8.0%)*<br>*540–510 cal BC (38.7%)* | *690–680 cal BC (1.0%)*<br>*660–625 cal BC (25.2%)*<br>*610–500 cal BC (69.2%)* | 72.00<br>\28.90 | 4.688<br>\11.071 |
| T-60 | *490–480 cal BC (14.1%)*<br>*470–445 cal BC (23.9%)*<br>*430–395 cal BC (30.2%)* | *495–395 cal BC* | 72.70<br>\35.40 | 3.25<br>\7.815 |
| T-48 | *690–680 cal BC (6.3%)*<br>*500–430 cal BC(61.9%)* | *705–670 cal BC (13.2%)*<br>*660–640 cal BC (3.1%)*<br>*515–400 cal BC (79.0%)* | 99.60<br>\35.40 | 1.525<br>\7.815 |

Four of the wiggle-matched timbers came from Structure 1: T-966 and T-967 from context [525=638] and T-41 and T-44 from context [630] (Tables 6.15 to 6.17)(Figures 6.47 to 6.50).Both contexts form a part of the earliest floor of the structure. Context [630] also contained the legacy wiggle-match T-901.

- First of the four new wiggle-matches is T-44, and alder horizontal that lived for 44 years, retained bark edge, and was wiggle-matched with eight measurements. One of the measurements on the outermost rings, SUERC-56592, was too old when compared to the repeat measurements ($\chi^2$= 6.3; 5% critical value = 6.0) and, belonging to an outermost decadal block, was removed. The timber was selected to evaluate the performance of wiggle-matches on timbers that lived for less than 50 years.

- T-41, the second timber, was an alder log that lived for 94 years and retained bark edge. Altogether 14 measurements were made, two of which, SUERC-56599 and -56604, had to be rejected on account of being too old or too young relative to the repeat measurements. Both determinations come from batch 37/14, which posed a number of other issues and SUERC-56599 is an outermost ring with an apparent offset towards too old ages.

- T-967 was an alder log that lived for 92 years and retained bark edge, albeit its outermost 25 rings suffered from extensive decay and hence the wiggle-match dated section begins only with the decade 16-25. Still even that decade suffered from systematic offsets towards older ages and its two measurements SUERC-56610 and SUERC-58862 have been rejected.

- T-966 was an alder log of 75 rings, which retained bark edge and was measured with six determinations covering the outermost six decades. All the measurements are included in the wiggle-match.

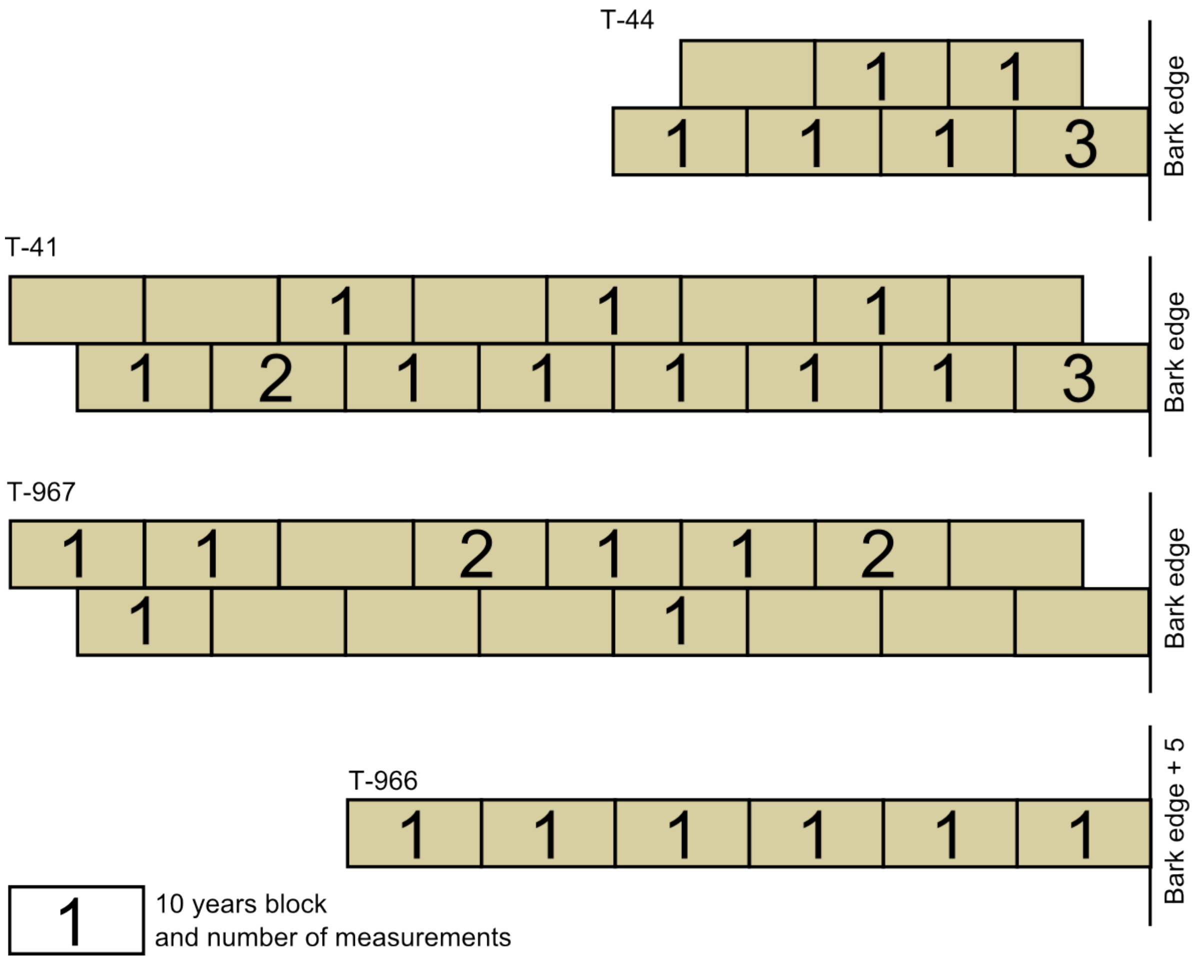



Figure 6.46: Sampling pattern for Cults Loch 3 Structure 1 timbers.

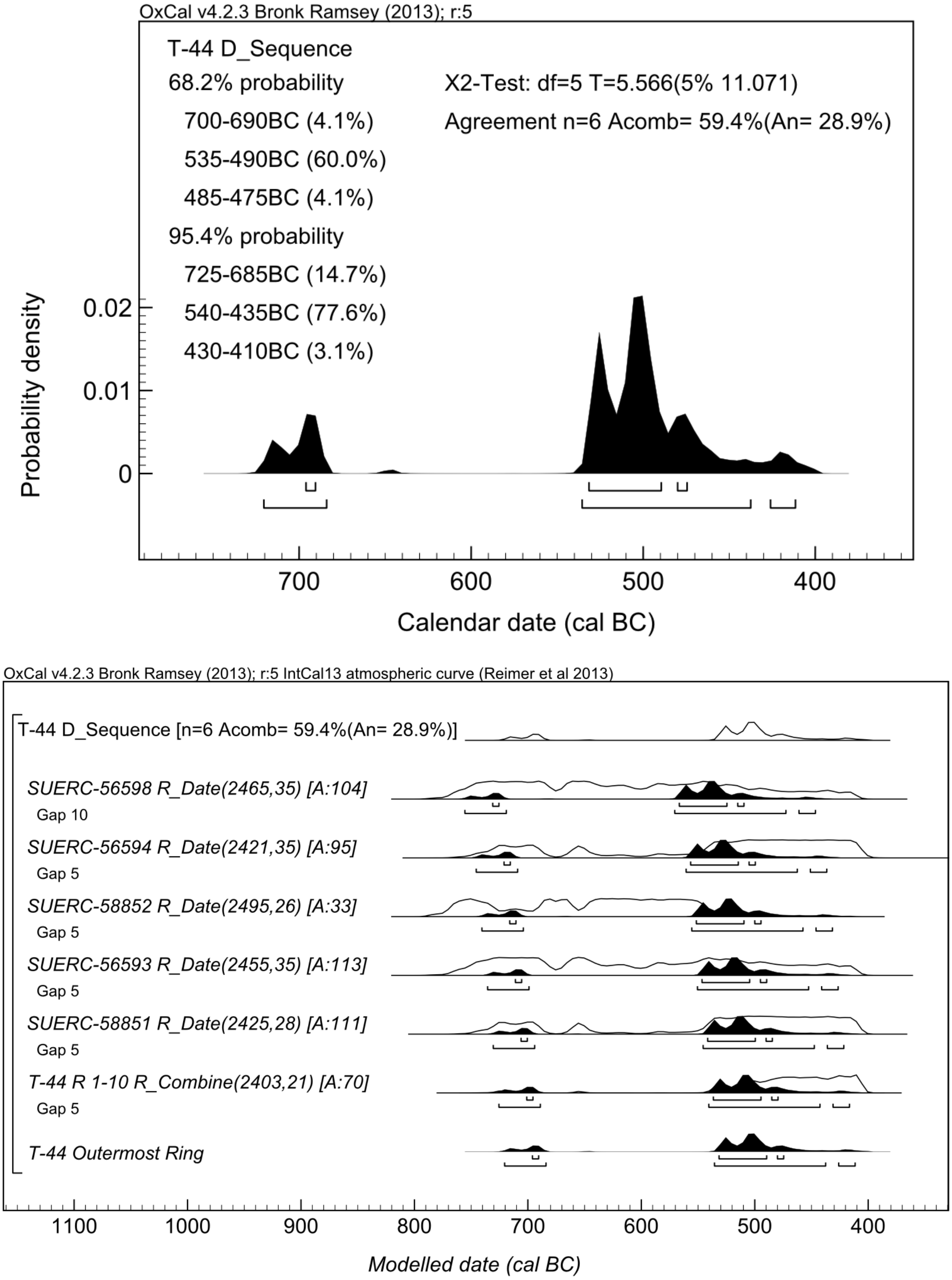



Figure 6.47: Results of the wiggle-match on Cults Loch 3 timber T-44: summary (top), and the individual determinations (bottom).

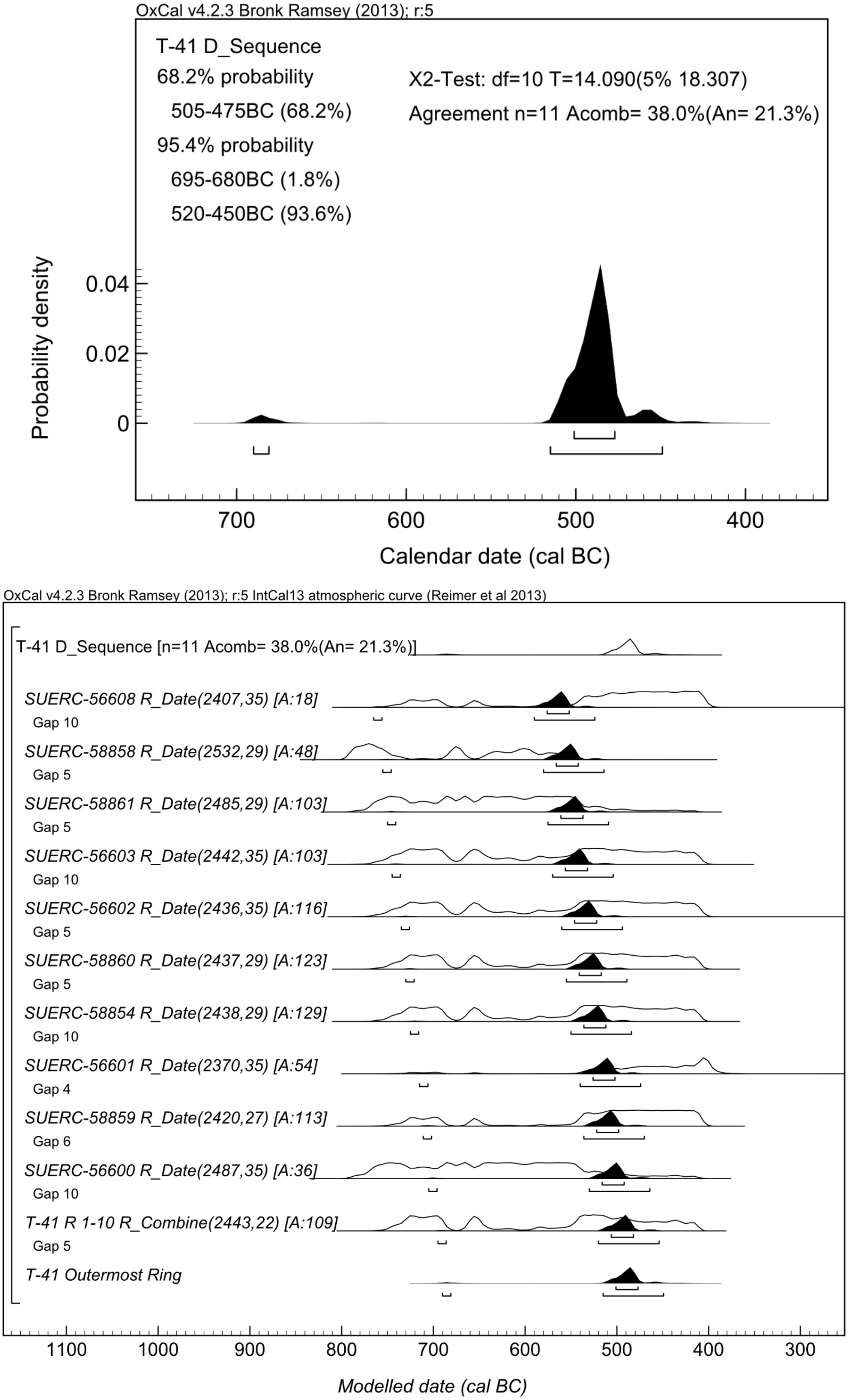



Figure 6.48: Results of the wiggle-match on Cults Loch 3 timber T-41: summary (top), and the individual determinations (bottom).

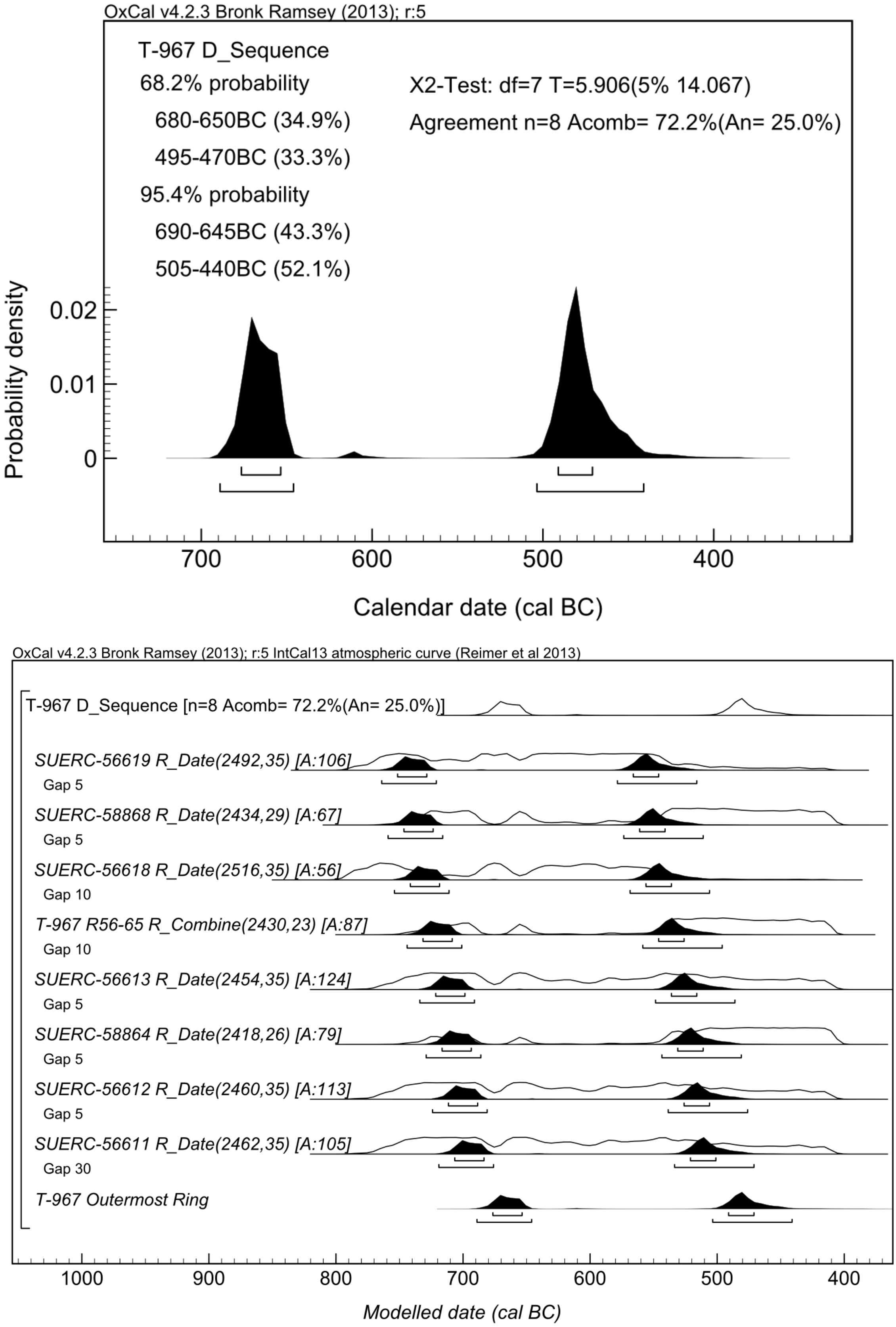
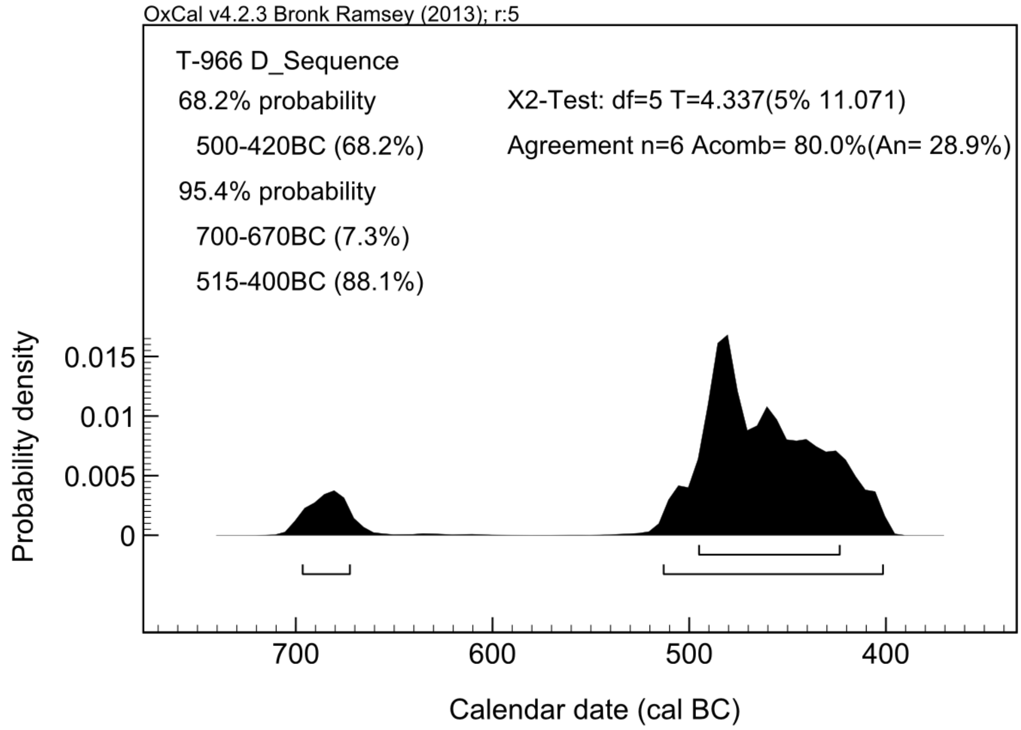



Figure 6.49: Results of the wiggle-match on Cults Loch 3 timber T-967: summary (top), and the individual determinations (bottom).



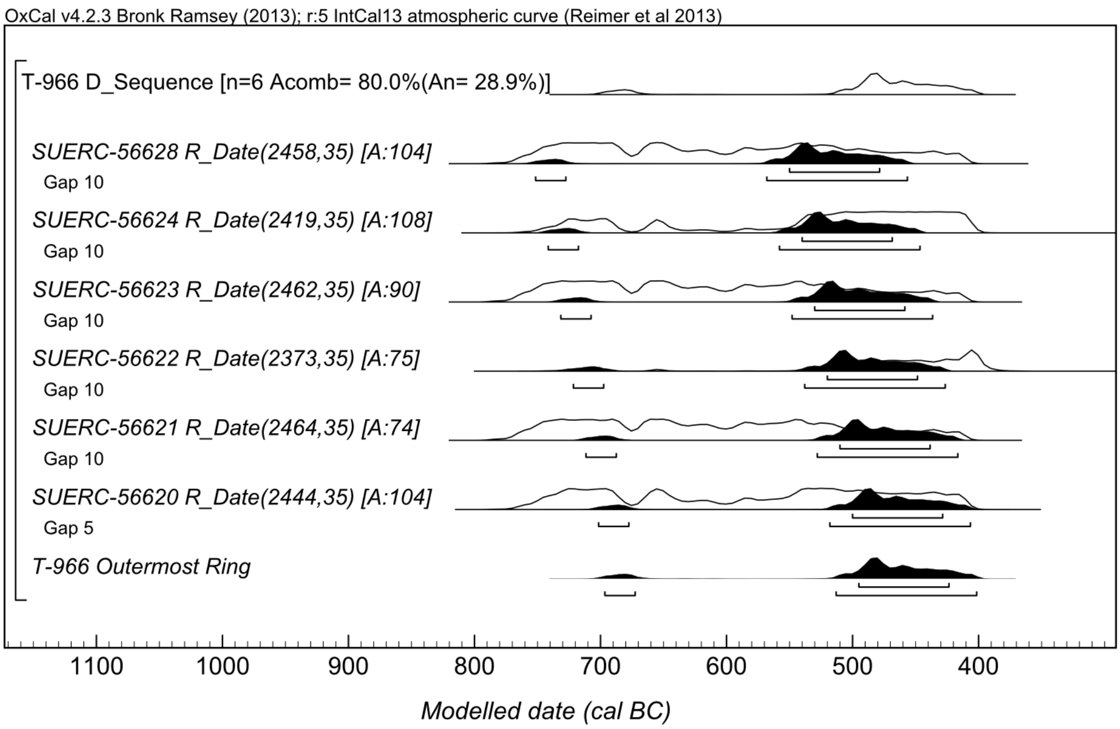




Figure 6.50: Results of the wiggle-match on Cults Loch 3 timber T-966: summary (top), and the individual determinations (bottom).

Table 6.15: Results of the radiocarbon determinations on the timbers from Structure 1 at Cults Loch 3. All the timbers are alder (*Alnus sp.*).

| Timber | Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| T-44 | 1–10 | 35571 | 56592 | 2504 | 35 | -25.5 |
| | 1–10 | 36616 | 58850 | 2407 | 29 | -26.1 |
| | 1–10 | 36630 | 58869 | 2399 | 29 | -26.6 |
| | 6–15 | 36617 | 58851 | 2425 | 28 | -26.0 |
| | 11–20 | 35572 | 56593 | 2455 | 35 | -27.2 |
| | 16–25 | 36618 | 58852 | 2495 | 26 | -26.7 |
| | 21–30 | 35573 | 56594 | 2421 | 35 | -26.7 |
| | 31–40 | 35574 | 56598 | 2465 | 35 | -26.5 |
| T-41 | 1–10 | 35575 | 56599 | 2519 | 35 | -25.7 |
| | 1–10 | 36620 | 58853 | 2442 | 30 | -25.0 |
| | 1–10 | 36631 | 58870 | 2443 | 30 | -26.0 |
| | 11–20 | 35576 | 56600 | 2487 | 35 | -25.2 |
| | 17–26 | 36623 | 58859 | 2420 | 27 | -25.4 |
| | 21–30 | 35577 | 56601 | 2370 | 35 | -25.2 |
| | 31–40 | 36621 | 58854 | 2438 | 29 | -25.7 |
| | 36–45 | 36624 | 58860 | 2437 | 29 | -25.6 |
| | 41–50 | 35579 | 56602 | 2436 | 35 | -26.2 |
| | 51–60 | 35580 | 56603 | 2442 | 35 | -26.4 |
| | 56–65 | 35525 | 58861 | 2485 | 29 | -26.0 |
| | 61–70 | 35581 | 56604 | 2360 | 35 | -28.2 |
| | 61–70 | 36622 | 58858 | 2532 | 29 | -26.2 |
| | 71–80 | 35582 | 56608 | 2407 | 35 | -26.3 |
| T-967 | 16–25 | 36626 | 58862 | 2482 | 29 | -25.8 |
| | 16–25 | 35584 | 56610 | 2506 | 35 | -25.3 |
| | 26–35 | 35585 | 56611 | 2462 | 35 | -25.4 |
| | 36–45 | 35586 | 56612 | 2460 | 35 | -25.1 |
| | 41–50 | 36628 | 58864 | 2418 | 26 | -25.8 |
| | 46–55 | 35587 | 56613 | 2454 | 35 | -25.8 |
| | 56–65 | 35588 | 56614 | 2402 | 35 | -25.9 |
| | 56–65 | 36627 | 58863 | 2449 | 29 | -26.3 |
| | 66–75 | 35589 | 56618 | 2516 | 35 | -26.0 |
| | 71–80 | 36629 | 58868 | 2434 | 29 | -25.9 |
| | 76–85 | 35590 | 56619 | 2492 | 35 | -27.5 |
| T-966 | 1–10 | 35591 | 56620 | 2444 | 35 | -24.2 |
| | 11–20 | 35592 | 56621 | 2464 | 35 | -24.6 |
| | 21–30 | 35593 | 56622 | 2373 | 35 | -25.0 |
| | 31–40 | 35594 | 56623 | 2462 | 35 | -24.9 |
| | 41–50 | 35595 | 56624 | 2419 | 35 | -24.4 |
| | 51–60 | 35596 | 56628 | 2458 | 35 | -24.5 |

Table 6.16: The $\chi^2$ test statistics between measurements on overlapping decadal blocks from Cults Loch 3 Structure 1. 5% critical value for the $\chi^2$ test statistic is 3.8.

| Timber | Rings | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ | Combined Age | Combined 1-$\sigma$ error |
|---|---|---|---|---|---|---|---|
| T-44 | 1–10 | 58850 | 2407 | 29 | 0.0 | 2403 | 21 |
| | | 58869 | 2399 | 29 | | | |
| T-41 | 1–10 | 58853 | 2442 | 30 | 0.0 | 2443 | 22 |
| | | 58870 | 2443 | 30 | | | |
| T-967 | 56–65 | 56614 | 2402 | 35 | 1.1 | 2430 | 23 |
| | | 58863 | 2449 | 29 | | | |

Table 6.17: Results of the individual wiggle-matches for Cults Loch 3 Structure 1. Posterior probabilities are displayed in Figures 6.47 to 6.50.

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine \An (%) | $\chi^2$ \5% crit |
|---|---|---|---|---|
| T-44 | *700–690 cal BC (4.1%)*<br>*535–490 cal BC (60.0%)*<br>*485–475 cal BC (4.1%)* | *725–685 cal BC (14.7%)*<br>*540–435 cal BC (77.6%)*<br>*430–410 cal BC (3.1%)* | 59.40<br>\28.90 | 5.566<br>\11.071 |
| T-41 | *505–475 cal BC* | *695–680 cal BC (1.8%)*<br>*520–450 cal BC (93.6%)* | 38.00<br>\21.30 | 14.09<br>\18.307 |
| T-967 | *680–650 cal BC (34.9%)*<br>*495–470 cal BC (33.3%)* | *690–645 cal BC (43.3%)*<br>*505–440 cal BC (52.1%)* | 72.20<br>\25.00 | 5.906<br>\14.067 |
| T-966 | *500–420 cal BC* | *700–670 cal BC (7.3%)*<br>*515–400 cal BC (88.1%)* | 80.00<br>\28.90 | 4.337<br>\11.071 |

Five new wiggle-matches were commissioned for Structure 2: T-24 from context [642], T-67 and T-37 from context [630] and two stakes, T-59 and T-64, that cut through the context [609], but are sealed by context [602] (Tables 6.18 to 6.20)(Figures 6.52 to 6.56). The first three timbers relate to the original construction of Structure 2, while the two stakes are close to the final stage activity within the roundhouse.

- The alder log T-24 had in excess of 86 rings, retained bark edge and was wiggle-matched based on six measurements.
- T-36 was an alder log of 77 rings, retaining bark edge and dated with nine determinations. The decayed innermost rings produced what appears to be a too old age and the related measurement SUERC-55950 is excluded from the wiggle-match.
- T-37 was an alder log of 85 rings and retaining bark edge, from which six decadal blocks were sampled. The two innermost measurements displayed very old ages, suggesting that the timber may have started to grow before the onset of the Hallstatt plateau. However, upon repeat measurement these ages have been rejected and are not included in the wiggle-match. The original offset can be either the result of too gentle pre-treatment, or be related to the decay near the pith. Because both T-36 and T-37 are older than the two stakes T-48 and T-60 from the settlement mound, it is assumed that they are recycled, much like the timber [046]-15 from Black Loch of Myrton (section 6.3) and hence are included in the modelling process as *TPQs*.
- T-59 was a stake of 65 rings, retaining bark edge and its wiggle-match is based on five measurements.
- T-64 was a stake of 62 rings, retaining bark edge and its wiggle-match is based on five measurements.

The stakes T-64 and T-59 form the alder-alder relative chronology ALSP3x2, according to which they have been felled in the same year. As the posterior distributions of their wiggle-matches are statistically indistiguishable ($\chi^2$= 0.843; 5% critical value = 3.841), there is nothing in the radiocarbon data to refute this chronology. The timber T-37 is part of the alder-alder chronology ALSP4x3, which also included the timber T-135.

T-135 had a total of 60 rings and retained bark edge, however the wiggle-match based four determinations (Tables 6.21 to 6.22)(Figures 6.57 to 6.58) is statistically different from T-37 ($\chi^2$= 5.684; 5% critical value = 3.841) and hence the radiocarbon results appear to be at odds with the particular chronology.

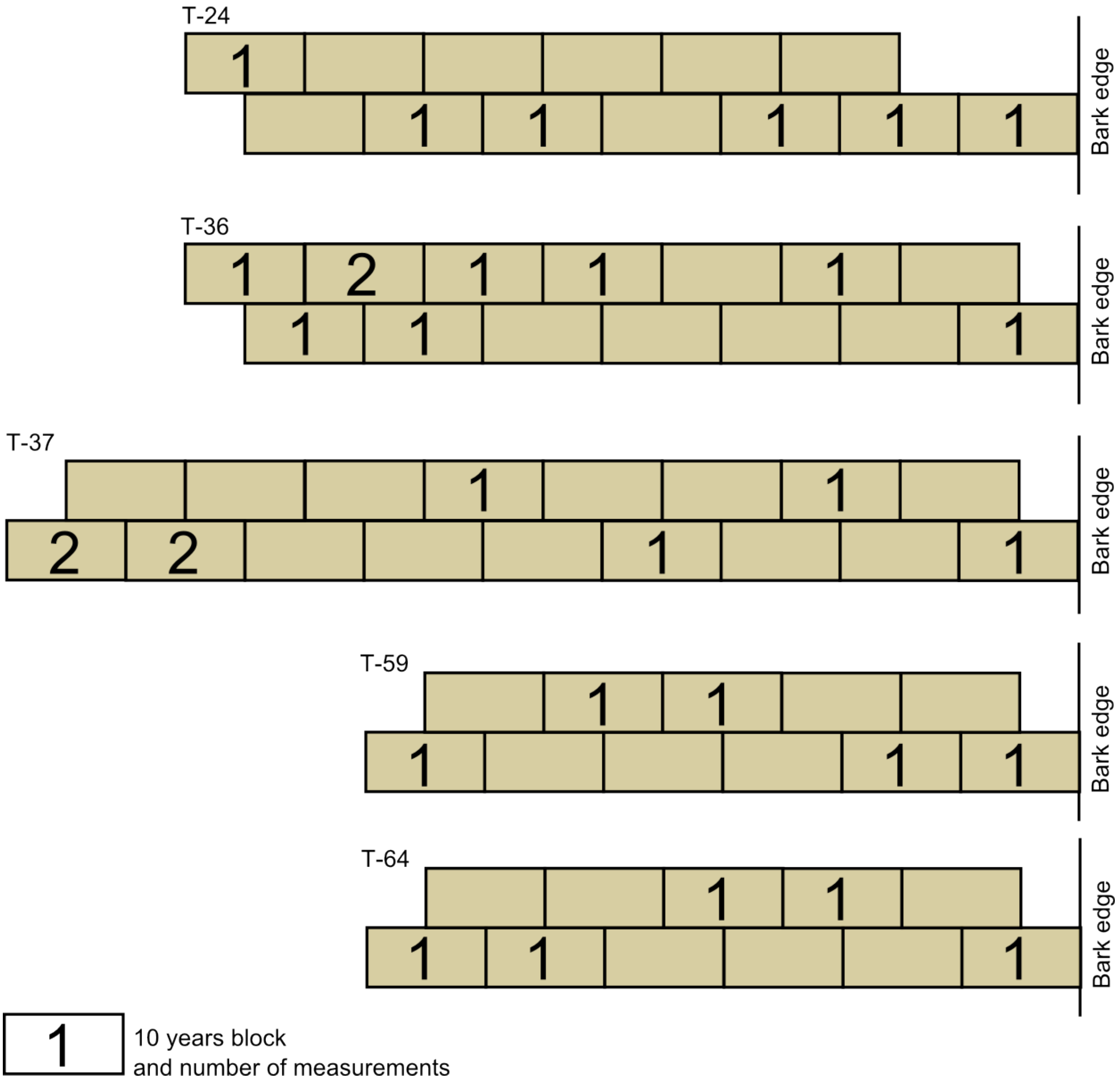



Figure 6.51: Sampling pattern for Cults Loch 3 Structure 2 timbers.

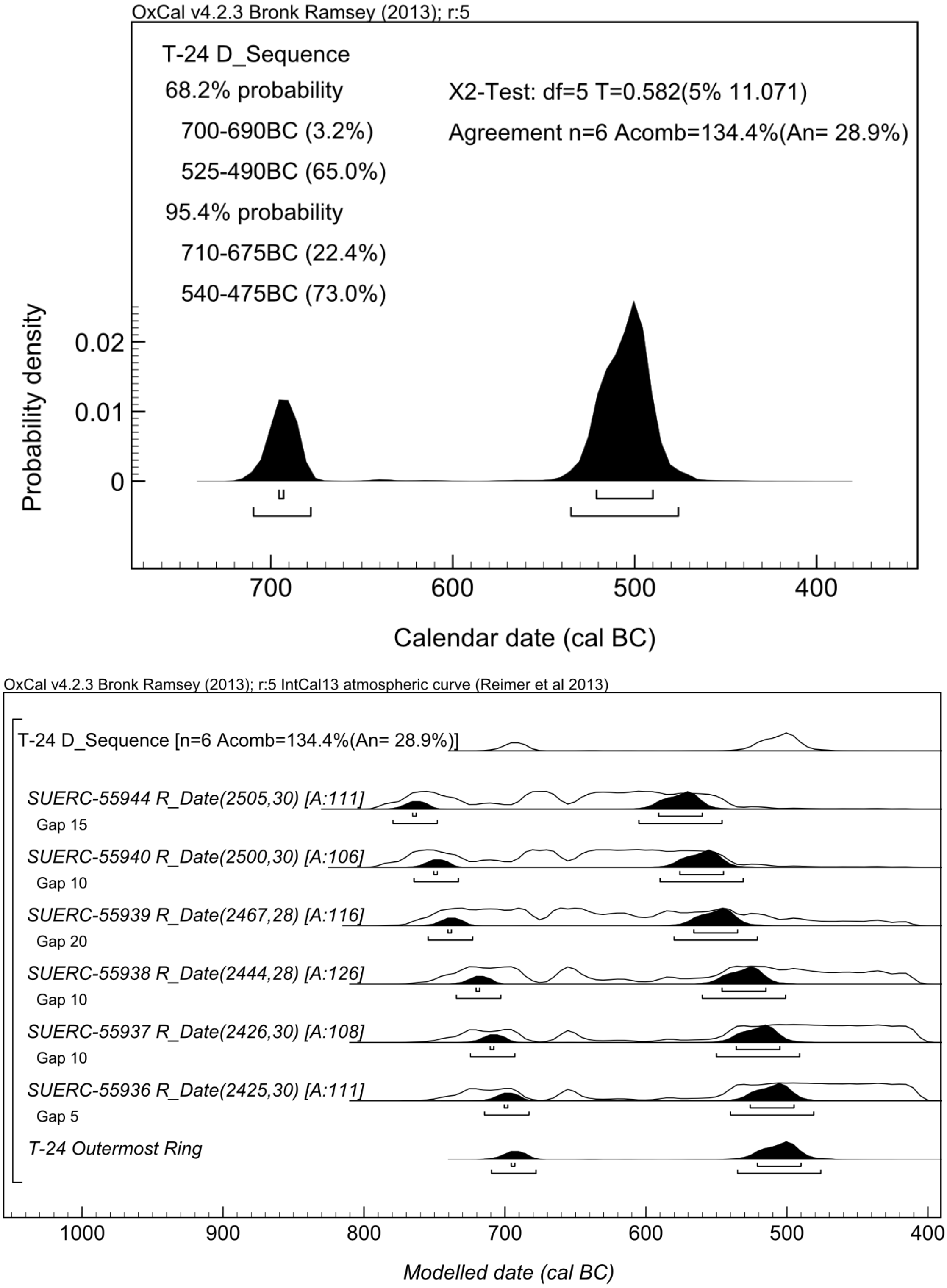
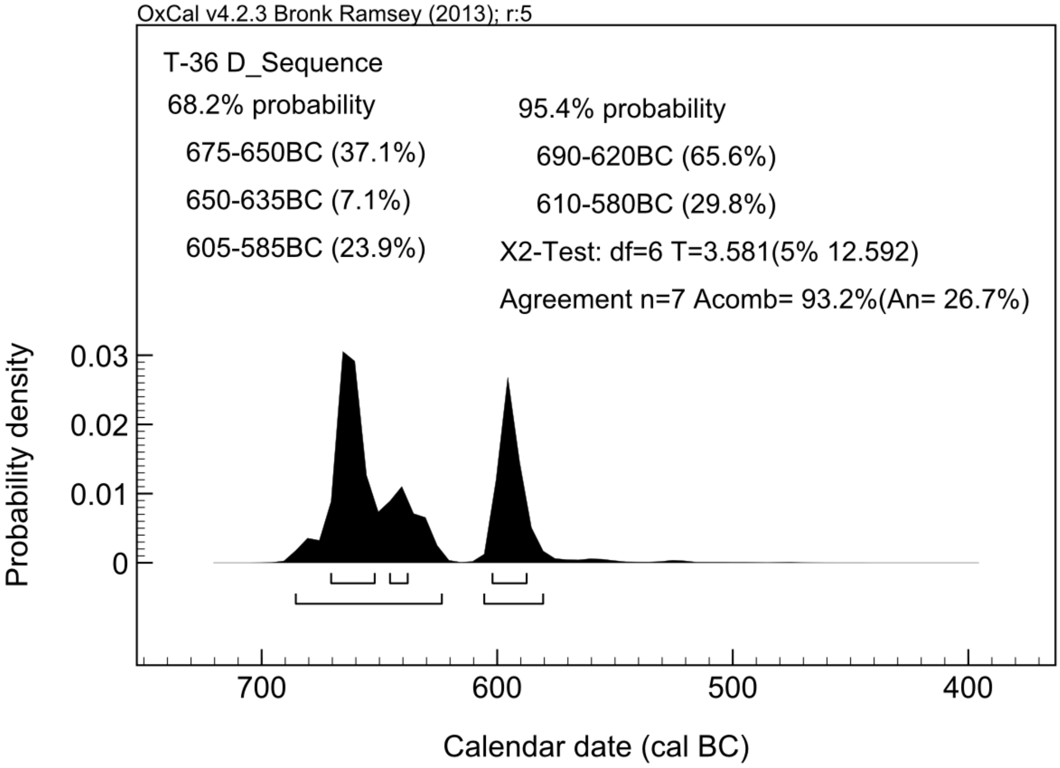



Figure 6.52: Results of the wiggle-match on Cults Loch 3 timber T-24: summary (top), and the individual determinations (bottom).



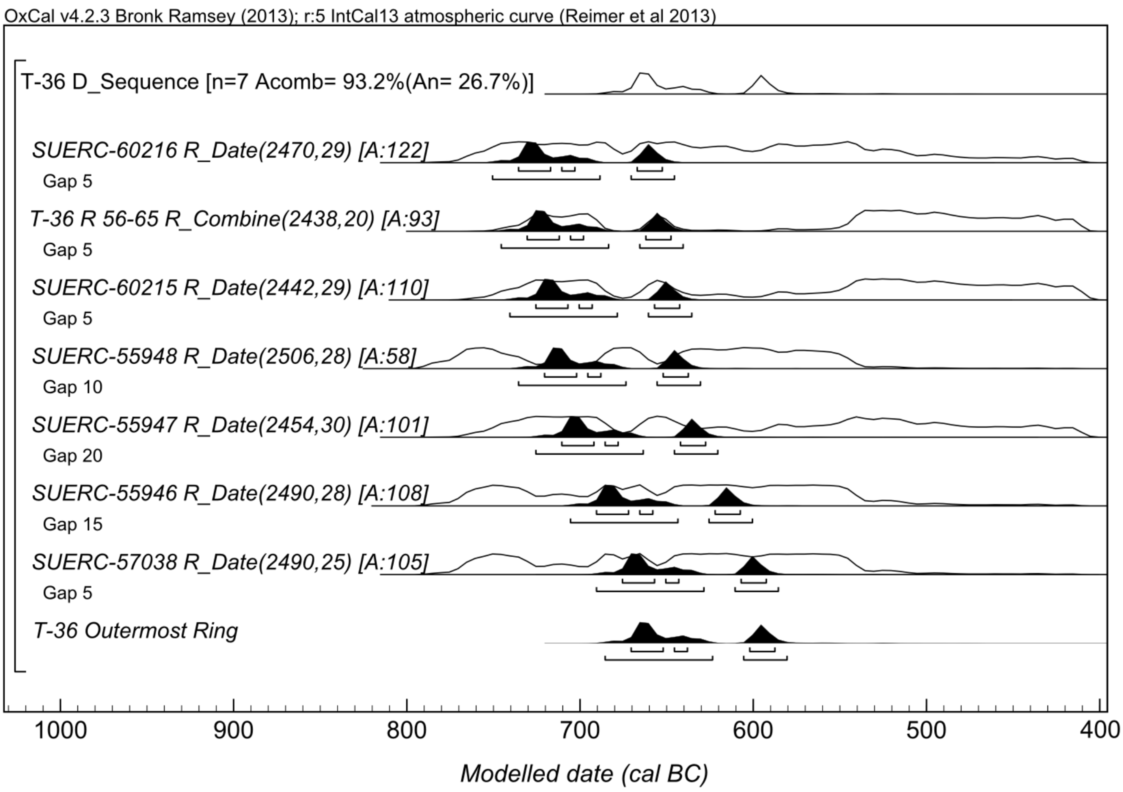




Figure 6.53: Results of the wiggle-match on Cults Loch 3 timber T-36: summary (top), and the individual determinations (bottom).

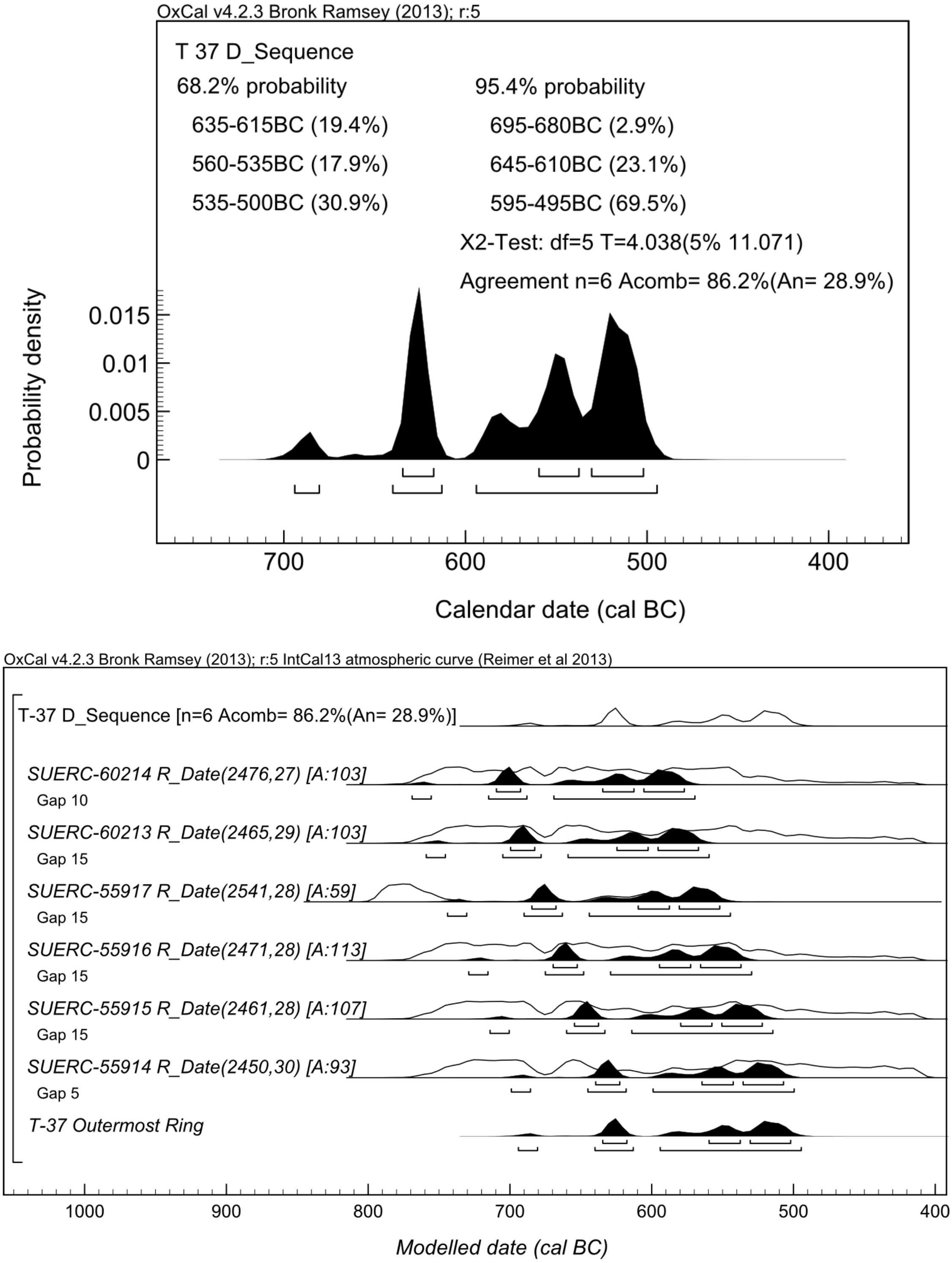



Figure 6.54: Results of the wiggle-match on Cults Loch 3 timber T-37: summary (top), and the individual determinations (bottom).

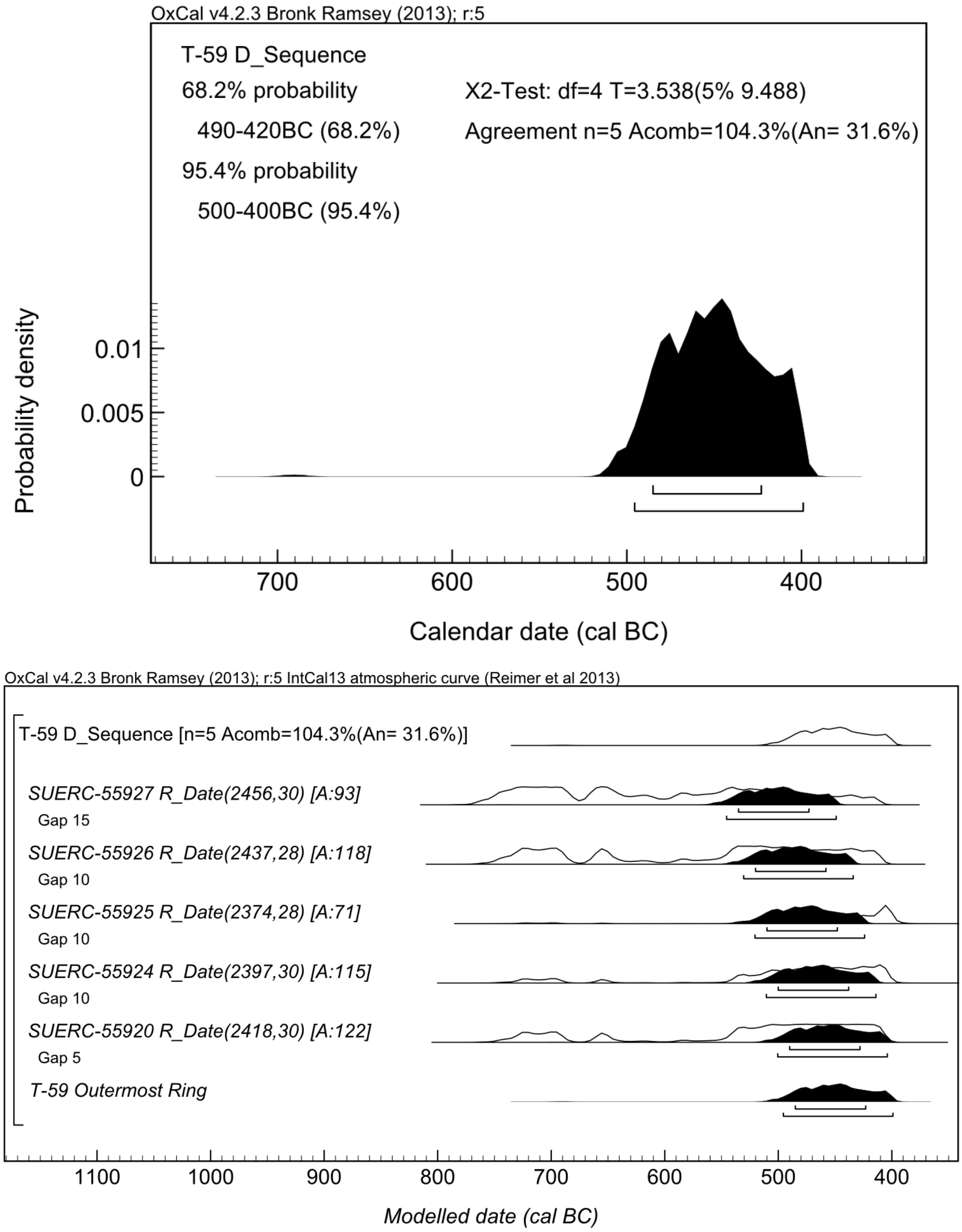



Figure 6.55: Results of the wiggle-match on Cults Loch 3 timber T-59: summary (top), and the individual determinations (bottom).

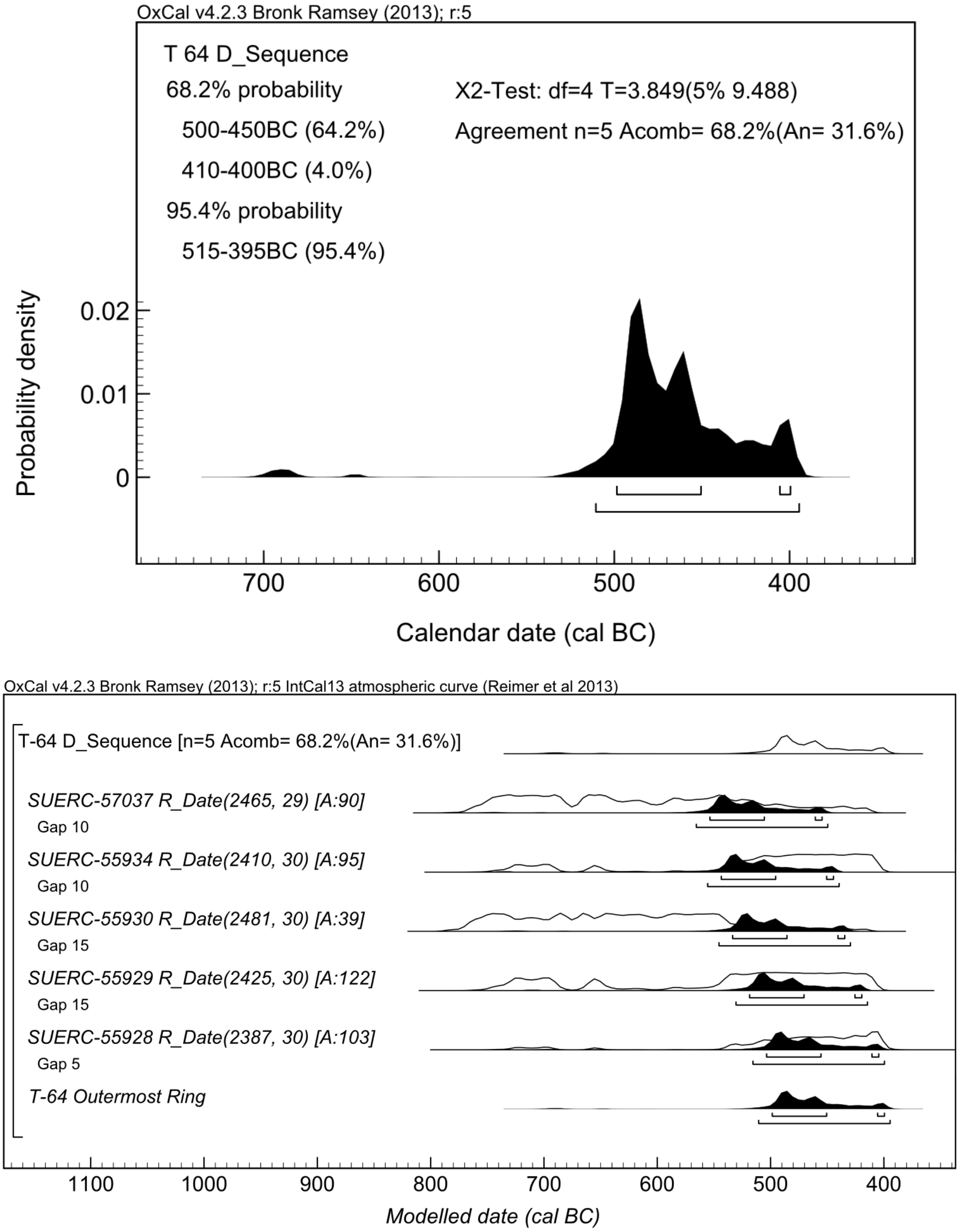



Figure 6.56: Results of the wiggle-match on Cults Loch 3 timber T-64: summary (top), and the individual determinations (bottom).

Table 6.18: Results of the radiocarbon determinations on the timbers from Structure 2 at Cults Loch 3. All the timbers are alder (*Alnus sp.*).

| Timber | Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| T-24 | 1–10 | 35208 | 55936 | 2425 | 30 | -25.1 |
| | 11–20 | 35209 | 55937 | 2426 | 30 | -25.4 |
| | 21–30 | 35210 | 55938 | 2444 | 28 | -25.0 |
| | 41–50 | 35211 | 55939 | 2467 | 28 | -25.0 |
| | 51–60 | 35212 | 55940 | 2500 | 30 | -25.5 |
| | 66–75 | 35213 | 55944 | 2505 | 30 | -25.4 |
| T-36 | 1–10 | 35929 | 57038 | 2490 | 25 | -24.8 |
| | 16–25 | 35215 | 55946 | 2490 | 28 | -24.9 |
| | 36–45 | 35216 | 55947 | 2454 | 30 | -24.9 |
| | 46–55 | 35217 | 55948 | 2506 | 28 | -25.0 |
| | 51–60 | 37210 | 60215 | 2442 | 29 | -26.4 |
| | 56–65 | 35930 | 57039 | 2442 | 26 | -25.9 |
| | 56–65 | 35218 | 55949 | 2434 | 28 | -26.0 |
| | 61–70 | 37211 | 60216 | 2470 | 29 | -26.0 |
| | 66–75 | 35219 | 55950 | 2570 | 30 | -26.4 |
| T-37 | 1–10 | 35027 | 55914 | 2450 | 30 | -24.7 |
| | 16–25 | 35028 | 55915 | 2461 | 28 | -24.4 |
| | 31–40 | 35029 | 55916 | 2471 | 28 | -24.9 |
| | 46–55 | 35030 | 55917 | 2541 | 28 | -24.9 |
| | 61–70 | 35031 | 55918 | 2602 | 28 | -25.2 |
| | 61–70 | 37208 | 60213 | 2465 | 29 | -24.4 |
| | 71–80 | 35203 | 55919 | 2612 | 30 | -25.7 |
| | 71–80 | 37209 | 60214 | 2476 | 27 | -23.3 |
| T-59 | 1–10 | 35087 | 55920 | 2418 | 30 | -23.9 |
| | 11–20 | 35088 | 55924 | 2397 | 30 | -24.9 |
| | 26–35 | 35089 | 55925 | 2374 | 28 | -24.3 |
| | 35–45 | 35090 | 55926 | 2437 | 28 | -25.6 |
| | 51–60 | 35091 | 55927 | 2456 | 30 | -25.3 |
| T-64 | 1–10 | 35092 | 55928 | 2387 | 30 | -26.2 |
| | 16–25 | 35093 | 55929 | 2425 | 30 | -25.2 |
| | 26–35 | 35094 | 55930 | 2481 | 30 | -25.1 |
| | 41–50 | 35095 | 55934 | 2410 | 30 | -25.6 |
| | 51–60 | 35928 | 57037 | 2465 | 29 | -25.0 |

Table 6.19: The $\chi^2$ test statistics between measurements on overlapping decadal blocks from Cults Loch 3 Structure 2. 5% critical value for the $\chi^2$ test statistic is 3.8.

| Timber | Rings | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\chi^2$ | Combined Age | Combined 1-$\sigma$ error |
|---|---|---|---|---|---|---|---|
| T-36 | 56–65 | 57039 | 2442 | 26 | 3.8 | 2438 | 20 |
| | | 55949 | 2434 | 28 | | | |

Table 6.20: Results of the individual wiggle-matches for Cults Loch 3 Structure 2. Posterior probabilities are displayed in Figures 6.52 to 6.56.

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine \An (%) | $\chi^2$ \5% crit |
|---|---|---|---|---|
| T-24 | *700–690 cal BC (3.2%)*<br>*525–490 cal BC (65.0%)* | *710–675 cal BC (22.4%)*<br>*540–475 cal BC (73.0%)* | 134.40<br>\28.90 | 0.582<br>\11.071 |
| T-36 | *675–635 cal BC (44.2%)*<br>*605–585 cal BC (23.9%)* | *690–620 cal BC (65.6%)*<br>*610–580 cal BC (29.8%)* | 93.20<br>\26.70 | 3.581<br>\12.592 |
| T-37 | *635–615 cal BC (19.4%)*<br>*560–500 cal BC (48.8%)* | *695–680 cal BC (2.9%)*<br>*645–610 cal BC (23.1%)*<br>595–495 cal BC (69.5%) | 86.20<br>\28.90 | 4.038<br>\11.071 |
| T-59 | *490–420 cal BC* | *500–400 cal BC* | 104.30<br>\31.60 | 3.538<br>\9.488 |
| T-64 | *500–450 cal BC (64.2%)*<br>*410–400 cal BC (4.0%)* | *515–395 cal BC* | 68.20<br>\31.60 | 3.849<br>\9.488 |

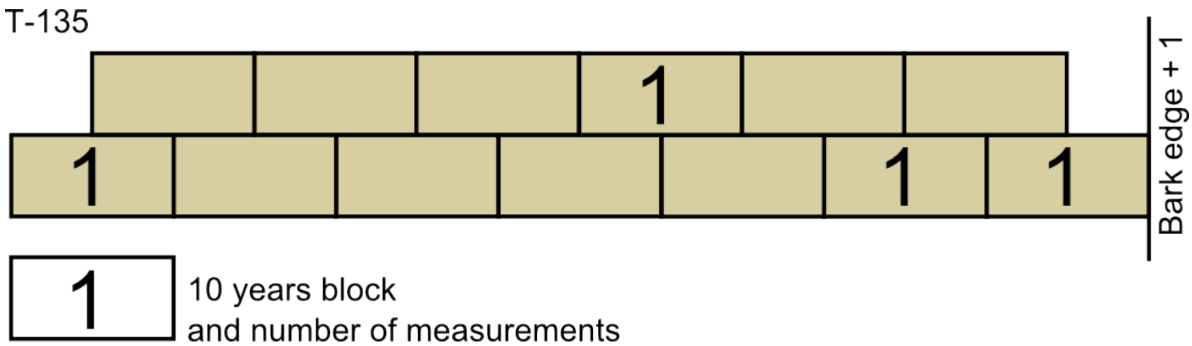



Figure 6.57: Sampling pattern for Cults Loch 3 timber T-135 timbers.

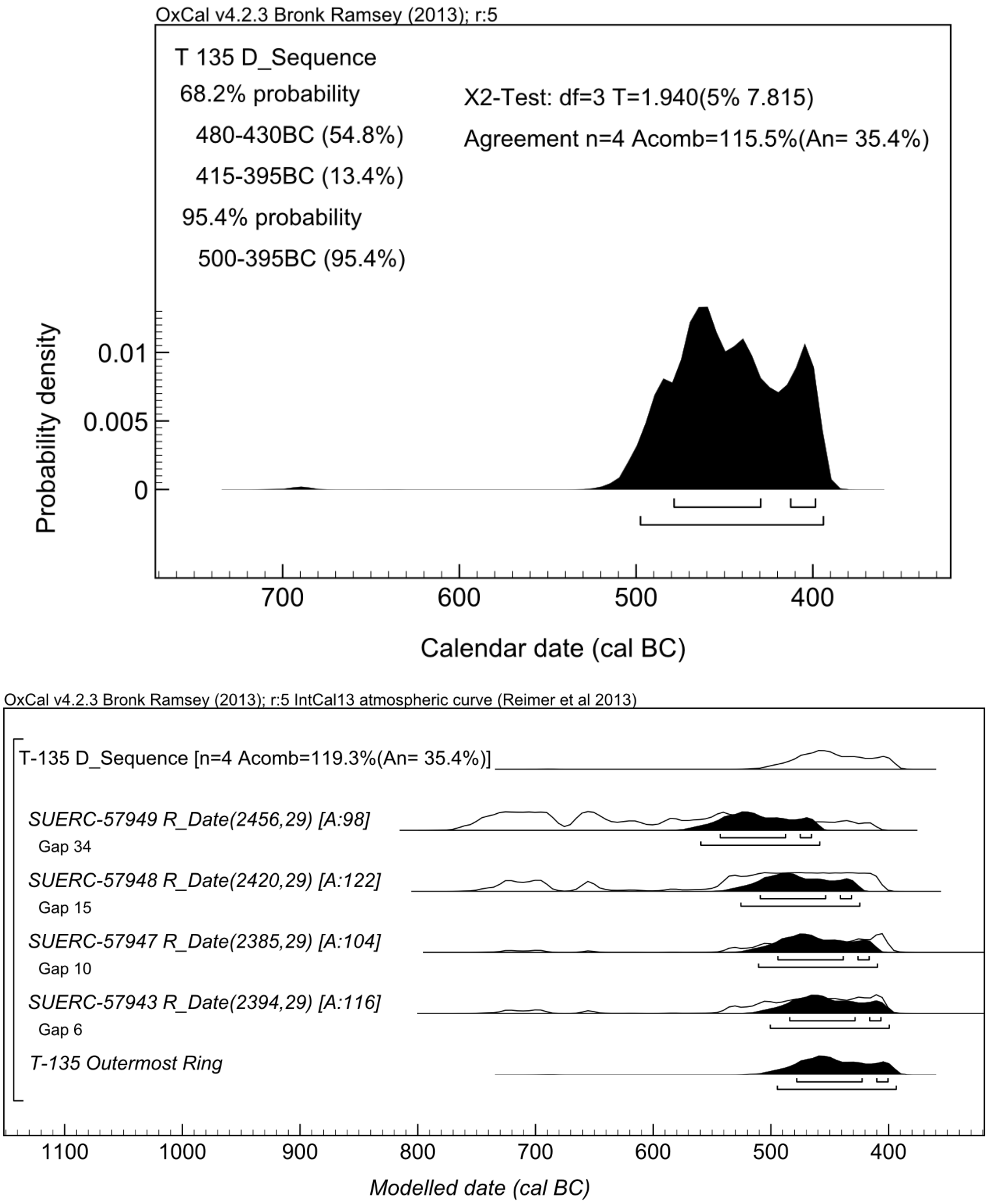



Figure 6.58: Results of the wiggle-match on Cults Loch 3 timber T-135: summary (top), and the individual determinations (bottom).

Besides the measurements for the wiggle-match dates, two individual determinations were conducted: SUERC-59316 and SUERC-59317 (Table 6.23). The former is a fragment of hazel roundwood from context [206]; it was the only reliable sample available from the much-decayed Structure 3. The latter determination, SUERC-59317, is based on a fragment of alder roundwood and was intended to better define context [602], the final activity phase at Structure 2.

As stated in section 6.4.1, the aim of this wiggle-match dating study was to define whether Structure 1 at Cults Loch 3 preceded Structure 2, or whether the converse is more plausible. The most straightforward way to assess this is to evaluate the probabilities that the felling of timbers within one structure preceded the felling in another structure. This provides the basis for a general site model, which in turn can be compared to alternative interpretations, so as to evaluate whether it is indeed the most plausible reading of the sequence of events at Cults Loch 3.

Note that at this point the computational requirements become too great to work with entire wiggle-matches. Instead posterior distributions for individual wiggle-match models have been exported and introduced into the overall model as *.prior files. This can be identified in the model output by the change from D_Sequence() to Prior() command. Using *.prior files reduces the number of parameters involved in the MCMC simulation: using the D_Sequence() means that for a wiggle-match based on five determinations six parameters have to be calculated (one for each of the measurements and one for the wiggle-match posterior). With a *.prior model only one parameter is estimated. One point to bear in mind is that while this approach produces parameters that are indistinguishable from those produced by complete models containing all the individual measurements, the model and overall agreement indices are calculated based on overall results of the individual wiggle-matches and not on all the component measurements. Hence, if any particular determination is not in agreement with the model, it will not become apparent in the quality agreement indices. Because of this it is important to ensure good wiggle-match fit in these kinds of more complex models at an early stage, which is one of the reasons for the large number of measurements put into the Cults Loch 3 wiggle-match dates.

Table 6.21: Results of the radiocarbon determinations on the timber T-135 at Cults Loch 3. The timber is alder (*Alnus sp.*).

| Rings | GU- number | SUERC- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| 2–11 | 36127 | 57943 | 2394 | 29 | -25.8 |
| 12–21 | 36128 | 57947 | 2385 | 29 | -25.7 |
| 27–36 | 36129 | 57948 | 2420 | 29 | -25.7 |
| 61–69 | 36130 | 57949 | 2456 | 29 | -26.3 |

Table 6.22: The wiggle-match date of the timber T-135 from Cults Loch 3. Posterior probabilities are displayed in Figure 6.84

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine \An (%) | $\chi^2$ \5% crit |
|---|---|---|---|---|
| T-135 | *480–430 cal BC (54.8%)*<br>*415–395 cal BC (13.4%)* | *500–395 cal BC* | 115.50<br>\35.40 | 1.94<br>\7.815 |

Table 6.23: Results of the new radiocarbon determinations on short-lived samples from Cults Loch 3.

| Context | Sample type | Species | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|---|
| 206.1 | Roundwood charcoal | *Crylus avellana* | 37217 | 59316 | 2193 | 26 | -27.4 |
| 602.1 | Roundwood charcoal | *Alnus sp.* | 37218 | 59317 | 2415 | 29 | -27.7 |

### 6.4.3 Cults Loch 3 analyses

#### Order of events at Cults Loch 3

The most straightforward way to evaluate which of the two structures came first is to estimate the probabilities of their component elements preceding one another, which can be done using OxCals Order(); function. In principle this is the most conservative way of approaching the problem, as any results it produces are not affected by assumptions regarding the relationships of the two structures; in other words, the prior is uninformative. The key practical weakness of the approach is that it allows the two structures to be seen by the model as contemporaneous and hence the information about their overlap in plan is not used.

The model itself is a bounded uniform phase model containing three main elements (Fig. 6.4.21):

- Structure 1 is represented by a bounded uniform phase including the wiggle-match dates T-41, -44, -901, -966 and -967, as well as the legacy single radiocarbon determination SUERC-27664.
- Structure 2 is represented by a sequence beginning with T-24, as well as T-36 and -37 acting as TPQ parameters. This is succeeded by the wiggle-matches T-59 and -64, bound into a single phase with a maximum span of a single year, as indicated by the alder-alder chronology ALSP4x3. The Structure 2 sequence concludes with the single determinations SUERC-34786 and -59317.
- The mound is represented by a uniform bounded phase including the T-963 wiggle-match and the information of the alder-alder dendrochronology ALSP1x10, represented by a phase that consists of the wiggle-matches T-60 and T-48 and limited to a single year span.

Results of this model do not support the primacy of any one particular structure (Table 6.4.16). The probabilities that the timbers from Structure 1 pre-date timber

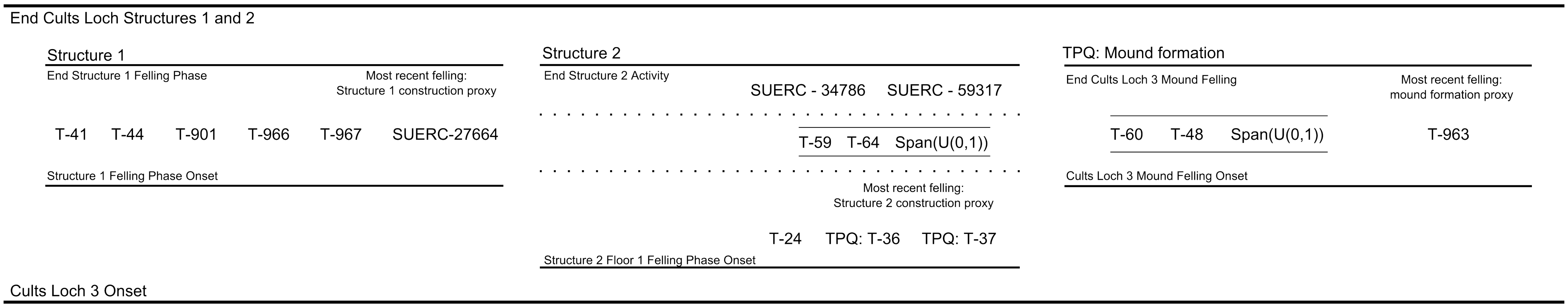



Figure 6.59: Schematic representation of the model design for resolving the relationship between the Structure 1 and Structure 2 timbers using the Order(); command. Both structures are placed as discrete entities within a broader site model and the crannog mound is used as a *TPQ*. Because the timbers T-36 and -37 from Structure 2 produced dates that are older than the mound formation, they are also included in the model as *TPQs*.

T-24, which is the most recent date from the construction phase of Structure 2, range from 8.14% to 20.55%. At the same time, however, Structure 1 timbers pre-date the stakes from underneath the final floor of Structure 2 with probabilities of 62.75% to 79.64% and the individual determination from the final context of Structure 2 with probabilities ranging from 69.11% to 83.96%. Hence, the picture that emerges is one where some of Structure 2 events would have happened before the activity at Structure 1, while the remainder would have taken place after the end of activity at Structure 1. This result can be interpreted in four ways.

In the first interpretation, the apparent interjection of Structure 1 between the phases of Structure 2 activity is seen as an analytical artefact emerging from the assumptions of the model itself; as the Structure 2 data was placed in a sequence it became more spread out, while the Structure 1 data, placed in a bound uniform phase, was compressed into a narrower distribution. The second possible interpretation is that Structure 2 succeeds Structure 1, but that timber T-24 was re-cycled from some earlier deposit, as seems to have been the case with timbers T-36 and T-37. The third alternative is that the results of the model using the Order(); function are correct and that the original construction of Structure 2 was followed by a hiatus event during which Structure 1 was built and only after the abandonment of the latter the former was re-occupied; this interpretation might be supported by evidence of flooding and abandonment between the contexts forming the original Structure 2 floor ([622][623][624] and [642]) and the succeeding refurbishment context [621]. This scenario might also account for the difficulty in interpreting the succession of the structures in the field. The fourth interpretation is that what appeared in plan as two partially overlapping roundhouses, indeed constituted for some time a "figure-of-eight" structure, whereby Structure 2 would have been built first, and Structure 1 would have been an appendix building - something that may be supported by the small diameter of the latter. Such double-roundhouse arrangements have been identified hitherto, for example at Broxmouth, where the close proximity of roundhouses 1 and 2 from the Late Iron Age village suggests that the two formed a complex (Armit and McKenzie 2013). Having said that, both Structure 1 and 2 at Cults Loch 3 have hearth remains, suggesting that, if the "figure of eight" interpretation were to be true, there would be a degree of redundancy between the two components, or some functional variability. The second and third possibilities, which assume that the results of the Order(); function are valid are discussed next as the two most plausible site models, while the first possibility, that the results above are an analytical artefact, is discussed afterwards in the context of subsequent sensitivity analyses. From a modelling perspective, the fourth scenario ("figure of eight") is not so much different from the third scenario ("interjected Structure 1") and hence the two are discussed as one model.

Table 6.24: Probabilities that specific Structure 1 timbers (T-44, -41, -967, -966 and -901) precede specific Structure 2 timbers and individual radiocarbon determinations (T-24, -59, -64 and SUERC- 34786 and -59317). Results from the model using the Order(); function, schematized inFigure 6.59.

| | *T-24* | *T-59* | *T-64* | *SUERC-34786* | *SUERC-59317* |
|---|---|---|---|---|---|
| *T-44* | *20.55%* | *77.14%* | *77.14%* | *80.95%* | *81.07%* |
| *T-41* | *14.95%* | *79.64%* | *79.64%* | *83.96%* | *84.07%* |
| *T-967* | *8.70%* | *69.09%* | *69.07%* | *74.43%* | *74.55%* |
| *T-966* | *10.32%* | *67.96%* | *67.95%* | *72.91%* | *73.06%* |
| *T-901* | *8.14%* | *63.75%* | *63.75%* | *69.11%* | *69.24%* |
| *SUERC-27664* | *14.71%* | *68.95%* | *68.94%* | *73.44%* | *73.56%* |

### Cults loch 3 site models

There are two plausible interpretations as to the structural history of Cults Loch 3:

1. Structure 1 was built first, followed by Structure 2. All the wiggle-match dated timbers from the original floor of Structure 2 were recycled.

2. Structure 2 was built first, and then abandoned, during which period Structure 1 was built. After the end of activity at Structure 1, Structure 2 was re-built.

These two scenarios can be developed into site models that use all the available data. For the first scenario the mound construction phase remains unaltered and is included into the Structure 1 felling phase as a TPQ. Next is the phase with Structure 2 material that includes the sapwood estimate for the timber T-947 and the single determination SUERC-27666, as well as a sequence beginning with a phase including the stakes T-59 and -64, alongside the wiggle-matches T-24, -36 and -37 included as TPQs. The second part of this sequence consists of the context [602] short-lived samples. The Structure 2 phase is succeeded by the Structure 3 date. The remainder of the information is placed in the overall site phase (Figure 6.60). The results of this model are as follows (Figure 6.61):

- Onset of activity is estimated to *540–480 cal BC (95.4%)*, with the highest probability in the range *515–485 cal BC (68.2%)*.

- The construction date for Structure 1 is *510–430 cal BC (95.4%)*, with the highest probability in the range *495–460 cal BC (68.2%)*.

- The construction date for Structure 2 cannot be estimated, as all the timbers dating this event are assumed to be re-used.

- The end of the earlier Iron Age activity dates to *395–315 cal BC (95.4%)*, with the highest probability in the range *380–340 cal BC (68.2%)*.

- The interval between Structure 1 felling phase and the stakes T-59 and -64 is *0–30 years (95.4%)*, with the highest probability in the range *0–15 years (68.2%)*(Figure 6.62)

- The interval between the end of Structure 2 activity and the deposition of the Structure 3 context [206] is *0–70 years (95.4%)*, with the highest probability in the range *10–50 years (68.2%)*(Figure 6.63)
- Model agreement is good (Amodel = 121.3%)
- The only one date with a low individual agreement is SUERC-59316 from context [206] (A= 45.9%) the only dated sample from Structure 3.

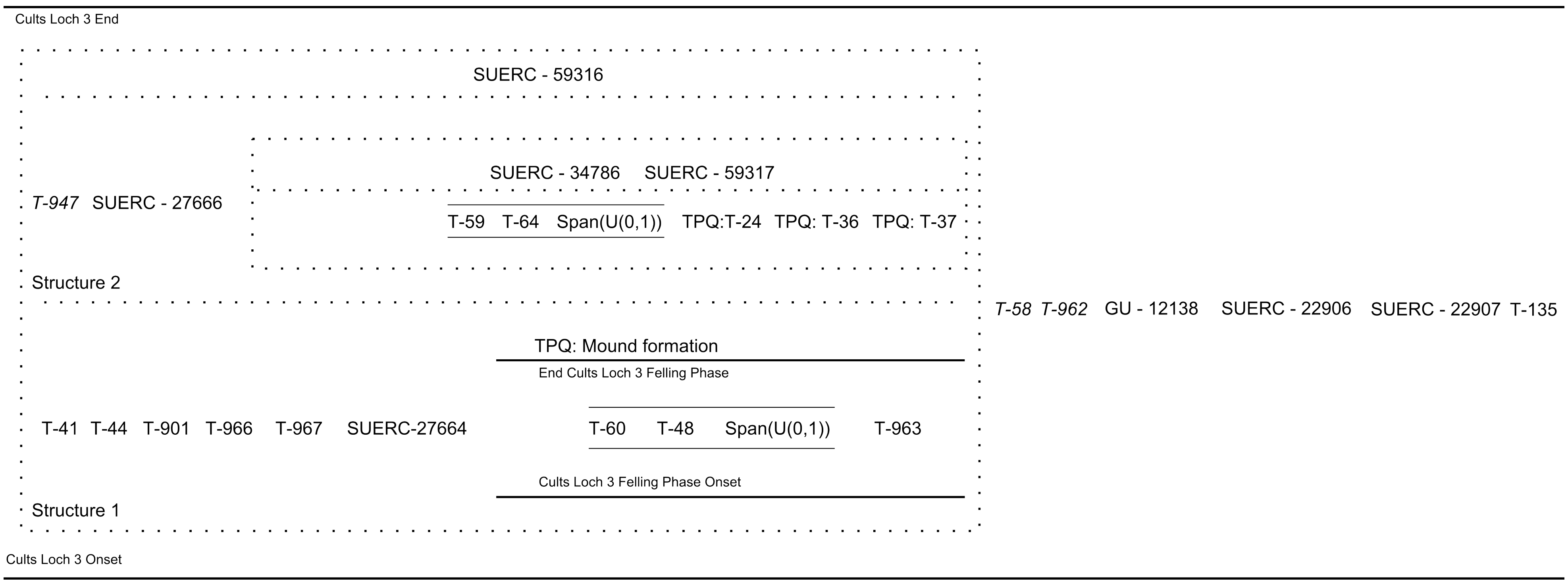



Figure 6.60: Schematic representation of the Bayesian model for Cults Loch 3 based on the assumption that the timbers from the original floor of Structure 2 are all re-used and that all of Structure 2 succeeds Structure 1. Dendrochronological determinations are in italics.

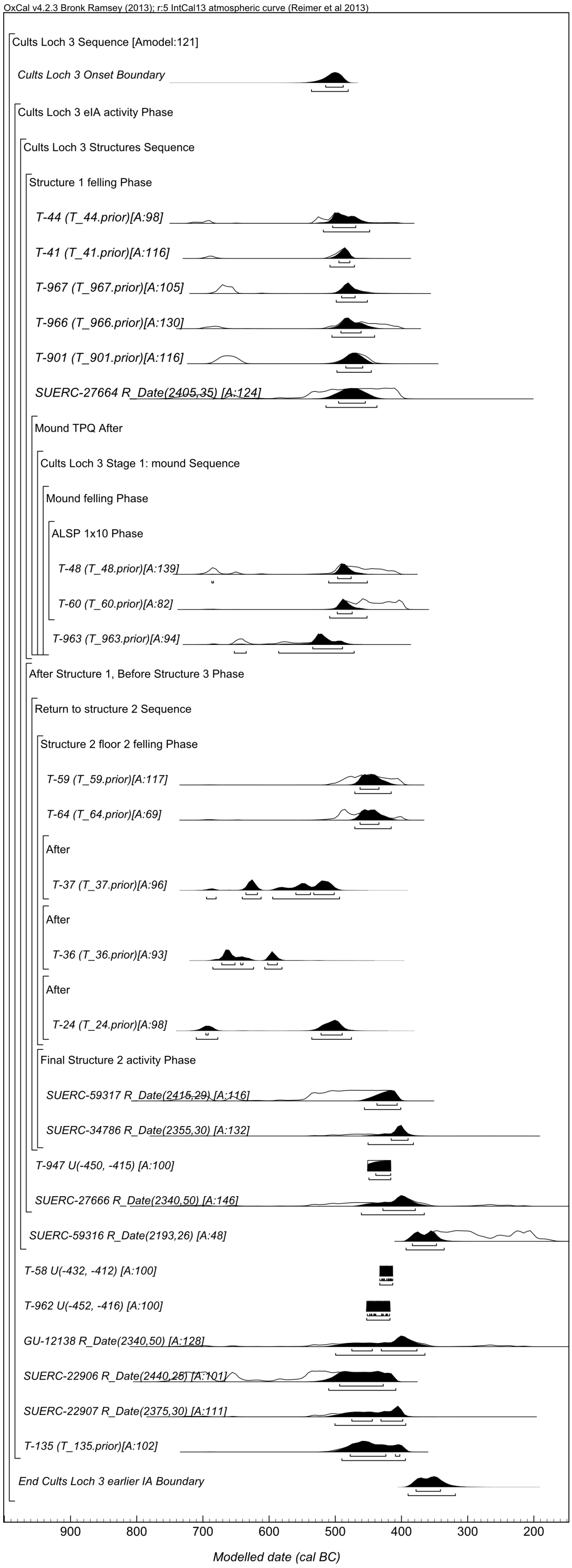



Figure 6.61: The output of the model for Cults Loch 3 based on the assumption that the timbers from the earliest floor of Structure 2 are all re-used.

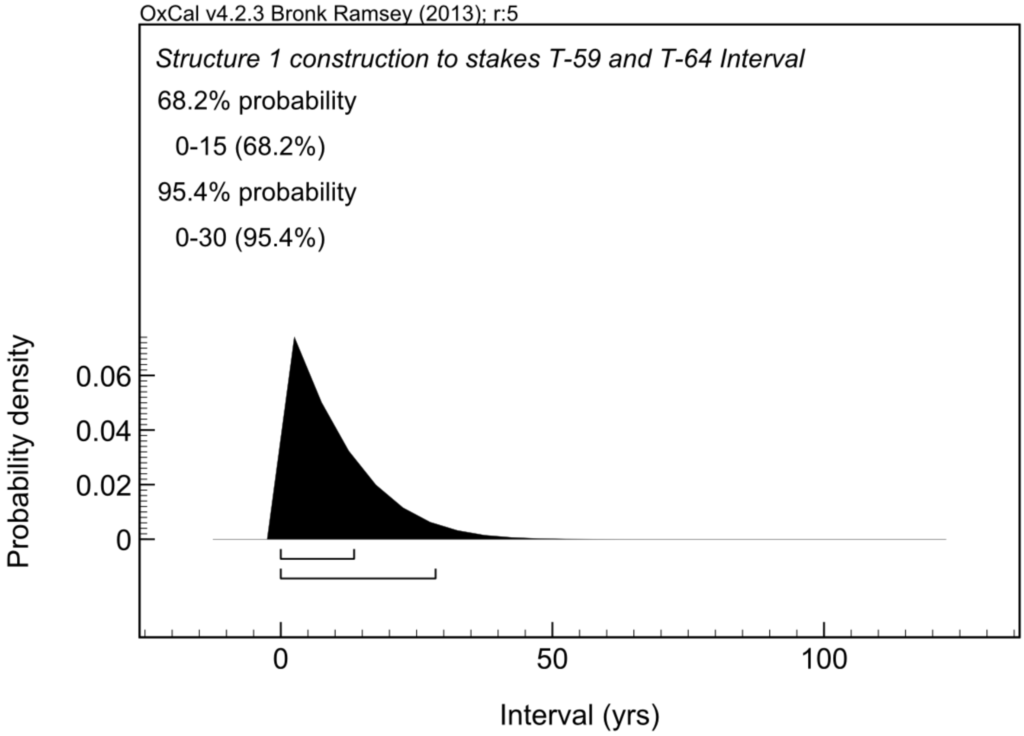



Figure 6.62: The interval between the felling of Structure 1 timbers and the felling of the stakes T-59 and -64 from Structure 2, in the model based on the assumption that the timbers from the earliest floor of Structure 2 are all re-used.

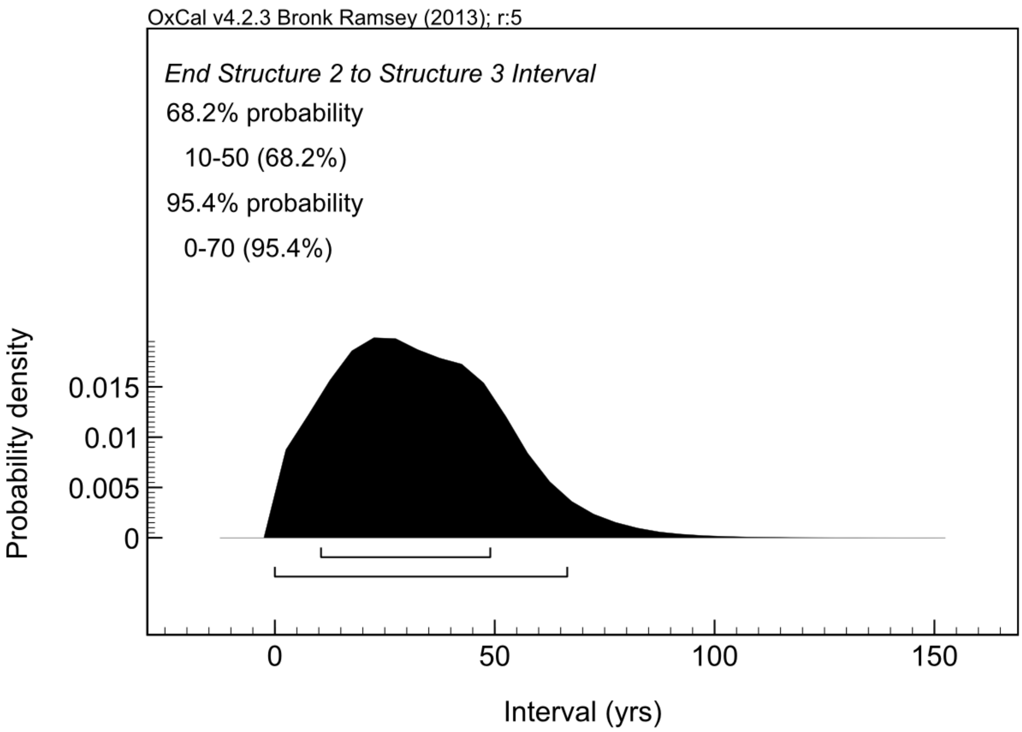



Figure 6.63: The interval between the end of the activity at Structure 2 and the dated activity at Structure 3 at Cults Loch 3, in the model based on the assumption that the timbers from the earliest floor of Structure 2 are all re-used.

The other interpretation assumes that Structure 2 was built before Structure 1, but then abandoned during the period of Structure 1 activity, before subsequent re-occupation. The alternative interpretation based on the same belief about the relative dates of the timbers involved is that Structure 1 constituted an annex of the larger Structure 2 and the two formed a "figure of eight" complex. The changes from the previous model are that the wiggle-matches T-24, -36 and -37 are now placed into a phase preceding the Structure 1 felling; T-24 as a date and T-36 and -37 as TPQs, as both appear to be older than the underlying stake T-60. The mound construction phase is now placed into the Structure 2 felling phase as TPQ. The remainder of the model remains unaltered (Figure 6.64). The results are as follows (Figure 6.65):

- Onset of activity is estimated to *540–485 cal BC (95.4%)*, with the highest probability in the range *520–490 cal BC (68.2%)*.
- The construction date for Structure 2 is *520–480 cal BC (95.4%)*, with the highest probability in the range *510–485 cal BC (68.2%)*.
- The construction date for Structure 1 is *485–435 cal BC (95.4%)*, with the highest probability in the range *475–450 cal BC (68.2%)*.
- The end of the earlier Iron Age activity dates to *395–320 cal BC (95.4%)*, with the highest probability in the range *385–340 cal BC (68.2%)*.
- The interval between the construction of Structures 2 and 1 is *0–20 years (95.4%)*, with the highest probability in the range *0–10 years (68.2%)*(Figure 6.66)
- The interval between the construction of Structure 1 and the stakes T-59 and -64 is *0–30 years (95.4%)*, with the highest probability in the range *0–15 years (68.2%)*(Figure 6.67)
- The interval between the end of Structure 2 activity and the deposition of the Structure 3 context [206] is *0–70 years (95.4%)*, with the highest probability in the range *10–50 years (68.2%)*(Figure 6.68)
- The model agreement is good (Amodel = 83.9%)
- There are two dates with low individual agreements: SUERC-59316 from context [206] (A= 46.1%) and the wiggle-match date for the stake T-60, which pinned the mound (A= 26.4%).

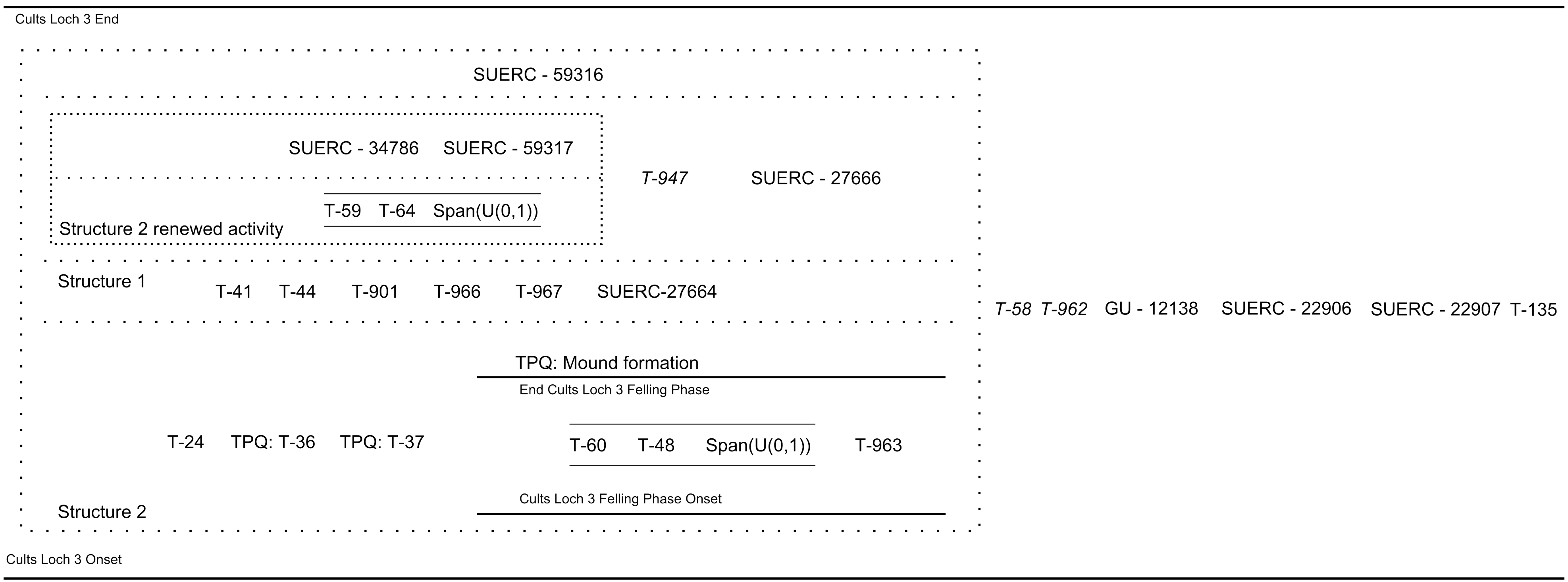



Figure 6.64: Schematic representation of the Bayesian model for Cults Loch 3 based on the assumption that Structure 1 was built and constructed during a hiatus in the use of Structure 2. Dendrochronological determinations are in italics.

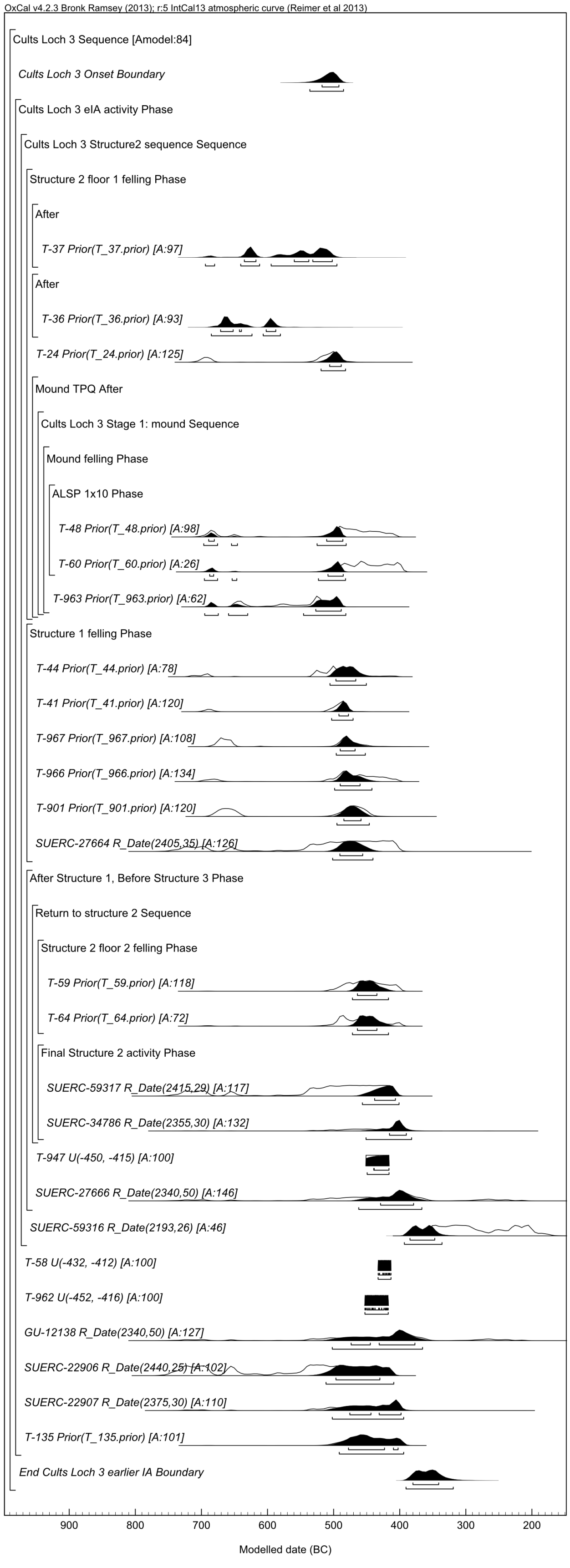



Figure 6.65: The output of the model for Cults Loch 3 based on the assumption that Structure 1 was built and constructed during a hiatus in the use of Structure 2.

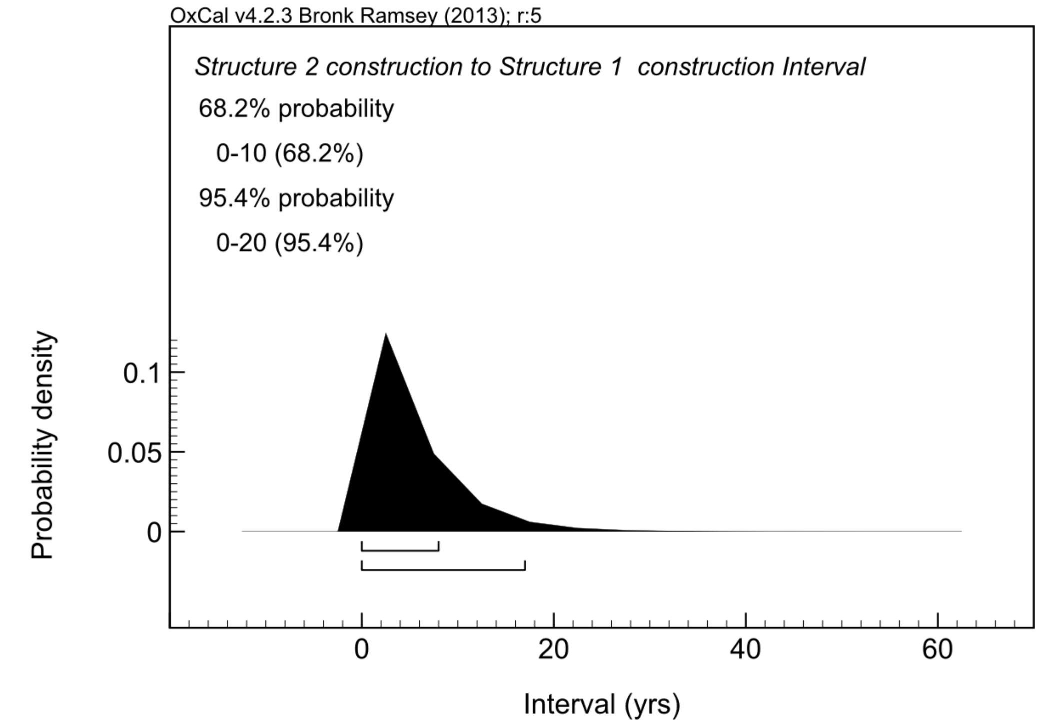



Figure 6.66: The interval between the constructions of Structures 2 and 1 in the model based on the assumption that Structure 1 was built and constructed during a hiatus in the use of Structure 2.

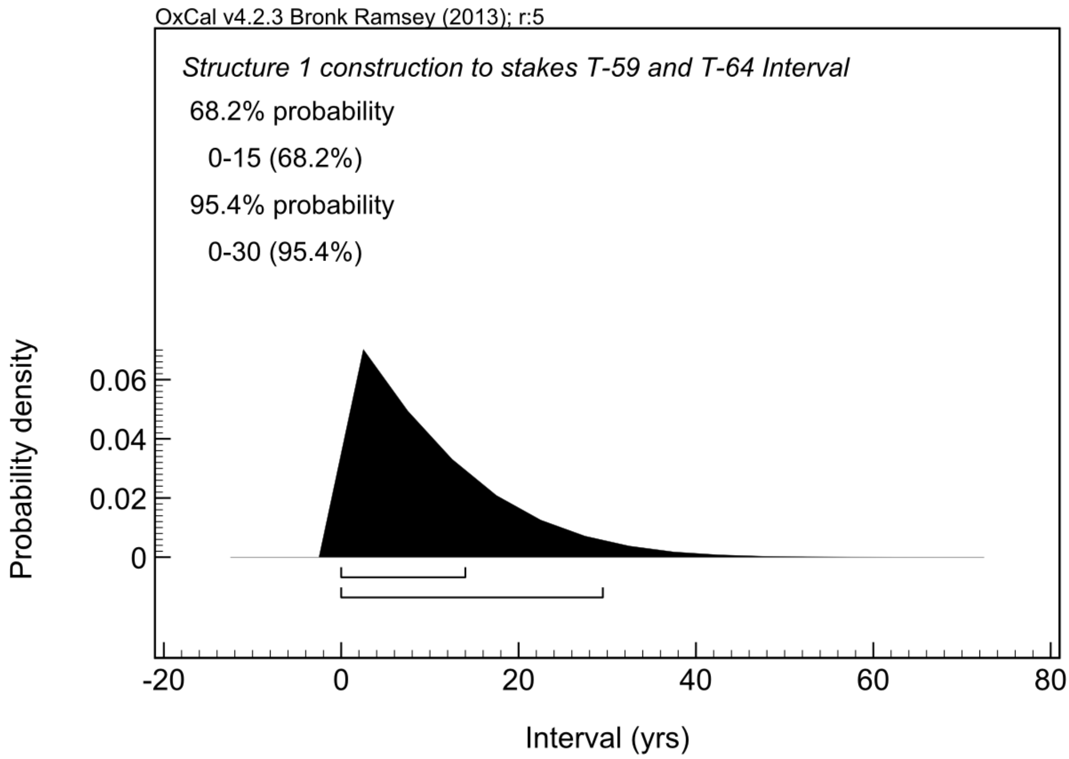



Figure 6.67: The interval between the felling of Structure 1 timbers and the felling of the stakes T-59 and -64 from Structure 2, in the model based on the assumption that Structure 1 was built and constructed during a hiatus in the use of Structure 2.

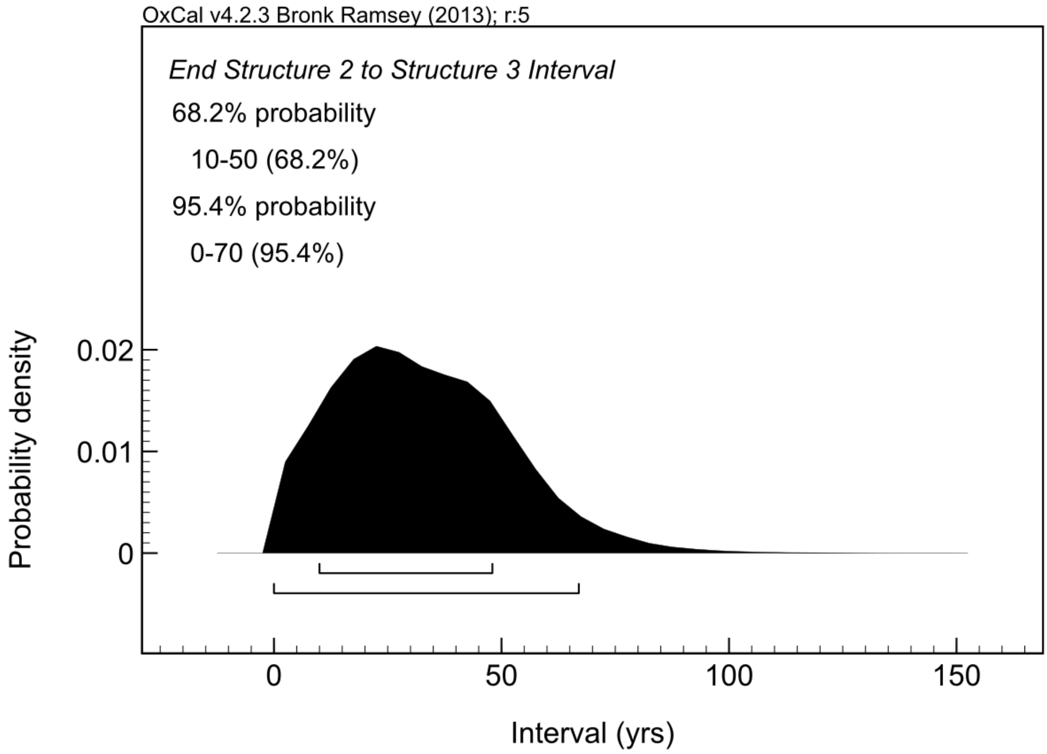



Figure 6.68: The interval between the end of the activity at Structure 2 and the dated activity at Structure 3 at Cults Loch 3, in the model based on the assumption that Structure 1 was built and constructed during a hiatus in the use of Structure 2.

The choice between the two possible site models is difficult to make without recourse to overall site interpretation. While the first model, assuming that Structure 2 was built first after the use of Structure 1 appears to be in agreement with all the individual data save SUERC-59316, it also forces a very specific interpretation of the structures on the site; with the interval between Structure 1 construction and the felling of the stakes T-59 and -64 at most 30 years, this model would require accepting a very high refurbishment rate, as it implies that the three successive Structure 1 floors and the three Structure 2 floors that preceded the stakes happened during this time, alongside the hiatus deposit below context [621]. The other possibility relaxes this rate of change, as it gives up to 20 years between the building of Structures 2 and 1, as well as up to 30 years between the felling of timbers for Structure 1 and the felling of stakes T-59 and -64. However, this latter model also has one more case of low individual agreement, T-60. This can be attributed to the effect of the older date of the wiggle-match T-24, which constitutes the main dating evidence for the construction of Structure 2 under this model and as the model states that T-60 acts as *TPQ* for T-24, a conflict arises. Nevertheless, these same is not true for T-48, which, according to the dendrochronology ALSP1x10, was felled in the same year as T-60, and hence it may very well be that this particular case of low agreement is an effect of measurement uncertainties. Therefore, choosing between the two models requires making a decision as to whether a very high refurbishment rate is more plausible than the possibility that the low individual agreement for the T-60 wiggle-match is the result of analytical uncertainties associated with wiggle-match dating.

One last thing to consider is the question of the end of the earlier Iron Age activity on the site. Due to the limited availability of good samples from Structure 3 this becomes difficult to assess; the low individual agreement of SUERC-59316, the only date from Structure 3, indicates that the uniform phase prior in this case might not be applicable and it could be that as a result the end boundary for the site is inaccurate. Nevertheless, given the lack of evidence for abandonment deposits between Structure 3 and the preceding phase of activity associated with Structure 2, it becomes improbable that the activity at Structure 3 would have begun long after the end of the Hallstatt calibration plateau (which contains almost all of the Structure 2 material), thus, given the limited longevity of Iron Age roundhouses, making it improbable that the site would have continued beyond 300 BC.

#### Sensitivity analyses

The models presented above are based on the assumption that the timbers of Structure 1 are younger than T-24 from Structure 2. However, as this could be an effect of an analytical artefact it is important to assess whether the two alternative scenarios:

1. All Structure 2 material precedes Structure 1
2. Structure 1 precedes Structure 2 and timber T-24 is not recycled

To evaluate this, corresponding models were built, by modifying the relevant site models. The first of these alternatives is very implausible, as the model has a poor agreement Amodel = 7.8%. The other alternative is also less plausible than the site models proposed above; although the model agreement is good (Amodel = 68.4%) the timber T-24 has a low individual agreement (A= 5.5%), indicating that it is out of its place within the site model. As re-use is the most plausible explanation for this, this model becomes no different from that which was presented near the beginning of this sub-section.

#### Answering the archaeological question and the methodological implications

The modelling of the chronological data from Cults Loch 3 makes a strong case for that the final activity at Structure 2 succeeded the construction of Structure 1. What remains unclear is the relationship between the construction of the two roundhouses; it is both possible that Structure 2 was built before Structure 1 and then abandoned for a period (or that the two formed a “figure of eight complex”), but it is also plausible that this picture emerges as a result of the first floor of Structure 2 being built from recycled material. There is no direct evidence to support one interpretation over the other and hence any arguments have to rely on more tangential information, such as the length of the intervals between different events. It is based on this evidence that the model whereby Structure 1 is built during the hiatus in Structure 2 activity more plausible; the rate of refurbishment events that would be otherwise required to account for all the events within the stratigraphic sequence becomes too high to be practical and would make the case against the domestic nature of the site  something supported by palaeoenvironmental data from Cults Loch 3 (Cavers and Crone, forthcoming). Nevertheless, this kind of argument remains rooted in both modern preconceptions of what is practical, as well as using circumstantial evidence and hence is far from sufficient to choose one model over the other.

On a methodological level this result shows that it is possible to derive answers to some questions regarding site formation processes during the Hallstatt calibration plateau, if sufficient timbers are dated and additional stratigraphic and dendrochronological evidence is available. Re-doing the analyses with the evidence limited to only the radiocarbon-based data from the two structures and the mound (Figure 6.69), showed that without the additional dendrochronological information the archaeological questions could not be resolved; the resulting models were for the most part identical in the posterior distribution of the construction parameters (Figures 6.70 to 6.72) and hence making any decisions could not be justified. This ambiguity, coupled with the large investment required to run this kind of projects means that addressing site-formation questions during the period of the calibration plateau is not realistic at the moment on a routine basis, albeit it might be done if there is sufficient supporting data and the potential knowledge gains offset the high costs and failure risk.

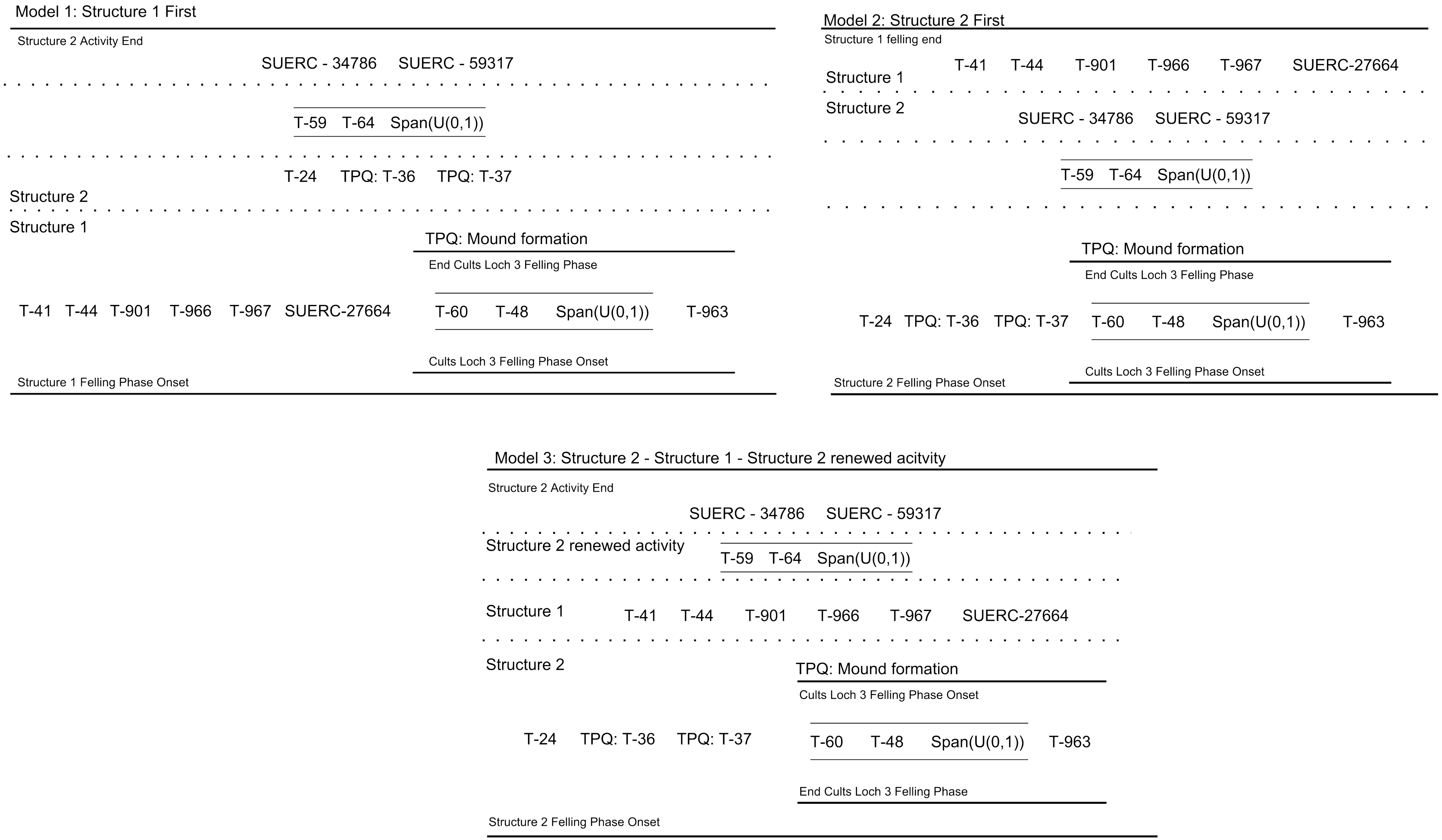



Figure 6.69: Schematic representations of alternative models exploring whether the question of relative chronology of Structures 1 and 2 can be answered from the radiocarbon-based data from within the structures themselves. From the top left-hand corner clockwise: the model assuming that Structure 1 was built before Structure 2, the model assuming that Structure 2 was built and used before Structure 1 and the model assuming that Structure 1 was built and used during the hiatus in Structure 2.

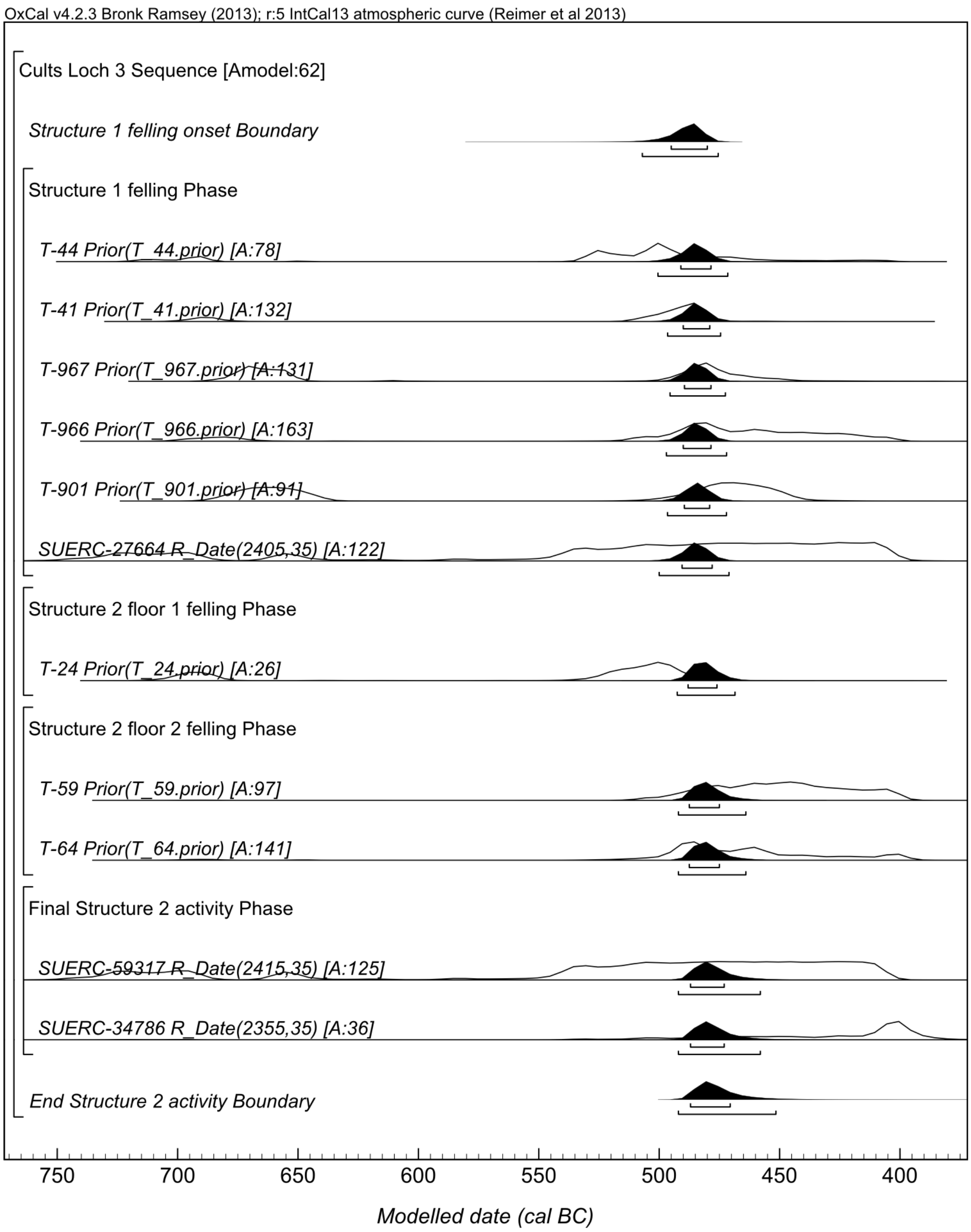



Figure 6.70: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that Structure 1 preceded Structure 2. Note that the results are near identical to those presented in Figures 6.71 to 6.72. *TPQ* output hidden for clarity.

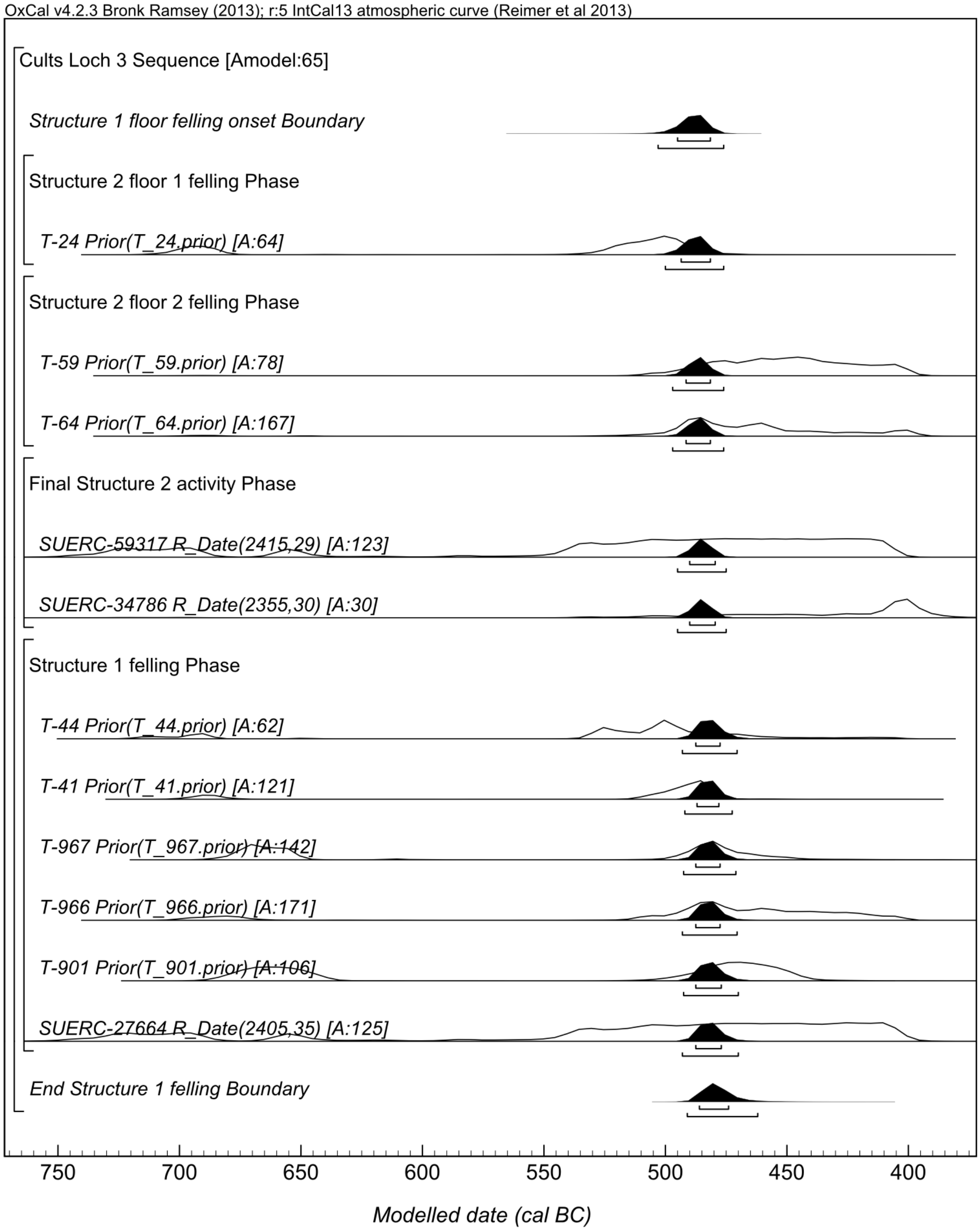



Figure 6.71: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that the construction and activity within Structure 2 preceded Structure 1. Note that the results are near identical to those presented in Figure 6.70 and Figure 6.72. *TPQ* output hidden for clarity.

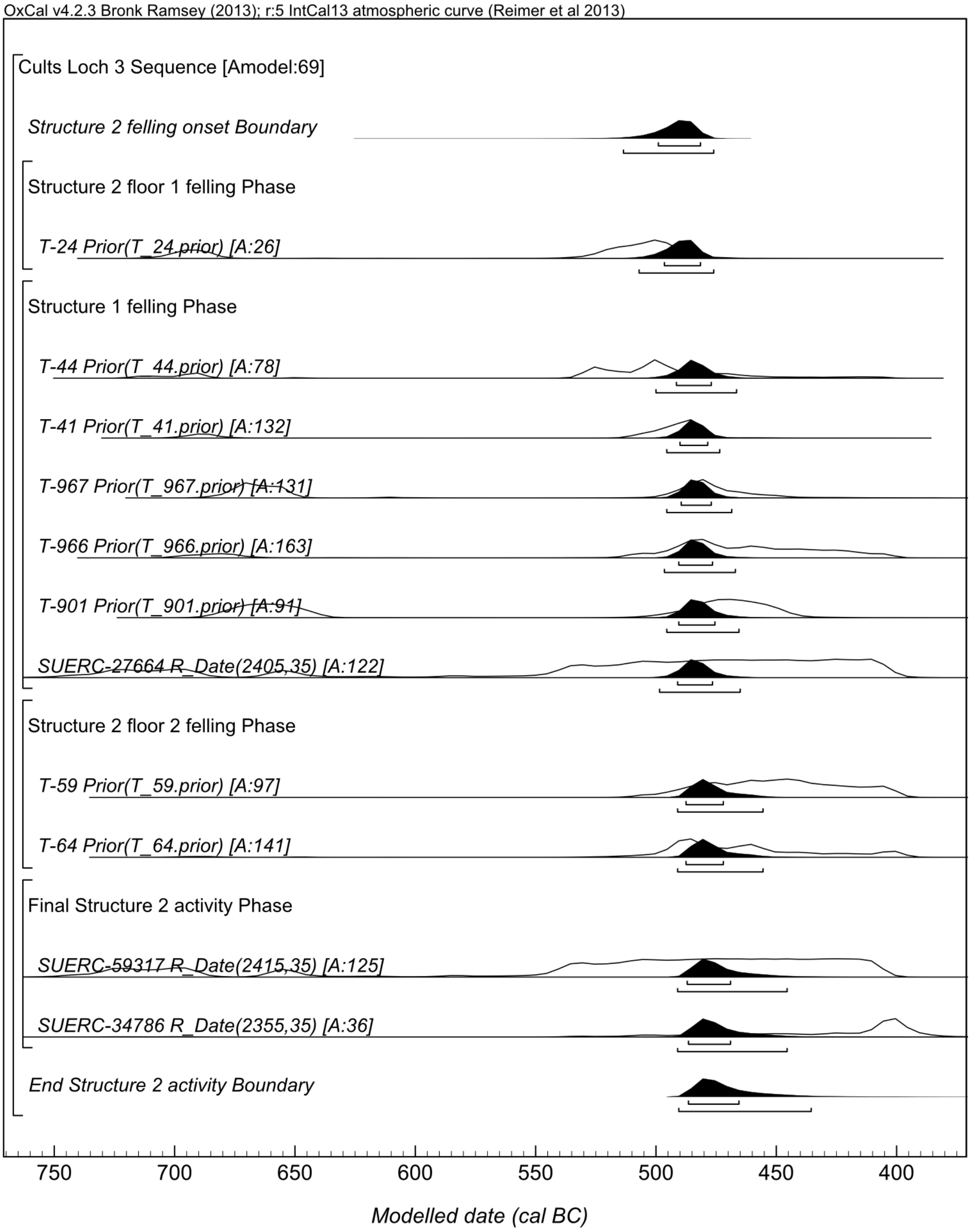



Figure 6.72: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that Structure 1 was built and used during the hiatus in Structure 2. Note that the results are near identical to those presented in Figures 6.70 to 6.71. *TPQ* output hidden for clarity.

### 6.4.4 Further implications of Cults Loch 3 data

The data from Cults Loch 3 can also be used to further explore the properties of working with wiggle-match dates under the conditions of the calibration plateau.

#### Inducing strong adverse shrinkage

An additional analysis that can be conducted with the Cults Loch 3 data is to explore the effects that different model structures will induce in it. Similar questions were raised by Steier and Rom (2000), however their work was based on simulated data. Cults Loch 3 provides the possibility of exploring these effects with real data.

One analysis which is of particular relevance to Bayesian modelling of wiggle-match dates is the effect of grouping all the wiggle-matches under a bounded uniform phase model. This is important because the bounded uniform phase model is considered the least informative of the typical models used in Bayesian modelling of radiocarbon dates (Bayliss et al. 2007, 17) and hence often acts as a safe option when more detailed stratigraphic information is not available. Nevertheless, within the calibration plateau, it is possible that the wiggle-matches may suffer from adverse effects of shrinkage (see section 6.2.2) and thus it is worth evaluating whether this takes place for Cults Loch 3 data. To this end all of the Cults Loch 3 wiggle-match dates relating to the Structures 1 and 2, as well as the associated single radiocarbon determinations, have been placed within a bounded uniform phase model without any internal sub-divisions (Figure 6.73). It has to be stressed that this model has no bearing on the interpretation of the actual site and is meant as a means of exploring the technical properties of the wiggle-match dates and Bayesian modelling.

The results of the analysis confirm that within this kind of model design adverse effects of shrinkage will take hold (Figure 6.74). The posterior distributions of the individual parameters all converge to a single region *500–475 cal BC (95.4%)*, and the duration of the entire phase is limited to between *0–25 years (95.4%)*, with the highest probability in the range *0-10 years (68.2%)*. Considering that the wiggle-match determinations and the single radiocarbon dates are derived from two structures, all with multiple refurbishment phases, these results are very unrealistic and show that adverse shrinkage is taking place. Hence, under these conditions the uniform prior has a significant effect on the shape of the posterior distributions of the parameters, and so, in future research design it is advisable to avoid relying on large numbers of wiggle-match dates from disparate contexts placed within single phase models, a temptation that may arise if the understanding of site formation is insufficient for resolving actual structural events.

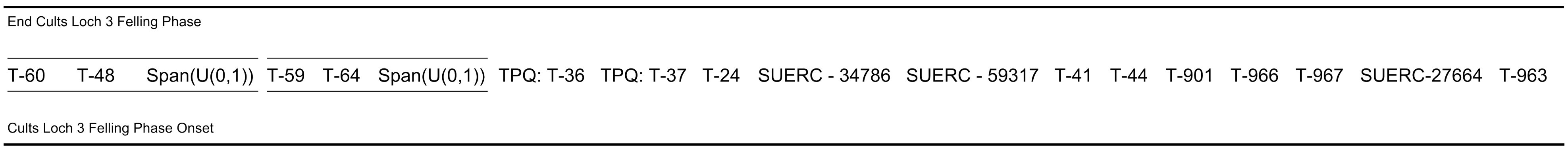



Figure 6.73: Schematic representation of the model placing all of the radiocarbon-based data from Structures 1 and 2 at Cults Loch 3 within a bound uniform phase model.

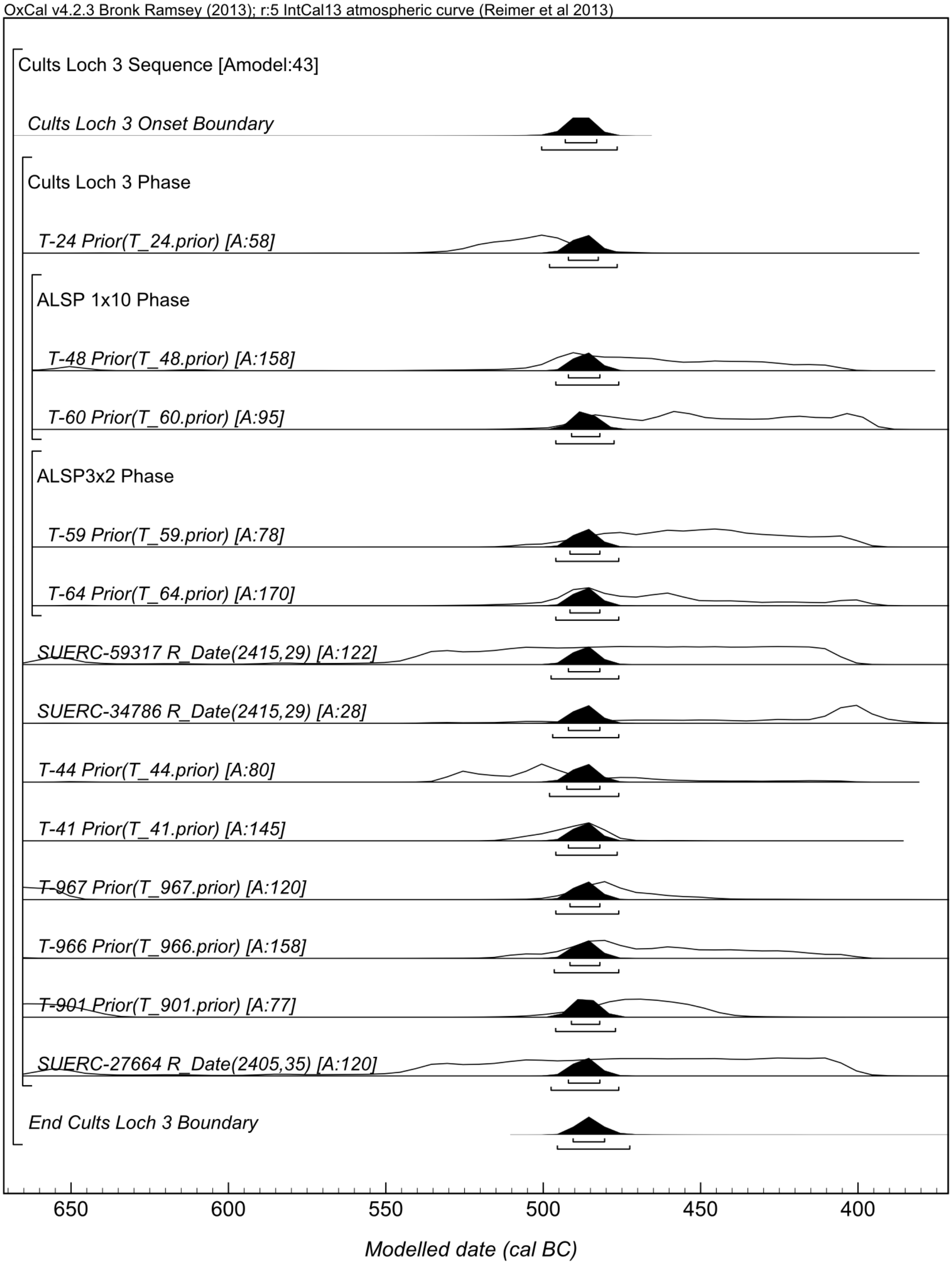



Figure 6.74: Output of the model within which all the radiocarbon-based data from Structures 1 and 2 at Cults Loch 3 was placed within a uniform bound phase model. Notice that all the posteriors cover the same 25 year period, making this output unrealistic and indicating the presence of strong adverse shrinkage.

#### Working with the T-947 augmented curve

Another point to consider is the potential effects of improving the precision of the calibration curve on the analysis of site formation processes during the calibration plateau. To this end, the radiocarbon-only models have been re-run against the curve augmented with the T-947 data. As was the case with a similar analysis at Black Loch of Myrton (see section 6.3.4), it is essential to remember that the T-947 augmented curve has not been ratified and hence any results of this analysis are only exploratory in nature and cannot be treated as recommended models.

The results of this analyses show that using the augmented curve may improve our ability to resolve relative chronological uncertainties. Two models that have been rejected as lacking credibility, one where all of Structure 2 precedes Structure 1 and the other where Structure 2 succeeds Structure 1 and T-24 is not treated as a *TPQ*, both produce low model agreement indices when conducted against the T-947 augmented curve: Amodel = 32.2% for the former and 31.2% for the latter. The model that assumes that Structure 1 was built during the activity hiatus in Structure 2, on the other hand, has a good index Amodel= 78.2%. The differences are also visible in the model output themselves: while the two poor models appear to shrink the posterior distributions of the individual dates into very narrow and almost identical distributions, in the preferred model the posterior distributions of individual parameters retain elements of their original shape (Figures 6.75 to 6.77). Hence, the more precise augmented curve does seem to make a difference in the performance of the Bayesian models to an extent where we can hope that with improvements in calibration it will become possible to address site formation processes during the Hallstatt plateau through wiggle-match dating.

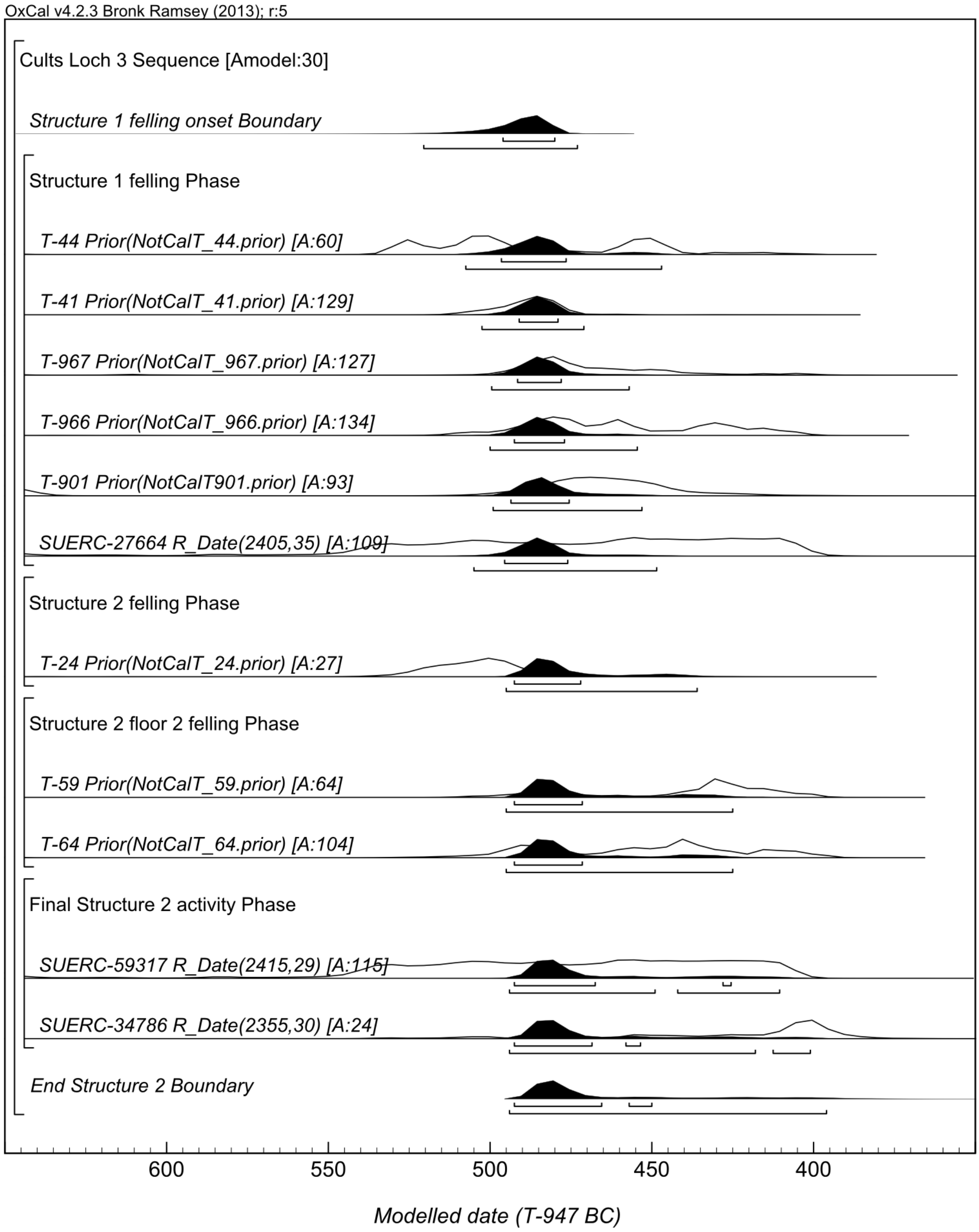



Figure 6.75: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that Structure 1 preceded Structure 2, with all the calibrations conducted against a curve augmented with T-947 data. Note that the results are near identical to those presented in Figures 6.70 to 6.72 and Figure 6.76. *TPQ* output hidden for clarity.

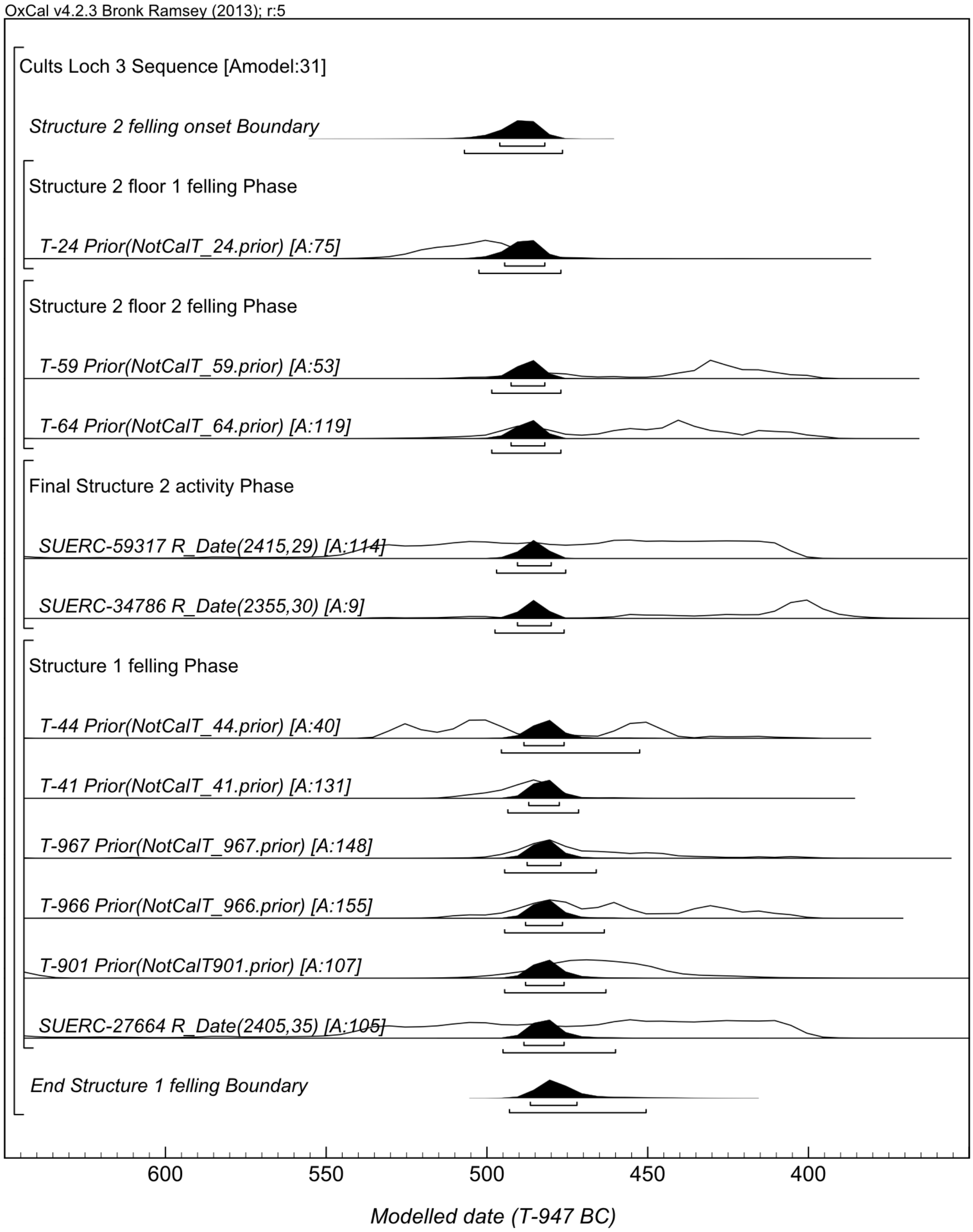



Figure 6.76: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that the construction and activity within Structure 2 preceded Structure 1, with all the calibrations conducted against a curve augmented with T-947 data. Note that the results are near identical to those presented in Figures 6.70 to 6.72 and Figure 6.75. *TPQ* output hidden for clarity.

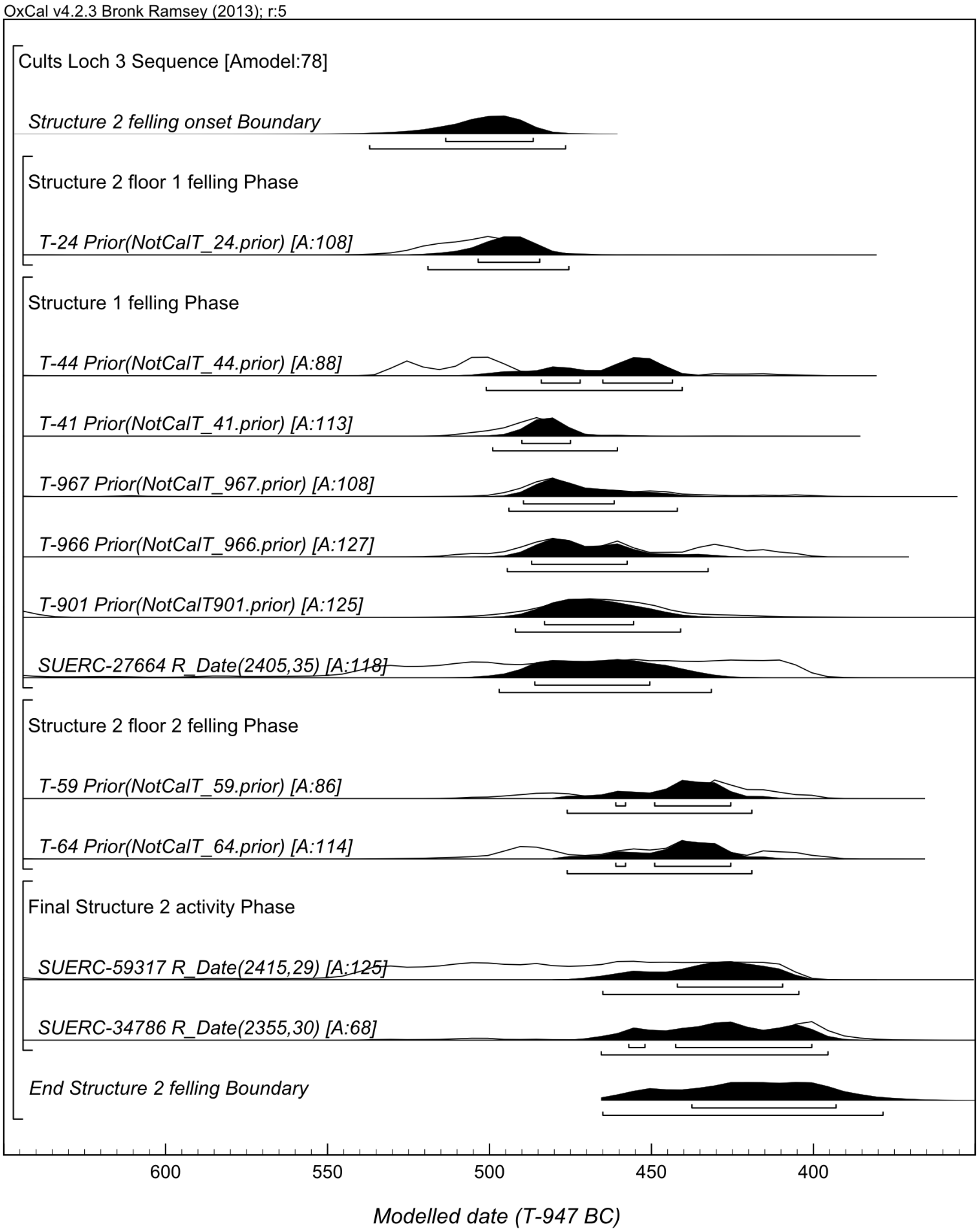



Figure 6.77: Results of the model using only the radiocarbon based data from within the structures at Cults loch 3, built on the assumption that Structure 1 was built and used during the hiatus in Structure 2, with all the calibrations conducted against a curve augmented with T-947 data. Note how the posterior distributions of the parameters show a development sequence throughout the duration of the century that is consistent with the model assumptions. *TPQ* output hidden for clarity. These results were obtained for experimental purposes by using an unratified curve and cannot be recommended as a site model.

### 6.4.5 Section conclusions

The wiggle-match dating at Cults Loch 3 showed that the construction of Structure 1 preceded the end of activity at Structure 2 beyond any reasonable doubt. What remains unresolved is whether the original construction of Structure 2 preceded that of Structure 1 or not. The apparent hiatus between the first occupation in the former roundhouse and the successive deposits means that this is not beyond the realm of possibility. Furthermore, the modelling suggests that this scenario also offers more time for the development of successive deposits. Nevertheless, this evidence might not be sufficient to resolve the question of the structural sequence at Cults Loch 3 to a satisfactory degree and hence the success of the wiggle-match dating study is only partial. This, coupled with the substantial investment and the apparent impossibility of reproducing even the more successful aspects of the study through radiocarbon-based evidence from the two structures alone, suggests that it is unreasonable to expect that site formation issues can be resolved by wiggle-match dating during the duration of the Hallstatt calibration plateau on a routine basis.

Nevertheless, it may be that with improvements in the calibration curve the resolutions of such questions will become viable. Some of the aspects of the Cults Loch 3 study also have further importance beyond addressing site formation processes themselves. The dating of the crannog mound proved decisive in resolving whether the timbers T-36 and -37 have been re-used (or subject to some inexplicable systematic offset) and as such it shows the value of establishing site *TPQs* in the more complex studies. Moreover, Cults Loch 3 study also used wiggle-match dating to establish viable dates for a series of archaeological features from the Hallstatt plateau, thus demonstrating the reproducibility of the success of the Black Loch of Myrton study.

## 6.5 Dating and site formation off the Hallstatt plateau: Clyde crannogs

The case studies of Black Loch of Myrton and Cults Loch 3 both addressed the issue of wiggle-match dating during the Hallstatt plateau. This was done to check how the technique works in practice when applied under the most demanding conditions. Nevertheless, not all Scottish wetland settlement occurred under plateau conditions. To evaluate how the wiggle-match dating technique performs when applied under more favourable conditions, two sites, Dumbuck and Erskine Crannogs, were chosen.

Dumbuck and Erskine Crannogs are two of four confirmed intertidal crannog sites in the Clyde Estuary (Figure 6.78) (Hale 2000, 2004). During the 1990s, four timbers from each of the two sites were radiocarbon dated. The resultant calibrated radiocarbon dates had very broad ranges covering over 600 years (Table 6.25). At Dumbuck Crannog, three samples appeared to have originated before the turn of the first millennia and one after this time (Figure 6.79). At Erskine Crannog, the pattern was repeated, but with the difference that the two earlier dates belong to the large wiggle in the calibration curve that follows the end of the Hallstatt plateau (Figure 6.80). These results raise the question as to whether the broad spread of dates from the two sites was due to timber re-use, presence of multiple activity phases, or some unknown technical issue.


Figure 6.78: Satellite photograph of the Clyde estuary with the four crannogs. Source: Google Earth

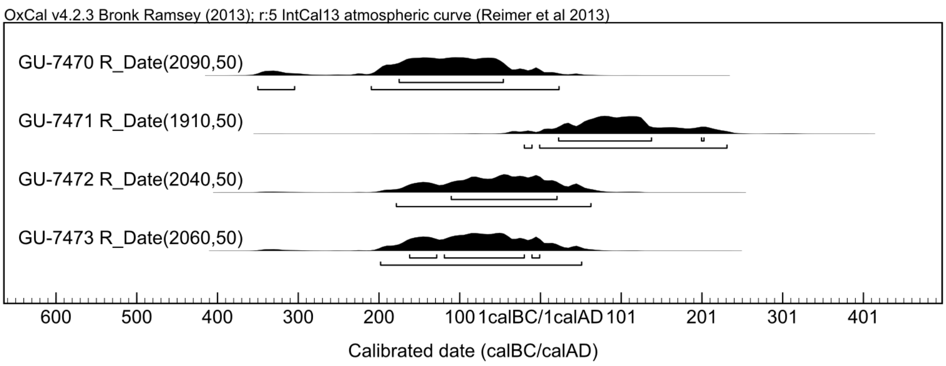



Figure 6.79: Calibrated radiocarbon legacy dates from Dumbuck.

To resolve this question, a program of wiggle-match dating based on the notion of feature-oriented sampling was developed. Samples were collected from groups of timbers with visible structural association, so that if timber re-use had been frequent enough to cause the discordant ages, some information on it would be retrieved in the form of intra-feature variability. If, on the other hand, long site duration was the cause for the discordant ages, some of the features could be expected to produce dates that would be different from the remaining ones.

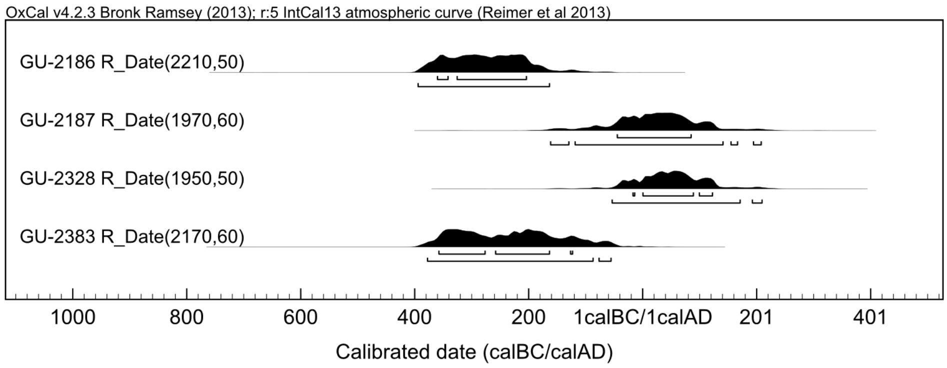



Figure 6.80: Calibrated radiocarbon legacy dates from Erskine Crannog.

Table 6.25: Legacy radiocarbon determinations from the Clyde crannogs (Sands and Hale 2002, 48)

| Site | Sample type | Species | GU- number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| Dumbuck | Pile | *Quercus* | GU-7470 | 2090 | 50 | -27.2 |
| | Horizontal | *Alnus* | GU-7471 | 1910 | 50 | -27.6 |
| | Pile | *Quercus* | GU-7472 | 2040 | 50 | -26.1 |
| | Horizontal | *Alnus* | GU-7473 | 2060 | 50 | -27.9 |
| Erskine | Horizontal | *Alnus* | GU-2186 | 2210 | 50 | -25.8 |
| | Pile | *Quercus* | GU-2187 | 1970 | 60 | -25.3 |
| | Pile | *Quercus* | GU-2328 | 1950 | 50 | -24.4 |
| | Pile | *Quercus* | GU-2383 | 2170 | 60 | -28.0 |

### 6.5.1 Dumbuck crannog

The site of Dumbuck Crannog (NGR NS 4157 7392) lies in the intertidal zone on the north shore of the Firth of Clyde, within several hours walk of the possible Iron Age settlements on top of Sheeps Hill and Dumbarton Rock. The site was first excavated in 1898-9 by Robert Bruce and William Donnelly, who, among other items, discovered a series of unusual slate figurines came to light (Bruce 1900). Albeit, these figurines were proven to be forgeries (Hale and Sands 2005, 48-55), the site itself is beyond reasonable doubt Iron Age in date.

Dumbuck Crannog consists of a circle of oak posts that surrounds an alder floor (Figure 6.81). In its centre is a pit, and Bruce and Donnelly also reported the presence of a canoe dock, but this could not be re-located during the course of a number of site visits from the 1990s to the present day. The stone mound that capped the site prior to the Bruce and Donnelly excavations has never been replaced and so the circle of surrounding piles, as well as floors in the middle of the site, are undergoing active erosion that helped with both sample collection and basic site interpretation. The most important aspect of the latter is that it is difficult to conceive a series of successive reconstructions at Dumbuck Crannog; had the site been re-occupied at any point in time beyond its original use, the new activity would have either had to be very ephemeral, or a perfect complement to the earlier design.

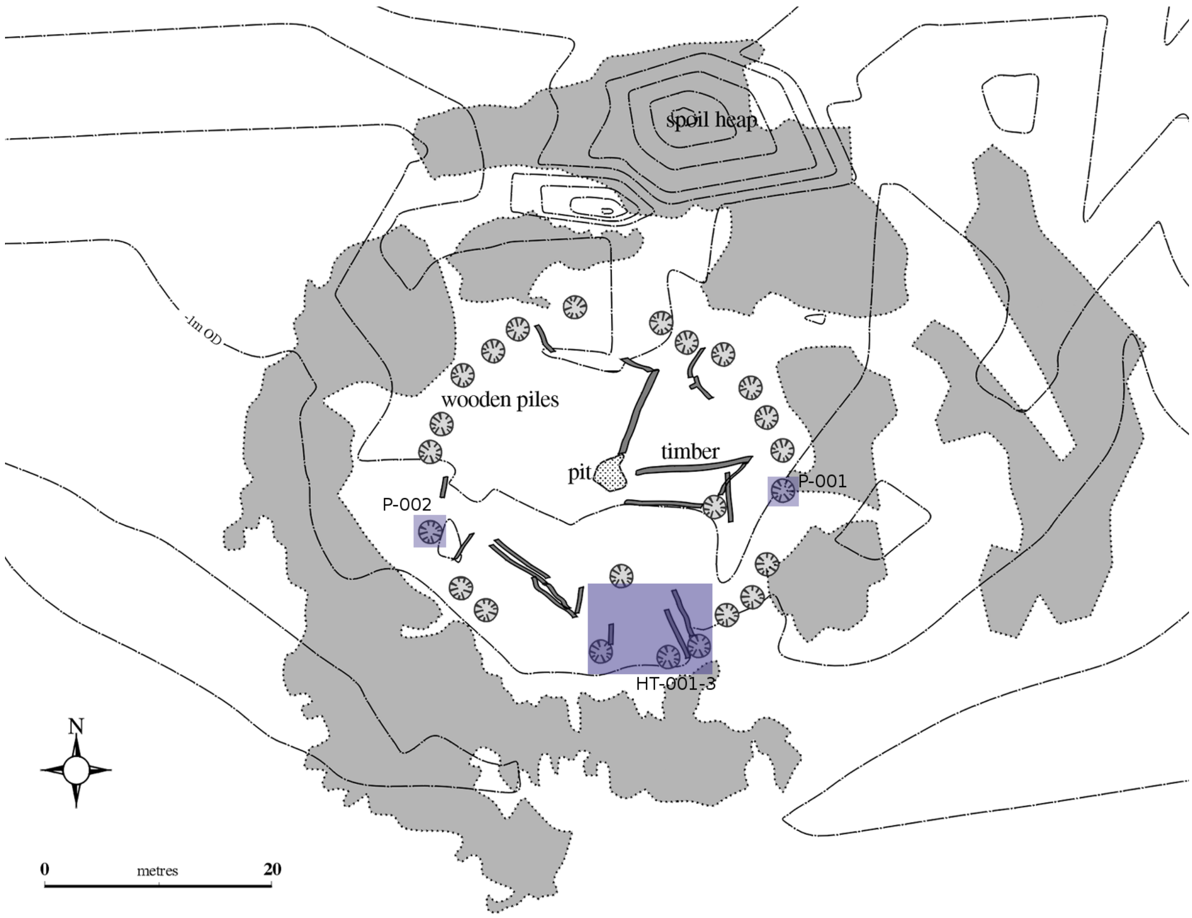



Figure 6.81: Plan of Dumbuck Crannog (Hale 2000, 548). Locations of sampled timbers are highlighted. The piles sampled are represented on the plan; however, the sediments that covered the horizontals had not been eroded when this plan was made and hence are not visible.

Taking advantage of the exposed nature of Dumbuck Crannog, two features were sampled. First was the oak post ring that surrounds the site and from which two piles were cut. The two oak piles were labelled P-001 and P-002. P-001 had 59 rings, P-002 had 53 rings and both timbers retained bark edge, although the sapwood suffered substantial decay and shipworm attack. Eleven decadal blocks were analysed from these timbers (Figure 6.82): six from P-01 and five from P-02. The less substantial alder timbers were labelled HT-001, -002 and -003. HT-001 had 54 rings, HT-002 had 37 rings and HT-003 had 29 rings, with all the timbers retaining bark edge; a total of 12 decadal sample blocks were submitted for radiocarbon measurement.

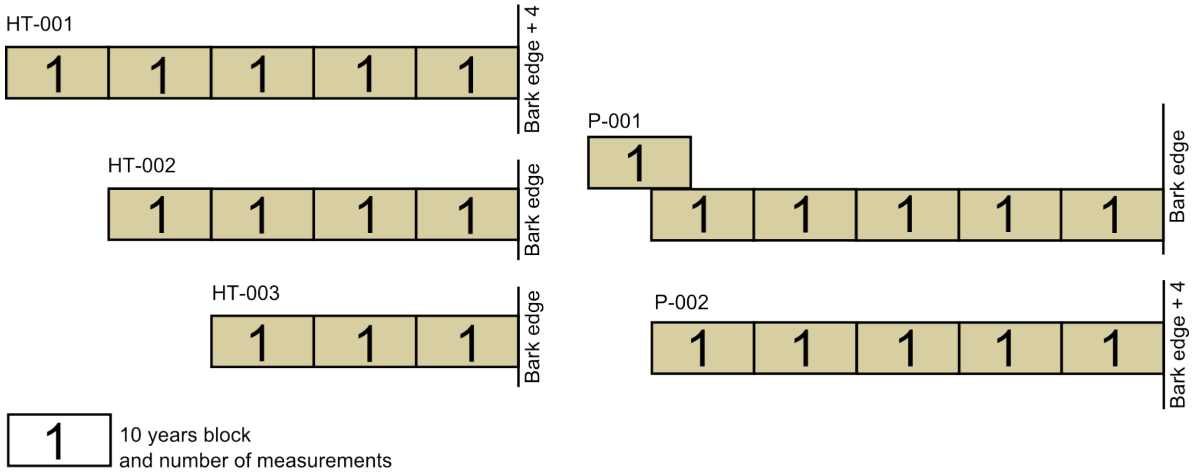



Figure 6.82: Sampling pattern for the Dumbuck timbers.

The results of the individual wiggle-matches point to all the timbers being felled sometime in the first half of the first century AD, yet a technical issue was also present. Within each of the five wiggle-matches, the measurement of the third, or, in the case of P-002, the fourth, decadal block from the bark edge had a poor individual agreement index. This phenomenon can be explained in terms of a small offset from the calibration curve caused by the over-smoothing of the calibration data in the course of curve modelling (Fig. 6.83). All the decadal blocks in question have a deflection towards greater ages and, once wiggle-matched, all fall in the vicinity of a wiggle in the calibration curve around 5 BC. This wiggle is dated by two University of Washington measurements, both of which also display a deflection towards greater ages. Hence, the simplest explanation for the incongruence with the calibration curve in this case is that the wiggle at 5 BC has been over-smoothed. This is possible as the degree of variability within IntCal is controlled by the variability in the calibration data surrounding the point of interest; if this was less than at 5 BC for enough of the preceding and succeeding decades, the magnitude of the wiggle would be underestimated. In practice, this offset had little effect on the oak piles, but it did affect the horizontal timbers. In the case of HT-001, the problem derived from the presence of other measurements in poor agreement with the calibration curve. Although none of them changed the overall position of the wiggle-match alone, when combined with the third decadal block (in this case SUERC-60764), the distribution of the wiggle-match changed position. Given the knowledge about the effects of the third decade on this particular site, the measurement SUERC-60764 was removed from the wiggle-match.

The other two wiggle-matches, HT-002 and HT-003 are both short lived (¡50 years) and the presence of the third decade in both cases causes a substantial shift to older dates and hence the problematic measurements were removed. Hence, the wiggle-matches used in further modelling accept all the measurements, save the third decades from the bark edge in the cases of timbers HT-001, -002 and -003 (measurements SUERC-60764, -60772 and -60779)(Tables 6.26 to 6.27; Figures 6.84 to 6.88).

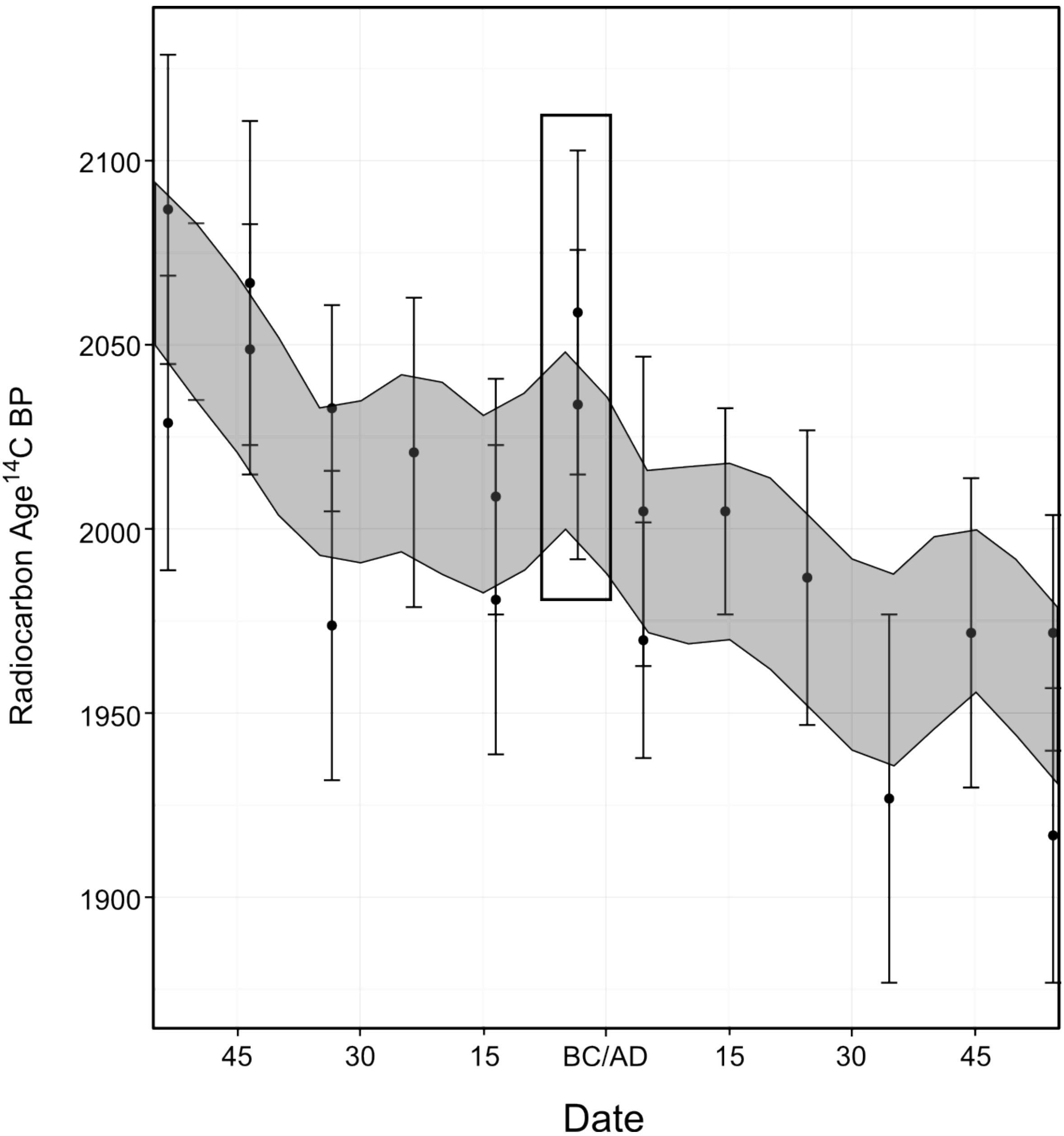



Figure 6.83: IntCal13 calibration curve and the corresponding University of Washington (QL-) calibration measurements between 50 BC and AD 50. Note that although the QL- data for the wiggle around 5 cal BC (highlighted) overlap with the calibration curve, their measurement uncertainties reach up to over 50 radiocarbon years above the 2- envelope of the calibration curve. All the error bars and the calibration curve uncertainty are at 2-.

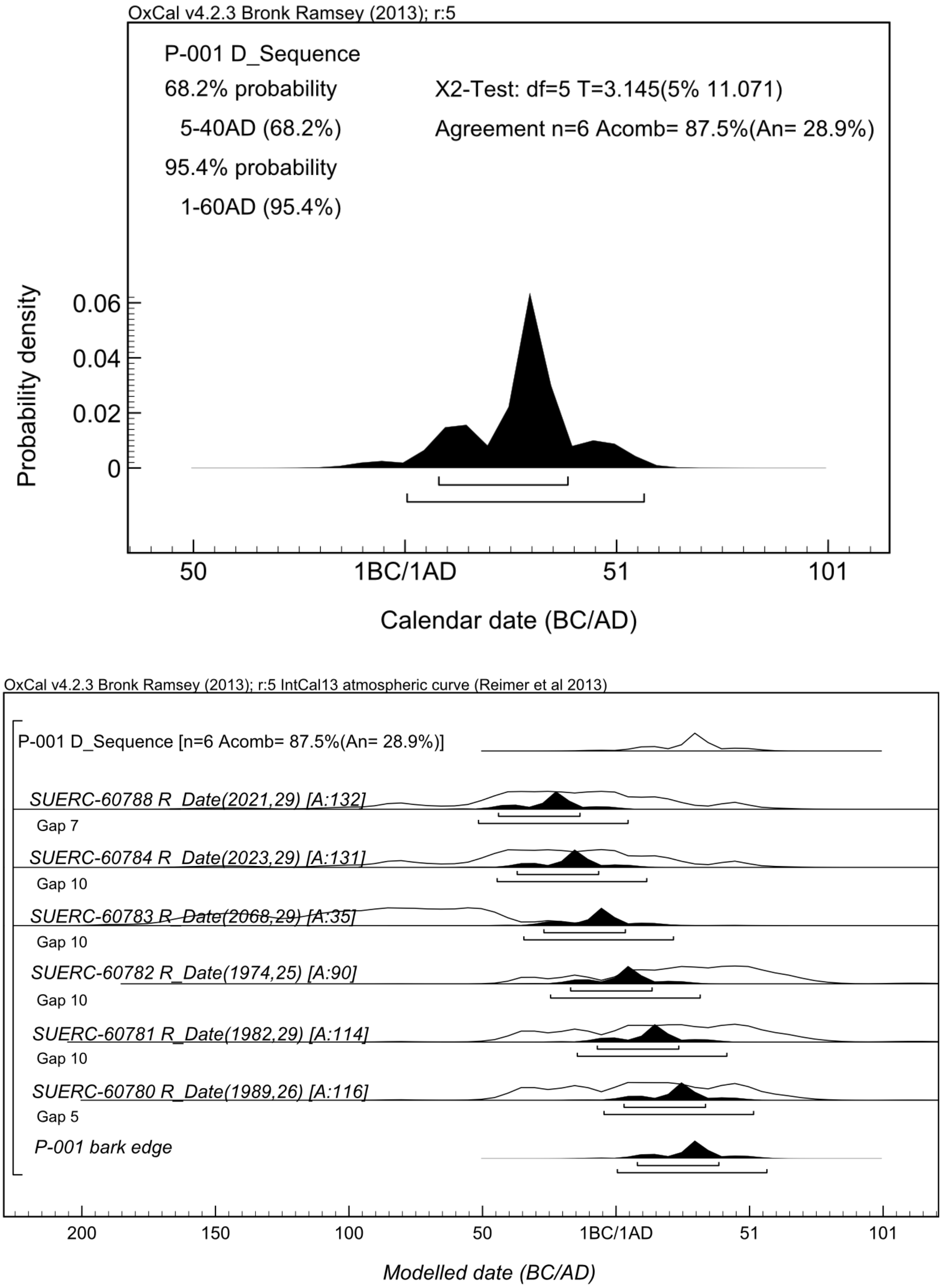
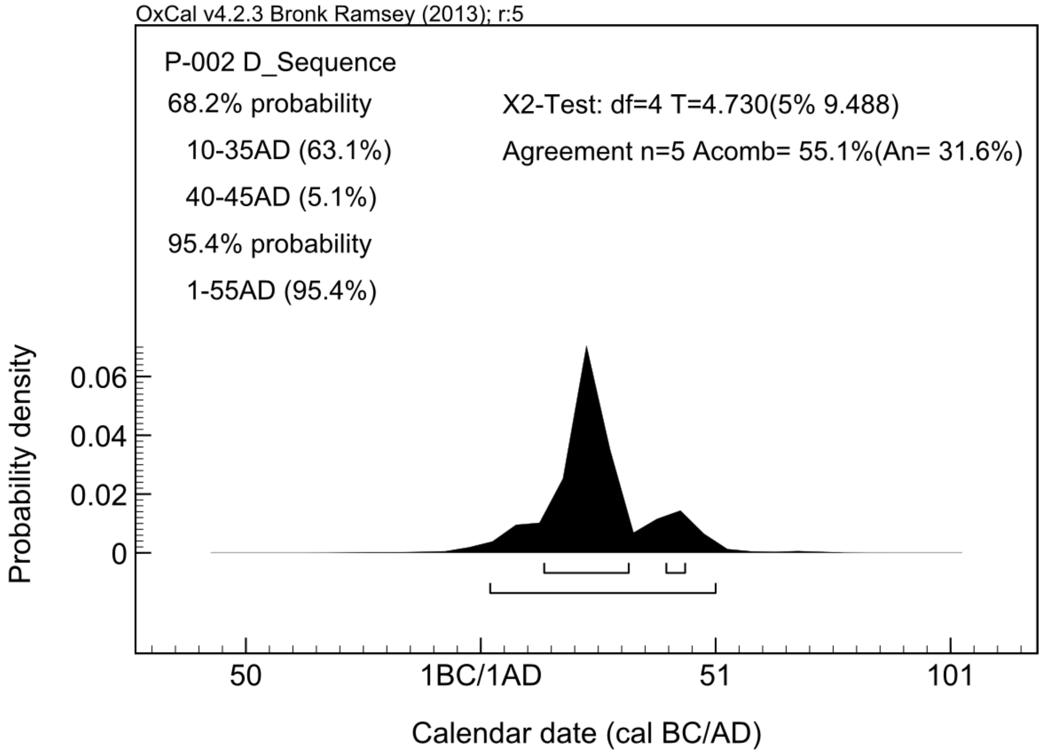



Figure 6.84: Results of the wiggle-match on Dumbuck timber P-001: summary (top), and the individual determinations (bottom).



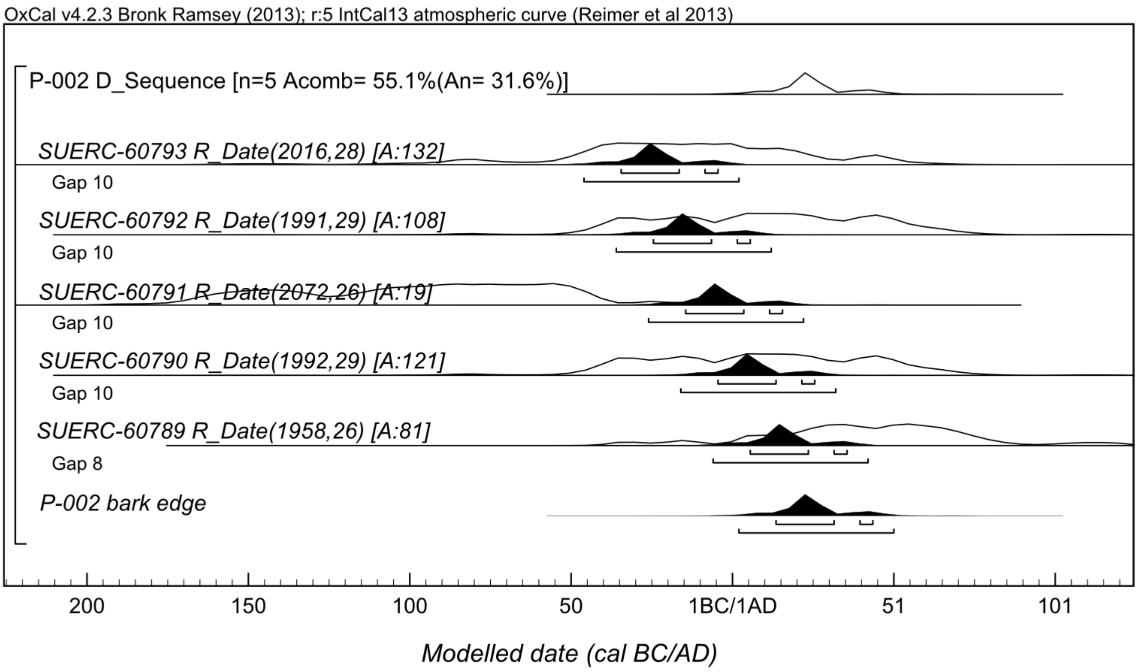
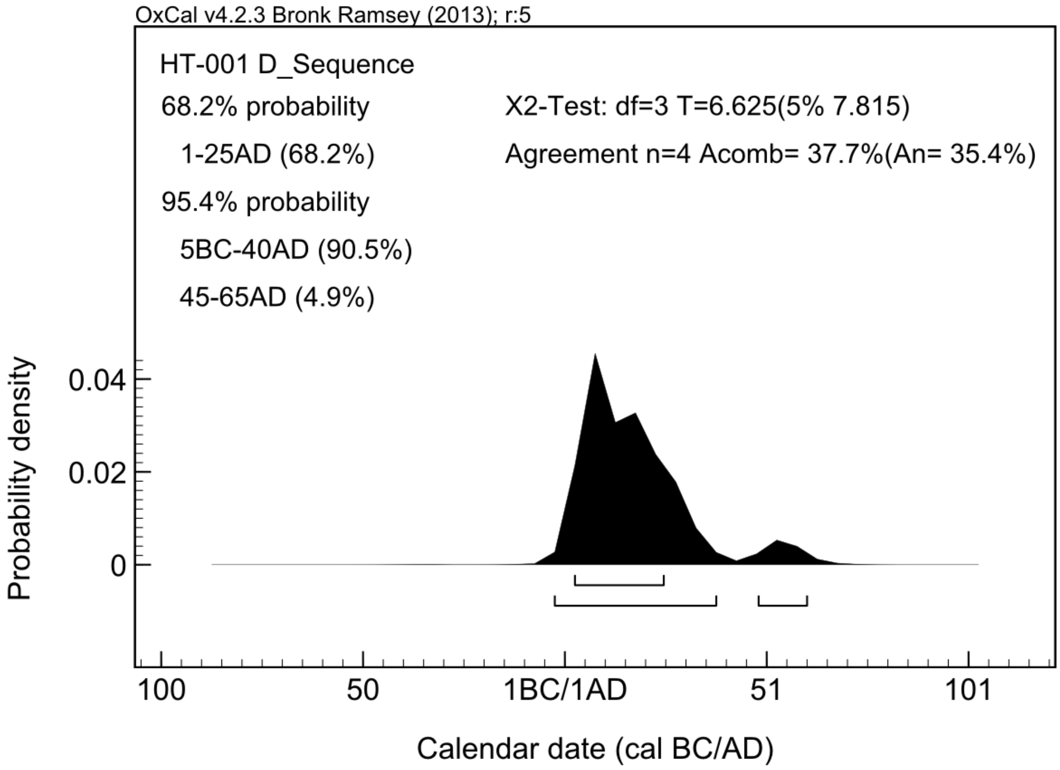




Figure 6.85: Results of the wiggle-match on Dumbuck timber P-002: summary (top), and the individual determinations (bottom).



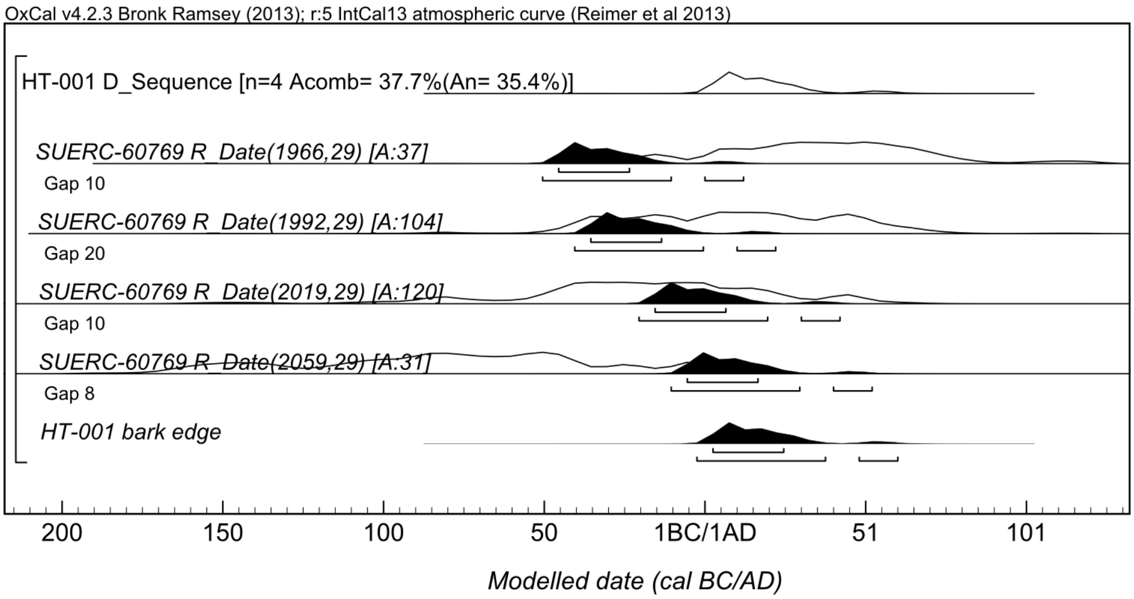




Figure 6.86: Results of the wiggle-match on Dumbuck timber HT-001: summary (top), and the individual determinations (bottom).

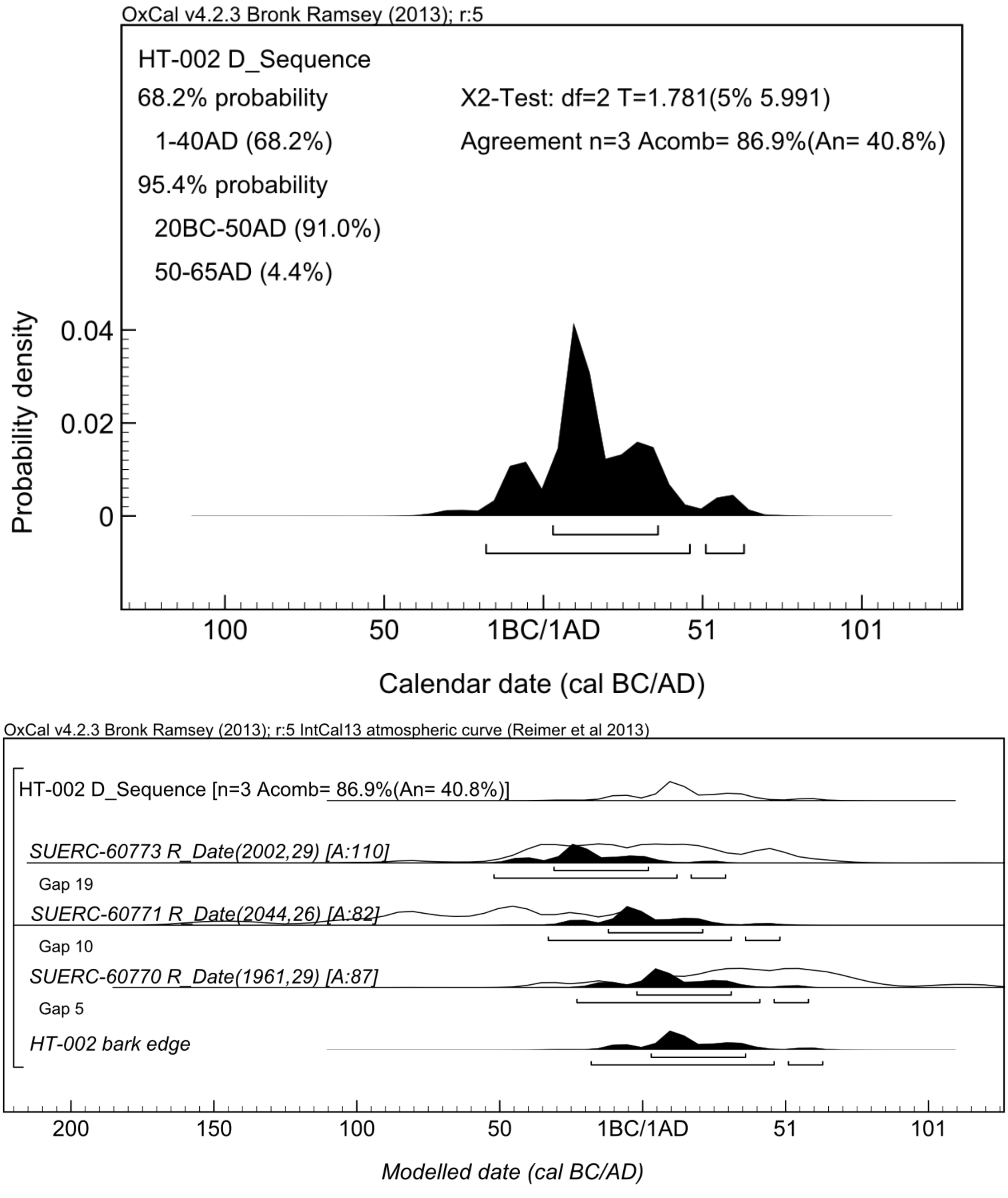



Figure 6.87: Results of the wiggle-match on Dumbuck timber HT-002: summary (top), and the individual determinations (bottom).

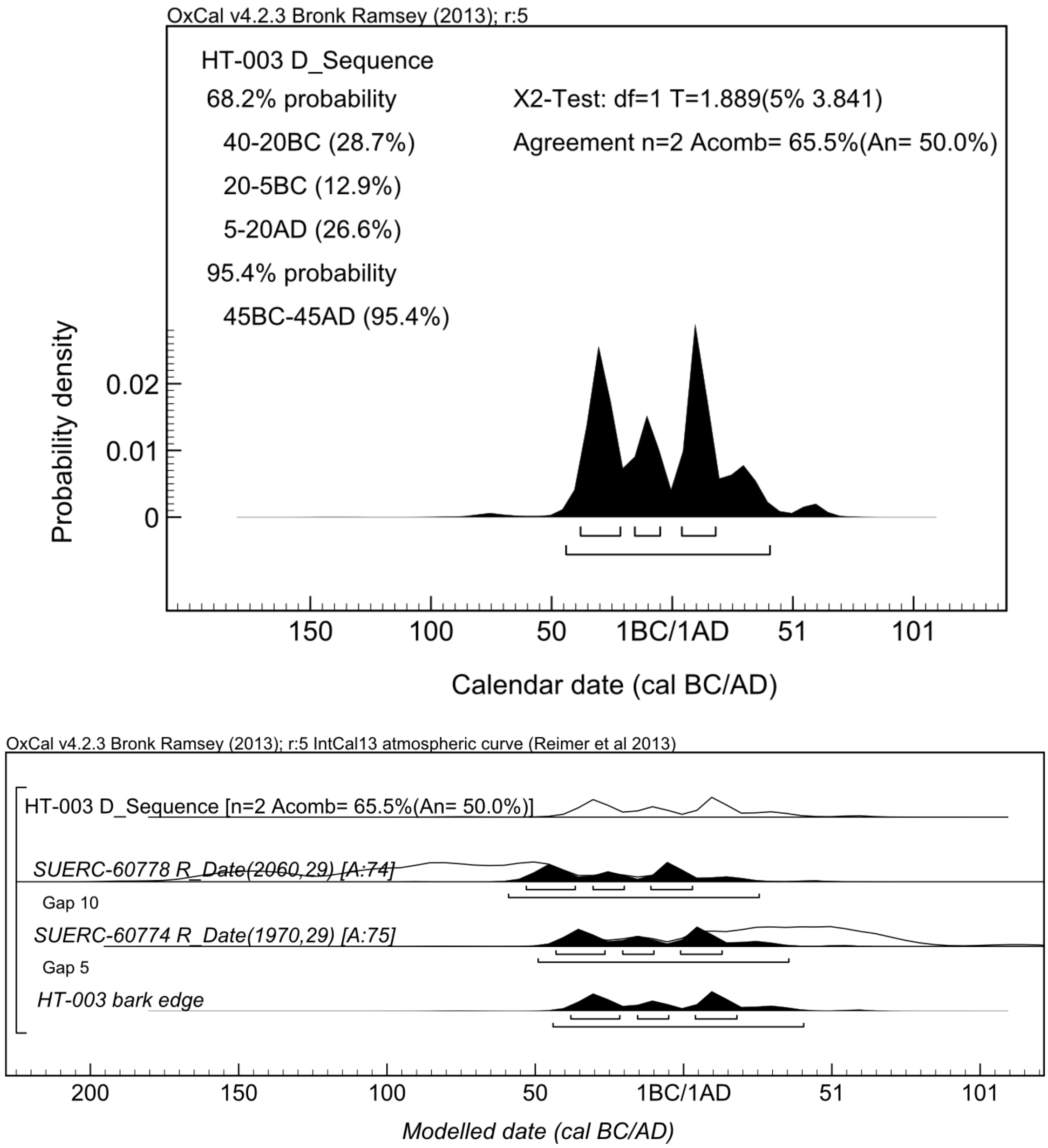



Figure 6.88: Results of the wiggle-match on Dumbuck timber HT-003: summary (top), and the individual determinations (bottom).

Table 6.26: Results of the radiocarbon measurements on the five Dumbuck Crannog timbers. P-001 and -002 were oak (*Quercus sp.*) and the horizontals HT-001 – 3 were alder (*Alnus sp.*)

| Timber | Rings | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| P-001 | 1–10 | 37475 | 60780 | 1989 | 26 | -25.4 |
| | 11–20 | 37476 | 60781 | 1982 | 29 | -25.5 |
| | 21–30 | 37477 | 60782 | 1974 | 25 | -24.2 |
| | 31–40 | 37478 | 60783 | 2068 | 29 | -22.9 |
| | 41–50 | 37479 | 60784 | 2023 | 29 | -23.7 |
| | 51–60 | 37480 | 60788 | 2021 | 29 | -24.9 |
| P-002 | 4–13 | 37481 | 60789 | 1958 | 26 | -25.2 |
| | 14–23 | 37482 | 60790 | 1992 | 29 | -24.9 |
| | 24–33 | 37483 | 60791 | 2072 | 26 | -26.1 |
| | 34–43 | 37484 | 60792 | 1991 | 29 | -26.1 |
| | 44–53 | 37485 | 60793 | 2016 | 28 | -25.9 |
| HT-001 | 4–13 | 37463 | 60762 | 2059 | 29 | -24.6 |
| | 14–23 | 37464 | 60763 | 2019 | 29 | -25.2 |
| | 24–33 | 37465 | 60764 | 2096 | 29 | -25.4 |
| | 34–43 | 37466 | 60768 | 1992 | 29 | -24.5 |
| | 44–53 | 37467 | 60769 | 1966 | 29 | -25.0 |
| HT-002 | 1–10 | 37468 | 60770 | 1961 | 29 | -24.1 |
| | 11–20 | 37469 | 60771 | 2044 | 26 | -24.6 |
| | 21–30 | 37470 | 60772 | 2059 | 29 | -24.1 |
| | 30–39 | 37471 | 60773 | 2002 | 29 | -24.2 |
| HT-003 | 1–10 | 37472 | 60774 | 1970 | 29 | -25.0 |
| | 11–20 | 37473 | 60778 | 2060 | 29 | -25.8 |
| | 20–29 | 37474 | 60779 | 2228 | 27 | -27.1 |

Table 6.27: Results of the individual wiggle-matches for Dumbuck Crannog timbers. Posterior probabilities are displayed in Figures 6.84 to 6.88.

| Timber | 68.2% HPD area | 95.4% HPD area | Acombine \An (%) | $\chi^2$ \5% crit |
|---|---|---|---|---|
| P-001 | *cal AD 5–40* | *cal AD 1–60* | 87.50 \28.9 | 3.145 \11.071 |
| P-002 | *cal AD 15–35(63.1%)*<br>*cal AD 40–45 (5.1%)* | *cal AD 1–55* | 86.90 \31.6 | 1.781 \5.991 |
| HT-001 | *cal AD 1–25* | *5 cal BC–cal AD 40 (90.5%)*<br>*cal AD 45–65 (4.9%)* | 37.70 \35.4 | 6.625 \7.815 |
| HT-002 | *cal AD 1–40* | *20 cal BC–cal AD 65* | 86.90 \40.8 | 1.781 \5.991 |
| HT-003 | *40–5 cal BC (41.6%)*<br>*cal AD 5–20 (26.6%)* | *45 cal BC – cal AD 45* | 65.50 \50 | 1.889 \3.841 |

Based on the results of the wiggle-matches, it is possible to build a Bayesian model that also incorporates the four legacy dates (Figure 6.89). The parameters sought are the most recent plausible felling, used as a construction proxy, and the span of the felling phase. The results are unequivocal in placing the construction of Dumbuck Crannog in the first half of the first century cal AD (Figure 6.90):

- The construction can be estimated to *cal AD 5–55 (95.4%)*, with the highest probabilitiy in *cal AD 10–35 (68.2%)* (Figure 6.91).
- The felling phase can be estimated to have lasted *0–85 years (95.4%)*, with the highest probabilitiy in *0–30 years (68.2%)* and a mode that is very close to 0 (Figure 6.92).
- Model agreement when using complete wiggle-matches is poor (Amodel = 20.9%). To clarify how much of this is caused by the results of the wiggle-matches and how much by the presence of two discordant measurements among the legacy data (GU-7470 and-7471), the model has been re-run using only the wiggle-match output, as defined using the *.prior files. The resulting model still has poor agreement (Amodel = 46.0%). Hence, the legacy dates contribute to the poor model agreement and, if they are removed, the Amodel improves to 75.4%. While there is nothing within the model parameters that would warrant implementing this rejection (removal of both of these samples, or either of them has negligible effect on the overall model results), the origin of these offsets still needs clarification. The determination with the deflection towards older ages, GU-7470, is easy to explain away  the sample may have included portions of the third decade and hence the offset represents the same process that affects the rest of the timbers. The second outlier is more difficult. Given its standard deviation of 50 $^{14}C$ years, it is identical to the outermost rings of most of the wiggle-matched timbers, and hence best explained as a statistical outlier. Yet, it may also be the case that the timber has been a later addition. Nevertheless, for the time being there is nothing else on the site to suggest the presence of a later activity phase and so the latter interpretation lacks credibility until such evidence emerges.

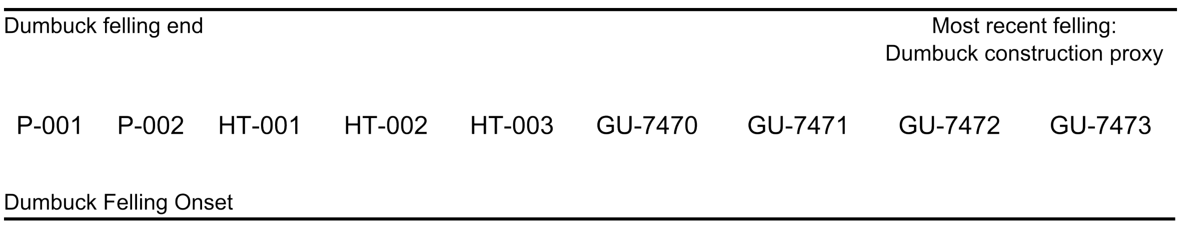



Figure 6.89: Schematic representation of the uniform bounded phase model for the felling of the timbers that constitute Dumbuck Crannog.

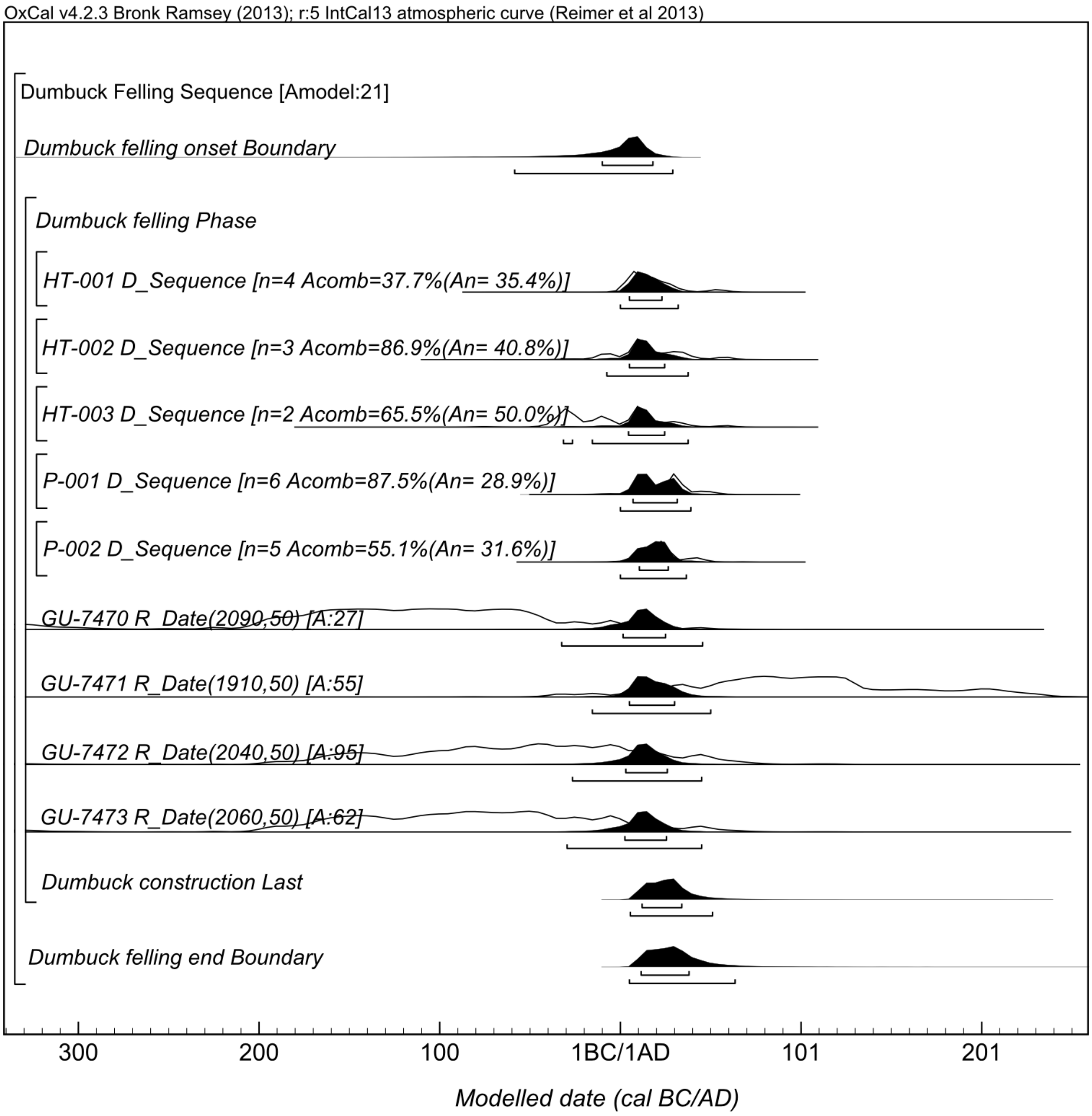



Figure 6.90: Results of the uniform bounded phase model used for the felling of the timbers that constitute Dumbuck Crannog.

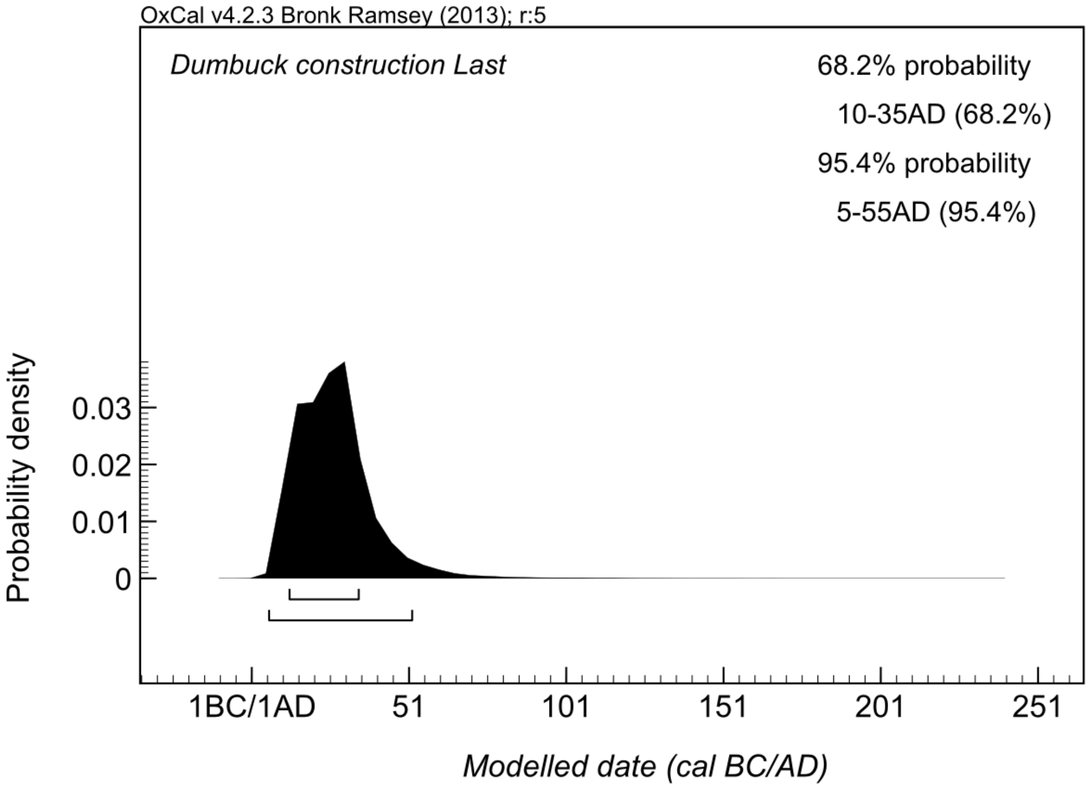



Figure 6.91: Estimate of the construction date for Dumbuck crannog, based on the more recent plausible felling date among the timbers dated.

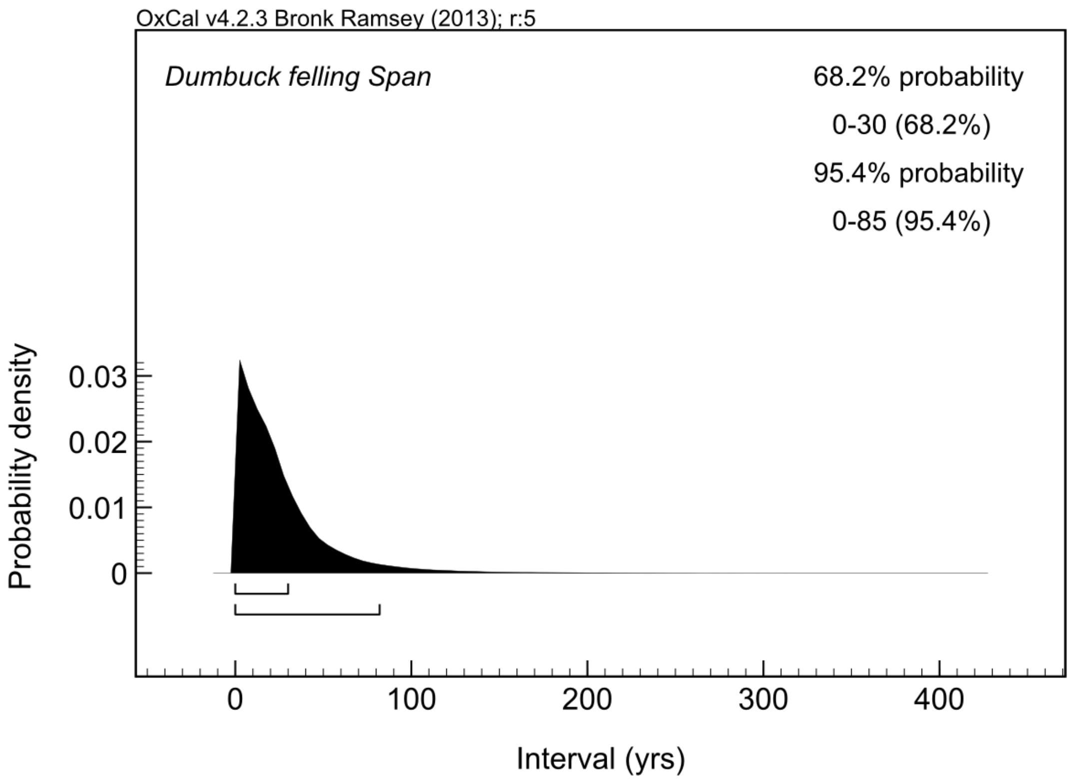



Figure 6.92: Estimate of the duration of the felling of timbers at Dumbuck.

The results for Dumbuck Crannog point to the structure being built and used in the first half of the first century AD. The only potential evidence for later activity phase comes from a single pile that may well be a statistical outlier and so there is not enough evidence to support a multi-phase interpretation. The one remaining question, regarding the length of activity on the site has to remain unanswered at this point as there is no dating evidence that could be used to address it.

### 6.5.2 Erskine Crannog

Erskine Crannog (NGR NS 45482 72901) lies on the southern shore of the Clyde estuary, very close to the mouth of the river. It is within a short walk from the site of the Iron Age enclosure at Mar Hall. The site itself is different from the three other Clyde sites in that there is no record of it being a stone-covered circular mound. Instead, it consists of a circular arrangement of timbers and multiple stones, with an irregular stone mound on the north-west side of the site (Figure 6.89). This may be the result of quarrying the site for stone sometime following its original abandonment.

The sampling at the site focussed on two pairs of horizontal timbers and a group of short-lived stakes (Figure 6.94; Table 6.28). The first of the timber pairs, designated feature F-01, lay near the junction of the circular timber arrangement and the irregular stone mound. The first timber, F-01 H-01, yielded just over 100 rings, while the second timber, F-01 H-02 had 87 countable rings, with further rings in the innermost section too decayed for a reproducible count. The second feature, F-02, consists of two parallel alder timbers, diagonal to the F-01 timbers, located on the east side of the mound. The first timber, F-02 H-01 yielded 91 rings, and the second, F-02 H-02, yielded 76 rings. Clear bark-edge could not be recognized on any of the major timbers, as the constraints introduced by the scheduled monument consent prevented excavating underneath these substantial horizontals to reach the most well-preserved material. Nevertheless, based on the observations in the field, as well as the shape of the timbers themselves, it is almost certain that the outermost counted rings from F-01 and -02 horizontal are within close proximity to the bark edge. Bark was retained on the three stakes, F-03 H01, -02 and -03, recovered from a larger group of horizontal stakes that formed feature F-03 at the north-east edge of the site. Five decadal blocks were sampled from each of the F-01 and F-02 timbers, two blocks were sampled from the stakes F-03 H-01 and -02 and only a single decadal block was sampled from F-03 H-03 (Fig. 6.4.17).

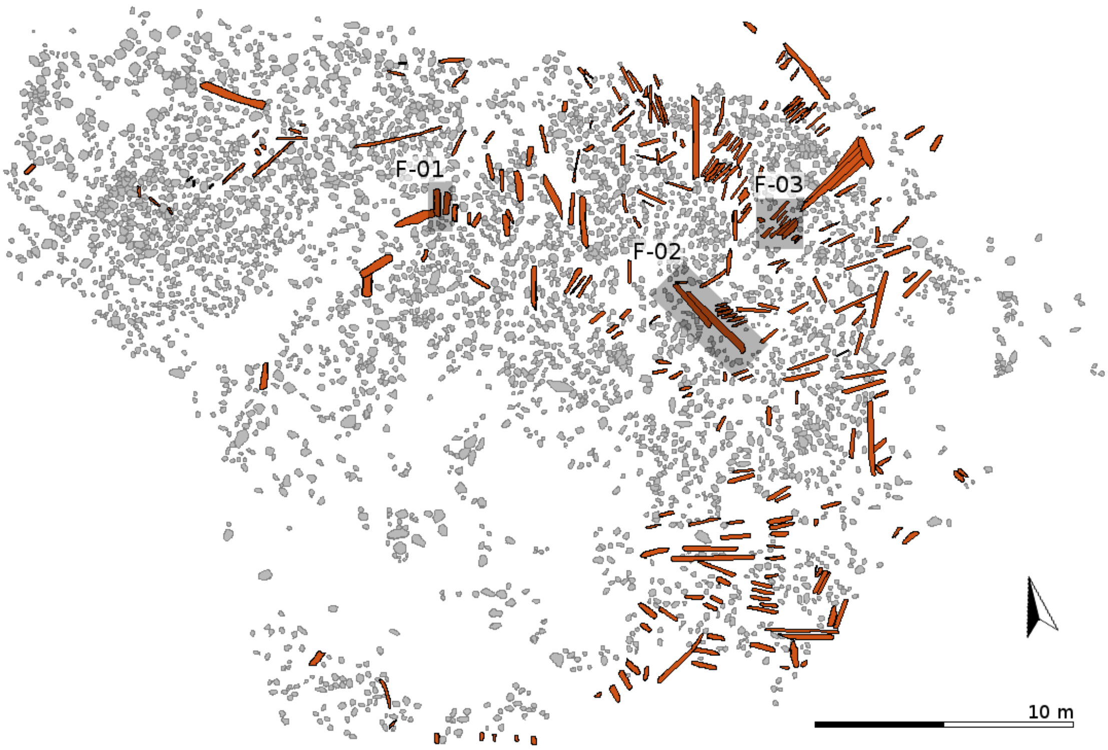



Figure 6.93: Erskine Crannog site plan (based on Hansens photogrammetric plan, as reprinted in Hale 1999, Figure 2.9). Sampled timbers have been highlighted. Note that the timbers in the south and extreme east parts of the site could not be re-located during the 2014 and 2015 field visits, either due to sedimentation or erosion.

Table 6.28: Results of the radiocarbon measurements of the six Erskine Crannog timbers.

| Timber | Rings | GU-number | SUERC-number | Age ($^{14}$C years BP) | 1-$\sigma$ error | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|---|
| F-01 H-01 | 6–15 | 37557 | 60810 | 2263 | 29 | -23.5 |
| | 26–35 | 37558 | 60811 | 2274 | 26 | -24.8 |
| | 46–55 | 37559 | 60812 | 2384 | 33 | -24.6 |
| | 66–75 | 37560 | 60813 | 2434 | 29 | -24.4 |
| | 92–101 | 37561 | 60814 | 2461 | 26 | -24.7 |
| F-01 H-02 | 1–10 | 37562 | 60818 | 2198 | 26 | -25.4 |
| | 21–30 | 37563 | 60819 | 2130 | 29 | -26.6 |
| | 51–60 | 37564 | 60820 | 2379 | 29 | -26.1 |
| | 71–80 | 37565 | 60821 | 2544 | 29 | -25.7 |
| | Approx 95–100 | 37566 | 60822 | 2520 | 29 | -25.6 |
| F-02 H-01 | 2–11 | 37552 | 60802 | 2342 | 30 | -25.3 |
| | 22–31 | 37553 | 60803 | 2237 | 26 | -25.1 |
| | 42–51 | 37554 | 60804 | 2247 | 26 | -25.1 |
| | 62–71 | 37555 | 60808 | 2430 | 26 | -25.5 |
| | 82–91 | 37556 | 60809 | 2486 | 29 | -25.3 |
| F-02 H-02 | 4–13 | 37547 | 60794 | 2330 | 26 | -25.8 |
| | 14–23 | 37548 | 60798 | 2196 | 29 | -25.4 |
| | 34–43 | 37549 | 60799 | 2271 | 26 | -24.8 |
| | 54–63 | 37550 | 60800 | 2355 | 29 | -25.1 |
| | 64–73 | 37551 | 60801 | 2253 | 29 | -24.9 |
| F-03 H-01 | 1–10 | 37567 | 60823 | 2141 | 25 | -26.1 |
| | 9–18 | 37568 | 60824 | 2302 | 29 | -26.4 |
| F-03 H-02 | 1–10 | 37569 | 60828 | 2258 | 25 | -27.3 |
| | 9–18 | 37570 | 60829 | 2240 | 29 | -27.2 |
| F-03 H-03 | 1–10 | 37571 | 60830 | 2313 | 29 | -27.4 |

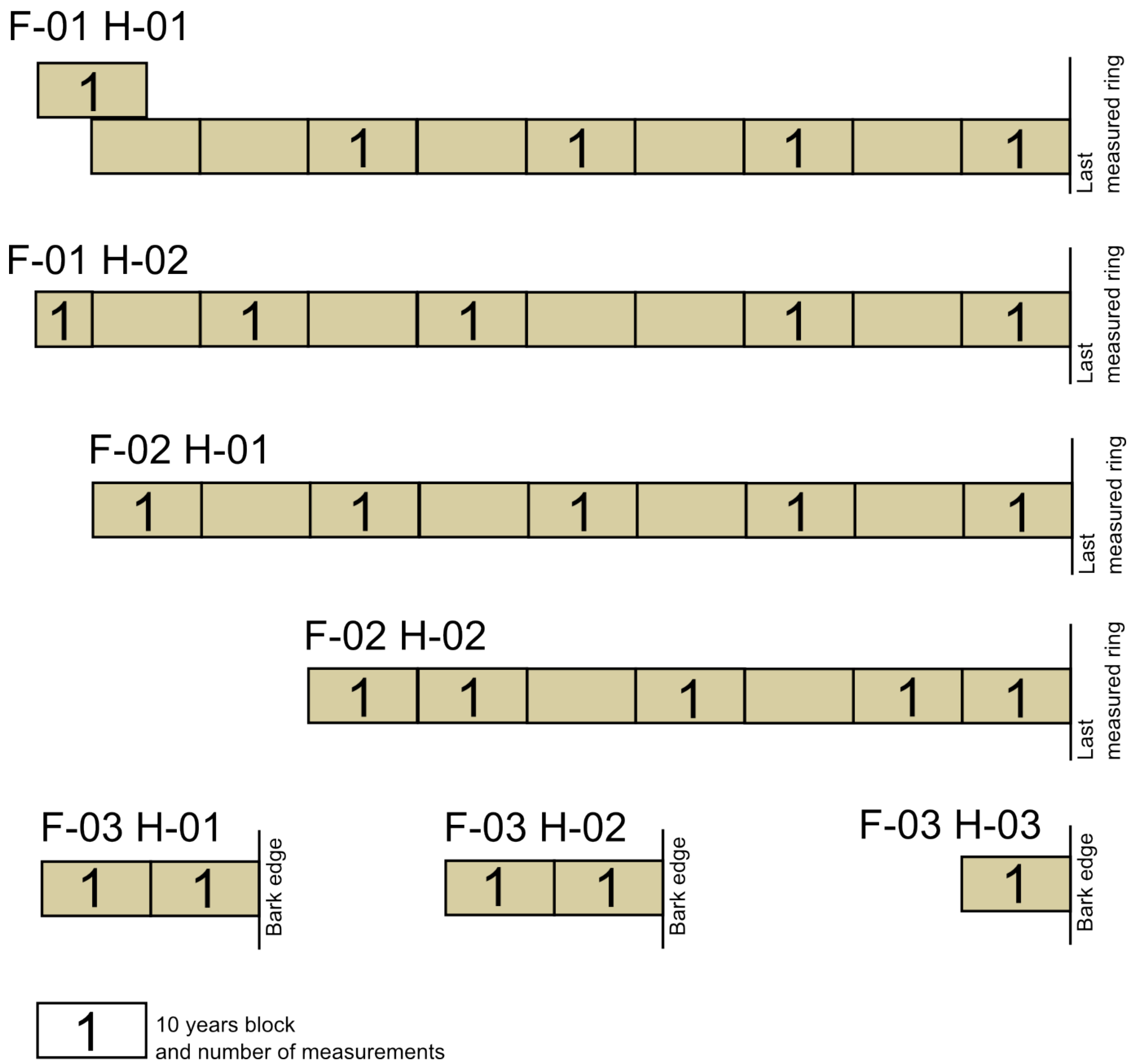
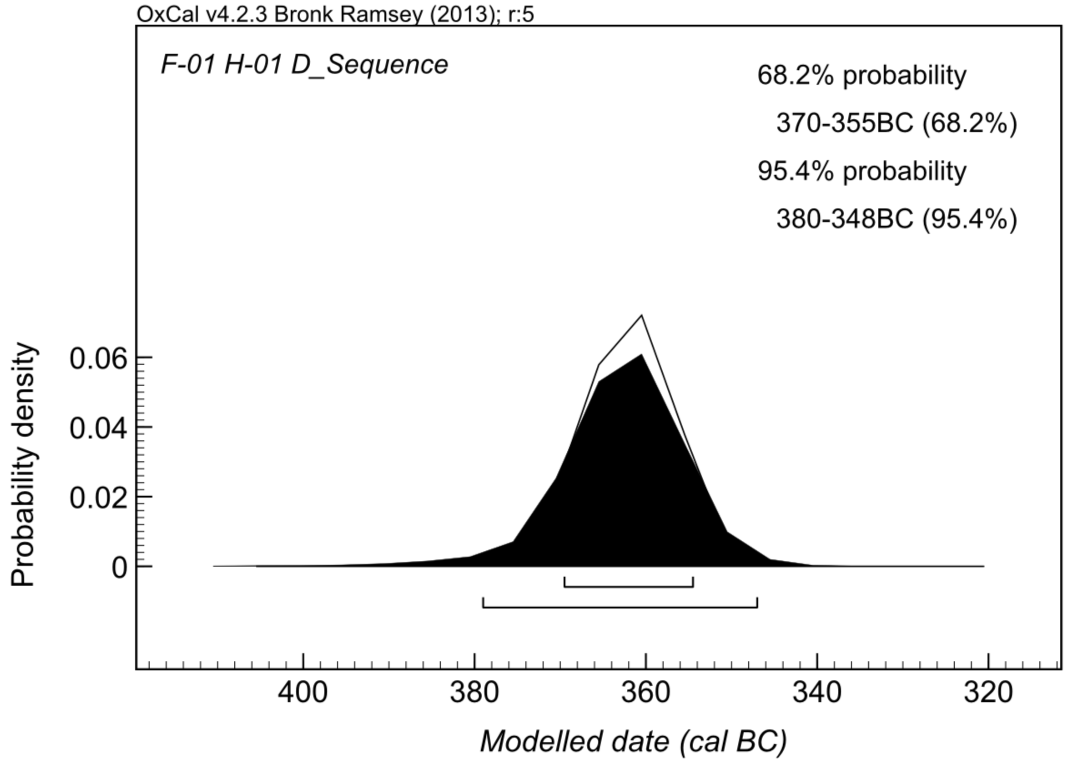



Figure 6.94: Schematic representation of the sampling pattern for the timbers from Erskine Crannog.

The Erskine Crannog timbers had suffered extensive decay and, as other decayed timbers throughout this project, their ages are subject to an offset towards greater radiocarbon ages (see section 6.2.1). Unlike at the other sites though, the extent of the damage to the timbers at Erskine Crannog was much greater and substantial shipworm attack meant that the innermost rings also became affected. This is clearest in the case of the measurements SUERC-60821 and -60822 from the very decayed innermost sections of the timber F-01 H-02. Because of this, the wiggle-matches were built using the General outlier model (Bronk Ramsey 2009b), within which each radiocarbon determination is assigned a certain probability that its uncertainty has a component deriving from a heavy-tailed t distribution  thus modelling the situation where some of the dates might have ages that are subject to some kind of systematic offset in any possible direction. This model requires the assignment of a prior probability to each determination as to whether it is an outlier and, in this particular case this was set for all the measurements to Poutlier = 0.5. This makes for wide modelled date ranges (Table 6.29; Figures 6.95 to 6.100), which mitigate the problems associated with the issue of decayed wood. The results obtained using the outlier model are statistically identical with those obtained from wiggle-matches that excluded the decayed material and in only one case different from the wiggle-matches including all the data (Figure 6.101; ; Table 6.30). The one exception is F-02 H-02, a timber whose unmodified wiggle-match is younger than all the other wiggle-matches, suffers from poor agreement indices and fails the $\chi^2$ test ($\chi^2$= 5.224; 5% critical value = 3.841), which indicates that the unmodified version of the model does not fit the data.



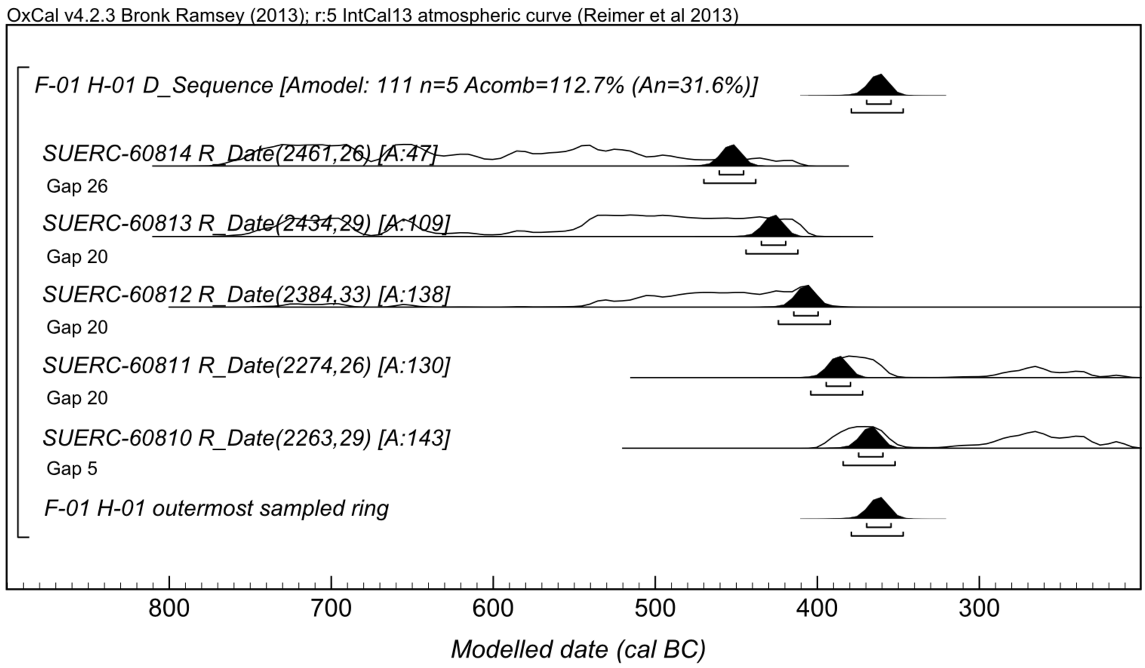




Figure 6.95: Results of the wiggle-match on Erskine Crannog timber F-01 H-01: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.

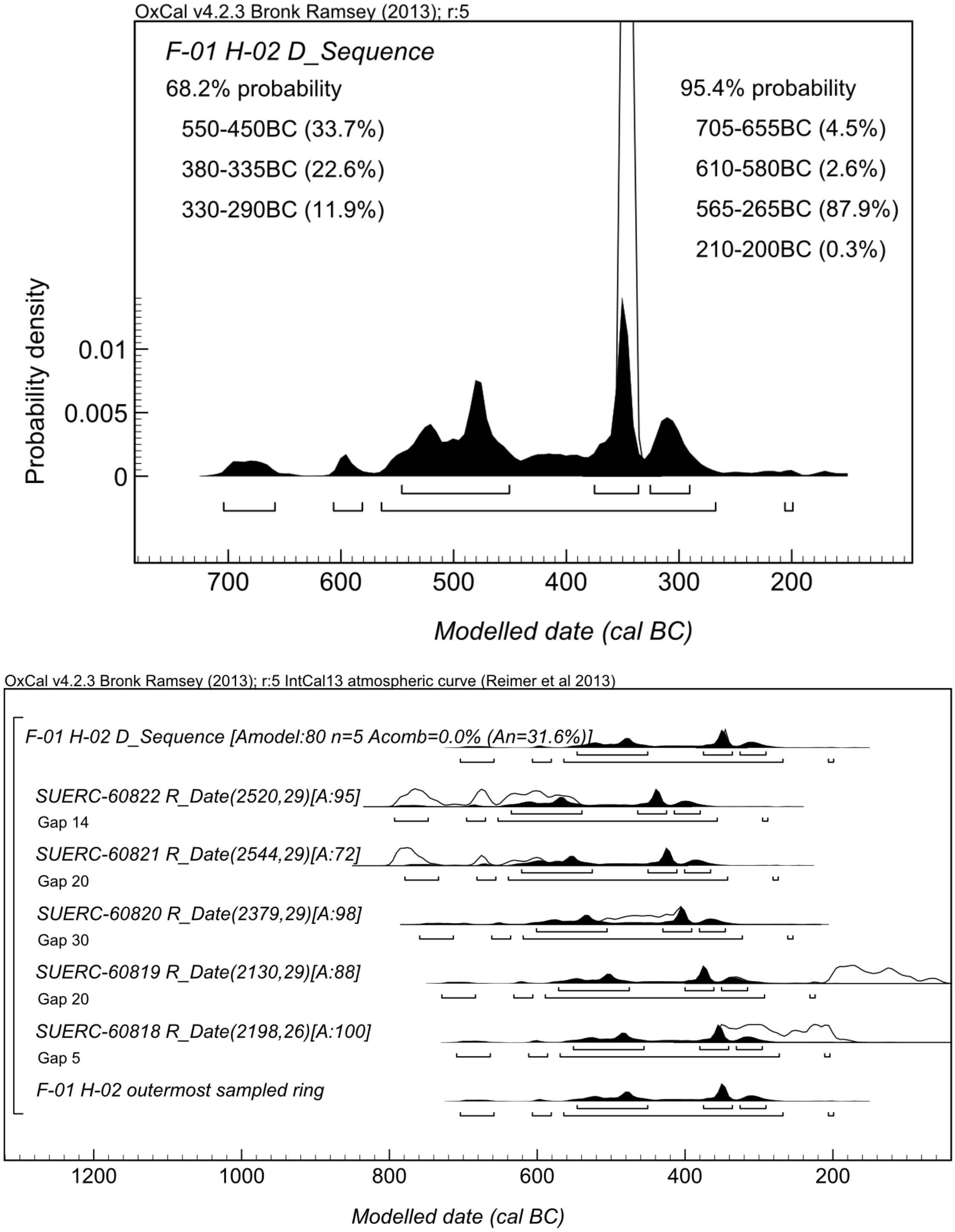
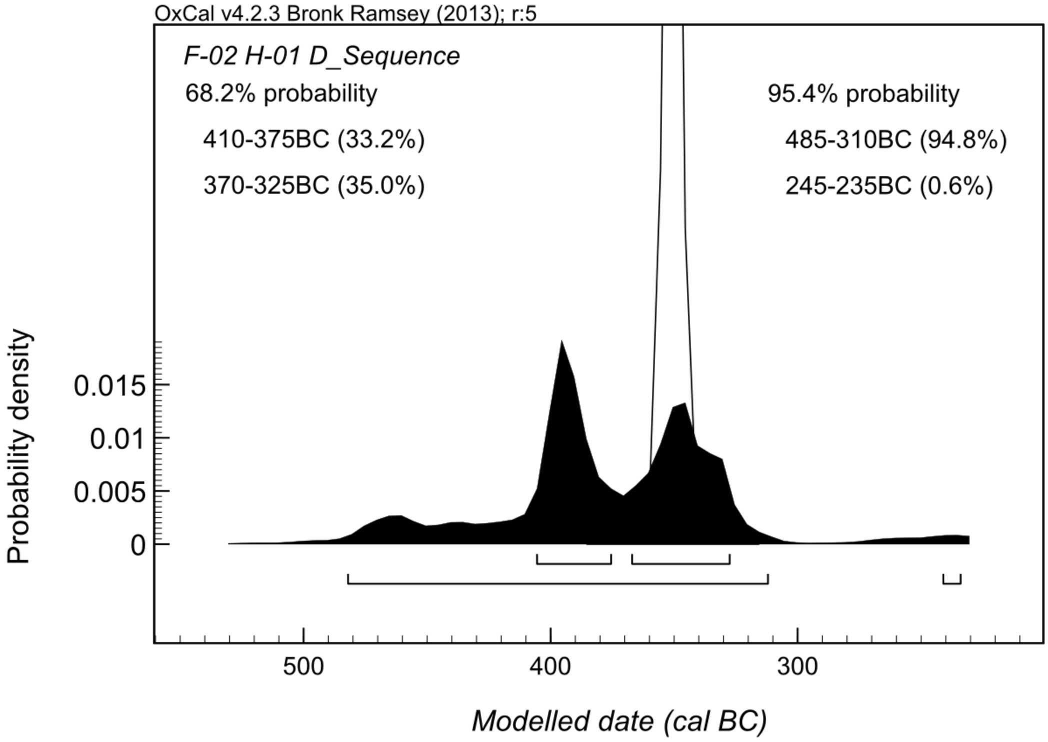



Figure 6.96: Results of the wiggle-match on Erskine Crannog timber F-01 H-02: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.



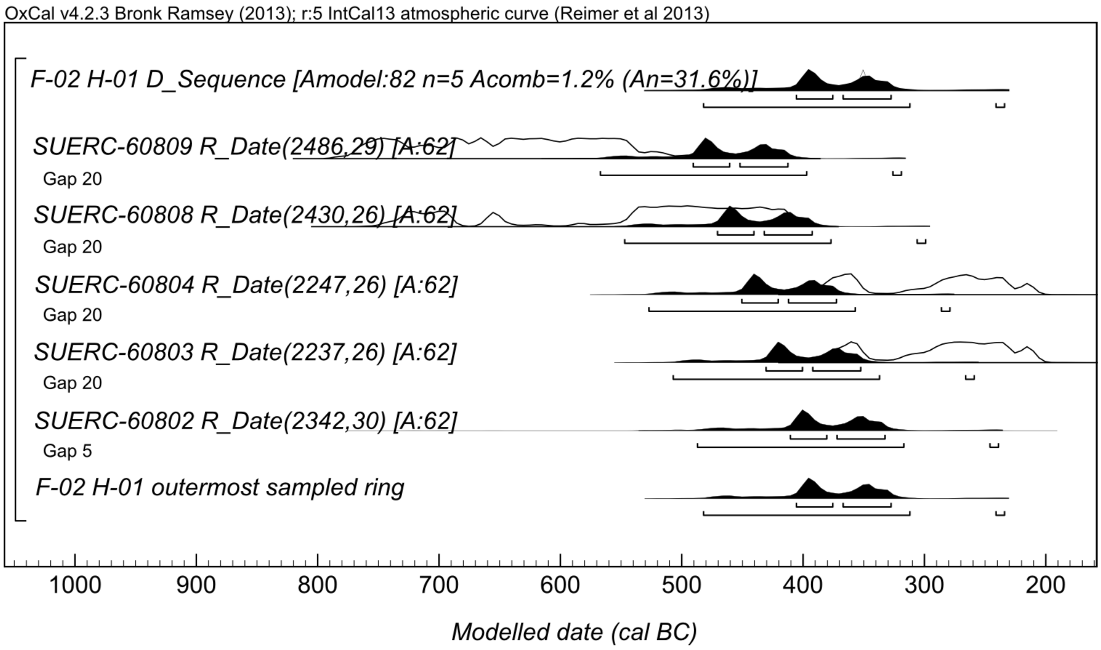




Figure 6.97: Results of the wiggle-match on Erskine Crannog timber F-02 H-01: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.

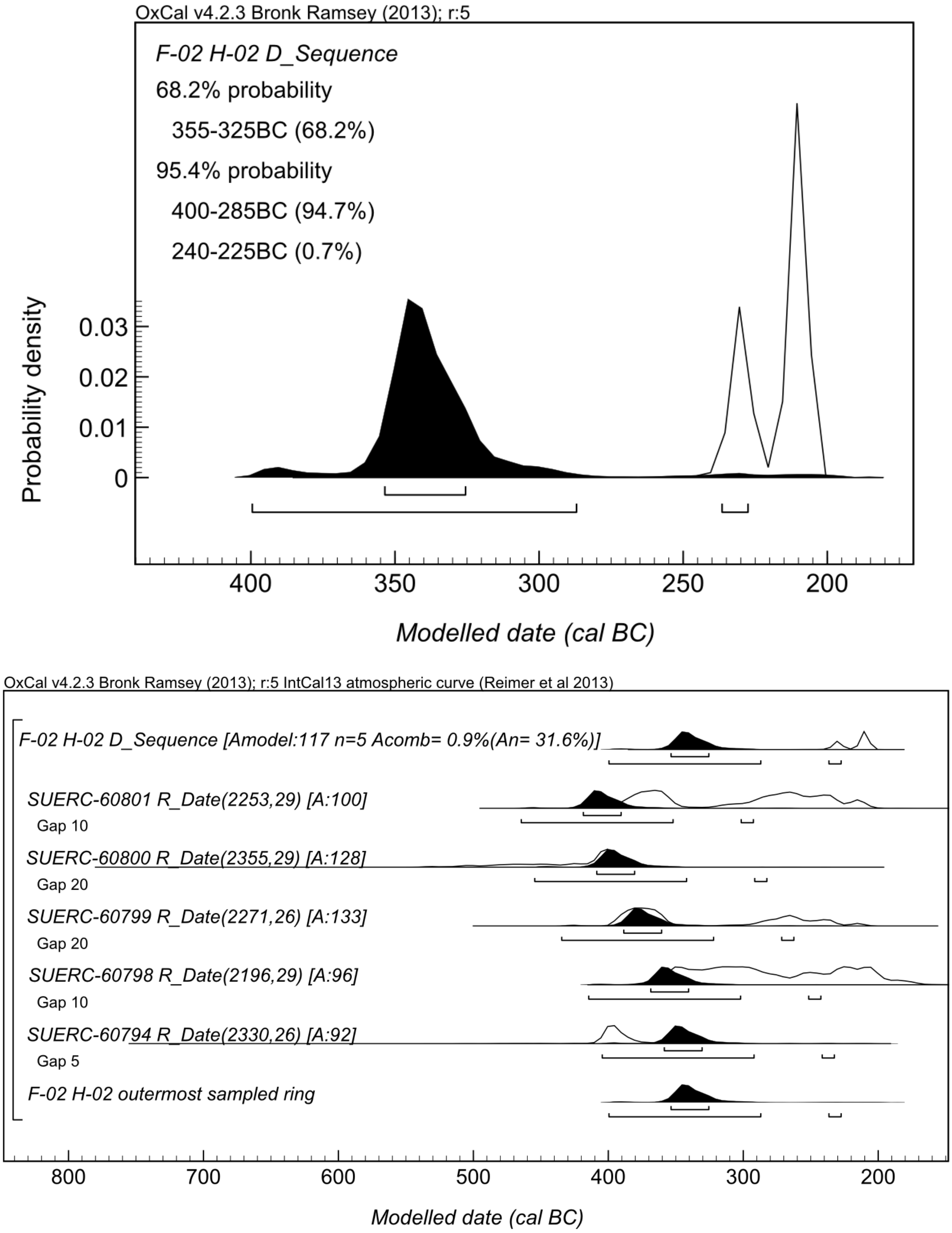



Figure 6.98: Results of the wiggle-match on Erskine Crannog timber F-02 H-02: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.

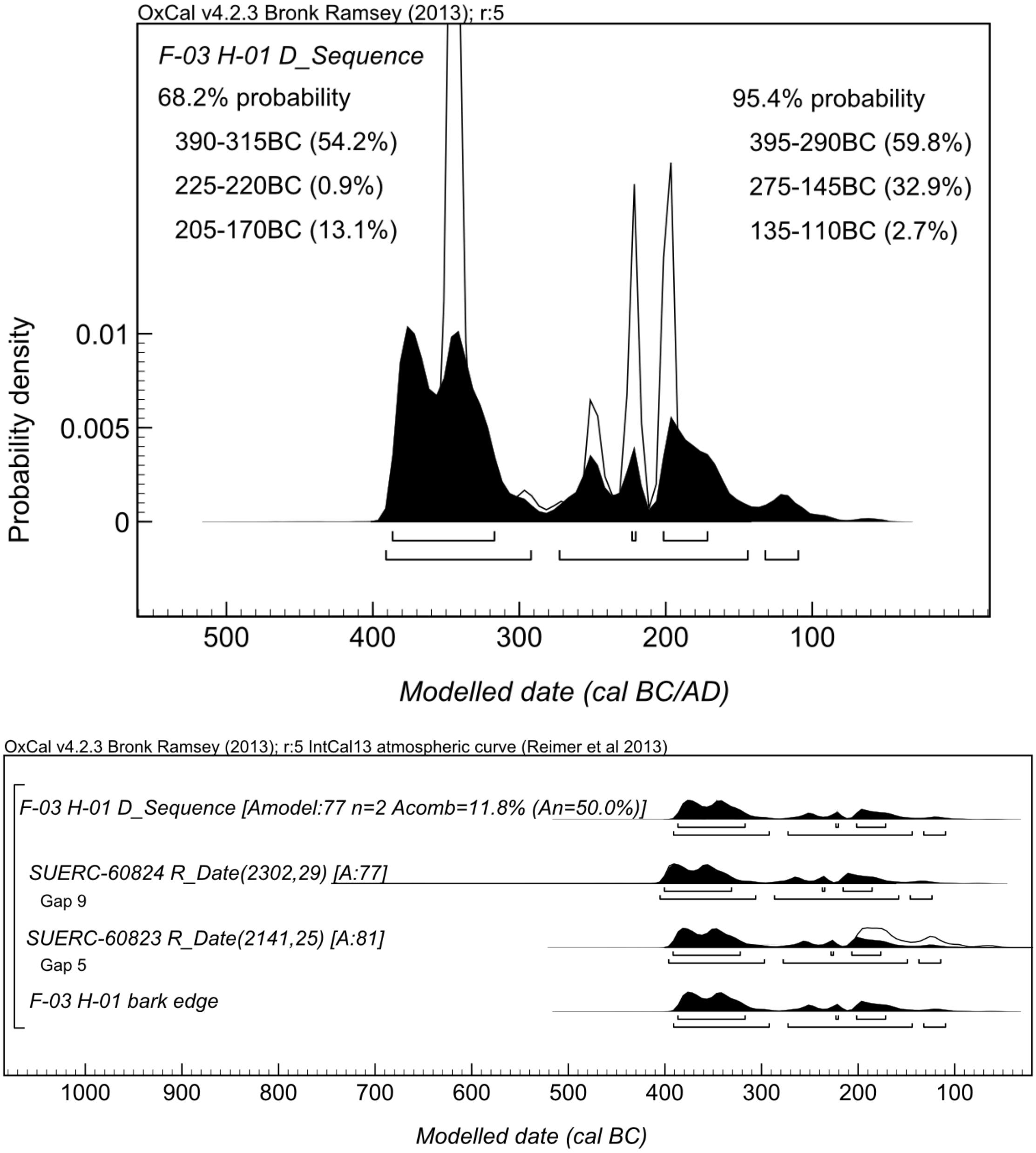



Figure 6.99: Results of the wiggle-match on Erskine Crannog timber F-03 H-01: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.

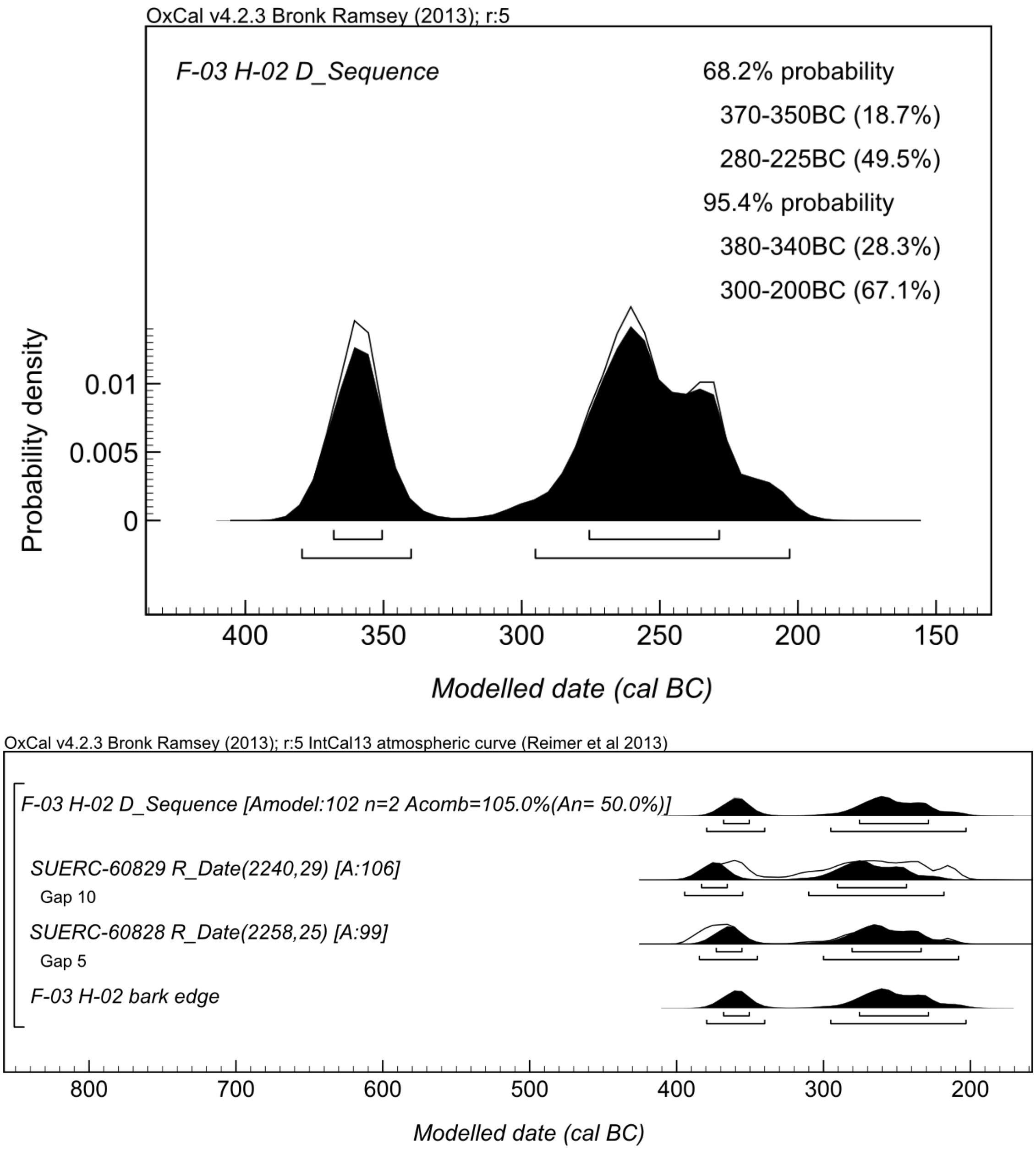



Figure 6.100: Results of the wiggle-match on Erskine Crannog timber F-03 H-02: summary (top), and the individual determinations (bottom). The white outline on the summary estimate indicates the distribution of the wiggle-match without the application of the outlier model.

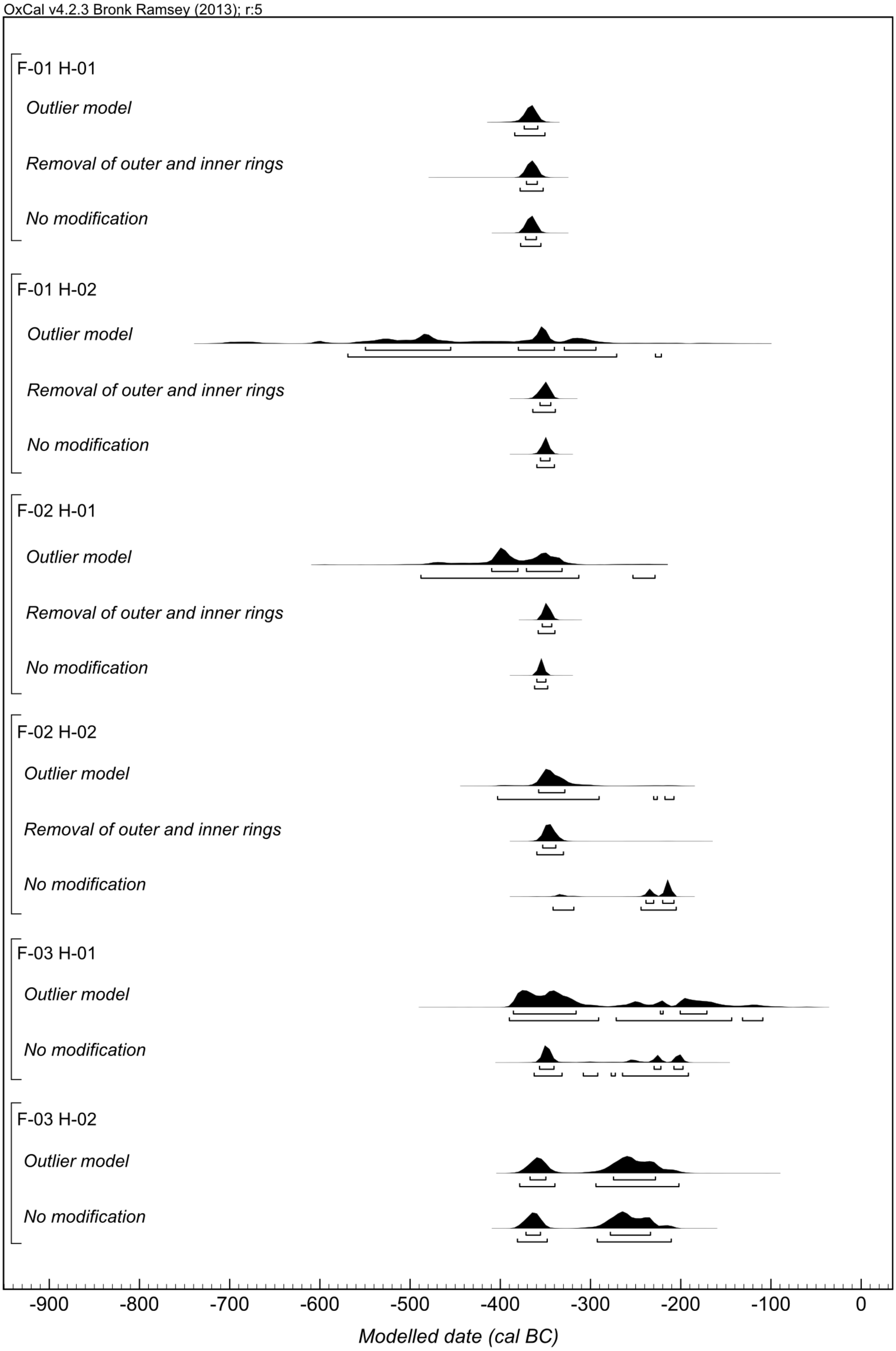



Figure 6.101: Comparison of wiggle-matches based on the outlier model, relying on the removal of the outermost and innermost rings and those without any modification.

Table 6.29: Results of the individual wiggle-matches from Erskine Crannog. Posterior probabilities are displayed in Figures 6.4.18-23.

| Timber | 68.2% HPD area | 95.4% HPD area | Amodel (%) |
|---|---|---|---|
| F-01 H-01 | *370–355 cal BC* | *380–345 cal BC* | 111 |
| F-01 H-02 | *550–450 cal BC (33.7%)*<br>*380–335 cal BC (22.6%)*<br>*330–290 cal BC (11.9%)* | *705–655 cal BC (4.5%)*<br>*610–580 cal BC (2.6%)*<br>*565–265 cal BC (87.9%)*<br>*210–200 cal BC (0.3%)* | 80.40 |
| F-02 H-01 | *410–375 cal BC (33.2%)*<br>*370–325 cal BC (35.0%)* | *485–310 cal BC (94.8%)*<br>*245–235 cal BC (0.6%)* | 82.20 |
| F-02 H-02 | *355–360 cal BC* | *400–285 cal BC (94.7%)*<br>*240–225 cal BC (0.7%)* | 117.10 |
| F-03 H-01 | *390–315 cal BC (54.3%)*<br>*225–220 cal BC (0.9%)*<br>*205–170 cal BC (12.9%)* | *395–290 cal BC (59.8%)*<br>*275–145 cal BC (32.8%)*<br>*135–105 cal BC (2.7%)* | 76.80 |
| F-03 H-02 | *370–350 cal BC (18.9%)*<br>*280–230 cal BC (49.3%)* | *380–340 cal BC (28.5%)*<br>*300–200 cal BC (66.9%)* | 102 |

Table 6.30: $\chi^2$ test statistics between the outlier model-based wiggle-matches, the wiggle-matches with outermost and innermost rings removed and wiggle-matches including all of the data. As the wiggle-matches F-03 H-01 and -02 are based on only two determinations each, removing the outermost and innermost rings is impossible. The 5% critical value at 2 df is 3.841.

| Timber | $\chi^2$ test statistics between the wiggle-matches based on the outlier models and those with the outermost and innermost rings removed | $\chi^2$ test statistics between the wiggle-matches based on the outlier models and those based on all the available measurements |
|---|---|---|
| F-01 H-01 | 0 | 0 |
| F-01 H-02 | 0.519 | 0.519 |
| F-02 H-01 | 0.696 | 0.829 |
| F-02 H-02 | 0.104 | 5.224 |
| F-03 H-01 | N/A | 0.603 |
| F-03 H-02 | N/A | 0.192 |

The site model has been built using the wiggle-matches derived through outlier analyses, as these are most conservative and also valid even if the assumptions about the relationship of the wood decay and the systematic offsets were to be proved invalid. Due to the computational load involved in calculating outlier models, the wiggle-match results were included in the site model as *.prior files. The uncertainties regarding the location of the bark edge on the major horizontals were represented using a uniform distribution assigning up to 20 years between the outermost counted ring and the bark edge. Besides the new wiggle-match dates, two of the legacy dates, GU-2186 and -2383, were also included (Figure 6.102). The ages of the other two legacy dates, GU-2187 and -2328, are much younger, and it is difficult to conceive how they could belong to the same activity phase as the wiggle-match dated timbers. The results point to the construction of the dated elements of Erskine Crannog being sometime in the 4th century cal BC (Figure 6.103):

- The construction date, as defined by the most recent plausible felling, is estimated to *370–290 cal BC (95.4%)*, with the highest probability in *360–325 cal BC (68.2%)* (Figure 6.104).
- The duration of the felling phase is estimated to *0–95 years (95.4%)*, with the highest probability in the interval *10–55 years (68.2%)* (Figure 6.105).
- Model agreement is good at Amodel = 116.7%. The determination whose individual agreement was not good is SUERC-60830 (A = 55.6%), which is caused by a somewhat older radiocarbon age. This may be the result of measurement uncertainty or a drift towards greater ages observed in other samples collected from outer rings. Regardless of the reason, the determination has little effect on the model and there are no good grounds for removing it.

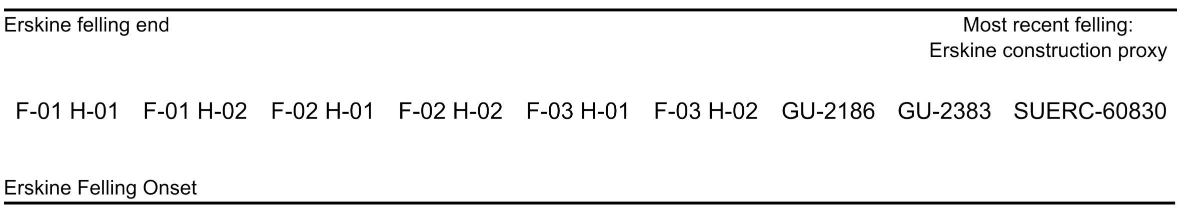



Figure 6.102: Schematic representation of the uniform bound phase model for the felling of the timbers that constitute Erskine Crannog.

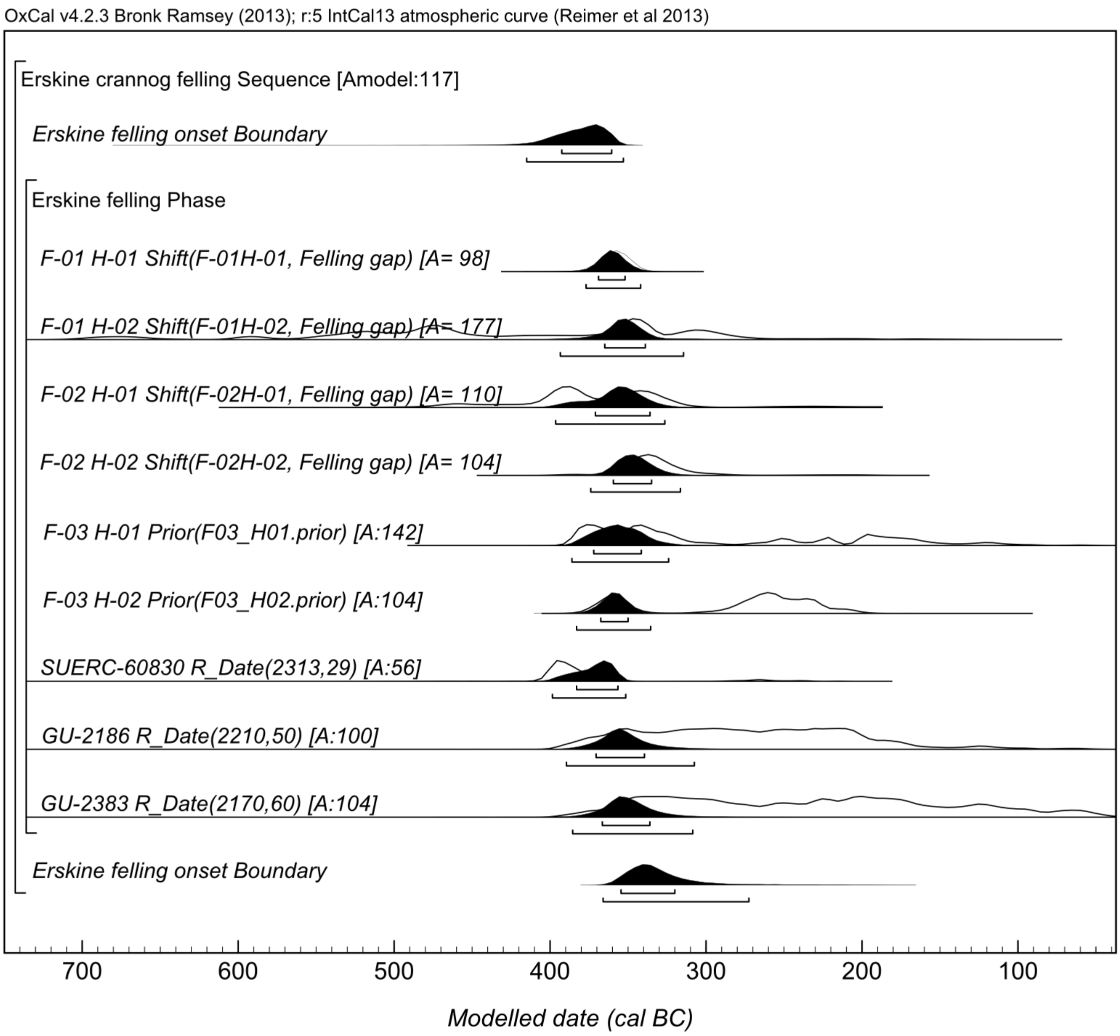



Figure 6.103: Results of the uniform bound phase model used for the felling of the timbers that constitute Erskine Crannog.

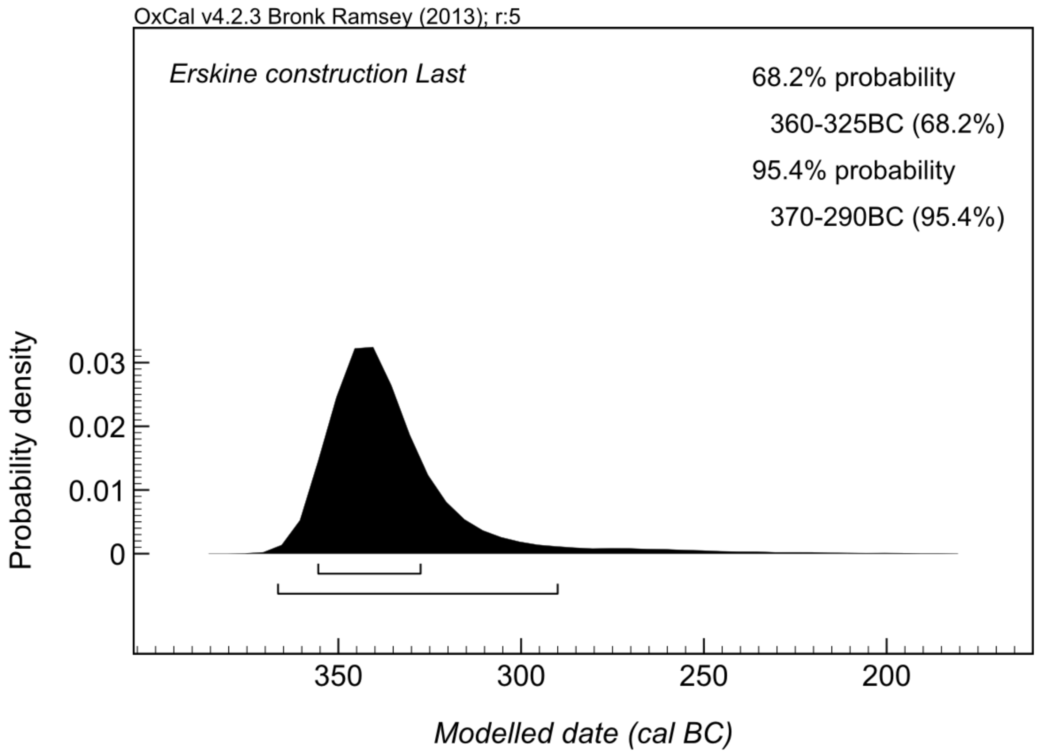



Figure 6.104: Estimate of the construction date for Erskine Crannog, based on the more recent plausible felling date among the timbers dated.

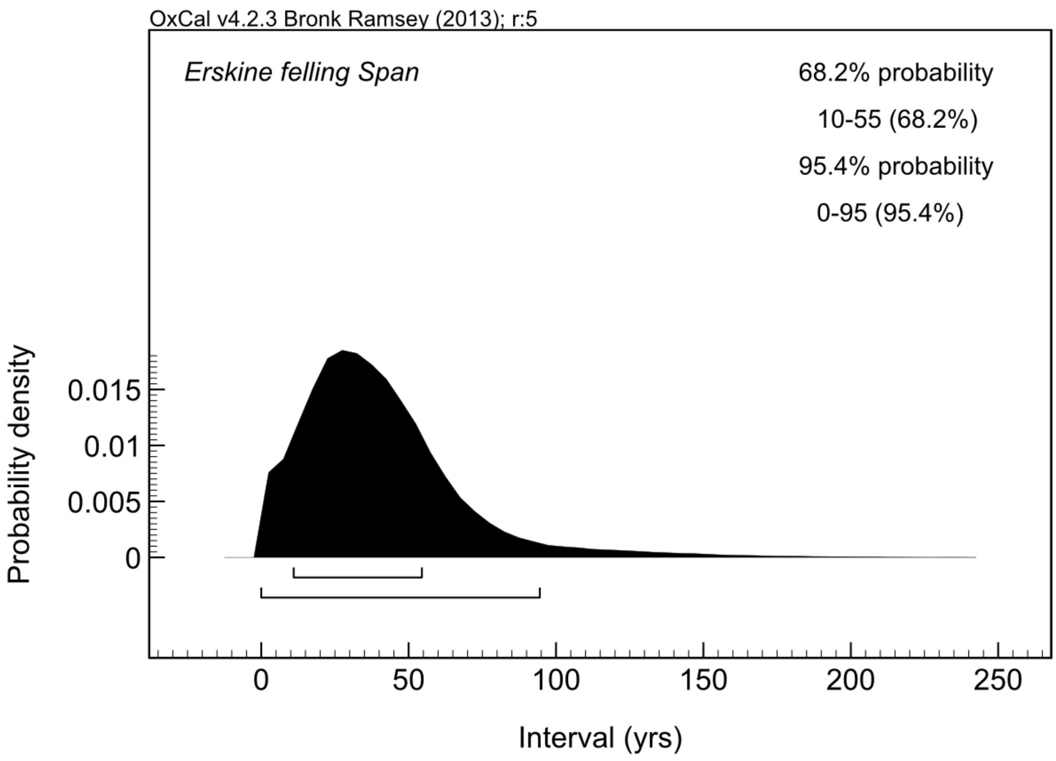



Figure 6.105: Estimate of the duration of the felling of timbers at Erskine Crannog.

These results indicate that the structure which was dated derives from the 4th century cal BC and no unambiguous signs of later structures or timber re-use could be identified. There does remain the case of the two younger determinations, GU-2187 and -2383. These can be attributed to some form of a pre-treatment problem, but may also be the remains of some later activity not identified in the wiggle-match dating study, and perhaps related to the breaking of the stone mound (if the interpretation presented earlier is true). In any case, these two dates constitute only limited evidence of activity and ought to be treated with caution until further research can corroborate those results. The other question that emerges is whether the model for Erskine Crannog represents a discrete felling phase, or perhaps the accretion of timbers during a period of construction and maintenance activity on the site. The 68.2% HPD area of the span estimate suggests that the latter might be what happened, though given that the 95.4% HPD area includes 0, the question remains unanswered. In any case, the results of the wiggle-match study are unanimous in that they show that Erskine Crannog, understood as the circular arrangement of timbers, was built in the 4th century cal BC, with possible, but unconfirmed, later activity on the site that perhaps relates to breaking up of the stone mound.

### 6.5.3 Section conclusions

From a practical perspective, the work on the Clyde crannogs is very encouraging for the development of wetland archaeology in Scotland. At both Erskine and Dumbuck, questions of the complexity akin to that encountered at Cults Loch 3 have been addressed and at both sites these questions have been resolved with 25 or fewer new radiocarbon determinations, despite the presence of technical difficulties arising from measurement bias that appears to be related to wood decay and small-scale offsets in the calibration curve. Furthermore, the results of the individual wiggle-matches, after modelling, are also promising, with modelled date ranges of up to no more than *85 years* (*95.4% probability*; Table 6.31). This indicates that from a practical point of view there are no known obstacles to the routine development of high-precision chronologies and developing complex archaeological research programmes on wetland settlement in Scotland following the end of the Hallstatt plateau.

Table 6.31: Spans of the date ranges of the wiggle-matches within Dumbuck and Erskine Crannog models.

| Timber | Span of the 68.2% HPD | Span of the 95.4% HPD |
|---|---|---|
| F-01 H-01 | *20* | *35* |
| F-01 H-02 | *30* | *85* |
| F-02 H-01 | *35* | *75* |
| F-02 H-02 | *25* | *60* |
| F-03 H-01 | *35* | *65* |
| F-03 H-02 | *20* | *50* |
| P-001 | *25* | *40* |
| P-002 | *20* | *35* |
| HT-001 | *20* | *35* |
| HT-002 | *25* | *30* |
| HT-003 | *20* | *60* |

## 6.6 Chapter conclusions

The practice of wiggle-match date modelling on the level of individual sites can be seen as navigating between the archaeological questions asked, the samples available, and the technical ability to attain the desired results. The interlinking of these three aspects was illustrated with reference to legacy dates from Dormans Island and Loch Arthur, where different sampling techniques and issues of calibration meant that not all archaeological questions of interest could be addressed. The case studies thereafter focussed on the issue of relating questions to technique. First of these was Black Loch of Myrton, where a single construction of a roundhouse from the latter part of the Hallstatt plateau was dated to less than a century. Next was Cults Loch 3, where an attempt was made to resolve a question regarding site formation processes from the Hallstatt plateau through wiggle-match dating. Although the aims of this study were not reached in full, the results from Black Loch were re-confirmed and a number of important observations became possible on the back of the large data set created. The final case study, focussing on Clyde crannogs showed that of the Hallstatt plateau construction estimates precise to half a century are viable in absence of technical complications, and that questions regarding site formation processes are viable.

These results are important because they allow making estimates for what can be achieved in future projects. For Scottish wetland sites it is reasonable to expect construction dates precise to less than a century to be achieved during the Hallstatt calibration plateau and even better precision is attainable for other part of the calibration curve. Furthermore, the results also indicate that it might be possible to aid the understanding of wetland site formation processes through wiggle-match dating projects, at least during the parts of the calibration curve other than calibration plateaux. For both these kinds of questions feature-oriented dating is key to ensuring that any outliers are identified and that suitable mitigating action is implemented, be it through further sampling, or through appropriate adjustments to the relevant site models.

Furthermore, in the course of the current analyses a number of important lessons were learned. From a technical perspective, perhaps the most important thing is the realization that our understanding of wood taphonomy with regards to radiocarbon dating needs improvement; the greater assurance about the reliability of measurements from decayed samples and outermost rings of alder timbers is essential to the long-term reduction of costs. The economic aspect is also linked to the need for allowing a degree of flexibility into research design, as the presence of recycled timbers, or other outlying wiggle-matches can lead to the need for greater sampling investment, but, at the same time, in absence of such outliers good precision can be obtained within smaller numbers of measurements. Another thing to bear in mind is that the technical reality apparent throughout this chapter is not static. As the experiments with the T-947 augmented curve demonstrated, improvements in calibration will make attaining better precisions possible and also make more complex site-formation research designs viable, even during calibration plateaux. Hence, future practice is not locked within the realm of possibilities outlined by the case studies presented, but will expand as current limitations are explored and dealt with and forthcoming projects discover new obstacles and possibilities.

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current limitations are explored and dealt with and forthcoming projects discover new obstacles and possibilities.

One last thing that the analyses presented in this chapter demonstrated is the importance of the attention to modelling assumptions and prior choices. The extreme cases of shrinkage induced by a single uniform bound phase prior when applied to the Cults Loch 3 wiggle-matches (section section 6.4.4), are one extreme example of what may happen if the modelling process is uncritical. In practice, this means that whenever working with such projects, it is paramount that the analyst is able to assess the relative virtues of alternative models in terms of how parsimonious they are in relationship to the archaeological evidence, technical underpinnings of the data and the statistical methods invoked. In case of the excessive shrinkage of the Cults Loch 3 wiggle-match dates under the uniform bound phase model we knew that the particular prior was inappropriate because the results would be very difficult to account for in archaeological terms. In more realistic situations the decision process may not always be as simple and may require more in-dpeth sensitivity analyses, but the basic principle, based on seeking the interpretation with fewest contingencies (in other words based on the application of Occham's razor), still holds. Note that the assessment of model reliability is only a specific case of comparing different models, and, as discussed in the section on Cults Loch 3, similar logic is also applicable when multiple interpretations seem plausible.

# 7 Towards meaning: wiggle-match dating research design

The key concept of the previous chapter was that the efficient use of the wiggle-match dating technique (or any dating technique for that instance) relies on a keen awareness of the relationship between the archaeological questions asked, the samples available and the technical capacity to provide the results required to answer the question. If the archaeological aims of the project are too vague, or require information that cannot be attained from the fieldwork and samples, or need dating results that are not achievable from a technical standpoint, it becomes difficult to lead the project to a successful conclusion. Hence, clarity of the research design, and its awareness of the nature of the data and the techniques available are as important for improving the chronology of wetland settlement as the technical and practical concerns presented in the preceding chapters.

This chapter outlines some research design considerations, the importance of which became clear over the duration of the current project, relating to increasing geographic scales. The case of the individual site lies at the foundation of any conceivable dating project for the Scottish Iron Age; although alternative, typology-based approaches are possible (eg. Jay et al. 2012), in practice, the lack of suitable artefact assemblages (see Chapter 2), means that they cannot be implemented. Thus, the better our understanding of the limitation and potential of individual wetland sites, the better the conceptual foundation for wetland archaeology in Scotland and its extension into the overall Iron Age debate. Individual sites can also be networked on a local scale. This provides new inferential opportunities, as knowledge gains in a single excavation trench can become meaningful over a broader area. Beyond the local scale of a loch or glen and its immediate surroundings are the broader regional and supra-regional scales. These entities hold major promise in that they allow the tracing of historical processes that have to be understood before interpretation of individual sites can be well-contextualized. Having said that, the logical modality involved in making arguments at regional and broader scales means that, for the time being, this potential is to a large extent locked and more lower-scale research is required to resolve the underpinning uncertainties. The most efficient way to address this may be the development of such projects that deal with issues relevant to multiple scales.

## 7.1 Site level considerations

In its most basic form, wiggle-match dating in the context of individual wetland sites can be reduced to the issue of finding a reliable date for particular structural features, much as was the case for the hearth structure of Structure 1 of Black Loch of Myrton. Chapter 6 covered most of the research design concerns applicable to these kinds of questions; the key issue is to ensure that the results of the wiggle-match dates are reliable, which in most cases will involve dating more than a single timber from any given feature of interest. While it is only in exceptional cases that the results of dating features from individual sites have significant worth in their own right, it is only through the ability to obtain reliable dates at this stage, that projects of greater interpretive value become viable. One way that dates from individual sites can be used is through tying them into broader scales that will be covered in the succeeding two sections. However, the research design might also be turned towards knowledge that can be extracted from the specific site, either through obtaining dates for events of interest, or through helping to understand the sites' history. What follows is a brief summary of three possible approaches that can be taken to give meaning to the dating of individual sites as entities in their own right. This list is by no means complete and exclusive and only serves to demonstrate the ways in which wiggle-match dating can aid archaeological interpretation at this level.

One way to approach the dating of individual wetland sites is to think in terms of dating specific techniques or practices. An example for this comes from Black Loch of Myrton, where the excavation of Structure 1 uncovered a range of Iron Age technical solutions, such as the use of posts with concave bases (Figure 7.1) that can rest on horizontal timbers and so overcome the problems of driving structural verticals into the peat, or the evidence of successive piling of heavy stone hearths, which, as they sunk into the peat, would also create a sink that would improve the drainage within the structure. Hence dating Structure 1 not only tells us something about when that particular building was built, but also places those technical solutions at a particular point in time. Another example would be the evidence of the palynological and macrobotanical assemblages from Dumbuck Crannog, which traced a number of past choices and practices. Pollen cores show no signs of any woodland other than alder carr in the vicinity of the site, so the oak posts P-001 and -002, wiggle-matched in the previous chapter, may have been brought in from a considerable distance (Miller and Ramsay 2001, 12-3). Also, the weed assemblages show the presence of near-ground taxa indicating that the cereals would have been sickled near the ground, or even uprooted (Miller and Ramsay 2001, 10). Although amassing such evidence might not appear as much at first, each of these examples shows preference for particular solutions over others, a preference that would be rooted in the culture of the Iron Age people. Hence, recording these practices amounts to developing an ethnography of the Iron Age and wiggle-match dating makes it possible to place such ethnographies in specific times, thus amplifying their informative value.

Figure 7.1: A three-dimensional scan of a base of an oak timber discovered at Black Loch of Myrton. When discovered, this base rested upon an alder horizontal pointing upwards, suggesting that the oak timber was a vertical. Photograph from Crone and Cavers 2015, Figure 38C.

A different way of using wiggle-match dating in the context of individual sites is to aid the understanding of site histories. This approach, sometimes termed as biographical (O'Sullivan and van de Noort 2007), seeks to reconstruct the development of different sites and superior preservation means that it is well-suited to wetland sites. The attempt to establish the sequence of events at Cults Loch 3 can be seen as falling within this category of projects and its alternative outcomes show the kinds of knowledge that can be gained from these kinds of projects. Had Structure 1 been built during the hiatus in Structure 2 occupation, this would show the willingness to deconstruct and rebuild roundhouses. If, on the other hand, Structure 2 was built after Structure 1, the frequency of refurbishment would appear to suggest that the maintenance of these roundhouses may have formed some form of a regular and frequent activity cycle. As each wetland site will have a deposition history tracing human choices and practices, through using wiggle-match dating to understand the site formation processes, we can also better understand past societies.

The focus on site histories can also be merged with the approach of dating specific practices through identifying aspects of construction technology or patterns of site maintenance. One example of this that was mentioned in Chapter 6 was the question of the crannog mound in Loch Arthur and the time over which it had developed. While the limitations of the dating technique and the sampling strategy meant that obtaining an answer to this question was impossible, one can speculate about the potential of resolving this issue, for, had the mound in Loch Arthur been built in a single event, then this would mean the felling of about 1500m$^3$ of timber, creation of a corresponding opening in the local woodland and the mobilization of labour required for the task. All of these pieces of information would be substantial to our understanding of the relationships between the people of the Iron Age, as well as their relationship with the environment. The junction between cultural practices and site history also goes beyond the initial construction, as the maintenance of wetland dwelling appears to have required a continuing mobilization of labour and material (see Chapter 2). Indeed, one of the more interesting potential long term aims for chronological research in Scottish Iron age wetland archaeology is to evaluate the longevity of individual activity phases, as they might bear hints at the longevity of Iron Age socio-political structures, such as kinship groups, tribes, or whatever other entity was responsible for the building of wetland sites.

The examples above only outline the different ways that the wiggle-match dating can contribute to our knowledge, when deployed on individual sites. Other approaches are possible and the only limitation to working them is the quality of preservation and excavation and the breadth of our theoretical imagination. Developing projects that deal with such aspects of archaeological interpretation is of specific value in the context of wetland archaeology, as it makes the most of the superior preservation of organic material and helps build up knowledge on past cultural behaviour that could not be attained from terrestrial sites (see van de Noort and O'Sullivan 2006). Yet even if the focus of the project is more limited than that and the main question asked is only about the dating of particular features for the purpose of linking them into broader scales of research, good site-level dating based on and expanding upon the principles outlined in the preceding chapter remains paramount.

## 7.2 Local scales

The term local scale denotes the area of a single loch, glen, firth, or a comparable geographic unit. Local scale frameworks can be small, as at Cults Loch, or large, as in the case of the Firth of Clyde. What binds them is the presence of some connecting geographic feature, such as a shared water-way, based on which it is reasonable to discuss sites within them as parts of the same unit. Such geographic linkage can be further extended through means of GIS analyses, such as estimation of travel costs, intervisibility, or perhaps the use of other, more complex models. This is to an extent arbitrary, but at the same time provides a workable basis upon which to group sites and move beyond the scale of a single site. The notion of the local scale as used here might be comparable to some instances of the notion of a landscape; however the latter term is avoided on account of its theoretical baggage (eg. Thomas 2012).

At local scales the function of chronological improvement, including wiggle-match dating, expands to include the establishment of local histories and, through this, forming linkage between sites based on spatial and temporal proximity. This enables the knowledge gains from a particular location to act as contextual information for other sites and hence allows the development of more in-depth narratives of the Iron Age and also makes economic sense. Focus on the developing of linkage also has the advantage of avoiding some of the issues related to demonstrating absences in the archaeological record, as the onus of the argument is on demonstrating contemporaneity of already identified features. Hence, within this approach, the issue of when does absence of evidence for activity during a given period constitute genuine evidence of absence, is bypassed through basing the argument on positive findings. This does not substitute a comprehensive local history, but gives tactical possibilities in situations where resources are limited, or when designing small-scale projects. The remainder of this section illustrates these broad notions in more with reference to case studies from Cults Loch and the Firth of Clyde.

### 7.2.1 Building local chronologies: Cults Loch

The crannog Cults Loch 3, discussed in Chapter 6, is just one of four sites associated with a small body of water that is Cults Loch, in Galloway (Figure 7.2). The other three sites are a crannog in the middle of the loch (Cults Loch 1), a small promontory fort (Cults Loch 4), and an enclosure on the east coast of the loch (Cults Loch 5). While Cults Loch 1 has not undergone any significant fieldwork in recent times, the two terrestrial sites, Cults Loch 4 and 5, have been excavated during the course of the same project as Cults Loch 3 (Cavers and Crone, forthcoming) and both yielded sufficient radiocarbon samples for meaningful Bayesian analysis (Figure 7.3) (Hamilton, forthcoming).

From these analyses we know that the Iron Age settlement around Cults Loch begins during the first part of the Hallstatt plateau with the onset of activity at Cults Loch 5 in *895–555 cal BC* (*95.4% probability; Cults Loch 5 phase 1 onset*).This enclosure remains in use until *730–325 cal BC* (*95.4% probability; Cults Loch 5 phase 1 end*) when it is abandoned until renewed activity towards the end of the first millennium BC. It is unclear whether the end of the first phase of activity at Cults Loch 5 took place before or after the onset of activity at Cults Loch 4 (*615–420 cal BC; 95.4% probability; Cults Loch 4 onset*) and Cults Loch 3 (*540–480 cal BC; 95.4% probability; Cults Loch 3 onset*), however, it is also almost certain that the latter two sites would have been contemporary with one another, at least through some of their existence. The estimates for the end of activity at Cults Loch 3 and 4 are also similar, with Cults Loch 4 having ended in *395–255 cal BC* (*95.4% probability; Cults Loch 4 end*) and the final identifiable structure at Cults Loch 3 dating to sometime in the 4th or early 3rd century cal BC (see Chapter 6 for the uncertainties regarding the end of activity at Cults Loch 3). Thereafter a hiatus ensues, until activity at Cults Loch 5 is resumed in *220–55 cal BC* (*95.4% probability; Cults Loch 5 phase 2 onset*). This renewed activity ends in in *150 cal BC–cal AD 15* (*95.4% probability; Cults Loch 5 phase 2 end*) marking the end of the recognized Iron Age chronology for Cults Loch. As only one radiocarbon determination and no dendrochronological dates are available from Cults Loch 1, we cannot say with any certainty where that site belongs in this sequence.


Figure 7.2: Satellite photograph of Cults Loch with sites mentioned in the text highlighted. Modified from Google Earth.

The dating of Iron Age settlements around Cults Loch demonstrates both the possibility and the importance of developing local chronologies. Without the radiocarbon-based chronology there would be the temptation to see the four sites as contemporary, thus leading to false linkage. Furthermore, the apparent contemporaneity and spatial proximity of Cults Loch 3 and 4 begs the question of whether these two sites should be considered as two distinct settlements, or a single settlement. This has twofold effects on archaeological interpretation. On the one hand, whenever thinking of the activities taking place at either location, it is important to bear in mind that they may pertain to a larger site with a terrestrial and a wetland component. On the other hand, it demonstrates the importance of choices made when choosing crannog locations relative to terrestrial settlement; with its close association to Cults Loch 4, the crannog Cults Loch 3 would have played a very different role from that of crannogs such as Loch Heron II, which could have been contemporary (Crone 2012, 142) and built using a similar technique, but lack associated terrestrial settlements. Awareness of such differences is essential if we are to avoid the error of grouping all the crannogs from a given period together based on some aspects of their construction, or their shared wetland location, but ignoring their context.

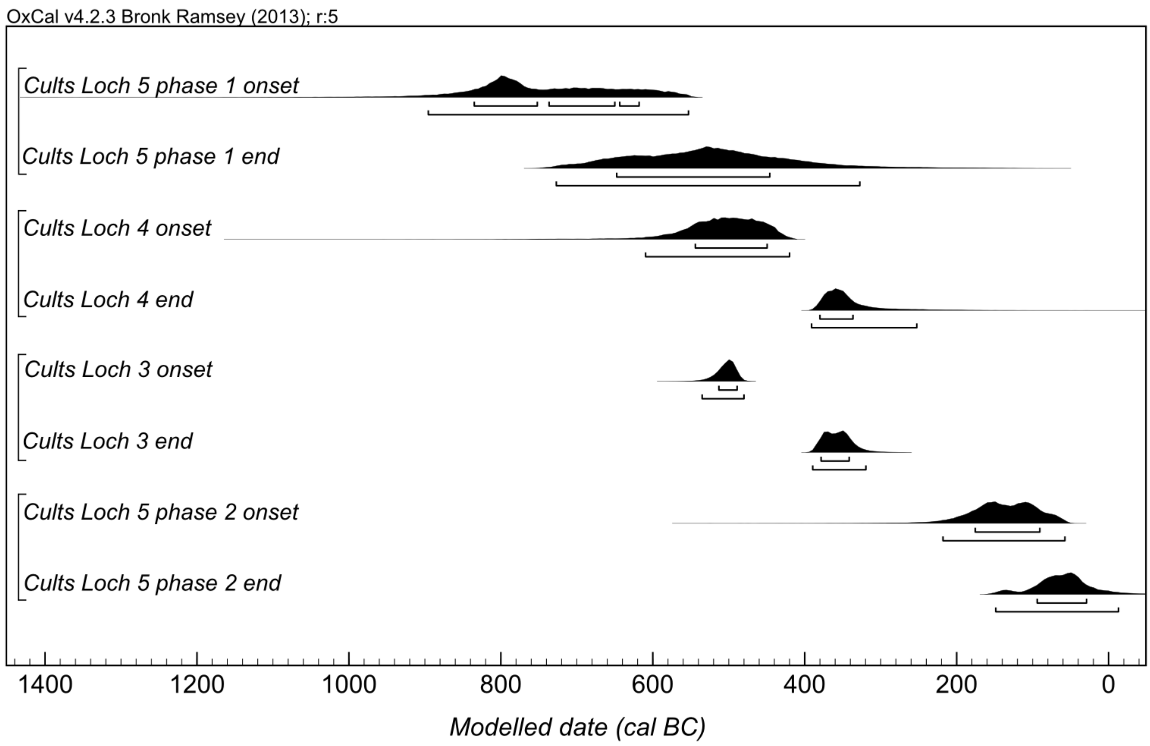


Figure 7.3: Estimates of activity onsets and ends at Cults Loch sites. Cults Loch 1 not included due to lack of sufficient data. The results for Cults Loch 4 and 5 are based on Hamilton, (forthcoming), while the results for Cults Loch 3 are based on the wiggle-match dating study presented in Chapter 6 of this thesis.

Yet perhaps the greatest achievement of the Cults Loch dating project was that it proved that it is possible to build a local chronology with a centennial resolution that includes not only wetland, but also terrestrial sites, even during the Hallstatt plateau and despite the absence of complex stratigraphy. This provides the necessary proof that future research can tackle such problems and that it is viable to design projects that will require the achievement of comparable results.

### 7.2.2 Targeted local scale research: Clyde crannogs

The development of the local history at Cults Loch happened on a back of a broader research project with a wide range of aims. It is, however, also possible to design projects at local scales that seek specific chronological information, so as to choose between a narrow range of possible answers. The two key limitations of such projects is that they require some pre-existing information to define the range of possible answers and they also run the risk of ignoring other possible routes of research. Nevertheless, targeted designs are possible to carry out with more limited resources, and so, in some contexts where sufficient information is available to state specific questions, such projects may prove a viable alternative to the approach followed at Cults Loch.

The targeted approach permeated the Clyde crannogs research design. As summarized in Chapter 6, the 1980s and 1990s dates from the two accessible sites, Dumbuck and Erskine Crannog, pointed to a wide range of possible dates during which these sites may have been occupied. This sparked the question whether the two sites may be synchronous, and if so, what would have been the motivation for placing several inter-tidal platforms so close to one another at a single point in time. Considering that the legacy dates covered a range of historic events, such as Agricolas invasion (AD 81) or the activity on the nearby Antonine wall in the mid-second century AD (Harding 2004, 188-9), the interpretation of these sites hinged on whether they were associated with any such event. Thus the main motivation behind the wiggle-match dating project was not only to discern whether the sites in question were single-occupancy or multi-period (see Chapter 6), but also to evaluate whether the two exposed Clyde crannogs may have been contemporary, because if they were, it would be probable that they have been built in the context of the same historical process.

The results of the wiggle-match dating project provided very strong evidence against Dumbuck and Erskine Crannog being synchronous. The difference between the construction of the two sites, as defined by the most recent plausible felling for each of the structural groups is *410-300 years (95.4%)* (Figure 7.4). The only possible argument for contemporaneity is that the two young radiocarbon ages from Erskine, GU-2187 and GU-2328, mark some later activity on the site, perhaps related to the breakup of the crannog mound. Yet there is nothing besides these two determinations, with their very broad calibrated date ranges, to suggest that this may have been the case and so the possibility that the two sites were contemporary at any point in time ought to be entertained with extreme caution. In any case, the dates are sufficient to refute the association between the original construction of the two sites and any of the episodes of Roman activity.

There are two main limitations to this kind of targeted approach. First of all, it benefits from prior knowledge; for example, had there been no legacy dates available for the Clyde crannogs, the formulation of the research design in a targeted form would have been impossible. Therefore, in areas where the dating evidence is limited or non-existent, this approach may not be possible to implement before some preliminary

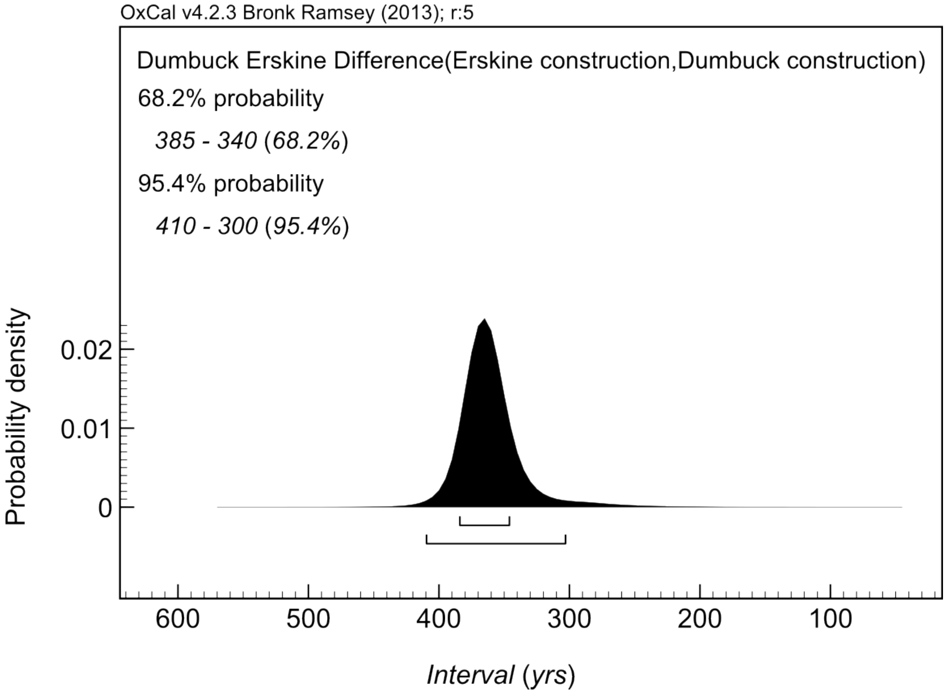


Figure 7.4: The difference between the construction dates for the Dumbuck and Erskine Crannogs, as determined from the models of Chapter 6.

dates are obtained. Second, deductive schemes will focus on specific questions and hence will bias the picture produced towards some issues over others. In the Clyde crannogs example, the case study could be extended towards at least five sites: the fort in Craigmarloch Wood and the one atop Sheep Hill (RCHAMS 2015), the palisaded enclosure at Mar Hall (Cavers et al. 2012), or the two remaining intertidal platforms at Langbank East and West (Sands and Hale 2002). For each of these sites specific questions regarding their relationship with the already dated sites can be asked.

The Clyde crannogs case study only brushes the surface of targeted research designs as applied to local scales, but it still demonstrates some of the characteristics of such approach. First of all, the end product of a targeted research design might be very similar to that of more open-ended projects. However, the path to this point is different, requiring greater care in interpreting the outcomes, but also minimizing resource expenditure at any point in the research process by focussing on specific archaeological issues. Furthermore, because successive deductive steps can only take place once some knowledge has been gained in the preceding stages, the approach as a whole involves less risk of overstretching limited resources. This may seem irrelevant when comparing the Clyde and Cults Loch case studies, both of which relate to small numbers of sites, but if we would want to address chronology of sites in a body of water with a significant number of crannogs, such as Loch Tay, Perthshire, where there are 18 different sites (Dixon 2007), appropriate nesting and focussing of questions becomes a necessity.

### 7.2.3 Local scales: section conclusions

By allowing linkage, working with local scales opens new interpretive possibilities for working with wetland sites. In the Scottish Iron Age context the first and foremost of these is the possibility of developing projects such as Cults Loch, where the whole issue of the interpretive rift between wetland and terrestrial archaeologies is bypassed. Beyond this there are also a series of other benefits. First of these is the possibility to contextualize the sites in their surroundings and hence better describe past choices as to location  here the relationship between Cults Loch 3 and 4 provides the clearest example. Then there is also the issue of tracing connections between sites; while none of the case studies provided a suitable example of this, it is not inconceivable that the evidence for specific practices, as defined in the section regarding single sites, can be linked across sites in a local area to provide a basis for a more in-depth understanding of the economic and technological aspects of Iron Age societies. One other significant advantage of scaling up from single sites is the possibility of linking absences across sites and hence providing more conclusive evidence of absence: if a specific chronological horizon is not observed on a single mound, this may be an issue of sampling; if it is absent from a whole set of sites across an area, the chances are that the absence is true. Hence, working on local scales means that greater amount of knowledge is gained than if each individual site was viewed in separation and thus the fieldwork and post-excavation costs become more justified.

## 7.3 Extending beyond the local scale

The move beyond local scales of research alters the nature of archaeological inference. Linkage between sites is no longer rooted in spatial proximity, but is justified in terms of historical process, whereby gaining knowledge of specific sites allows us to better understand past societies as a whole. These broader scales also act as contextual information in interpreting specific sites; it is only through the appreciation of the British Iron Age as a whole that we can see the importance of monumental communal projects (Sharples 2007), which might include some of the crannog sites (Cavers 2008, 19-20). Hence, the development of broader scales of research is paramount to the development of our interpretive capabilities. Having said that most questions that we might be tempted to ask at such scales cannot be tackled in a direct way. For example, a project on spatiotemporal variability of crannog construction techniques throughout the entirety of the Scottish Iron Age would be untenable due to not only the enormous financial investment required, but also due to the sheer lack of trained personnel required to excavate a representative sample of sites. Hence, the development of knowledge on scales greater than that of a single loch or a glen for the most part has to rely either on the accretion of knowledge from more localized projects, or, in some cases, developing targeted localized projects whose results are meaningful to broader scales.

The growth of the understanding of the Iron Age in the region between the Clyde and the Solway is an example of both how relevant knowledge can accrete through separate excavation projects and how such knowledge can become the basis for developing more specific targeted projects. When, the agenda for the British Iron Age was formulated in 2001, this part of the island was considered to contain several areas requiring more intensive research, including "black holes" such as Galloway (Haselgrove et al. 2001). Since then the publication of a number of projects, both commercial (eg. Cook 2006; Ellis 2007; Gordon 2009) and academic (eg. Cavers and Crone ming; Henderson et al. 2006; Thomas 2007), has improved our understanding of the region to an extent where targeted local and site-level research can be executed. For example, there is still no good evidence for the construction of wetland sites between the onset of the Iron Age and the period around 500 BC; the only available data comes from individual determinations from Loch Heron II and Milton Loch 1 (Crone 2012, 142). However, because this knowledge is in place, it becomes possible to conceive a project aimed at exploring each of these wetland mounds and improving their dating to further explore whether any of them belongs to this earliest part of the Iron Age. A more complex question can be raised about the events happening around the turn of the first millennia. During that period first evidence of upland Iron Age settlement emerges in the region (Banks 2000; Johnston 1994; RCHAMS 2015) and there is also an apparent decline in wetland settlement (Crone 2012, 147). However, the data set remains limited and the breadth of the calibrated and modelled date ranges means that it is still uncertain whether this impression is true and, if so, whether changes occurred as an event or as part of an extended process. It was with this possible transition in mind that the Clyde crannogs dating project was conceived: the legacy dates suggested that Dumbuck and Erskine may be contemporary around the turn of the millennium, suggesting that the motivations behind their construction could have been a part of a broader process of change. The wiggle-match dates from these two sites disproved this and hence failed to bring any new evidence on the subject of the nature of the transition, but likewise they showed that there is no substantial evidence for activity at either of these sites after AD 50, thus contributing to the notion of reduced wetland activity in the region in the first half of the first millennium AD (Crone 2012).

The potential project focussing on the presence of wetland settlement between the Clyde and the Solway in the earliest centuries of the Iron Age, as well as the effect that the Clyde crannogs project had on the notion of a settlement transition around the turn of the millennium demonstrate two logical and practical difficulties involved when making postulates that extend beyond local scales. The need to amass evidence of absence convincing enough for a broad region comes first. If we are to conclude that there is no wetland settlement at any given point in time in a large area and hence form the basis for inferences about changes to settlement patters, we need to have dated sufficient sites. One approach would be to designate a large enough random sample for excavation, however this verges on impossible on account of the costs involved. The other approach is to obtain a broad coverage of the region in question through dating material collected in survey and then investigate sites that returned radiocarbon determinations from a period of proposed absence; in the case of the south-west that would be Milton Loch 1 and Loch Heron II for the first two centuries of the Iron Age and Cults Loch 1 and Black Loch of Sanquahar (Crone 2012, 141-2) for the first half of the first millennium AD. Note that if the preliminary surveys produce multiple dates from a given period on a number of sites, then claims of absence lose their viability. The relationship between guiding dates in survey and the determination of absences brings about the next challenge of working on broader scales and that is the need for breadth of coverage. At the moment any regional patterns of wetland settlement can only be speculated for the region between the Clyde and the Solway because it is the only part of Scotland where continuous survey has been conducted with radiocarbon samples collected in its course to evaluate the basic chronology of the region (eg. Crone 1993; Henderson et al. 2003, 2006). Hence, any attempts of extending regional interpretations elsewhere in Scotland would have to be preceded by similar survey efforts as a basis for further targeted research and the development of a comparable understanding of the terrestrial Iron Age.

In more general terms, the construction of regional chronologies can be envisaged as a three-movement process. The first movement is the characterization of the available material and identification of viable archaeological questions that can be addressed on its basis. This focussing of research effort is essential on account of the need to cover large numbers of sites; trying to build regional chronologies without limiting the project aims to key research questions in all probability would prove untenable on account of the costs involved and the amount of material required. The second movementis to choose and date the material from relevant sites and archaeological contexts that may be relevant to the specific historical question. This may entail the evaluation of an absence of certain feature or settlement form in a given time period (as outlined above for crannogs in the first half of the first millennium cal AD in Scotland), or the tracing of the development of a particular settlement or feature form (for example evaluating the chronological extent of the palisaded packwerk crannog mounds of the kind encountered at Buiston and Lochlea). While such focus on specific questions might come across as limiting, in practice it means that the project thus designed focuses from the very outset on developing linkage on regional scales, thus providing the grounds for aiding the interpretation of particular locales. The third movement involves the resolution of the specific questions and also consideration of the further implications of the data produced; for example, once the chronological extent of the palisaded packwerk crannog mounds is known, the data might be sufficient to provide a suggestion of interrelationship with some other settlement form, or diachrnic change tot his particular kind of features. At this point the research program loops and the first movement may be repeated. The generalized form of this iterative research design was discussed in depth by the French archaeologist J-C. Gardin (1980).

## 7.4 Chapter conclusions

The discussion above is rooted in a personal perspective and the technical and economic conditions of 2015. For one, the stress of some potential approaches over others comes from a specific theoretical background, as well as experiences gathered over the course of the case studies discussed in Chapter 6; coming from a different background could mean that less weight would be given to issues of evidencing absence, or practice-oriented research questions. Hence with different approaches to archaeology as a discipline, as well as with different sites, some of the suggestions presented above might need modification. Furthermore, the guidelines suggested are based on the mid-2010s technical and economic capacities. If the ongoing research on miniaturization of the AMS equipment (Wacker et al. 2010) and the automatization of graphitization process (Rinyu et al. 2013; Ruff et al. 2010) lead to a significant reduction in the costs of radiocarbon dating, then riskier projects, for example involving issues of site formation during the Hallstatt plateau, may become tenable. Last but not least is the issue of improving the calibration curve; the day single-year calibration data becomes available for the Iron Age, research design suggestions of this and the preceding Chapter might need to be re-evaluated altogether.

However, regardless of theoretical position or technological milieu, some aspects of research design that came across here are of continuing relevance to the development of wiggle-match dating for wetland sites in Scotland and, in all probability, beyond. First and foremost of these is the close relationship between the choices regarding fieldwork and the kinds of research that can be developed from the samples obtained. In general, comprehensive excavation is a necessary pre-requisite for discussing chronology of any one wetland mound, more limited projects focussing on individual features might have a role when they are related to questions which do not require evidence of absences and samples collected from timbers protruding from the mounds have a part to play in providing basis for more specific research design. The next aspect to consider is the nature and logical structure of the questions asked. One way to approach this is to consider what the questions ask about and what kinds of evidence they require. For example, in the practice-focused approach outlined in section 7.1, the chronological evidence is used to nest evidence of particular choices and practices in a point in time. Hence, the issue of demonstrating absences is bypassed. On the other hand, if we are interested in establishing the history of a site, bypassing the issue of absences becomes impossible. Thus, the approach to the question determines the nature of practical concerns that will arise and the fieldwork choices that will have to be made. Another way to think about questions is to consider whether they are an open form, or whether they are focussed on choosing from a set of possibilities emerging from ambiguities in some pre-existing data. The difference between the two was illustrated in the comparison of the local-scale projects for Cults Loch and the Clyde crannogs, where at Cults Loch no specific alternatives existed before the onset of the project, while for the Clyde crannogs it was the existence of prior knowledge that prompted the project. The move towards more closed question forms may prove important when designing projects encapsulating numerous sites, as it allows to better focus resources. This in turn relates to the final and perhaps most fundamental concern, one of limiting the question aims; the more limited and specific the aims of any particular archaeological question, the more limited the investment required and lesser the risks of project failure. Hence as a whole, the development of Scottish wetland archaeology ought to benefit from approaches that are as targeted as possible, while still retaining cultural meaning. If these targeted questions focus of specific areas and envelop both terrestrial and wetland sites, the progress made will also bypass the issue of the interpretive rift between wetland and terrestrial archaeology, leading to a situation where the superior preservation on wetland sites makes a proportional contribution to our understanding of the Iron Age as a whole.

# 8 Conclusion

This PhD discussed the application of the radiocarbon wiggle-match dating technique to Scottish Iron Age wetland archaeology. The key archaeological problem discussed herein was the issue of integrating the wetland and terrestrial archaeologies of the Iron Age: as the nature of the archaeological record throughout the period in Scotland precludes the development of narratives that envelop different groups of archaeological data, a more conscious effort is necessary to develop linkage between different sites and hence lead to a situation where the superior wetland preservation will have a bearing on improving the knowledge of the Iron Age in general (see Chapter 2). One way to develop such linkage is through the improvement in the understanding of chronological relationships between different sites, but this requires the means for routine dating of wetland sites to a precision meaningful on sub-centennial scales. This is not always achievable through dendrochronology under Scottish conditions and hence a radiocarbon-based methodology becomes a necessity. Having said that, much of the Iron Age is covered by challenging features of the radiocarbon calibration curve, such as the Hallstatt calibration plateau, and hence the development of the required chronology called for the employment of the wiggle-match dating technique (see Chapter 3).

The efficient use of the wiggle-match dating technique called for its evaluation from both technical and practical standpoints. Dating 50 consecutive rings from a known-age timber led to the understanding that, for the time being, the optimal size of individual wiggle-match dating samples for timbers from the Iron Age is a decadal block, which matches the resolution of the underlying calibration data. What also became clear in the course of the study of the known-age timber is that small systematic offsets may be present between the mean of the calibration curve and the actual trend of past radiocarbon. Although these offsets are of little consequence to most radiocarbon-based dating methods, in wiggle-match dating they can lead to biases if the sampling frame for any particular timber is too precise and, hence, it is more reliable to undertake multiple lower-precision wiggle-matches and then introduce them into Bayesian models (Chapter 5).

The practical aspects of wiggle-match application were explored through a series of case studies from south-west Scotland that covered the issues of dating particular features and exploration of site formation processes (Chapter 6). The first of the case studies, Black Loch of Myrton, produced a modelled date range for a Hallstatt plateau feature with a *95.4%* HPD area of less than 70 calendar years, thus proving that wiggle-match dating can attain the precision required to build the archaeological narratives outlined in Chapter 2. Furthermore, the date of the construction *515-445 cal BC*, is close enough to the dendrochronological determination from the same structure (461-429 BC), to provide assurance that the method is reliable. The second case study, Cults Loch 3, undertook the more ambitious aim of exploring the possibility of applying the wiggle-match dating to understanding site formation processes during the Hallstatt plateau. Although the study only attained partial success, it produced a wealth of wiggle-match data from archaeological contexts that confirm the results of the Black Loch of Myrton case study, made it possible to explore technical aspects of grouping wiggle-matches in Bayesian models with real data and also hint at possible future developments. The third case study, focussing on the Clyde crannogs explored the applicability of the wiggle-match dating technique beyond the Hallstatt calibration plateau. It showed that under more favourable conditions it is possible to both obtain dates for particular features and resolve site formation questions, even in the light of small-scale curve offsets and the presence of technical difficulties. The overall results of the work showed the importance of flexible research design and feature-oriented dating as a means of overcoming practical challenges.

One other key point of the work on the practice of wiggle-match dating in the context of Scottish wetland archaeology was the close relationship between the archaeological questions, data available and the technical ability to produce the required results. While the case studies and the data of Chapters 5 and 6 covered much of the final of these two concerns, they bypassed the issue of developing archaeological questions on wetland chronology. This led to the need for a more explicit treatment of research design (Chapter 7), which focussed on the changing properties, possibilities and challenges of working at different geographic scales. While work at the level of single sites can contribute to the understanding of individual site histories or timing of practices evidenced by the deposits discovered therein, work at local scales permits the development of aspects of linkage between sites based on spatial and temporal relationships, while work on regional and broader scales offers the basis for framing linkage in terms of historical processes that can in turn act as a context for subsequent discoveries. Differences between possible archaeological questions depending on the scale at which the project is happening mean that wiggle-match dating research design needs to align the questions asked with the data that is retrieved in the field and the technical capacity to produce the results required. In an ideal world, the dating projects would be developed in such a way as to address multiple questions relevant to multiple scales from a single set of wiggle-match dates. This kind of design was developed for the Clyde crannogs case study as an example.

Hence, the main theme of the thesis was the relationship between technique, practice and meaning of wiggle-match dating in the context of Scottish wetland archaeology. The creation of archaeological meaning can only proceed if it is practical to produce the knowledge required to address specific questions; while excavating a representative sample of Scottish crannogs would be very meaningful, it is impracticable and hence other, less direct approaches need to be taken. Yet practice itself relies on a technical basis, for without the technical means to resolve particular questions, no practical design will be able to deliver them. This thesis presented the relationship between technique, practice and meaning of wiggle-match dating in the context of Scottish wetland archaeology.

## 8.1 Main recommendations for research design

Over the course of the current thesis a number of observations relevant to future research design involving wiggle-match dating in the context of Scottish wetland archaeology became clear. Most of these are summarized in section conclusions within Chapters 5 and 6 and ought to be viewed in reference to the material covered therein. Nevertheless, four major recommendations are worth re-iterating here:

1. Selection of sample spans within individual wiggle-matches ought to match the resolution of the relevant calibration data, which is for the most part decadal throughout the Scottish Iron Age. Using longer sample spans means that dating information is lost, while short sample spans introduce redundant information that leads to lowering the agreement with the calibration curve and which, in some cases, may induce spurious results.

2. Avoid making individual wiggle-matches over-precise, as the short-term autocorrelations of errors within the calibration curve can lead to biases in wiggle-match dating, most so if it is applied to short sequences (<50 years). One way to bypass the issue is to conduct multiple wiggle-matches to a lower precision and then regain the lost precision through the Bayesian analysis of their outputs.

3. In most cases the use of feature-oriented dating is recommended. By recognizing any potential chronological variability on the level of defined structural features it becomes possible to identify the presence of timbers that have been re-used, as well as the presence of technical issues, such as the offset associated with decayed waterlogged wood. Hence, in most cases dating multiple timbers from a single feature and using the stratigraphic relationships between features to develop the desired site model is preferable to dating the same number of timbers distributed throughout the site.

4. Whenever possible, research design ought to allow for flexibility in resource allocation. Wiggle-matches, by their very nature, can be sensitive to individual outliers, so that any minimalist research design might fail and further dating might be required. Yet at the same time, the minimalist designs may be successful, in which case up-front allocation of a large number of measurements to a wiggle-match can lead to needless redundancy. Flexible design allowing for preliminary wiggle-match dating also has the advantage of narrowing the range of possible solutions to any one chronological question, thus permitting a more efficient design overall.

## 8.2 Applications beyond the Scottish Iron Age

The analytical funding for the current project was provided with the clear intention of addressing issues pertinent to the Scottish Iron Age and so most of the conclusions and recommendations have been phrased in the context of the Scottish Iron Age. Nevertheless, most of the recommendations and observations summarized throughout this thesis ought to have a much broader applicability. In essence, the results and conclusions of Chapter 5, which dealt with the technical underpinnings of wiggle-match dating with a special reference to short-lived(<50 years) timbers, should have universal application and as such be useful in any context where timbers that display growth-rings survive, but cannot be dated through dendrochronological means for whatever reason. Likewise, most of the practical observations of Chapter 6 are relevant to any context within which wiggle-match dating might be deployed; the feature-oriented approach to dating will help to identify and overcome technical and site-formation issues regardless of the time and place from which a site derives and flexibility in research design will be helpful regardless of the exact nature of the questions asked.

The main difference between the applications presented throughout this thesis and potential projects beyond the Scottish Iron Age lies with the meaning of wiggle-match dating results. The archaeology of the Scottish Iron Age does not lend itself to culture historical analysis and hence wiggle-match dating is invoked as one of the means of bypassing this limitation. In other contexts the situation might be different, as the practice of wiggle-match dating projects might be better applied to concerns relevant to the particular research tradition, be they timing of cultural change, or synchronization with particular environmental proxies. Hence, the main volume of work involved in applying the findings of the current project to issues other than the Scottish Iron Age, will be the definition of the aims of chronological research and ensuring that they correspond to what wiggle-match dating might achieve on the relevant parts of the calibration curve and to the data that can be recovered in the field.

The main difference between the applications presented throughout this thesis and potential projects beyond the Scottish Iron Age lies with the meaning of wiggle-match dating results. The archaeology of the Scottish Iron Age is unique in that it does not lend itself to culture historical analysis and hence wiggle-match dating is invoked as one of the means of bypassing this limitation. In other contexts, the situation might be different, as the practice of wiggle-match dating projects might be better applied to concerns relevant to the particular research tradition, be they timing of cultural change, or synchronization with particular environmental proxies. Hence, the main volume of work involved in applying the findings of the current project to issues other than the Scottish Iron Age will be the definition of the aims of chronological research and ensuring that they correspond to what wiggle-match dating might achieve on the relevant parts of the calibration curve and to the data that can be recovered in the field.

## 8.3 Directions for future research

The continuation of work presented in this thesis can take a number of directions, both focussed on the archaeological and technical aspects of wiggle-match dating. What follows is a brief overview of the main categories of such prospective research and is not meant to be exhaustive.

The first extension of the current work that comes to mind is the continuation of research into wetland chronology in the Scottish south-west. Some potential projects have been mentioned or implied throughout Chapters 6 and 7: estimating the felling span and formation date of the mound of the Loch Arthur crannog, the dating of Cults Loch 1 and Black Loch of Sanquhar, the only two south-western crannogs that produced dates from the first half of the first millennium cal AD. Likewise, a targeted dating project at Milton Loch 1 and Loch Heron II would help to evaluate whether there has or has not been wetland structural activity in the region prior to ca. 500 cal BC. Further potential projects in the south-west would include the dating of structures discovered in the course of the 2015 field season at Black Loch of Myrton, or a project designed to establish the chronological relationship between the White and Block Lochs of Myrton. One final avenue of enquiry in the south-west would be the extension of survey to the lochs in the uplands between Ayrshire and Galloway, an area that, to date, has witnessed no archaeological wetland research since Munros excavation of Lochspouts in the 1870s.

Developing research designs beyond the Scottish south-west is a very different matter. With the exception of Loch Tay, which had been subject to intensive survey and where several radiocarbon dates are available for most of the crannog sites, outside south-west Scotland the dating evidence on wetland sites is either absent or too discontinuous to develop targeted research designs. Hence, for most of the country, extension of survey and pilot dating analogous to that achieved by the South-West Crannog Survey, or by the Scottish Trust for Underwater Archaeology in Loch Tay, might prove necessary before targeted design is pursued for wetland sites. An alternative is to choose sites that might complement known terrestrial settlement, such as the possible artificial island in the Loch of Swanney, Orkney, which lies only 7km away from the Broch of Gurness (RCHAMS 2015).

As far as technical improvement is concerned, the single development that would lead to significant changes is the improvement of Holocene radiocarbon calibration, or at least for the period of interest. Needless to say, this would be a substantial project that would require the involvement of several laboratories and which would benefit from broad aims of not only improving the radiocarbon calibration for dating purposes, but also providing high quality data on the past carbon cycle and solar variability. Note that even in the absence of such grand designs, the calibration data sets are being improved (Taylor and Southon 2013), but at such a slow rate that noticeable changes to archaeological practice are difficult to conceive within the next decade. Beyond the basic level of improving the calibration data sets, there is also the issue of addressing the results that archive-dependent and georgraphic offsets might have on building radiocarbon chronologies (both in archaeology and environmental sciences); as the precision of measurements, models and the calibration curves increases, so will the effects of objective offsets. As it is difficult to comprehend how sufficient local curves could be constructed for all the possible radiocarbon archives, this will necessitate an improvement in our understanding of the radiocarbon cycle, so as to allow for the development of theoretical approaches to these issues.

A related technical improvement that may prove beneficial to the practice of wiggle-match dating research design and model critique would be the development of systematic simulation methods in radiocarbon dating. At the moment the vast majority of simulation studies have to be limited due to the lack of automatized algorithms that would allow definition of a realistic range of possible input conditions and scripts to summarize relevant information from the output data files. Without these two developments it becomes to uneconomic in terms of time to run simulation studies, which could provide samples suitable for further quantitative analyses and therefore enable a more systematic approach to both research design and model critique.

Nevertheless, there is a range of alternative technical improvements that might change our ability to tackle the chronology of wetland settlement. One of them would be to work towards a better understanding of the taphonomy of waterlogged wood, so as to remove the uncertainties when dealing with the outermost or decayed alder rings. Another significant development would be to explore the potential of stable isotope analysis and other methods of augmenting dendrochronology, which might not only provide climatic data (see Chapter 2), but also aid the cross-correlation of tree-ring sequences from which they were obtained. A third development would be the automatization of simulation methods, so that a broader range of research designs can be evaluated and subject to subsequent systematic analysis. This list of possible technical improvements could continue for as far as imagination and physical reality allow.

In summary, further development of the chronological aspects of the understanding of the Scottish Iron Age wetland settlement hinge on developments across a range of possible directions of research, all of which will affect how we see prehistory in a different way. Improvements in archaeological data and applied aspects of theory will spawn more relevant questions allowing for ever more conscious application of the limited research resources. Developments in technique, in turn, give greater freedom to ask a broader range of questions and through that give the researcher an expanding freedom of approach. It is through seeing the whole endeavour, from the understanding of the building blocks of the carbon cycle to the practicalities of how to make a most meaningful record of a context in the field, as a single connected entity, that the development of our understanding will be most conscious and hence most efficient.

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