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# "Bitter and Twisted"
# 1 Middle Row
# Chipping Norton
# Oxfordshire

## Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers

Martin Bridge, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, Michael Dee, Sanne Palstra, and Lukas Wacker

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Front Cover: “Bitter and Twisted”, Chipping Norton, Oxfordshire. Photograph by Martin Bridge

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SUMMARY
Elm samples were taken from the central and east trusses and their associated timbers in the east-west range roof. Dendrochronological analysis identified three pairs of samples that cross-matched each other. No other cross-matching was identified and no reliable cross-dating was found when these elm series were compared to the oak reference database, although a number of good statistical matches were identified at a position equivalent to the last rings being formed in the early sixteenth century. Samples were subsequently submitted for radiocarbon wiggle-matching which confirmed the spurious nature of the potential cross-dating. Radiocarbon dating was undertaken on fifteen single-ring samples from two timbers, one each from undated elm mean series b&t0506 and b&t810m. Wiggle-matching of these results indicates a felling date in the late AD 1660s or early AD 1670s for the two cross-matched purlins (b&t08 and b&t10) and a felling date in the AD 1670s or early AD 1680s for the two cross-matched principal rafters (b&t05 and b&t06) from the central truss (truss 2).

CONTRIBUTORS
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# CONTENTS

# INTRODUCTION

The investigation of the elm timbers from "Bitter and Twisted", 1 Middle Row, Chipping Norton, contributes to two on-going research programmes, funded by Historic England through its Heritage Protection Commissions programme. One is led by Martin Bridge from the Institute of Archaeology, University College London, whilst the other is led by Victoria Hubbard representing the Chipping Norton Buildings Record in association with the Oxfordshire Buildings Record.

## Developing the dendrochronology of elm in historic buildings

Ring-width dendrochronology of oak timbers from historic buildings in England is well established, with dating having been obtained on more than 3000 buildings (or parts thereof), with nearly one third of these having been funded by Historic England (and its predecessors). Dendrochronological evidence is a valuable component underpinning the discovery and identification of assets in the historic environment, aiding decisions relating to protection, management, and conservation, and enhancing appreciation and enjoyment of these buildings.

During this work on oak timbers, a significant amount of historic fabric constructed from timbers other than oak, most notably elm, has been identified, but this has previously been rejected as unsuitable for dendrochronological investigation. Elm in buildings has been identified in counties from Cornwall to Kent and up into the Midlands and beyond, but formal records of the presence of elm are scant as such buildings were generally dismissed for dating purposes and thus the presence of elm in the published record is rare. The inability to date historic buildings (or sections of buildings) constructed of elm by ring-width dendrochronology is seen as problematic in some areas of the country which have a comparatively high proportion of such buildings; buildings which nevertheless form a significant part of the historic environment but could not be afforded the same level of understanding in comparison to their oak counterparts.

Prior to the start of this elm project, only four instances of dating elm by ring-width dendrochronology have been successful (Groves and Hillam 1997; Haddon-Reece *et al* 1989, 1990; Bridge and Miles 2015). Each of these studies involved matching elm with oak from the same site, although the Ashdon, Essex example matched oak chronologies over a wide area (Bridge and Miles 2015). This project aimed to establish whether the use of standard ring-width dendrochronology could be extended to the dating of historic buildings in England where elm (*Ulmus* sp.) is the sole, or predominant species used rather than oak (*Quercus* sp.). A systematic approach was adopted concentrating on elm in the geographical areas where it is most commonly found. Buildings were thus sought that contained a significant number of elm timbers with sufficient numbers of rings that might be matched against either oak timbers in the same building or oak chronologies from the surrounding area (Fig 1).

An article will summarise the overall outcomes of the project (Bridge forthcoming). However, each building sampled for dendrochronology has an associated building survey report or similar publication, whilst the primary archive of the dendrochronological analysis is reported in the Historic England Research Report Series.

## Early Fabric in Chipping Norton Project

This particular building was initially investigated as part of the dendrochronological programme for the Chipping Norton Early Fabric in Historic Towns project but was one of two, the other being 9 Market Street, rejected at assessment stage as the timbers were elm.

Whilst Chipping Norton features in a study on historic towns in Oxfordshire (Rodwell 1975), and some buildings have been recorded and published in detail (eg Simons and Phimester 2005), no systematic research had been undertaken on the buildings of the town before this Early Fabric project.

The project examined vernacular historic buildings in the centre of Chipping Norton, aiming to improve understanding of the morphology and development of the historic town plan and to understand this within the framework of economic and social change. It aimed to identify early plan forms and to understand the dates of the introduction of vernacular architectural details (eg in materials, carpentry, fenestration, and decorative features), thus mapping the survival of early (pre-1900) fabric and revealing the architectural evolution of the town's buildings.

Initially, 21 properties were identified that were thought to be key to understanding the town's architectural development for a programme of comprehensive investigation. Nineteen of these properties were assessed for their suitability for dendrochronology and 12 that contained oak timbers considered suitable for analysis were initially sampled and analysed. Oak timbers from seven of these buildings could be dated by ring-width dendrochronology, whilst radiocarbon wiggle-matching was undertaken for one of the buildings where the ring-width dendrochronology had produced an undated site master chronology.

The results of the project are presented by Rosen and Cliffe (2017). The reports produced on the historic buildings recorded as part of this project by the Chipping Norton Buildings Record/Oxfordshire Buildings Record (OBR) will be deposited in the Oxfordshire Historic Environment Record. The primary archive of the dendrochronological analysis is, as with the elm project, reported in the Historic England Research Report Series.

## Bitter and Twisted, 1 Middle Row

This building is Grade II listed (LEN 1052630) as the Bunch of Grapes Public House, but is now known as "Bitter and Twisted". It is in multi-occupancy, with offices in the rear of the building and upper floors. It sits on the northern edge of the market area in the centre of Chipping Norton, Oxfordshire (Fig 2). Although listed as being of seventeenth-century origin, recent work by the Oxfordshire Building

Record (OBR) has identified a number of early sixteenth-century features (Rosen and Cliffe 2017). They give the following description:

> "It has a four-bay 2½-storey stone range with basement/cellar, running back (East-West) from High Street, probably originally with a second frontage facing south to Market Place but set back from it. Two adjacent subsidiary stone ranges of 2½ storeys and cellars project southwards and form the south-east corner of the block. The western of the two North-South ranges was until *c* AD 1950 a separate shop unit. It was of 3½ storeys over a basement, and had a cellar extending under the Market Place. Its south wall was timber-framed with jetties at first and second floors, and its north wall seems also to have been framed and was separated from the East-West range by a narrow space. Around AD 1950 this range was lowered and rebuilt in stone except for most of the west wall and parts of the east wall. It was incorporated into the public house and given the same floor levels. At the same time the whole of the building's eastern frontage to the High Street was rebuilt in stone with mullioned windows, and the south gable wall of the eastern North-South range was similarly re-faced. Recent single-storey infill replaces a garage and outbuildings on the site of a probable former courtyard at the south-west corner of the block."

The roof to the rear east-west range is all elm. Large but thin principal rafters support two tiers of purlins that are crudely scarfed over the principal rafters and slightly trenched (Fig 3).

## RING-WIDTH DENDROCHRONOLOGY

### Sampling

Fieldwork for the present study was carried out in November 2017, following an initial assessment of the potential for elm dendrochronology beforehand. In the initial assessment, based on the general criteria used for oak timbers, accessible elm timbers with more than 50 rings and where possible traces of sapwood were sought, although slightly shorter sequences are sometimes sampled if little other material is available. Those timbers judged to be potentially useful were cored using a 16mm auger attached to an electric drill. The cores were labelled, and stored for subsequent analysis.

### Methodology

The cores were polished on a belt sander using 80 to 400 grit abrasive paper to allow the ring boundaries to be clearly distinguished. The samples had their tree-ring sequences measured to an accuracy of 0.01mm, using a specially constructed system utilising a binocular microscope with the sample mounted on a travelling stage with a linear transducer linked to a PC, which recorded the ring widths into a dataset. The software used in measuring and subsequent analysis was written by Ian Tyers (2004). Cross-matching was attempted by a combination of visual matching and a process of qualified statistical comparison by computer. The ring-width series were compared for statistical cross-matching, using a variant of the Belfast CROS program (Baillie and Pilcher 1973). Ring sequences were plotted on the computer monitor to allow visual comparisons to be made between sequences.

This method provides a measure of quality control in identifying any potential errors in the measurements when the samples cross-match.

In comparing one oak sample or site master against other samples or chronologies, *t*-values over 3.5 are considered significant, although in reality it is common to find demonstrably spurious *t*-values of 4 and 5 because more than one matching position is indicated. For this reason, dendrochronologists prefer to see some *t*-value ranges of 5, 6, and higher, and for these to be well replicated from different, independent chronologies with both local and regional chronologies well represented, except where imported timbers are identified. Where two individual oak samples match together with a *t*-value of 10 or above, and visually exhibit exceptionally similar ring patterns, they may have originated from the same parent tree. Same-tree matches can also be identified through the external characteristics of the timber itself, such as knots and shake patterns. Lower *t*-values however do not preclude same tree derivation. Threshold values for elm samples are as yet unknown, but are likely to be similar.

Once a tree-ring sequence has been firmly dated in time, a felling date, or date range, is ascribed where possible. With samples which have sapwood complete to the underside of, or including bark, this process is relatively straightforward. Depending on the completeness of the final ring, ie if it has only the spring vessels or earlywood formed, or the latewood or summer growth, a precise felling date and season can be given. If the sapwood is partially missing, or if only a heartwood/sapwood transition boundary survives, then an estimated felling date range can be given for each sample. In oak, the number of sapwood rings can be estimated by using an empirically derived sapwood estimate with a given confidence limit. If no sapwood or heartwood/sapwood boundary survives then the minimum number of sapwood rings from the appropriate sapwood estimate is added to the last measured ring to give a *terminus post quem* (*tpq*) or felled-after date.

A review of the geographical distribution of dated sapwood data from historic oak timbers has shown that a sapwood estimate relevant to the region of origin should be used in interpretation, which in this area is 9–41 rings (Miles 1997). The equivalent values for elm are as yet unknown, but the results of this project suggest that the range of the number of sapwood rings in elm timbers is likely to be much lower. One problem that has been encountered in considering elm is that it has often proved very difficult to determine the position of the heartwood/sapwood boundary, even when it is known that the complete sapwood is present on a timber.

It must be emphasised that dendrochronology can only date when a tree has been felled, not when the timber was used to construct the structure or object under study.

## Results

Details of the samples are given in Table 1, and the locations of the sampled timbers are illustrated in Figure 4. The ring width measurements are given in the Appendix.

Two cores were taken from one of the principal rafters, b&t06a and b&t06b, because the first core broke into two parts between which approximately five rings were lost. The three resultant ring series were cross-matched (b&t06ai v b&t06b at $t$ = 3.4; b&t06aii v b&t06b at $t$ = 10.3) to form a single representative timber series, b&t06 which was used in subsequent analysis.

Cross-matching between the ring series revealed that b&t05 matched against b&t06 ($t$ = 7.1 with 54 years overlap), b&t07 matched b&t09 ($t$ = 6.7 with 45 years overlap), and b&t08 matched b&t10 ($t$ = 8.2 with 74 years overlap). The similarity of their plots (Figs 5–7) suggests the possibility that each of these pairs of timbers could be derived from individual parent trees. Each pair was combined into a single series, b&t56m, b&t79m, and b&t810m for further analysis. These three combined series were compared to each other and the remaining individual series but no further cross-matching was identified. All series were then compared with the oak reference database. Although a number of tenuous possible dating positions were identified for b&t56m and b&t810m, as well as for the four individual component series, the evidence was inconsistent and hence considered inconclusive.

It was, however, noticed that b&t56m gave a number of matches at a position of the outside ring possibly matching AD 1519 (Table 2a), and b&t810m gave matches for the outside ring possibly being AD 1516 (Table 2b), and thus the two series were re-assessed at these positions. The 'match' between these two mean series at this position was not statistically significant ($t$=0.6) but visual comparison of the ring-width plots showed some similarities, although the highly variable nature of the elm ring-width series, particularly the regular occurrence of bands of narrow rings, is highlighted (Fig 8). Since the analysis of elm is experimental, the two series were combined at this position to form a new series, bitwst2m. This mean series gave good matches to the oak database (Table 2c), much improved over those for the individual paired series, and with the prospect of the timbers having been felled within a few years of each other, it was proposed that the matches found could represent an actual felling date. It is important to note however that these matches were subsequently shown to be erroneous by the radiocarbon wiggle-matching reported below. This is significant, as it shows that a much higher threshold for accepting elm matches against oak data may be necessary for elm to be considered securely dated. Another case from Fulham Palace, London (Bridge *et al* 2020), also shows that matching against the oak database can be misleading. This is discussed further in Bridge (forthcoming).

The cores b&t05 and b&t06 both retained bark edge indicating that these principal rafters, from the central truss (truss 2), were felled at the same time. Core b&t08 also retained complete sapwood and it is thought likely that the two purlins represented by samples b&t08 and b&t10 were felled at the same time. Neither of the two other purlins, b&t07 and b&t09, retained complete sapwood or any identifiable sapwood but it appears that they are at least broadly coeval. It is noticeable that in all three instances where bark edge is present that the heartwood/sapwood boundary was impossible to determine, so the overall number of sapwood rings could not be determined.

## RADIOCARBON DATING

Following the failure of the ring-width dendrochronology to provide secure calendar dating for either of the pairs of cross-matched samples that had retained bark edge, samples b&t06b and b&t08 were selected for radiocarbon dating and wiggle-matching as they were the longest cross-matched elm samples from each site chronology that retain bark edge (Table 1).

Radiocarbon dating is based on the radioactive decay of $^{14}C$, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more $^{14}C$ is added to it, and so the proportion of $^{14}C$ versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 3, measure the proportion of $^{14}C$ in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Radiocarbon measurements have been obtained from five single annual tree-rings from timber b&t06b, and from 10 single annual tree-rings from timber b&t08 (Table 3; Figs 9–10). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen, the Netherlands in 2019–20 and at the Laboratory of Ion Beam Physics, ETH Zürich in 2019. In Groningen, each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee *et al* 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant $CO_2$ was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma *et al* 1996; Aerts-Bijma *et al* 1997). The graphite was then pressed into aluminium cathodes and dated by AMS (Synal *et al* 2007; Salehpour *et al* 2016). In Zürich, cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (Synal *et al* 2007; Wacker *et al* 2010b). At both laboratories data reduction was undertaken as described by Wacker *et al* (2010c). The facilities maintain a continual programme of quality assurance procedures (Aerts-Bijma *et al* forthcoming; Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977;

Table 3). The quoted δ$^{13}$C values provided by Groningen were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

## WIGGLE-MATCHING

Radiocarbon ages are not the same as calendar dates because the concentration of $^{14}$C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al* 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from b&t06b and b&t08, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 11 and 12.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al* (2004)

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.3 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 11 and 12 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 11 illustrates the chronological model for b&t06b. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 1 of the measured tree-ring series (GrM-21469) was laid down 18 years before the carbon in ring 19 of the series (GrM-21470); Fig 9), with the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 70.5, An: 31.6, n: 5; Fig 10), with only *GrM-21469* having low individual agreement (A: 57). This is within statistical expectation. It suggests that the final ring of b&t06b formed in *cal AD 1671–1684 (95% probability; b&t06b felling*; Fig 10), probably in *cal AD 1673–1682 (68% probability).*

Figure 12 illustrates the chronological model for b&t08. This model incorporates the gaps between each dated annual ring known from tree-ring counting (Fig 10), with the radiocarbon measurements (Table 3) again calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model also has good overall agreement (Acomb: 48.1, An: 22.4, n: 10; Fig 12), with only *ETH-99793* having low individual agreement (A: 8). This is again within statistical expectation. It suggests that the final ring of b&t08 formed in *cal AD 1666–1675 (95% probability; b&t08 felling*; Fig 12), probably in *cal AD 1670–1674 (68% probability).*

Clearly the date estimates produced by the radiocarbon wiggle-matching overlap, and could be compatible with the two mean chronologies, b&t0506 and b&t0810, ending in the same calendar year. There is, however, no significant cross-matching between the mean series at this position (*t*=0.31). If the two series are positioned as if felled in the same year (i.e. b&t06b spanning relative years 31–93, and b&t08 spanning relative years 1–93), then GrM-21470 and ETH-99793, both date ring 49 of the relative sequence, and so should be of the same radiocarbon age. The measurements are, however, significantly different at the 1% significance level (T′=9.7, T′(1%)=6.8, ν=1; Ward and Wilson 1978). This might cast doubt on the contemporaneity of these series, but we note that ETH-99793 is a significantly early outlier in the wiggle-match for b&t08 (A: 8; Fig 12).

We therefore constructed a combined wiggle-match, based on the relative positions of the two dated series if they were felled in the same year (Fig 13). The model has good overall agreement (Acomb: 56.4, An: 18.9, n: 14), with three dates having low individual agreement (*GrM-21469*, A:21; *ETH-99794*, A: 31, and *GrM-21592*, A: 34). This is within statistical expectation. It should be noted that the weighted mean of GrM-21470 and ETH-99793, *relative year 49*, has good individual agreement in this model (A: 111).

The radiocarbon wiggle-matching is, therefore, compatible with the interpretation that the two mean chronologies end in the same year, if ETH-99793 is considered to be a significantly early outlier. If this is the case, then the combined wiggle-match suggests that they end in *cal AD 1669–1676 (95% probability; b&t06b & b&t08 felling*; Fig 13), probably in *cal AD 1670–1674 (68% probability).*

## DISCUSSION

In previous examples of dating elm timbers by ring-width dendrochronology, the elm present in a structure has cross-dated with oak in the same building, and in the case of both Ashdon Street farmhouse, Essex (Bridge and Miles 2015) and Upwich (Groves and Hillam 1997), the elm site chronology also matched very well with oak chronologies from the wider region. The radiocarbon wiggle-matching has indicated a felling date in the late AD 1660s or early AD 1670s for the two cross-matched purlins (b&t08 and b&t10) and in the AD 1670s or early AD 1680s for the two cross-matched principal rafters (b&t05 and b&t06) from the central truss (truss 2). If it is considered plausible that these timbers represent a single felling episode, then this is most likely to have occurred in the earlier AD 1670s. However, none of the various tenuous possible dates identified during ring-width dendrochronological analysis (eg Table 2) were consistent with the radiocarbon wiggle-matching results. The inability to produce a well-replicated site elm chronology for this site significantly reduces the likelihood of obtaining reliable cross-dating for the elm series with the oak reference database, even though one good 'candidate' position was found, and highlights the likely need for employing other complementary scientific dating techniques on sites that comprise only elm timbers.

The presence of various early sixteenth century features noted in the building by Rosen and Cliffe (2017) combined with the identification of felling dates for four roof timbers in the second half of the seventeenth century through radiocarbon wiggle-matching highlights the potential complexities in relation to the historic development of this structure.

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# TABLES

*Table 1. Details of the samples taken from the roof of the east-west range of 1 Middle Row, Chipping Norton*

| Sample number | Timber and position | No of rings | Mean ring width (mm) | Sapwood rings | Mean sensitivity |
|---|---|---|---|---|---|
| b&t01 | North principal rafter to east truss (T3) | 70 | 1.31 | - | 0.20 |
| b&t02 | South principal rafter to east truss (T3) | 84 | 1.08 | - | 0.16 |
| b&t03 | Lower south purlin, bay 3-4 | 34 +30NM | 1.80 | - | 0.29 |
| b&t04 | Collar to east truss (T3) | 67 | 1.13 | - | 0.29 |
| b&t05 | South principal rafter to central truss (T2) | 54 | 1.45 | C | 0.22 |
| b&t06 | North principal rafter to central truss (T2) | 73 | 1.74 | C | 0.26 |
| b&t06ai | ditto (inner) | 29 | 1.67 | - | 0.26 |
| b&t06aii | ditto (outer) | 38 | 1.75 | C | 0.27 |
| b&t06b | ditto | 63 | 1.81 | C | 0.26 |
| b&t07 | North upper purlin, bay 2-3 | 45 | 1.70 | - | 0.27 |
| b&t08 | South upper purlin to bay 2-3 | 93 | 1.19 | C | 0.27 |
| b&t09 | North upper purlin, bay 3-4 | 62 +5C NM | 1.75 | - | 0.19 |
| b&t10 | South upper purlin, bay 3-4 | 74 | 1.20 | - | 0.26 |

C = complete sapwood, winter felled; NM = presence of unmeasured rings

*Table 2a: Statistical matches found for the combined elm sequence b&t56m against the oak database at a position corresponding to the outer ring having been formed in AD 1519 (subsequently proved erroneous)*

| Source region: | Chronology name: | Publication reference: | File name: | Span of chronology (AD) | Overlap (years) | *t*-value |
|---|---|---|---|---|---|---|
| Berkshire | Bailiff's Cottage, Barkham | (Miles and Worthington 2000) | bcb1 | 1470–1559 | 50 | 5.2 |
| Sussex | Causeway, Horsham | (Bridge 2002) | HORSHAM | 1394–1513 | 67 | 5.1 |
| Suffolk | Bellframe, All Saints Church, Hitcham | (Bridge *et al* forthcoming) | HITCHAM | 1425–1511 | 65 | 4.8 |
| Kent | Chartwell | (Bridge 2008) | CHARTWLL | 1440–1514 | 68 | 4.7 |
| Surrey | Vann, Hambledon | (Miles and Worthington 2000) | VANN | 1404–1593 | 73 | 4.5 |
| Kent | Stonepitts Manor, Seal | (Arnold *et al* 2003) | KSMASQ05 | 1445–1542 | 73 | 4.4 |

*Table 2b: Statistical matches found for the combined elm sequence b&t810m against the oak database at a position corresponding to the outer ring having been formed in AD 1516 (subsequently proved erroneous)*

| Source region: | Chronology name: | Publication reference: | File name: | Span of chronology (AD) | Overlap (years) | *t*-value |
|---|---|---|---|---|---|---|
| Berkshire | Shaw House, Newbury | (Miles *et al* 2004) | SHAW1 | 1391–1579 | 93 | 6.1 |
| Shropshire | Shrewsbury Abbey Church | (Nayling 1999) | SACM2 | 1375–1493 | 70 | 5.6 |
| Hampshire | St Michael's Cottage, Chilbolton | (Miles *et al* 2007) | CHLBLTN1 | 1421–1554 | 93 | 5.5 |
| Hampshire | Home Farm Barn, Farleigh Wallop | (Miles *et al* 2006) | FRLWLLP1 | 1368–1575 | 93 | 5.4 |
| Hampshire | Bramley Manor | (Miles and Worthington 1999) | BRAMLEY | 1364–1545 | 93 | 5.4 |
| West Sussex | Jarvis, Steyning | (Miles *et al* 2007) | JARVIS1 | 1384–1514 | 91 | 5.3 |
| Hampshire | Castlebridge Cottages, North Warnborough, | (Miles and Worthington 1997) | CSTLBRDG | 1347–1532 | 93 | 5.2 |
| Gloucestershire | Owlpen Manor | (Miles and Bridge 2010) | OWLPEN | 1424–1585 | 93 | 4.9 |
| Oxfordshire | Charlbury Church | (Miles and Bridge 2013) | CHRLBRY | 1404–1516 | 93 | 4.9 |

*Table 2c: Statistical matches found for the combined elm sequence bitwst2m against the oak database at a position corresponding to the outer ring having been formed in AD 1519 (subsequently proved erroneous)*

| Source region: | Chronology name: | Publication reference: | File name: | Span of chronology (AD) | Overlap (years) | *t*-value |
|---|---|---|---|---|---|---|
| Oxfordshire | Charlbury Church | (Miles and Bridge 2013) | CHRLBRY | 1404–1516 | 93 | 6.8 |
| Gloucestershire | Owlpen Manor | (Miles and Bridge 2010) | OWLPEN | 1424–1585 | 96 | 6.5 |
| Berkshire | Shaw House, Newbury | (Miles *et al* 2004) | SHAW1 | 1391–1579 | 96 | 6.2 |
| Berkshire | Greenham Mill, Newbury | (Miles and Worthington 2002) | GREENHAM | 1373–1589 | 96 | 6.2 |
| West Sussex | Jarvis, Steyning | (Miles *et al* 2007) | JARVIS1 | 1384–1514 | 91 | 6.0 |
| London | Wolsey Buttery Roof, Hampton Court | (Miles and Bridge 2013) | HMPTNCT4 | 1340–1516 | 93 | 6.0 |
| Buckinghamshire | Chenies Manor | (Miles *et al* 2004) | CHENIES1 | 1370–1551 | 96 | 5.9 |
| Warwickshire | Stoneleigh Abbey, Stoneleigh | (Howard *et al* 2000) | STOHSQ03 | 1405–1546 | 96 | 5.9 |
| Oxfordshire | Dower House, West Hanney | (Miles *et al* 2005) | WHANNEY | 1390–1517 | 94 | 5.8 |
| Warwickshire | Kenilworth Castle | (Howard *et al* 2006) | KNWESQ01 | 1354–1532 | 96 | 5.8 |
| Warwickshire | Cromwell Cottage, Tile Hill | (Arnold and Howard 2007) | COVBSQ01 | 1345–1575 | 96 | 5.8 |
| Hampshire | Roundhead Cottage, Old Basing | (Bridge *et al* 2010) | RONDHD1 | 1362–1550 | 96 | 5.8 |
| Hampshire | Church Cottage, Basingstoke | (Miles *et al* 2007) | BSNGSTK1 | 1364–1541 | 96 | 5.7 |

*Table 3: Radiocarbon measurements and associated δ13C values from elm samples b&t06b and b&t08*

| Laboratory Number | Sample | Radiocarbon Age (BP) | $\delta^{13}C_{AMS}$ (‰) | $\delta^{13}C_{IRMS}$ (‰) |
|---|---|---|---|---|
| GrM-21469 | b&t06b, ring 1 (*Ulmus* sp.) | 328±15 | | −20.97±0.15 |
| GrM-21470 | b&t06b, ring 19 (*Ulmus* sp.) | 316±11 | | −24.46±0.15 |
| GrM-21472 | b&t06b, ring 34 (*Ulmus* sp.) | 285±16 | | −24.23±0.15 |
| GrM-21592 | b&t06b, ring 43 (*Ulmus* sp.) | 216±16 | | −24.66±0.15 |
| GrM-21473 | b&t06b, ring 62 (*Ulmus* sp.) | 173±16 | | −25.04±0.15 |
| ETH-99789 | b&t08, ring 4 (*Ulmus* sp.) | 327±13 | −25.2 | |
| ETH-99790 | b&t08, ring 25 (*Ulmus* sp.) | 359±13 | −23.6 | |
| ETH-99791 | b&t08, ring 30 (*Ulmus* sp.) | 357±13 | −23.9 | |
| ETH-99792 | b&t08, ring 39 (*Ulmus* sp.) | 349±13 | −24.6 | |
| ETH-99793 | b&t08, ring 49 (*Ulmus* sp.) | 369±13 | −24.1 | |
| ETH-99794 | b&t08, ring 55 (*Ulmus* sp.) | 337±13 | −25.2 | |
| ETH-99795 | b&t08, ring 58 (*Ulmus* sp.) | 305±13 | −24.2 | |
| ETH-99796 | b&t08, ring 71 (*Ulmus* sp.) | 273±13 | −24.0 | |
| ETH-99797 | b&t08, ring 82 (*Ulmus* sp.) | 211±13 | −23.9 | |
| ETH-99798 | b&t08, ring 90 (*Ulmus* sp.) | 182±13 | −23.7 | |

# FIGURES

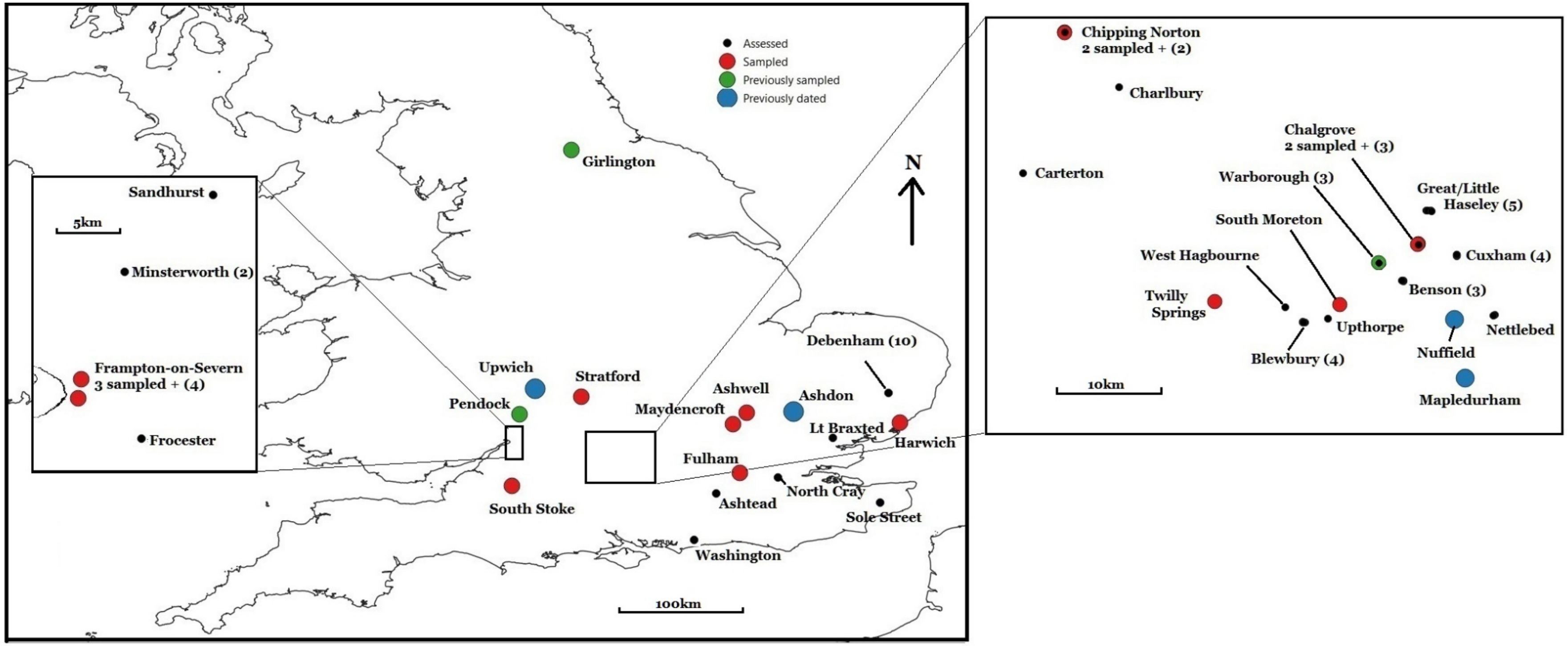


*Figure 1: Map showing the distribution of sites sampled, some of which were dated, prior to the start of this project, and sites assessed and sampled properties for this project. Numbers in brackets after a place name represent the number of properties assessed in that location*


*Figure 2: Map to show "Bitter and Twisted" on Middle Row in Chipping Norton, marked in red. Scale: top right 1:15000; bottom 1:2000. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England*

*Figure 3: Detail of truss, showing the collar pegged over the principal rafter, and the lower purlins crudely scarfed over the principal rafter and slightly trenched (photograph Martin Bridge)*

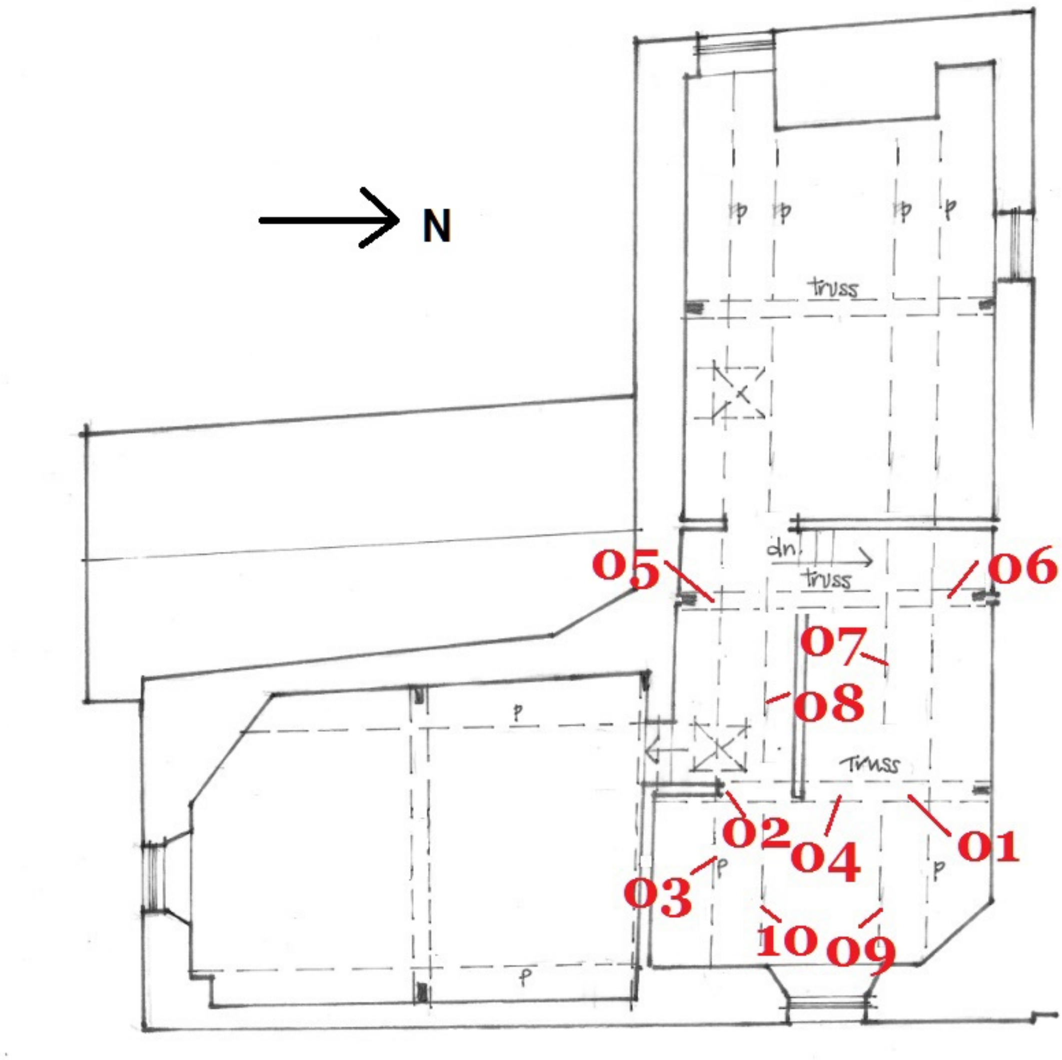


*Figure 4: Sketch plan of the second floor of 1 Middle Row, Chipping Norton, showing the approximate positions of the timbers sampled, adapted from an original drawing by the Oxfordshire Buildings Record*

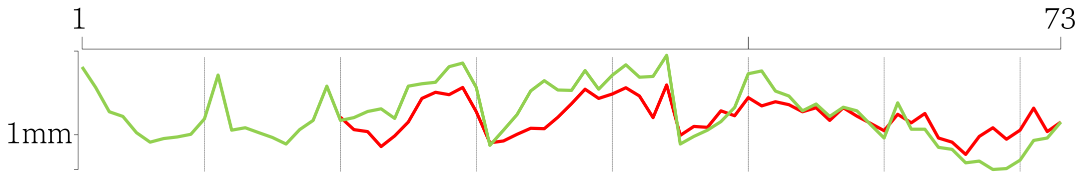


*Figure 5: Plots of b&t05 (red; relative years 20–73) and b&t06 (green; relative years 1–73) showing their similarity in growth. The y-axis is ring width on a logarithmic scale*

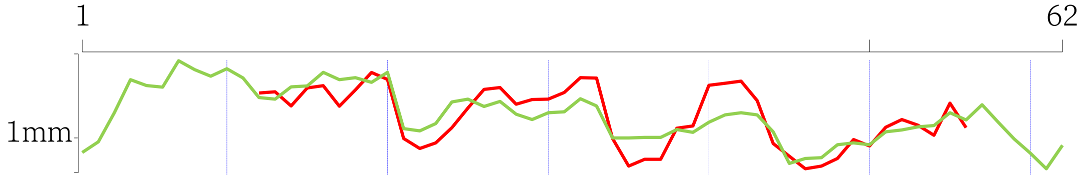


*Figure 6: Plots of b&t07 (red; relative years 12–56) and b&t09 (green; relative years 1–62) showing their similarity in growth. The y-axis is ring width on a logarithmic scale*

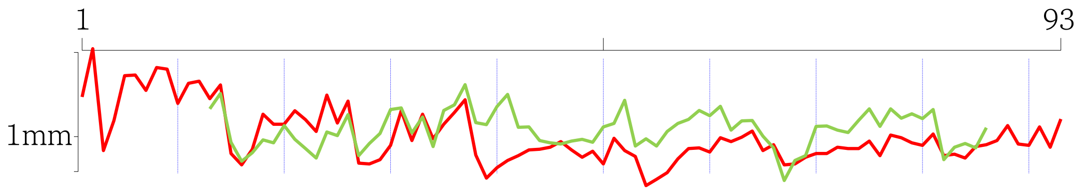


*Figure 7: Plots of b&t08 (red; relative years 1–93) and b&t10 (green; relative years 13–86) showing their similarity in growth. The y-axis is ring width on a logarithmic scale*

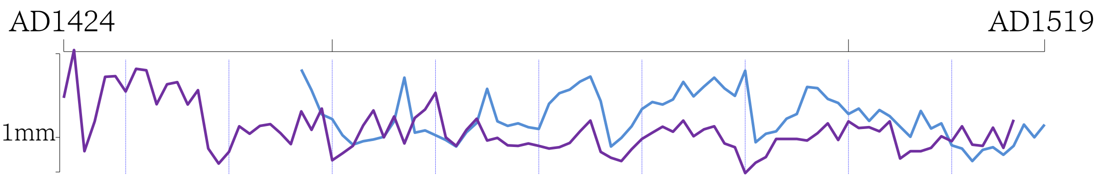


*Figure 8: Plots of b&t56m (purple) and b&t810m (blue) at positions corresponding to their experimental erroneous position against the oak database for the combined series bitwst2m. The y-axis is ring width on a logarithmic scale*

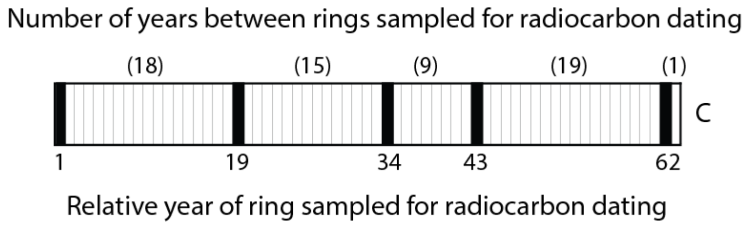

*Figure 9: Schematic illustration of sample b&t06b to locate the single-ring sub-samples submitted for radiocarbon dating. C = bark edge, winter felled*

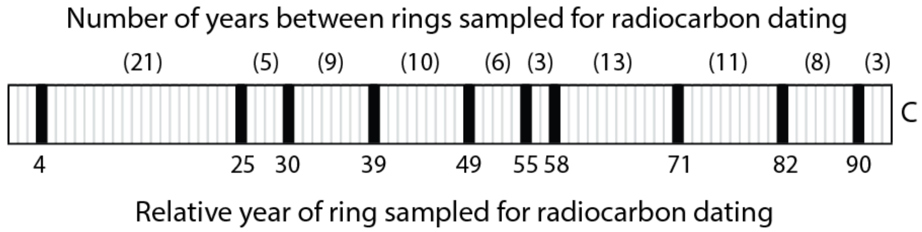

*Figure 10: Schematic illustration of sample b&t08 to locate the single-ring sub-samples submitted for radiocarbon dating. C = bark edge, winter felled*

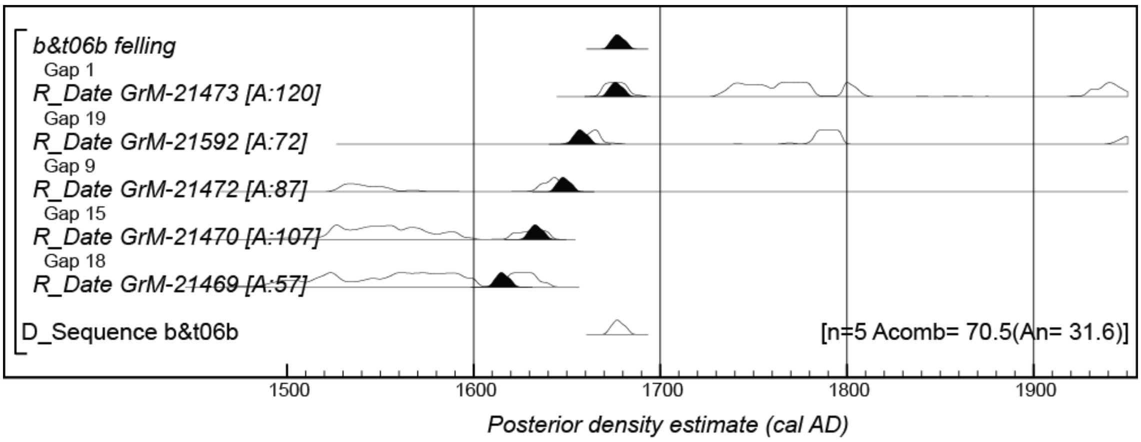

*Figure 11. Probability distributions of dates from timber b&t06b. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'b&t06b felling' is the estimated date when the tree which produced timber b&t06b was felled. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly*

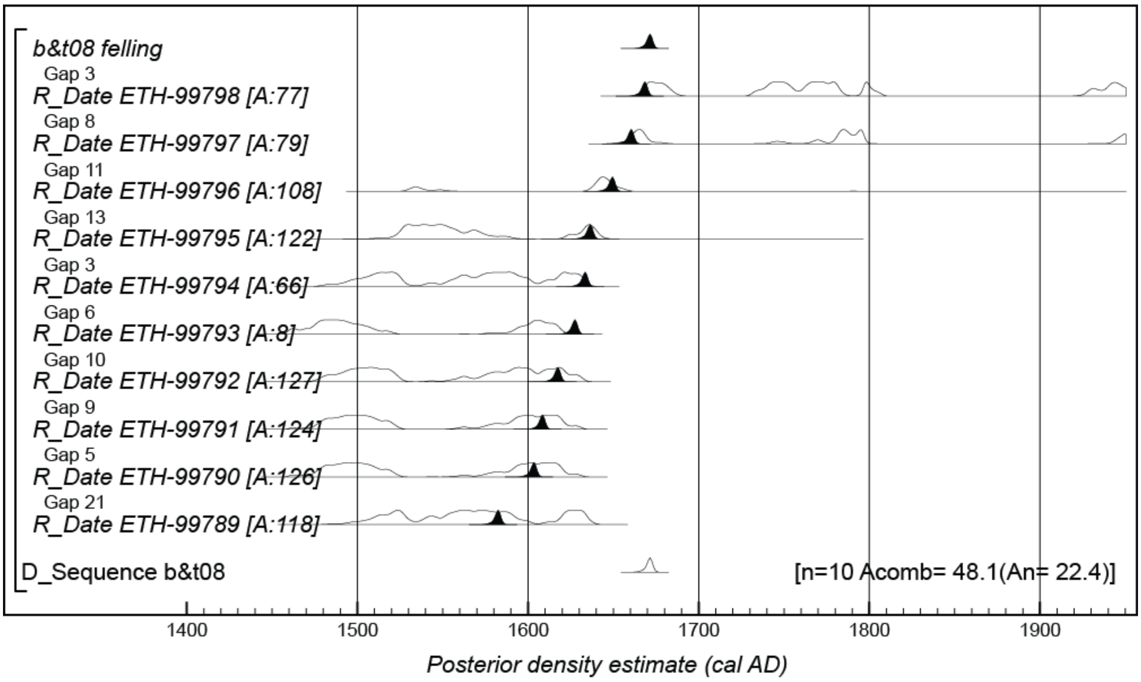


*Figure 12. Probability distributions of dates from timber b&t08. The format is identical to that of Figure 11. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly*

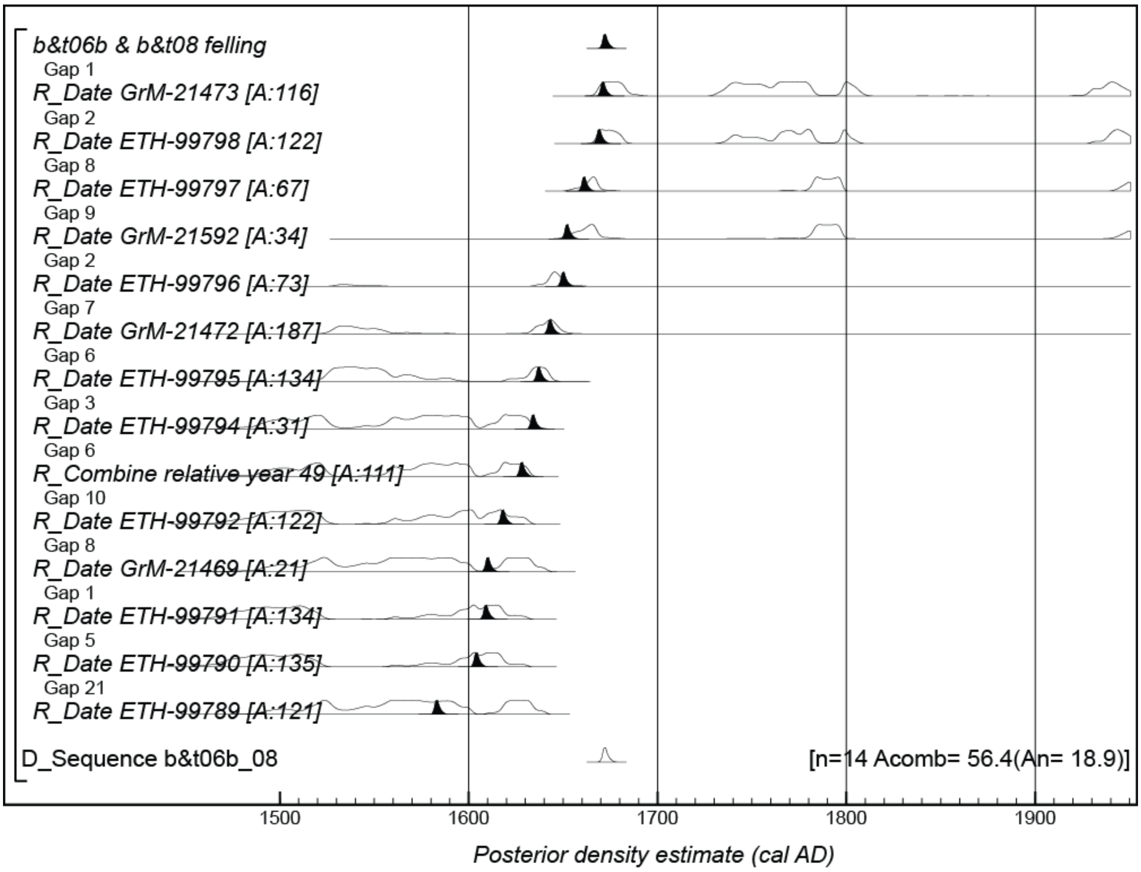


*Figure 13. Probability distributions of dates from timbers b&t06b and b&t08, following the assumption that both chronologies end in the same year. The format is identical to that of Figure 11. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly*

# APPENDIX

Ring width values (0.01mm) for the sequences measured

b&t01

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 639 | 311 | 246 | 248 | 421 | 127 | 124 | 89 | 113 | 70 |
| 87 | 89 | 78 | 74 | 101 | 73 | 78 | 92 | 87 | 87 |
| 81 | 63 | 69 | 77 | 81 | 84 | 81 | 74 | 82 | 77 |
| 103 | 116 | 102 | 97 | 82 | 92 | 109 | 104 | 108 | 107 |
| 136 | 161 | 176 | 206 | 159 | 133 | 125 | 159 | 113 | 130 |
| 142 | 274 | 157 | 142 | 138 | 138 | 121 | 167 | 142 | 193 |
| 142 | 199 | 192 | 82 | 89 | 77 | 77 | 52 | 41 | 60 |

b&t02

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 143 | 143 | 119 | 126 | 146 | 113 | 119 | 121 | 152 | 138 |
| 144 | 108 | 106 | 110 | 115 | 115 | 104 | 89 | 94 | 68 |
| 78 | 79 | 84 | 72 | 80 | 82 | 80 | 99 | 111 | 97 |
| 103 | 128 | 114 | 175 | 155 | 137 | 99 | 79 | 78 | 99 |
| 80 | 90 | 82 | 69 | 73 | 80 | 75 | 58 | 61 | 56 |
| 57 | 61 | 67 | 67 | 55 | 65 | 91 | 78 | 76 | 76 |
| 92 | 126 | 72 | 80 | 85 | 72 | 91 | 104 | 97 | 86 |
| 119 | 112 | 126 | 198 | 146 | 248 | 185 | 308 | 353 | 188 |
| 95 | 81 | 96 | 81 | | | | | | |

b&t03

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 520 | 410 | 330 | 94 | 85 | 103 | 188 | 280 | 378 | 247 |
| 378 | 132 | 135 | 211 | 371 | 254 | 196 | 181 | 251 | 258 |
| 184 | 151 | 133 | 135 | 94 | 87 | 63 | 37 | 45 | 41 |
| 36 | 35 | 31 | 48 | | | | | | |

b&t04

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 51 | 48 | 56 | 33 | 47 | 106 | 87 | 42 | 39 | 63 |
| 51 | 51 | 48 | 51 | 132 | 123 | 89 | 77 | 76 | 56 |
| 61 | 142 | 93 | 140 | 171 | 212 | 186 | 179 | 226 | 217 |
| 165 | 164 | 142 | 140 | 126 | 190 | 208 | 220 | 245 | 68 |
| 42 | 51 | 47 | 55 | 133 | 280 | 170 | 94 | 181 | 242 |
| 149 | 174 | 149 | 174 | 133 | 124 | 113 | 79 | 68 | 130 |
| 66 | 92 | 41 | 37 | 35 | 43 | 44 | | | |

b&t05

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 139 | 110 | 106 | 80 | 98 | 127 | 198 | 222 | 212 | 243 |
| 154 | 86 | 89 | 101 | 113 | 112 | 139 | 179 | 235 | 198 |
| 215 | 242 | 207 | 138 | 255 | 99 | 117 | 115 | 157 | 143 |
| 201 | 172 | 186 | 176 | 154 | 166 | 131 | 166 | 142 | 124 |
| 108 | 147 | 125 | 149 | 94 | 87 | 69 | 97 | 114 | 92 |
| 109 | 165 | 106 | 127 | | | | | | |

b&t06a1

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 358 | 243 | 154 | 141 | 104 | 87 | 93 | 96 | 101 | 135 |
| 249 | 115 | 122 | 108 | 98 | 79 | 104 | 124 | 222 | 137 |
| 128 | 160 | 202 | 128 | 248 | 204 | 204 | 325 | 368 | |

b&t06a2

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 166 | 184 | 307 | 216 | 305 | 398 | 349 | 333 | 468 | 91 |
| 103 | 103 | 95 | 128 | 317 | 385 | 258 | 240 | 167 | 185 |
| 132 | 179 | 163 | 120 | 85 | 181 | 108 | 112 | 77 | 72 |
| 57 | 54 | 54 | 56 | 65 | 90 | 101 | 145 | | |

b&t06b

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 366 | 103 | 107 | 100 | 92 | 89 | 117 | 138 | 277 | 126 |
| 148 | 150 | 125 | 144 | 250 | 319 | 332 | 393 | 403 | 243 |
| 82 | 109 | 146 | 228 | 276 | 298 | 277 | 361 | 255 | 308 |
| 347 | 242 | 266 | 423 | 78 | 92 | 115 | 162 | 206 | 314 |
| 279 | 197 | 175 | 147 | 172 | 150 | 158 | 151 | 122 | 103 |
| 184 | 114 | 110 | 81 | 80 | 61 | 69 | 50 | 50 | 59 |
| 91 | 88 | 109 | | | | | | | |

b&t07

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 232 | 237 | 182 | 255 | 266 | 181 | 246 | 341 | 299 | 99 |
| 82 | 91 | 121 | 175 | 248 | 257 | 188 | 205 | 207 | 234 |
| 309 | 307 | 99 | 59 | 67 | 67 | 120 | 125 | 268 | 278 |
| 290 | 201 | 90 | 71 | 56 | 59 | 68 | 97 | 86 | 122 |
| 141 | 127 | 105 | 192 | 121 | | | | | |

b&t08

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 210 | 517 | 77 | 135 | 312 | 316 | 237 | 363 | 353 | 186 |
| 271 | 282 | 203 | 263 | 73 | 59 | 79 | 152 | 126 | 126 |
| 162 | 137 | 110 | 217 | 129 | 194 | 61 | 60 | 65 | 85 |
| 162 | 93 | 152 | 96 | 126 | 157 | 199 | 71 | 46 | 56 |
| 64 | 70 | 78 | 79 | 82 | 91 | 78 | 68 | 76 | 60 |
| 97 | 77 | 69 | 40 | 45 | 51 | 66 | 80 | 81 | 75 |
| 98 | 91 | 99 | 111 | 77 | 86 | 59 | 60 | 68 | 73 |
| 73 | 82 | 80 | 80 | 92 | 70 | 103 | 98 | 89 | 85 |
| 105 | 70 | 72 | 67 | 83 | 86 | 93 | 123 | 87 | 85 |
| 120 | 82 | 139 | | | | | | | |

b&t09

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 76 | 93 | 160 | 298 | 267 | 259 | 425 | 359 | 318 | 366 |
| 308 | 213 | 207 | 260 | 265 | 342 | 298 | 309 | 283 | 342 |
| 119 | 114 | 131 | 196 | 207 | 180 | 198 | 156 | 141 | 160 |
| 163 | 208 | 182 | 100 | 100 | 101 | 101 | 117 | 111 | 134 |
| 154 | 160 | 154 | 112 | 62 | 68 | 69 | 88 | 91 | 88 |
| 112 | 116 | 123 | 126 | 160 | 140 | 186 | 134 | 98 | 75 |
| 56 | 87 | | | | | | | | |

b&t10

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 168 | 224 | 90 | 63 | 74 | 94 | 89 | 123 | 95 | 80 |
| 67 | 109 | 102 | 151 | 70 | 88 | 106 | 166 | 171 | 107 |
| 144 | 83 | 163 | 181 | 264 | 130 | 125 | 175 | 220 | 119 |
| 120 | 93 | 89 | 87 | 92 | 95 | 90 | 120 | 128 | 197 |
| 84 | 96 | 84 | 110 | 128 | 138 | 163 | 148 | 176 | 113 |
| 134 | 135 | 101 | 81 | 44 | 64 | 70 | 121 | 122 | 113 |
| 108 | 136 | 168 | 121 | 168 | 141 | 153 | 140 | 166 | 65 |
| 82 | 88 | 81 | 118 | | | | | | |

# Historic England Research and the Historic Environment

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A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

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