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Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers from The Old Hall, Dovecote and Barn

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Michael Dee, and Sanne Palstra

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SUMMARY
Tree-ring analysis undertaken on samples from roof timbers of the Dovecote, The Old Hall (hall and cross-wing), and the Barn, resulted in the dating of 25 samples in four site sequences by dendrochronology. Additionally, four samples which form a fifth site sequence have been dated by radiocarbon wiggle-matching.

Site sequence BARDSQ01 contains nine samples from the hall roof and spans the period AD 1418–84; analysis of sapwood suggests all timbers were felled in the AD 1480s, with construction likely to have followed shortly after. A second site sequence, BARDSQ02, contains two samples from the cross-wing roof and spans the period AD 1363–1502; the two timbers are coeval and have a felling date range of AD 1509–34. Four other timbers from the cross-wing form site sequence BARDSQ05, which has been dated by radiocarbon wiggle-matching indicating felling in the mid fifteenth-century AD.

Site sequence BARDSQ03 contains three samples from the roof of the dovecote and spans the period AD 1560–1634 with the timbers being felled in, or around, AD 1634, indicating a construction date shortly after felling in the AD 1630s. Finally, BARDSQ04 contains 11 samples from the barn and spans the period AD 1610–1730, with all timbers thought to have been felled in, or around, AD 1730, with construction again likely to have followed shortly after.

CONTRIBUTORS
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CONTENTS

Introduction ... 1
- Hall roof ... 1
- Cross-wing roof ... 1
- Dovecote ... 1
- Barn ... 2

Sampling ... 2
Tree-ring analysis and results ... 2
Radiocarbon dating ... 3
Wiggle-matching ... 4
Interpretation ... 5
- Hall roof ... 6
- Cross-wing roof ... 6
- Dovecote ... 6
- Barn ... 7

Discussion ... 7
References ... 9
Tables ... 14
Figures ... 19
Data Of Measured Samples ... 33
Appendix: Tree-Ring Dating ... 40
- The Principles of Tree-Ring Dating ... 40
- The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory ... 40
  1. Inspecting the Building and Sampling the Timbers. ... 40
  2. Measuring Ring Widths. ... 45
  3. Cross-Matching and Dating the Samples. ... 45
  4. Estimating the Felling Date. ... 46
  5. Estimating the Date of Construction. ... 47
  6. Master Chronological Sequences. ... 48
  7. Ring-Width Indices. ... 48
- References ... 52

INTRODUCTION

The Barholm Old Hall complex is located about 8km northeast of Stamford and 9km south of Bourne, in the district of South Kesteven, Lincolnshire (Fig 1). The Grade II* listed Old Hall (Listing Entry Number: 1062697) is thought to have originated as an open hall in the fifteenth century, being later floored and extended by the addition of a parlour block to the right, possibly in the seventeenth century. Further alterations were undertaken in the nineteenth century.

A few metres to the north-east of the house is the Scheduled Monument and Grade II listed dovecote (LEN: 1018683, LEN: 1360164). This is a rectangular stone building with a later lean-to extension against its east wall (Fig 2). It has a central stone table, possibly for the preparation of the birds, and stone nesting boxes surviving on three sides. Two timber lanterns are located over the central ridge of the roof to provide a place for the doves to alight. This is thought to slightly pre-date a late seventeenth-century remodelling phase of the hall.

To the north of the house is the single-storey barn (Fig 3) which is thought to date to the early seventeenth century with alterations undertaken in the nineteenth century. To the right of this is a lower range of outbuildings. The barn and outbuildings are Grade II listed (LEN: 1062698).

Hall roof

The roof over this part of the building consists of five smoke-blackened principal rafter and collar trusses, each with arch braces; between these are windbraces and a single tier of clasped purlins (Fig 4). Truss 3 is closed with close studding, beyond this (eastwards) are two further similar trusses which are not smoke blackened.

Cross-wing roof

This roof consists of 34 common rafter frames with collars every fourth frame; there are windbraces to each slope and a single tier of purlins. The collars to frames 27 and 31 are more substantial than those of other frames (Fig 5).

Dovecote

The dovecote roof structure consists of two pairs of trusses framing the two lanterns, between which are common rafters and purlins (Fig 6). Very few historic roof timbers survive as the roof has undergone modification and repair in the nineteenth and twentieth centuries.

Barn

The five-bay barn roof is of principal rafter and collar type with double staggered butt purlins between them; the central bay has wind-bracing. Four horizontal beams span the building at tiebeam level, located between trusses (Fig 7).

SAMPLING

Sampling was initially undertaken at the dovecote only, funded as part of a Historic England grant aided repair project. It was requested by Penny Evans, Historic England, Heritage at Risk Surveyor, to provide independent dating evidence and to enhance understanding of the structure and inform decisions concerning long-term management. Sampling was later extended to the hall and barn to increase the understanding of the complex as a whole and to place the dovecote within the overall historical development of the complex.

Forty core samples were taken from timbers of the dovecote, the hall and cross-wing roofs, and the barn. Each sample was given the code BAR-D and numbered 01–40. Further details relating to the samples can be found in Table 1. The location of all samples has been marked on Figures 8–10. Trusses have been numbered from north to south (cross-wing) or east to west (hall, dovecote, and barn).

TREE-RING ANALYSIS AND RESULTS

Six of the samples, four from the hall roof and two from the cross-wing roof, had too few rings for secure dating and so were rejected prior to measurement. The remaining 34 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 31 samples matching to form six groups.

Firstly, nine samples, all from the hall roof, cross-matched each other (minimum *t*-value of 3.9) and were combined at the relevant offset positions to form BARDSQ01, a site sequence of 67 rings (Fig 11). This was compared against a series of relevant reference chronologies for oak where it was found to cross-date at a first-measured ring date of AD 1418 and a last-measured ring date of AD 1484 (Table 2).

Two of the cross-wing samples also cross-matched (minimum *t*-value of 10.6) to form BARDSQ02, a site sequence of 140 rings (Fig 12). This site sequence was found to span the period AD 1363–1502 when compared to a series of relevant reference chronologies for oak (Table 3).

Of the three samples from the dovecote, BAR-D01 and BAR-D03 cross-matched with a *t*-value of 7.3, whilst BAR-D01 also cross-matched BAR-D02 with a *t*-value of 4.0, albeit with a short overlap. However all three individual ring series produced consistent cross-dating at the indicated offsets and thus they were combined at the relevant offset positions to form BARDSQ03, a site sequence of 75 rings (Fig 13). This site sequence, when compared against a series of relevant reference chronologies for oak, cross-dates securely and consistently at a first ring date of AD 1560 and a last-measured ring date of AD 1634 (Table 4).

Eleven samples, all taken from the barn, also cross-matched each other (minimum *t*-value of 5.1) and were combined at the relevant offset positions to form BARDSQ04, a site sequence of 121 rings (Fig 14). This site sequence was found to match against the reference chronologies at a first ring date of AD 1610 and a last-measured ring date of AD 1730 (Table 5).

Two further site sequences were constructed from samples of the cross-wing roof. BARDSQ05, a site sequence of 70 rings comprising ring series from four timbers, formed at a minimum *t*-value of 5.3 (Fig 15) and BARDSQ06, a site sequence of 69 rings from two timbers, formed at a minimum *t*-value of 6.1 (Fig 16). However, attempts to date these and the remaining ungrouped samples by dendrochronology were unsuccessful.

RADIOCARBON DATING

Following the tree-ring analysis, dating of the cross-wing was still uncertain, as only two samples, BAR-D28 and BAR-D29 which cross-match to form BARDSQ02, could be dated by dendrochronology (Fig 13). Ten of the sampled timbers from the cross-wing remained undated, although six of the common rafters were contained in the undated site master sequences BARDSQ05 and BARDSQ06. For this reason, the longest tree-ring sequence (BAR-D18) from undated site master sequence BARDSQ05, which contains the ring series from four collars in the cross-wing, was selected for radiocarbon dating and wiggle-matching.

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 6, 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).

Four radiocarbon measurements have been obtained from single annual tree-rings from timber BAR-D18 (Table 6). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to subsampling, 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. 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). Data reduction was undertaken as described by Wacker *et al* (2010). The facility maintains a continual programme of quality assurance procedures (Aerts-Bijma *et al* forthcoming), 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 6). The quoted $\delta^{13}C$ values 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, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 17.

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 Figure 17 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 17 illustrates the chronological model for BAR-D18. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 3 of the measured tree-ring series (GrM-18554) was laid down 56 years before the carbon in ring 59 of the series (GrM-18555; Fig 18), with the radiocarbon measurements (Table 6) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 110.6, An: 35.4, n: 4), and all four dates have good individual agreement (A: > 60.0). It suggests that the final ring of BAR-D18 formed in *cal AD 1444–1457 (95% probability; BAR-D18 (felling)*; Fig 17), probably in *cal AD 1447–1455 (68% probability)*. As complete sapwood was retained on this timber (Table 1), this date estimate is also that of when the parent tree was felled.

BAR-D18 is part of site sequence BARDSQ05, which contains four timbers (Fig 15). The overall variation in the relative date of the heartwood/sapwood boundaries of these timbers is only 16 years, and so it is very likely that they were all derived from trees felled as part of a single episode of felling from a single woodland source. This felling episode occurred in *cal AD 1444–1457 (95% probability; BAR-D18 (felling)*; Fig 17), probably in *cal AD 1447–1455 (68% probability)*.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 25 samples, and the radiocarbon wiggle-matching has dated a further four samples from the cross-wing (Fig 19). These are discussed by area below. Felling date ranges have been calculated using the estimate that 95% of mature oak trees in this area have between 15 and 40 sapwood rings.

Hall roof

Nine of these samples have been dated by dendrochronology, three of which have complete sapwood. Two of these have the last-measured ring date of AD 1480, the felling date for the two timbers represented. The third sample with complete sapwood has the slightly later last-measured ring, and hence felling, date of AD 1484. The other six dated samples all have the heartwood/sapwood boundary ring, the dates of which are broadly contemporary ranging from AD 1457 (BAR-D05) to AD 1470 (BAR-D04). The average heartwood/sapwood boundary ring date is AD 1463, giving an estimated felling date range of AD 1480–1503 for the timbers represented. One of these samples, BAR-D04, has a last-measured ring date of AD 1482 with incomplete sapwood and, therefore, cannot have been felled earlier than AD 1483 but may have been felled in AD 1484 with sample BAR-D08. The other samples could have been felled in either AD 1480 or AD 1484 or at some other point during the early AD 1480s and, whilst the felling dates may vary slightly within this group, the level of similarity suggests that they are derived from a single woodland source.

Cross-wing roof

Two collars from this roof have been dated by dendrochronology, both of which have similar heartwood/sapwood boundary ring dates. The average of these is AD 1494, allowing an estimated felling date to be calculated for the two timbers represented to within the range AD 1509–34. As well as similar heartwood/sapwood boundary ring dates, these two samples match each other at a value of t = 10.6 and are, therefore, potentially cut from the same tree and hence felled at the same time.

Four common rafters have been dated by radiocarbon wiggle-matching, all four having similar heartwood/sapwood boundary ring dates which suggest that they derived from a single felling episode. This is estimated to have occurred in *cal AD 1444–1457 (95% probability; BAR-D18 (felling)*; Fig 17).

Dovecote

The three samples taken from tiebeams in the dovecote have all been dated by dendrochronology. One of these, BAR-D02, has complete sapwood and the last-measured ring date of AD 1634, the felling date of the timber represented. Both of the other two samples have the heartwood/sapwood boundary, which in both cases is broadly contemporary. The average heartwood/sapwood boundary ring date is AD 1617, allowing an estimated felling date to be calculated for the two timbers represented of AD 1632–57, consistent with these timbers also being felled in, or around, AD 1634.

Barn

Eleven samples taken from the barn roof have been successfully dated by dendrochronology. One of these has complete sapwood and the last-measured ring date of AD 1730, the felling date of the timber represented. Another eight have the heartwood/sapwood boundary ring, the dates of which are broadly contemporary (ranging from AD 1706 (BAR-D33) to AD 1720 (BAR-D39 and BAR-D40) and, combined with the level of similarity between the individual series, suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1715, allowing an estimated felling date to be calculated for the eight timbers represented to within the range AD 1730–55, consistent with these timbers also having been felled in, or around, AD 1730.

The two remaining samples do not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated for them, except to say that with last-measured ring dates of AD 1680 (BAR-D35) and AD 1700 (BAR-D34), this would be estimated to be after AD 1695 and AD 1715, respectively. These *terminus post quem* dates for felling make it possible that these two samples were also felled in AD 1730. The level of cross-matching with the other dated samples in this group suggests that they are likely to be coeval and hence also felled in, or around, AD 1730. Indeed, sample BAR-D35 cross-matches BAR-D39 at $t = 12.6$, a level high enough to suggest that both timbers were potentially derived from the same tree.

DISCUSSION

Tree-ring analysis and radiocarbon wiggle-matching have dated timbers from all sampled areas and have identified five periods of building activity at Barholm Old Hall spanning the mid-fifteenth century to the first half of the eighteenth century.

The earliest dated timbers were found in the cross-wing, where a series of common rafters were felled in the mid-fifteenth century. However, this roof also contains two collars which have been found to be somewhat later, dating to AD 1509–34. These results might suggest that either the rafters are reused and the roof was constructed in the early sixteenth century, or the dated collars were inserted and this is in fact a mid fifteenth-century roof. It should be noted that it is the more substantial collars to frames 27 and 31 that have been dated by dendrochronology. This could support the suggestion that it is they that have been inserted into an existing mid fifteenth-century cross-wing.

Both felling phases identified within the timbers of the cross-wing predate the seventeenth-century date which had previously been suggested as a construction date for the cross-wing. Although evidence suggests that in most historical periods construction took place within a very few years of felling (Miles 2005), this is not the case with reused or inserted timbers. It is of course possible that the rafters were reused from elsewhere, and the construction date of the cross-wing is reflected by the time when the two collars were felled; or the two collars that have been dated could have been inserted (a suggestion potentially supported by their distinctive character); or, indeed, the cross-wing may have been constructed in the seventeenth century utilising a diverse collection of reused timber. Although no obvious signs of reuse or insertion were noted during sampling, the overall interpretation of this roof would benefit from more detailed building survey by a specialist buildings archaeologist.

The hall roof is now known to utilise timber felled in the early AD 1480s, with construction likely to have occurred shortly after. The hall range of The Old Hall was thought to date to the fifteenth century; this dating has now been supported by the dendrochronology which puts construction in the later part of the century.

Three of the few surviving historic timbers of the dovecote are now known to have been felled in, or around, AD 1634 with construction likely to have occurred shortly after. Work is known to have been undertaken on the hall in the late-seventeenth century and it had been suggested that the dovecote might relate to an earlier phase of building activity which would certainly be supported by a construction date in the mid-AD 1630s as suggested by the dendrochronological analysis.

The listing description of the barn suggests construction occurred in the early seventeenth century. However, it is now known that timbers utilised were felled in, or around, AD 1730, giving a date somewhat later than anticipated.

The levels of similarity shown with reference chronologies indicates that the timbers used in all four periods of building activity are likely to be derived from relatively local woodland sources. This is especially noticeable for site sequence BARDSQ04 where it can be seen to match very highly against reference chronologies related to sites in Lincolnshire and Northamptonshire (Table 5).

The level of similarity within each group of timbers suggests a single woodland source was used for each phase of construction. In addition to the possible same tree matches identified above in the cross-wing and barn roof, further examples of potential same tree derivation were identified amongst the timbers of the barn. Samples BAR-D31 and BAR-D32, both taken from the large beams spanning the building, cross-match each other at $t = 13.4$, whilst samples BAR-D37 and BAR-D40, both principal rafters, cross-match each other at $t = 14.4$.

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TABLES

Table 1: Details of samples taken from the Barholm Old Hall complex, Barholm, Lincolnshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Dovecote						
BAR-D01	Tiebeam 2	53	01	1568	1619	1620
BAR-D02	Tiebeam 3	40	13C	1595	1621	1634
BAR-D03	Tiebeam 4	55	h/s	1560	1614	1614
Hall roof						
BAR-D04	North common rafter 1, bay 2	58	12	1425	1470	1482
BAR-D05	South common rafter 1, bay 2	60	22	1420	1457	1479
BAR-D06	South common rafter 3, bay 2	NM	--	----	----	----
BAR-D07	North common rafter 3, bay 3	63	21	1418	1459	1480
BAR-D08	South common rafter 3, bay 3	65	19C	1420	1465	1484
BAR-D09	Collar, truss 3	56	23C	1425	1457	1480
BAR-D10	North purlin, bay 3	NM	--	----	----	----
BAR-D11	Collar, truss 4	NM	--	----	----	----
BAR-D12	North common rafter 2, bay 4	45	18	1435	1461	1479
BAR-D13	North brace, truss 5	63	--	----	----	----
BAR-D14	Collar, truss 5	NM	--	----	----	----
BAR-D15	North purlin, bay 5	50	08	1426	1467	1475
BAR-D16	North principal rafter, truss 6	45	14	1432	1462	1476
BAR-D17	South principal rafter, truss 6	55	19C	1426	1461	1480
Cross-wing roof						
BAR-D18	East common rafter 2	70	17C	----	----	----
BAR-D19	East common rafter 4	62	33C	----	----	----
BAR-D20	West common rafter 4	64	16	----	----	----
BAR-D21	East common rafter 5	55	h/s	----	----	----
BAR-D22	West common rafter 9	45	09	----	----	----
BAR-D23	Collar 10	NM	--	----	----	----

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
BAR-D24	West common rafter 14	59	20C	----	----	----
BAR-D25	Collar 18	64	19C	----	----	----
BAR-D26	East common rafter 22	48	h/s	----	----	----
BAR-D27	West common rafter 22	NM	--	----	----	----
BAR-D28	Collar 27	124	h/s	1363	1486	1486
BAR-D29	Collar 31	131	h/s	1372	1502	1502
Barn						
BAR-D30	Beam 1	96	27C	1635	1703	1730
BAR-D31	Beam 2	89	h/s	1627	1715	1715
BAR-D32	Beam 3	75	04	1645	1715	1719
BAR-D33	Beam 4	68	h/s	1639	1706	1706
BAR-D34	South principal rafter, truss 2	56	--	1645	----	1700
BAR-D35	North principal rafter, truss 2	71	--	1610	----	1680
BAR-D36	Collar, truss 3	84	08	1642	1717	1725
BAR-D37	South principal rafter, truss 5	76	07	1649	1717	1724
BAR-D38	Collar, truss 5	87	h/s	1627	1713	1713
BAR-D39	North principal rafter, truss 6	94	02	1629	1720	1722
BAR-D40	South principal rafter, truss 6	71	h/s	1650	1720	1720

NM = not measured

h/s = the heartwood/sapwood boundary is the last-measured ring

C = complete sapwood retained on sample, last-measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BARDSQ01 and relevant reference chronologies when the first-ring date is AD 1418 and the last-measured ring date is AD 1484

Reference chronology	*t* – value	Span of chronology	Reference
Woodmanton Manor, Clifton-on-Teme, Worcestershire	7.0	AD 1413–1589	Tyers 2001
Gorcott Hall, Redditch, Warwickshire	6.5	AD 1385–1531	Nayling 2006
The Gildhouse, Poundstock, Cornwall	5.8	AD 1405–1543	Arnold and Howard 2007
All Saints Church, Knipton, Leicestershire	5.8	AD 1414–1490	Arnold *et al* 2005
Auld Cottage, Norwell, Nottinghamshire	5.7	AD 1335–1512	Hurford *et al* 2010
Cavendish Arms, Market Place, Dalton-in-Furness, Cumbria	5.6	AD 1407–1537	Arnold and Howard 2014
Wakelyn Old Hall, Hilton, Derbyshire	5.6	AD 1415–1573	Arnold *et al* 2008a
Oakham Castle, Oakham, Rutland	5.3	AD 1383–1620	Arnold and Howard 2013a
Crowle Court barn, Worcestershire	5.3	AD 1412–1496	Hillam 1997
5/6 Kirkgate, Wakefield, West Yorkshire	5.2	AD 1360–1517	Morgan 1982

Table 3: Results of the cross-matching of site sequence BARDSQ02 and relevant reference chronologies when the first-ring date is AD 1363 and the last-measured ring date is AD 1502

Reference chronology	*t* – value	Span of chronology	Reference
Low Harperley Farmhouse, Wolsingham, County Durham	5.6	AD 1356–1604	Arnold *et al* 2006
Leicester's Building, Kenilworth Castle, Warwickshire	5.5	AD 1423–1550	Arnold *et al* 2007a
St Bartholomew's Church, Blore, Derbyshire	5.4	AD 1367–1443	Arnold *et al* 2007b
Chalgrove Manor, Chalgrove, Oxfordshire	5.4	AD 1355–1503	Arnold *et al* 2008b
St Nicholas' Church, Potter Heigham, Norfolk	5.3	AD 1456–1520	Arnold and Howard 2013b
1–3 Northgate, Newark, Nottinghamshire	5.3	AD 1339–1523	Arnold and Howard 2009 unpubl
Broad Street, Leominster, Herefordshire	5.2	AD 1338–1499	Miles 2001
Stoneleigh Abbey, Stoneleigh, Warwickshire	5.1	AD 1400–1570	Howard *et al* 2000
Old Oak House, Pembridge, Herefordshire	5.1	AD 1414–1550	Tyers 2004
St Mary's Church, Strethall, Essex	5.0	AD 1347–1511	Bridge 2004

Table 4: Results of the cross-matching of site sequence BARDSQ03 and relevant reference chronologies when the first-ring date is AD 1560 and the last-measured ring date is AD 1634

Reference chronology	*t* - value	Span of chronology	Reference
Apethorpe Hall, Northamptonshire	5.9	AD 1292–1639	Arnold *et al* 2008c
26 Westgate Street, Gloucester, Gloucestershire	5.9	AD 1399–1622	Howard *et al* 1998a
Old Hat Shop, Tewkesbury, Gloucestershire	5.8	AD 1484–1664	Nayling 2000
Breakspear House, Hillingdon, London	5.5	AD 1574–1694	Arnold and Howard 2011
Olney Bellframe, Buckinghamshire	5.4	AD 1472–1625	Miles *et al* 2009
Swaylands Barn, Penshurst, Kent	5.4	AD 1515–1616	Arnold *et al* 2001
Hill Hall, Theydon Mount, Essex	5.3	AD 1525–1691	Bridge 1999
Bucks Head, 27 High Street, Debenham, Suffolk	5.2	AD 1561–1620	Howard *et al* 2003
New House, Cressing Temple, Essex	5.2	AD 1560–1633	Tyers 1997
Buildwas Abbey, Ironbridge, Shropshire	5.1	AD 1563–1687	Miles 2002

Table 5: Results of the cross-matching of site sequence BARDSQ04 and relevant reference chronologies when the first-ring date is AD 1610 and the last-measured ring date is AD 1730

Reference chronology	*t* - value	Span of chronology	Reference
Apethorpe Hall, Northamptonshire	9.1	AD 1574–1749	Arnold *et al* 2008c
Old Church Cottage, Harmston Road, Aubourn, Lincolnshire	8.5	AD 1629–1743	Arnold and Howard 2006
Old Barn, Shottery, Stratford-upon-Avon, Warwickshire	8.4	AD 1591–1735	Howard *et al* 1996
Post Mill, Kibworth Harcourt, Leicestershire	8.3	AD 1582–1773	Arnold *et al* 2004
De Grey Mausoleum, Flitton, Bedfordshire	8.1	AD 1510–1726	Arnold *et al* 2003
Kirby Hall, Corby, Northamptonshire	7.8	AD 1378–1795	Arnold *et al* forthcoming a
Church Farm, Main Street, Hayton, Nottinghamshire	7.7	AD 1622–1721	Arnold *et al* 2008b
Bay Hall, Bennington, Lincolnshire	7.6	AD 1591–1717	Howard *et al* 1998b
Oakham Castle, Oakham, Rutland	7.4	AD 1598–1737	Arnold and Howard 2013
Beverley Minster, East Yorkshire	7.1	AD 1573–1736	Arnold *et al* forthcoming b

Table 6: Radiocarbon measurements and stable isotope measurements from Barholm Old Hall

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)
GrM-18554	BAR-D18, ring 3 (*Quercus* sp. heartwood)	665±23	−24.37±0.15
GrM-18555	BAR-D18, ring 59 (*Quercus* sp. sapwood)	479±16	−23.28±0.15
GrM-18556	BAR-D18, ring 64 (*Quercus* sp. sapwood)	432±18	−23.40±0.15
GrM-18557	BAR-D18, ring 68 (*Quercus* sp. sapwood)	425±16	−23.81±0.15

FIGURES

Figure 1:Maps to show the location of Barholm Old Hall in Barholm, Lincolnshire, circled. Scale: top right 1:5000; bottom the Old Hall (blue), the dovecote (red), and barn (purple)1:650. © 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 2: The dovecote, photograph taken from the north-west (photograph Alison Arnold)


Figure 3: The barn, photograph taken from the south-west (photograph Alison Arnold)

Figure 4: The hall roof, photograph taken from the east (photograph Alison Arnold)

Figure 5: Cross-wing roof, photograph taken from the north, the collar of frame 27 centre (photograph Alison Arnold)

Figure 6: Dovecote roof, photograph taken from the south-west (photograph Alison Arnold)

Figure 7: Barn roof, photograph taken from the north-east (photograph Alison Arnold)

Figure 8: Plan of the dovecote, showing the location of sampled timbers BAR-D01–3 (after Archaeological Project Services)

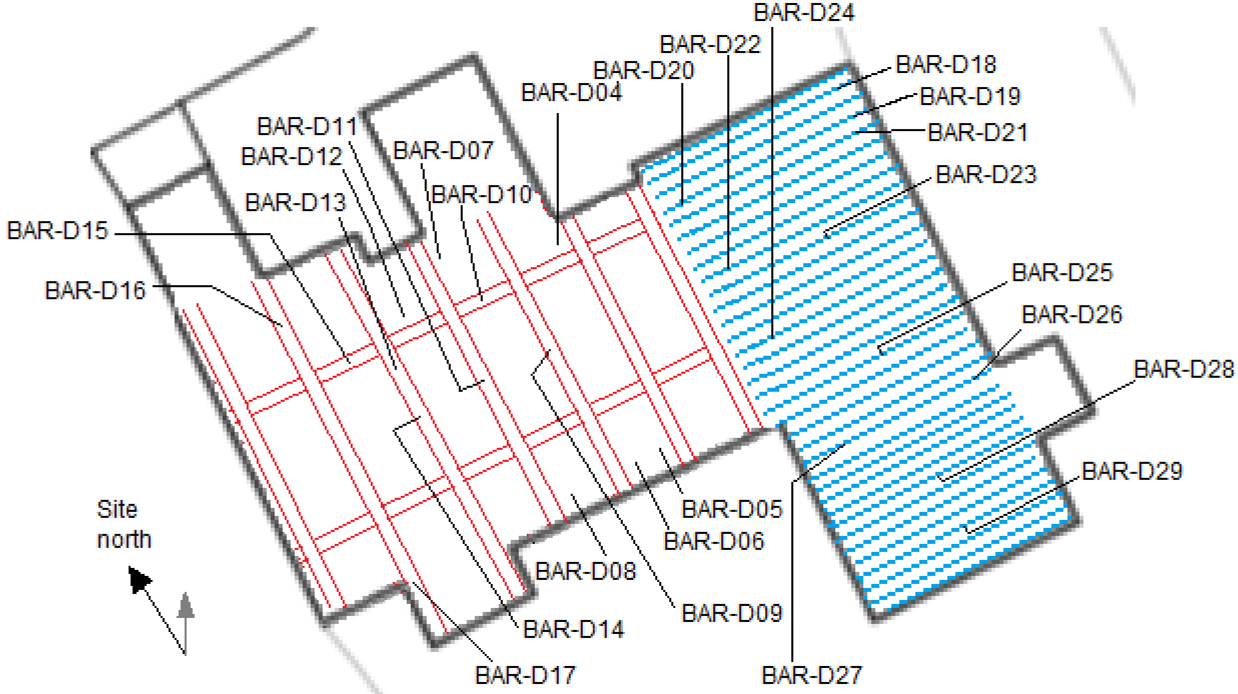

Figure 9: Plan of the hall and cross-wing roofs, showing the location of samples BAR-D04–29 (after Archaeological Project Services)

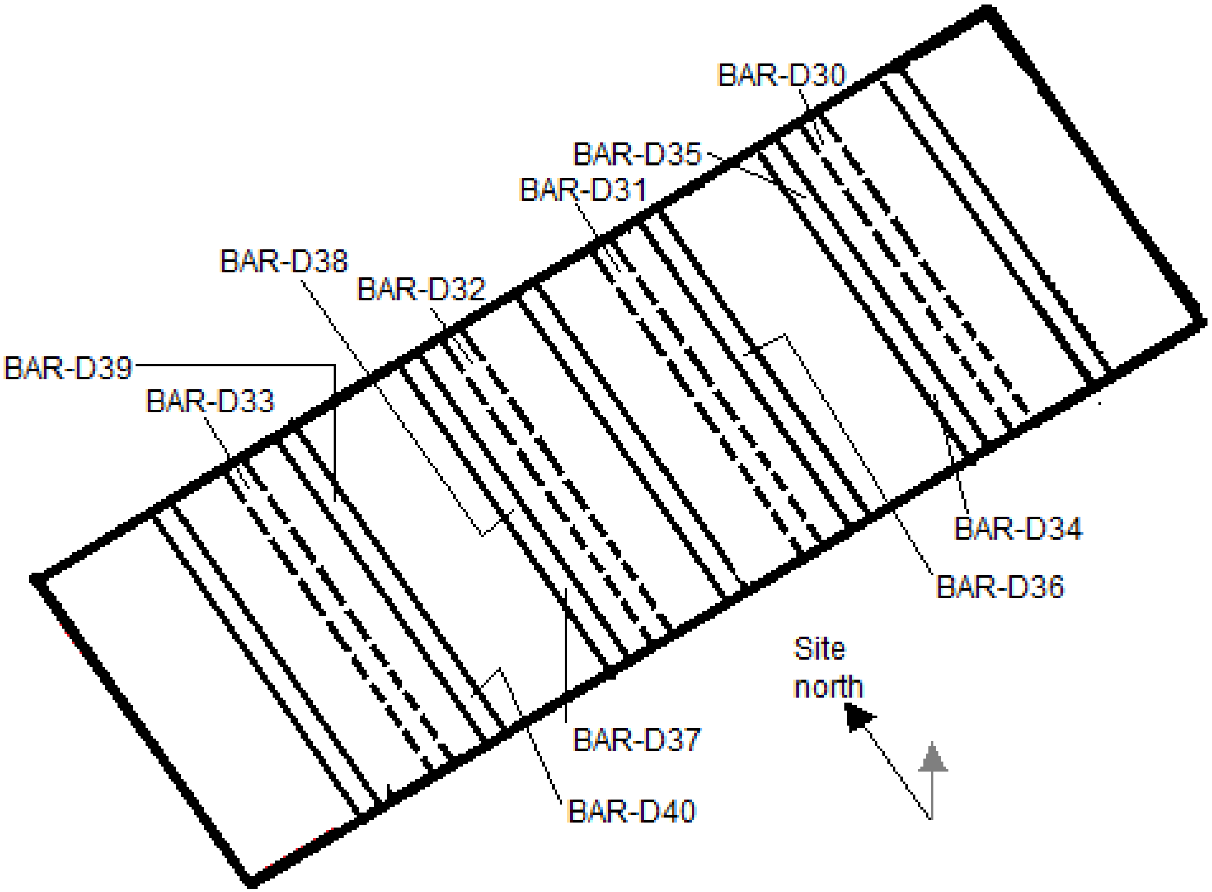

Figure 10: Sketch plan of the Barn, showing the location of samples BAR-D30–40

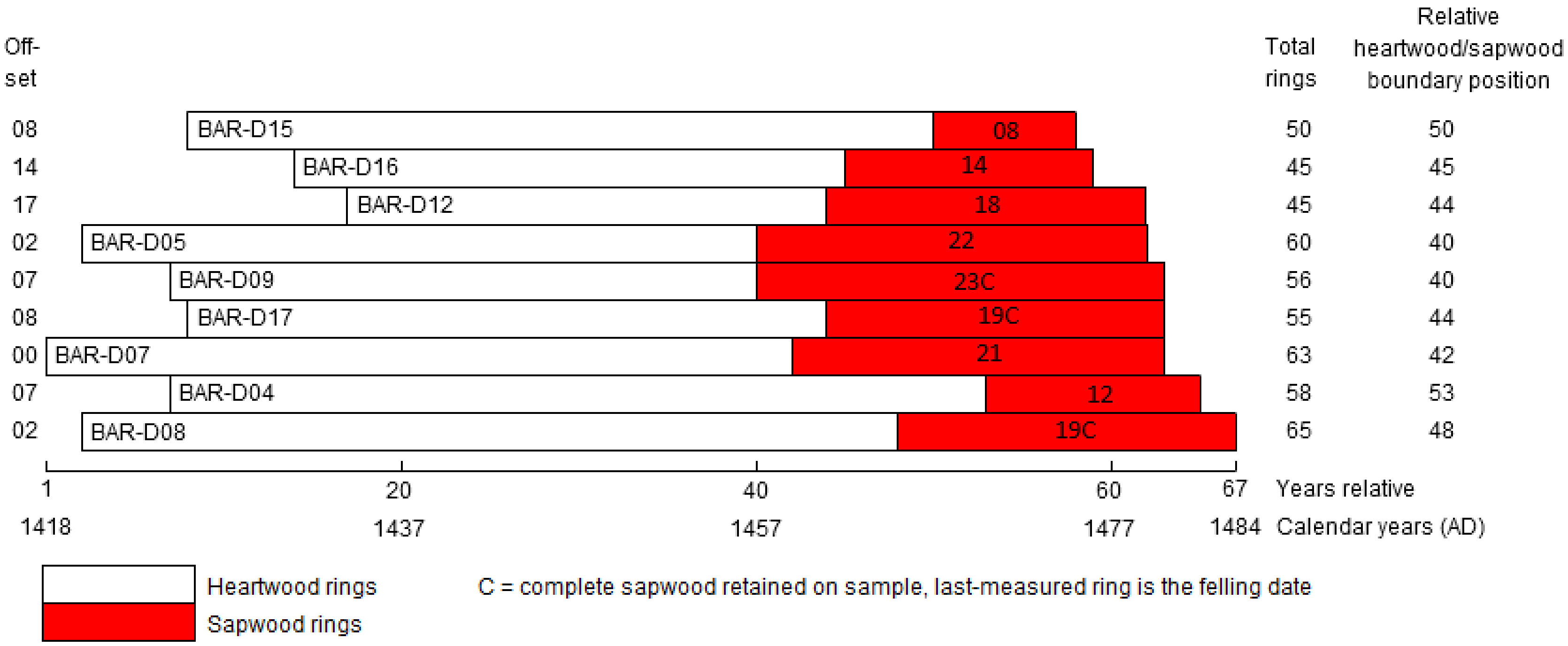

Figure 11: Bar diagram to show the relative position of samples from the hall roof in site sequence BARDSQ01

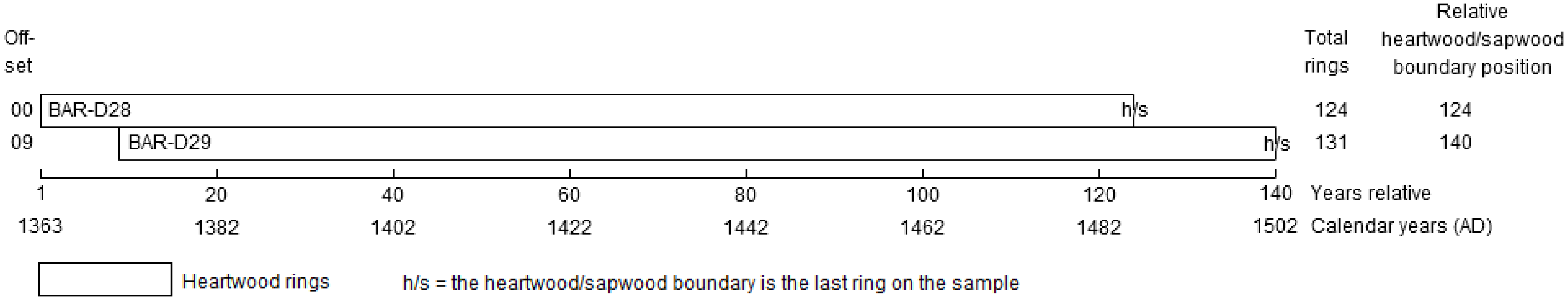

Figure 12: Bar diagram to show the relative position of samples from the cross wing roof in site sequence BARDSQ02

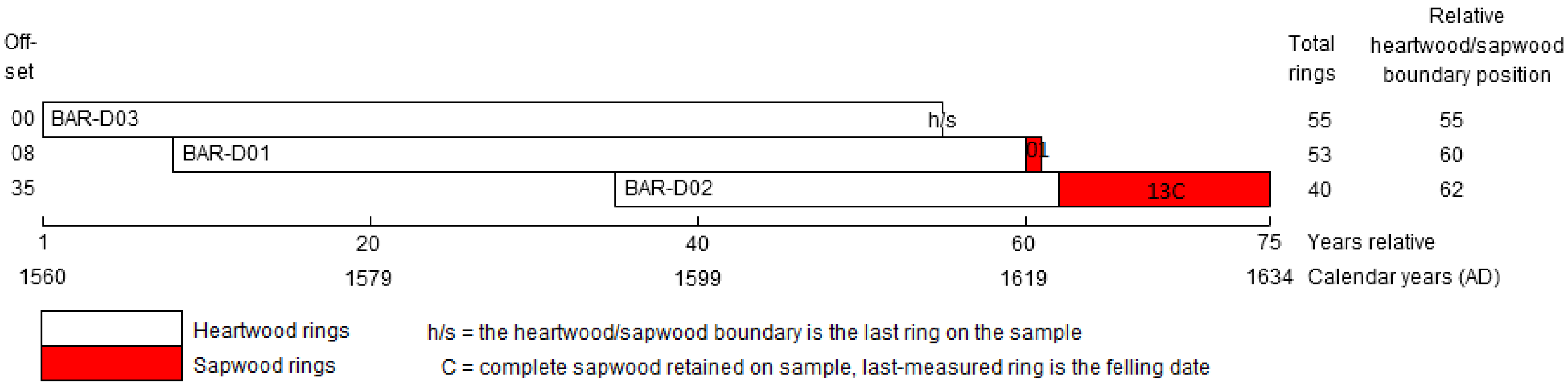

Figure 13: Bar diagram to show the relative position of samples from the dovecote roof in site sequence BARDSQ03

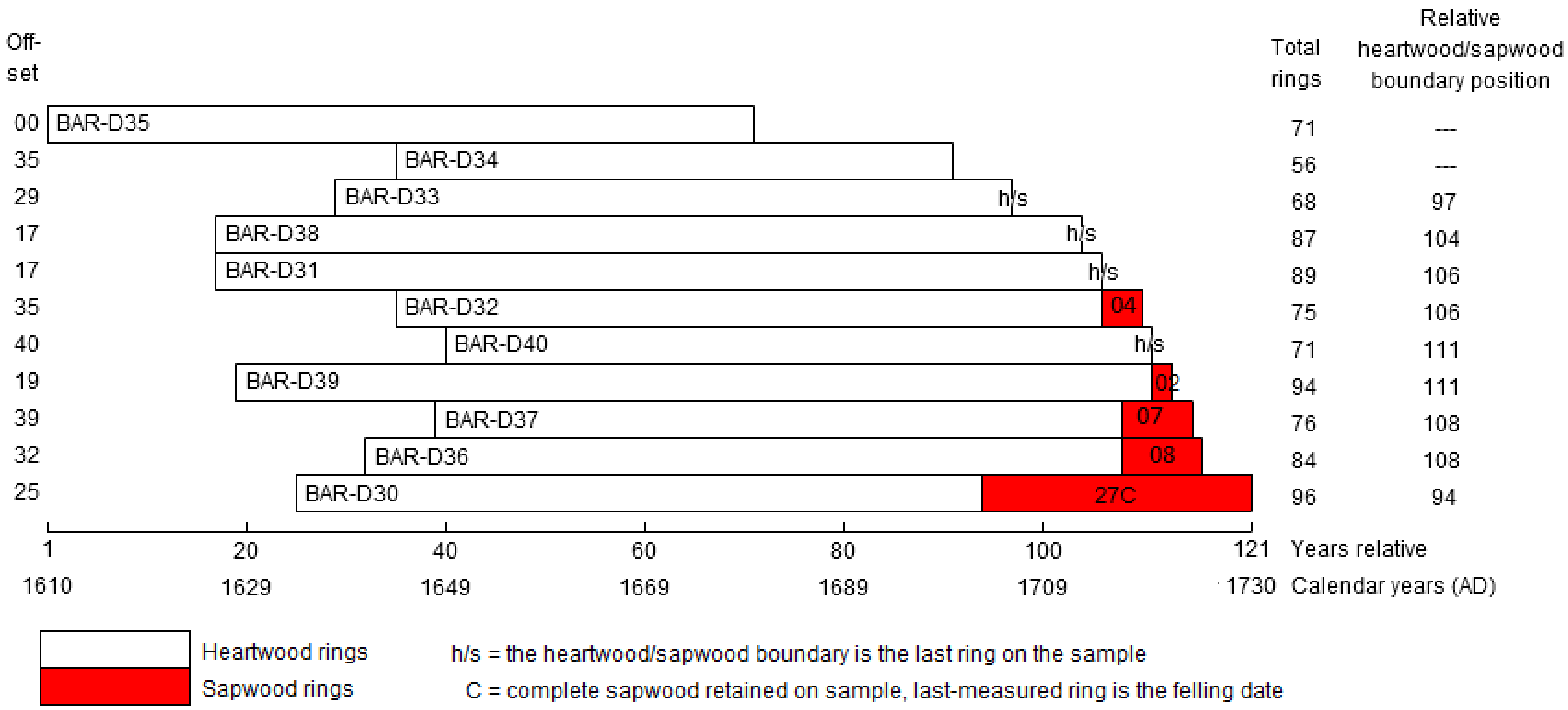

Figure 14: Bar diagram to show the relative position of samples from the barn in site sequence BARDSQ04

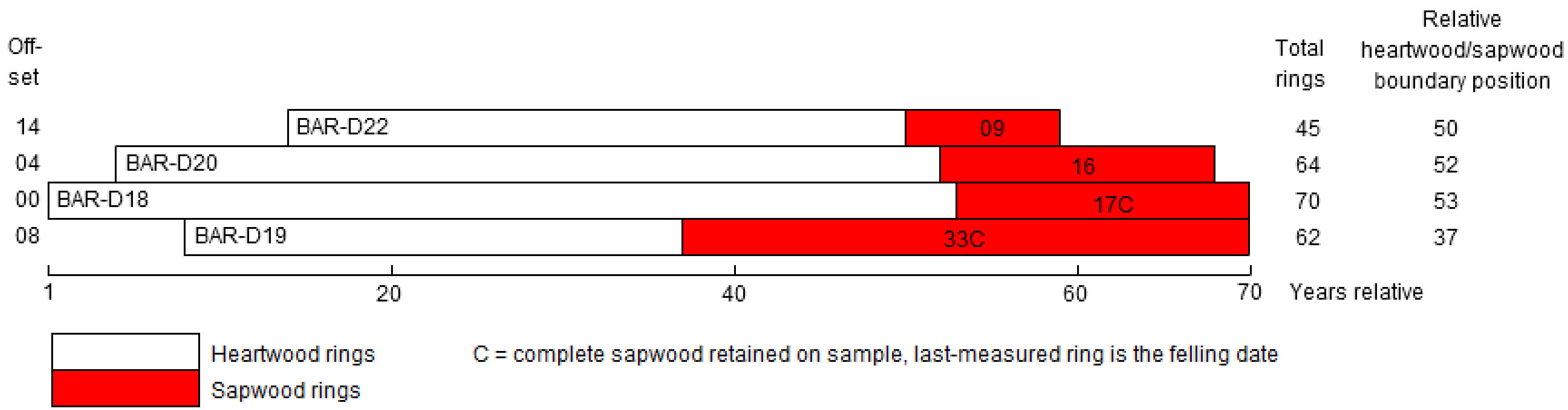

Figure 15: Bar diagram to show the relative position of samples from the cross wing roof in undated site sequence BARDSQ05

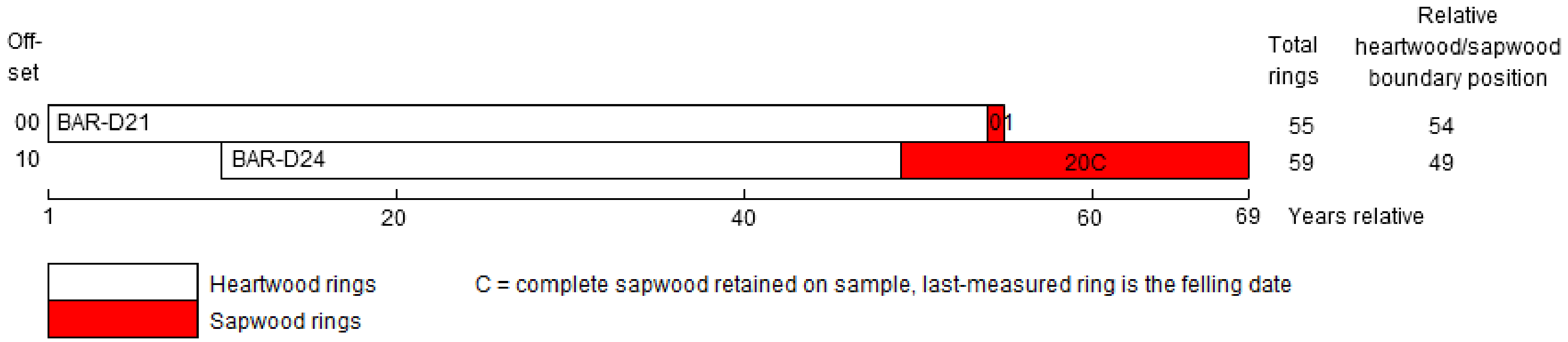

Figure 16: Bar diagram to show the relative position of samples from the cross wing roof in the undated site sequence BARDSQ06

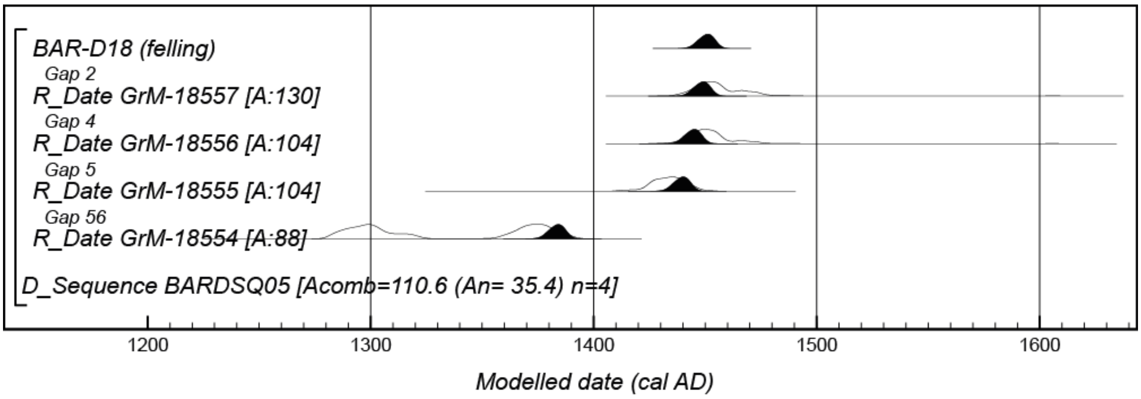

Figure 17: Probability distributions of dates from timber BAR-D18, east common rafter 2 from the cross-wing. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple 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 'BAR-D18 felling' is the estimated date when the timbers in site master sequence BARDSQ05 were felled. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

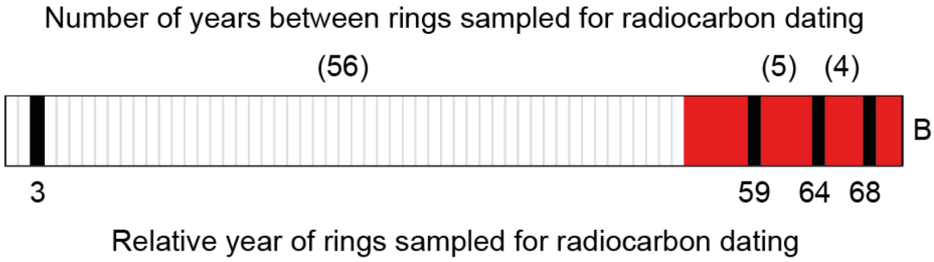

Figure 18: Schematic illustration of sample BAR-D18 to locate the single-ring sub-samples submitted for radiocarbon dating (heartwood rings in white; sapwood rings in red)

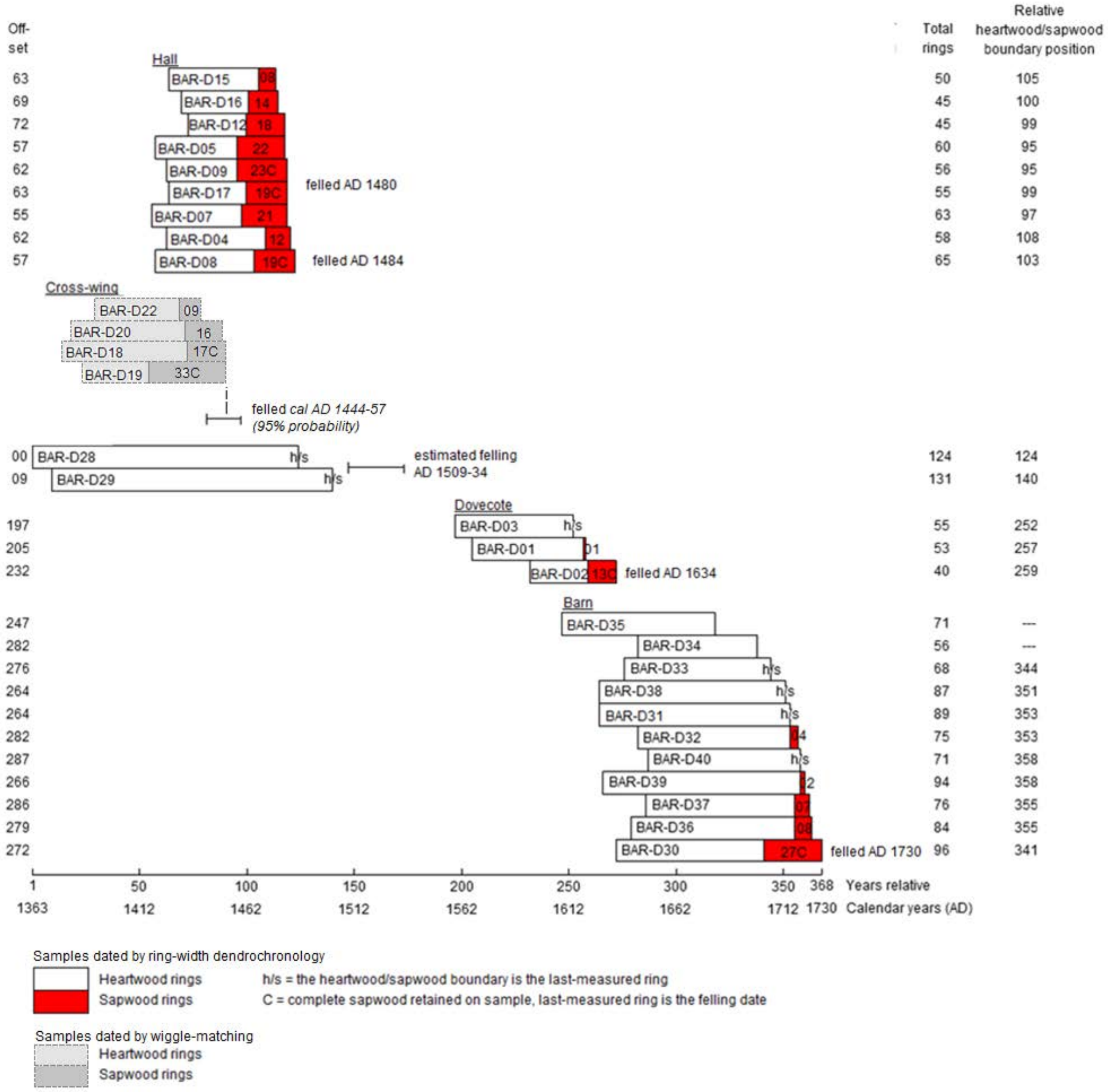

Figure 19: Bar diagram of all samples dated by the tree-ring analysis or radiocarbon wiggle-matching, sorted by area of the building

DATA OF MEASURED SAMPLES

BAR-D01A 53
429 440 472 490 456 381 372 458 396 263 263 209 288 233 150 217 175 244 366 319
357 309 124 142 138 247 332 270 417 358 313 259 192 195 180 165 186 148 234 197
235 196 212 185 175 212 147 141 204 250 225 152 155
BAR-D01B 53
416 448 472 494 448 376 374 462 395 268 263 211 283 237 158 218 171 252 376 316
345 298 125 134 140 236 328 257 403 356 306 240 174 193 160 150 171 143 237 197
225 204 209 166 173 219 146 143 202 264 214 156 145
BAR-D02A 40
372 340 280 298 223 182 138 157 191 204 196 262 267 315 249 339 301 328 338 198
200 301 389 447 271 220 259 335 242 198 300 292 326 271 297 180 267 212 300 185
BAR-D02B 40
368 340 282 292 227 183 132 155 196 196 200 265 234 331 255 320 359 311 345 231
223 290 411 448 298 225 261 324 248 187 288 304 326 280 307 183 264 206 301 190
BAR-D03A 55
253 174 469 285 311 339 214 201 298 306 250 242 239 215 143 210 163 121 102 120
229 231 192 276 242 262 300 280 335 247 86 156 149 214 320 204 232 223 273 206
179 179 154 120 126 116 158 161 222 182 151 199 192 261 167
BAR-D03B 55
196 179 447 286 309 317 227 228 296 311 254 229 241 216 142 207 159 113 112 124
226 241 190 301 241 281 291 288 320 273 89 155 148 218 302 195 232 234 271 216
174 179 147 135 126 127 167 167 207 178 148 194 182 270 168
BAR-D04A 58
438 308 312 325 234 262 239 195 140 167 158 132 143 61 128 78 98 82 76 79
38 45 55 47 86 44 65 63 69 75 66 37 45 60 52 71 64 35 64 59
66 71 64 71 99 104 98 97 86 84 94 88 61 60 64 52 46 41
BAR-D04B 58
388 307 276 320 234 264 239 194 142 169 153 133 140 74 123 84 97 80 80 82
48 46 54 52 80 51 64 66 67 78 61 39 43 60 56 71 60 43 65 52
67 61 51 65 80 101 104 88 105 67 89 70 63 56 66 57 52 39
BAR-D05A 60
271 313 141 246 235 276 288 335 350 286 307 323 401 218 306 319 274 217 176 234
206 199 133 231 212 137 132 140 132 181 104 136 117 122 150 94 125 95 116 124
52 47 58 58 46 62 50 42 36 35 80 67 85 59 73 79 56 85 55 53
BAR-D05B 60
271 315 137 247 228 284 250 330 360 294 300 325 404 217 315 316 272 222 170 236
193 196 139 229 210 147 132 135 130 175 109 135 113 130 166 98 118 97 98 123
62 52 53 54 43 63 55 43 40 34 83 64 69 61 74 84 58 79 59 64
BAR-D07A 63
75 165 422 439 200 213 291 396 434 379 394 291 230 169 210 161 203 206 151 131
83 97 137 154 136 159 158 99 69 101 90 85 88 107 88 95 119 109 85 97
78 95 115 125 98 97 101 106 97 73 67 52 67 68 68 68 60 81 65 76
81 91 86
BAR-D07B 63
75 163 432 410 199 235 287 403 418 386 392 293 192 175 214 151 215 199 164 144
71 109 121 162 131 167 148 94 73 93 90 90 86 108 90 93 117 107 99 93
86 99 119 111 99 96 95 103 96 68 63 45 60 66 73 70 61 80 61 80
80 97 73
BAR-D08A 65
70 127 71 47 76 238 163 143 175 118 168 144 248 156 237 163 165 196 140 161
175 206 122 191 180 128 89 111 100 124 85 99 92 105 110 124 104 72 138 142

195 133 116 121 85 118 122 92 98 82 124 91 94 98 101 160 137 133 138 140
166 158 153 144 85
BAR-D08B 65
66 130 59 51 81 231 159 154 172 120 168 137 256 167 225 162 165 194 138 162
178 204 122 185 187 118 95 114 96 122 84 101 95 98 116 123 102 77 131 145
193 129 123 116 93 116 117 95 98 74 115 94 92 108 96 157 148 140 134 155
163 158 163 144 89
BAR-D09A 56
501 283 250 306 291 329 354 490 325 377 328 511 410 214 197 187 266 151 198 188
123 129 145 140 190 148 191 166 189 114 91 82 71 73 76 97 70 69 81 64
88 95 83 84 38 69 59 70 62 86 114 99 67 72 82 91
BAR-D09B 56
496 412 247 290 293 328 347 503 319 383 335 514 417 207 204 191 259 152 200 189
126 125 142 148 194 145 178 187 194 114 98 83 85 77 76 91 70 72 75 77
75 103 83 93 38 69 70 61 58 90 118 86 70 67 82 101
BAR-D12A 45
238 213 167 133 105 91 153 111 302 165 68 116 138 170 244 112 220 168 160 268
174 158 119 151 173 240 160 137 145 116 124 76 124 106 96 186 131 175 106 152
198 108 103 120 157
BAR-D12B 45
251 222 165 114 100 82 155 101 289 150 72 115 132 209 238 113 225 163 162 275
173 156 116 159 163 195 153 150 128 119 113 86 121 107 88 184 126 182 114 158
201 118 96 118 165
BAR-D13A 63
328 328 302 257 411 353 291 247 360 392 378 174 142 294 238 233 208 274 356 282
379 258 299 314 305 362 270 254 285 199 248 241 166 161 186 210 108 102 58 67
103 103 130 154 138 171 178 134 127 127 109 112 95 84 161 102 126 110 155 189
212 123 190
BAR-D13B 63
326 335 284 283 391 343 263 274 342 388 383 171 147 297 237 240 207 266 368 307
375 271 293 293 303 341 307 289 300 194 242 263 179 165 187 212 110 107 57 69
95 103 140 159 143 175 165 126 124 124 107 114 93 88 149 115 118 108 165 182
217 131 195
BAR-D15A 50
158 430 386 253 279 329 481 322 423 392 507 475 306 450 422 466 238 459 363 264
298 238 242 280 164 279 178 190 85 57 95 82 71 81 110 115 142 130 115 118
164 172 124 108 244 284 173 247 157 282
BAR-D15B 50
163 428 387 253 278 335 470 335 421 391 507 482 320 429 414 475 235 467 368 262
299 239 235 286 157 281 176 190 87 60 93 58 82 82 106 121 149 128 113 145
159 193 155 147 219 283 192 221 167 272
BAR-D16A 45
474 580 501 380 486 521 231 230 265 370 259 438 353 213 272 287 257 354 186 288
227 244 120 69 108 57 61 106 157 134 81 100 76 96 88 84 74 74 96 143
117 138 119 162 110
BAR-D16B 45
401 465 462 378 468 462 214 227 256 366 263 431 354 216 274 290 253 350 190 289
231 260 108 74 103 44 77 109 160 162 70 96 76 86 83 72 84 57 104 119
115 135 122 164 81
BAR-D17A 55
114 313 307 281 275 448 581 516 474 379 276 218 138 155 190 194 114 184 185 99
119 111 117 138 87 132 162 153 159 132 145 120 142 167 187 151 118 102 85 83
87 84 82 47 107 93 84 87 97 101 63 56 63 79 97

BAR-D17B 55
100 326 307 278 277 440 588 533 486 359 274 208 141 158 187 191 124 186 185 96
121 116 104 148 100 131 152 149 133 152 146 118 147 161 188 163 113 100 85 83
95 81 80 44 128 89 88 85 101 99 62 58 64 82 114
BAR-D18A 70
176 215 271 283 258 288 291 232 143 124 128 136 150 144 159 172 167 182 215 195
274 250 252 201 197 206 186 187 175 106 88 101 85 77 117 103 89 77 75 120
119 83 91 97 104 110 125 101 114 105 115 125 83 76 82 59 91 109 89 110
98 67 76 73 77 103 68 99 79 66
BAR-D18B 70
185 210 277 254 223 268 300 225 145 125 127 133 157 143 159 167 164 179 219 189
279 247 252 202 200 202 186 184 175 122 75 107 74 80 116 102 88 89 67 117
119 81 95 95 102 113 120 110 113 110 115 122 85 72 88 55 91 104 94 100
113 61 77 70 82 100 76 89 79 62
BAR-D19A 62
170 156 157 210 155 154 170 144 171 166 145 202 191 223 259 185 182 223 149 97
94 80 53 81 68 49 109 83 53 81 55 54 54 50 53 62 85 83 79 63
70 74 67 60 26 26 41 62 55 66 69 104 108 81 68 61 59 84 45 53
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BAR-D19B 62
200 152 166 238 159 148 166 146 169 166 144 196 191 219 260 188 184 223 150 105
83 84 51 77 63 59 113 80 49 72 57 58 59 50 64 76 90 85 87 69
71 79 73 68 27 27 56 53 59 58 72 108 107 79 63 70 54 86 44 50
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BAR-D20A 64
224 231 247 278 233 171 150 164 174 152 162 165 191 184 229 367 349 344 277 221
250 224 216 215 207 156 98 96 68 52 97 91 79 95 113 106 141 99 104 144
162 157 146 153 141 153 158 137 104 82 87 62 87 77 82 89 93 54 45 45
51 67 48 67
BAR-D20B 64
256 231 266 216 205 154 160 160 141 165 178 180 189 172 230 351 306 350 298 241
273 214 213 221 199 154 100 88 69 58 82 81 90 100 118 112 146 81 109 138
173 157 134 162 136 142 156 150 112 86 91 57 74 73 80 92 87 53 48 52
51 82 48 58
BAR-D21A 55
343 283 294 210 65 64 93 98 83 109 105 94 124 114 123 163 148 192 282 216
152 139 232 271 224 175 188 120 103 106 91 125 186 128 114 110 129 278 206 97
70 130 170 196 232 254 292 169 165 175 102 112 87 78 83
BAR-D21B 55
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153 129 242 267 229 170 190 128 98 95 89 115 193 132 113 109 124 286 205 103
64 130 174 193 217 262 291 168 168 172 102 102 83 87 87
BAR-D22A 45
474 304 225 162 235 277 349 388 406 329 275 290 260 150 156 123 79 77 60 100
163 119 89 81 75 110 108 73 68 120 123 164 127 107 161 134 164 166 60 87
68 68 97 119 102
BAR-D22B 45
478 291 235 164 229 277 348 374 385 348 294 294 255 153 155 126 81 67 69 89
156 128 87 85 74 108 115 61 70 116 128 171 125 105 158 134 156 144 76 86
69 83 95 115 95
BAR-D24A 59
133 197 312 281 341 337 297 258 313 404 313 258 265 226 157 136 143 76 76 84
81 134 193 157 123 119 123 135 109 56 68 106 160 219 195 215 221 176 120 115

83 96 80 73 86 79 104 86 82 41 47 59 52 53 45 50 64 65 48
BAR-D24B 59
161 184 314 213 355 332 294 252 312 392 314 256 273 225 158 146 141 80 78 77
86 128 194 145 121 126 119 127 113 57 72 104 160 221 200 226 209 175 112 117
90 82 80 85 81 81 101 87 81 42 45 58 54 56 42 52 62 63 57
BAR-D25A 64
83 99 66 46 69 56 71 51 53 56 58 42 52 101 151
262 233 140 111 103 80 85 86 71 46 57 57 72 99 77 50 76 69 74 92
75 94 105 224 256 204 269 230 150 127 97 72 112 126 112 94 104 101 123 106
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BAR-D25B 64
82 96 70 47 69 58 69 57 50 54 62 46 52 101 160
259 238 143 105 104 77 81 89 66 48 65 49 76 97 83 36 84 68 73 95
82 100 104 234 234 212 251 236 135 130 95 72 106 124 113 99 108 97 125 109
95 108 87 103 113 84 64 88 95
BAR-D26A 48
144 95 348 100 126 203 196 245 224 137 181 115 115 123 114 88 64 70 45 40
27 32 30 54 66 92 48 60 69 50 30 24 25 22 73 55 81 115 76 96
71 63 40 82 48 90 107 105
BAR-D26B 48
143 96 345 91 115 202 206 249 224 143 164 118 121 113 116 97 66 56 58 21
29 26 38 51 63 77 45 63 68 47 28 34 23 24 85 61 84 114 80 94
65 63 48 75 49 90 100 110
BAR-D28A 124
312 506 293 293 412 552 322 263 282 410 329 350 369 303 283 153 144 157 163 144
184 137 206 205 198 171 151 168 177 208 106 195 166 167 92 102 140 145 103 137
220 138 125 123 150 84 150 146 105 107 80 82 90 63 101 140 137 113 138 161
176 185 111 124 150 179 184 86 160 232 158 126 196 100 123 181 72 181 139 158
114 117 86 131 102 69 118 90 152 202 230 161 130 146 133 96 88 143 151 102
97 111 95 110 108 101 115 140 146 111 129 101 168 132 133 113 69 119 163 95
94 126 166 119
BAR-D28B 124
318 507 282 292 408 554 320 273 277 405 334 347 365 298 280 159 141 163 153 142
186 155 220 209 205 183 145 149 160 207 100 203 162 170 94 98 140 140 112 135
218 139 122 123 117 115 147 137 109 110 80 87 94 54 113 142 136 112 146 144
176 189 126 114 157 177 181 95 158 234 156 122 189 104 134 166 69 179 131 145
116 131 95 115 103 66 119 77 145 194 228 188 128 153 143 104 90 147 154 103
107 115 102 116 109 104 127 144 149 103 128 114 169 135 133 118 69 110 185 80
77 153 166 115
BAR-D29A 131
277 331 361 383 401 386 244 172 275 348 352 373 263 336 353 327 319 207 164 191
168 122 263 161 172 105 113 107 137 151 132 166 114 94 136 106 108 163 110 108
93 81 64 98 55 69 73 66 79 129 75 131 155 119 151 201 161 126 75 78
101 92 86 100 46 59 91 54 101 64 66 44 61 40 55 68 31 63 37 68
87 102 82 68 74 72 45 37 51 55 45 56 43 47 42 64 57 49 50 49
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38 41 30 32 57 37 28 46 36 43 50
BAR-D29B 131
289 327 363 380 417 368 238 170 295 343 348 380 271 332 361 319 342 212 178 200
146 118 282 165 158 88 100 105 116 163 130 171 108 100 144 100 112 159 100 111
115 61 61 97 63 73 76 68 82 123 90 135 159 117 155 207 158 112 78 84
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87 106 87 65 71 72 45 42 45 57 43 56 48 43 40 60 60 49 55 49

30 38 25 68 40 57 66 42 56 91 29 31 48 54 53 66 32 38 53 44
33 44 27 30 58 42 31 42 37 39 51
BAR-D30A 96
310 465 391 397 344 315 435 360 327 359 376 296 334 372 319 207 224 257 180 205
194 262 284 279 232 168 192 217 224 162 134 147 232 208 194 220 142 260 154 140
144 144 182 202 159 193 171 256 143 86 136 193 151 252 310 160 201 74 119 87
92 92 103 173 101 50 69 66 111 164 129 101 79 84 121 87 125 64 114 90
92 110 93 60 56 90 106 123 73 88 66 98 67 67 59 58
BAR-D30B 96
327 459 389 401 340 318 426 359 328 363 373 303 316 344 305 214 215 251 181 204
183 257 277 271 230 167 178 211 234 175 117 163 230 196 210 243 146 262 154 138
148 138 188 197 165 187 172 273 141 87 131 196 149 249 308 193 166 71 119 89
94 87 99 170 96 52 62 69 102 154 130 102 83 85 116 92 127 61 119 97
92 103 86 64 61 86 110 123 70 84 79 80 61 49 39 87
BAR-D31A 89
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354 362 236 205 225 218 110 118 224 188 136 207 201 222 245 230 379 267 205 157
235 187 177 162 123 174 158 171 117 85 182 159 108 152 79 204 95 85 86 159
117 199 212 127 146 188 193 123 174 142 185 247 182 106 108 74 162 129 92 91
86 176 165 147 186 165 225 108 178
BAR-D31B 89
506 455 478 403 445 449 268 211 271 232 192 282 188 349 338 324 366 312 344 402
340 376 254 230 232 218 105 125 223 182 145 206 201 220 245 225 381 268 218 158
243 188 172 159 128 172 161 188 103 81 188 161 109 147 80 209 100 84 97 168
129 192 215 131 146 188 191 129 170 137 191 249 174 103 111 73 161 123 98 96
81 174 163 147 186 170 229 106 174
BAR-D32A 75
162 269 146 254 134 107 226 151 69 77 137 135 99 126 157 139 172 153 203 192
153 96 140 145 159 91 94 142 141 111 108 71 164 134 91 101 61 191 99 79
99 180 129 170 163 103 170 163 123 108 86 97 127 157 120 76 73 56 114 122
72 81 72 167 130 115 134 128 171 97 149 158 146 140 148
BAR-D32B 75
173 251 148 262 135 119 220 149 69 85 139 125 102 129 154 140 177 150 196 197
153 107 141 146 136 82 90 134 169 112 100 73 155 148 80 115 66 182 114 80
85 193 132 169 173 92 162 160 125 106 91 82 128 156 114 68 90 64 113 120
70 82 74 159 129 119 138 126 169 96 161 152 141 137 129
BAR-D33A 68
620 476 492 415 529 453 468 480 455 453 428 381 464 441 268 314 320 430 264 234
244 261 298 355 327 368 257 194 212 206 262 201 161 197 152 188 183 264 182 216
218 178 211 313 125 96 70 244 201 323 188 117 184 123 173 189 127 90 165 171
156 86 85 159 185 130 126 110
BAR-D33B 68
699 514 490 413 544 461 500 465 461 445 430 381 447 431 255 314 306 417 274 243
287 267 294 358 319 370 262 190 212 207 256 195 166 204 157 191 186 267 184 224
205 174 212 309 138 75 83 240 191 327 174 116 193 119 167 196 131 93 163 174
156 80 98 166 175 130 106 117
BAR-D34A 56
385 530 405 465 424 406 457 350 223 280 540 551 360 617 590 546 424 423 491 505
484 354 446 543 519 606 459 442 386 464 340 343 414 451 586 562 389 513 373 468
355 581 401 488 459 411 500 354 339 307 337 359 303 414 220 329
BAR-D34B 56
396 531 385 483 415 406 441 345 218 285 538 548 351 626 581 552 425 418 491 498
487 362 444 522 507 605 465 434 380 460 345 341 410 442 590 556 376 511 364 476

370 561 377 480 447 430 496 364 339 313 343 371 317 406 221 362
BAR-D35A 71
459 466 485 410 276 504 580 651 766 557 369 303 357 365 302 327 386 359 354 559
262 308 319 246 209 170 251 209 328 242 314 366 137 180 176 240 281 193 208 160
201 289 197 94 112 213 211 153 171 136 147 176 200 141 223 135 187 243 248 252
311 188 313 146 148 98 107 177 162 124 144
BAR-D35B 71
512 543 491 414 279 498 534 676 751 554 371 287 370 360 314 344 383 351 358 521
265 297 322 254 211 179 257 241 332 246 312 369 133 183 178 238 285 197 202 163
200 290 194 97 100 216 214 152 173 138 135 172 210 144 221 133 189 239 247 255
306 190 303 144 162 82 115 182 173 112 125
BAR-D36A 84
217 421 453 401 402 428 417 321 198 242 225 135 138 216 264 201 228 185 230 259
257 293 310 274 210 235 219 253 245 266 259 315 238 245 166 280 285 237 301 155
309 251 244 327 328 220 285 235 148 270 234 284 205 158 199 216 217 161 107 131
103 178 196 132 150 139 157 233 164 217 181 226 156 124 194 194 158 138 179 203
211 154 152 138
BAR-D36B 84
223 420 452 384 417 431 399 315 226 270 230 139 137 216 257 205 225 188 227 269
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316 258 246 332 328 218 285 243 141 267 242 297 204 148 198 211 215 162 100 135
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210 149 162 157
BAR-D37A 76
302 288 326 256 133 136 325 232 185 191 234 273 263 333 198 324 169 233 190 219
254 269 156 206 149 207 111 118 207 168 232 224 202 249 182 129 86 205 180 302
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218 188 262 159 313 243 195 161 110 97 83 129 120 154 84 101
BAR-D37B 76
314 287 346 259 134 127 328 245 194 196 235 282 237 333 192 295 160 195 191 231
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245 196 172 156 314 181 196 140 205 241 181 100 189 123 213 195 111 152 121 138
198 177 261 167 323 246 189 168 128 86 84 124 127 150 86 89
BAR-D38A 87
339 353 359 158 179 232 197 132 165 126 197 367 185 290 258 185 258 133 247 161
283 202 216 225 183 128 77 95 212 187 139 165 140 210 97 221 164 100 138 98
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BAR-D38B 87
317 353 350 161 175 231 166 124 175 107 220 330 183 286 252 172 261 154 255 184
270 200 216 229 183 128 77 98 208 200 128 172 132 216 98 221 168 101 135 101
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115 117 104 79 120 121 119 86 82 83 110 137 131 77 73 51 130 146 92 110
71 119 122 74 93 88 166
BAR-D39A 94
281 209 217 325 313 296 310 357 311 359 250 343 334 170 265 217 298 273 290 288
213 197 281 193 93 104 173 180 127 175 167 193 173 208 138 244 132 177 216 242
263 239 183 247 157 163 91 92 162 180 153 203 159 227 125 98 79 165 150 201
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138 157 163 247 265 175 195 115 84 73 90 129 137 143
BAR-D39B 94
294 195 213 341 304 293 331 368 317 355 257 341 333 174 261 215 288 268 290 311

211 193 277 190 96 100 171 189 140 169 170 172 170 207 131 247 133 178 216 234
259 238 183 244 160 161 93 89 161 180 148 213 154 225 127 97 81 167 143 193
160 107 129 131 212 130 122 84 142 133 97 75 109 103 141 106 101 108 95 87
145 156 177 251 271 166 193 115 82 79 83 141 122 154

BAR-D40A 71

386 401 361 119 105 240 265 187 153 210 278 290 353 207 387 278 342 271 342 282
335 142 289 176 297 148 196 328 222 269 418 263 498 210 218 163 455 258 584 349
274 290 185 514 172 231 179 241 234 221 101 197 125 222 221 142 139 128 159 233
199 295 205 493 277 264 278 175 156 117 198

BAR-D40B 71

408 392 361 133 104 251 251 184 157 218 252 287 352 205 378 283 333 262 346 283
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see

how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. Estimating the Felling Date. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of

the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two

corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

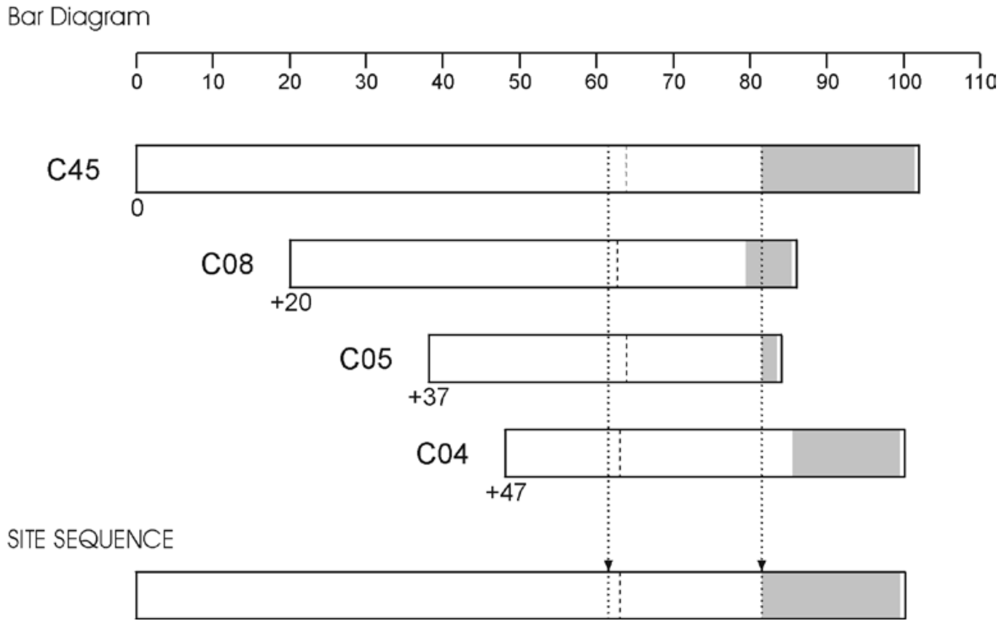


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

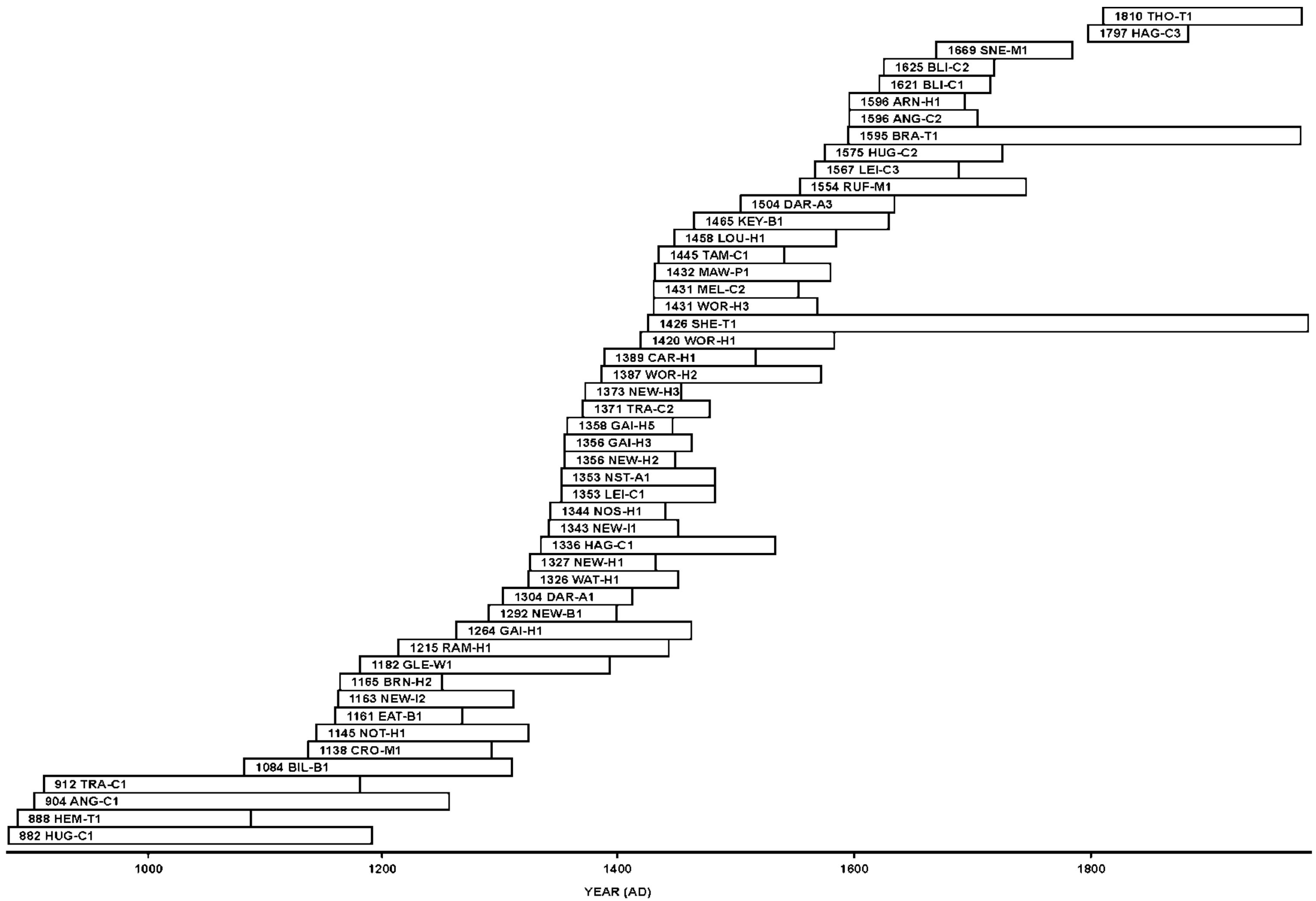
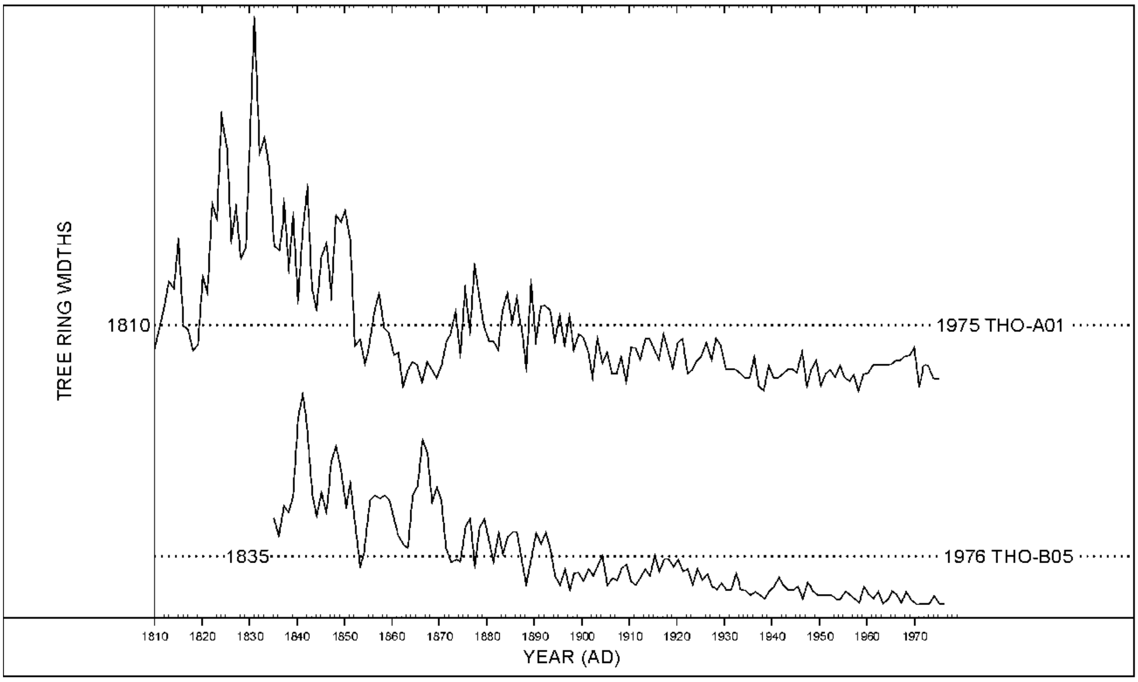


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

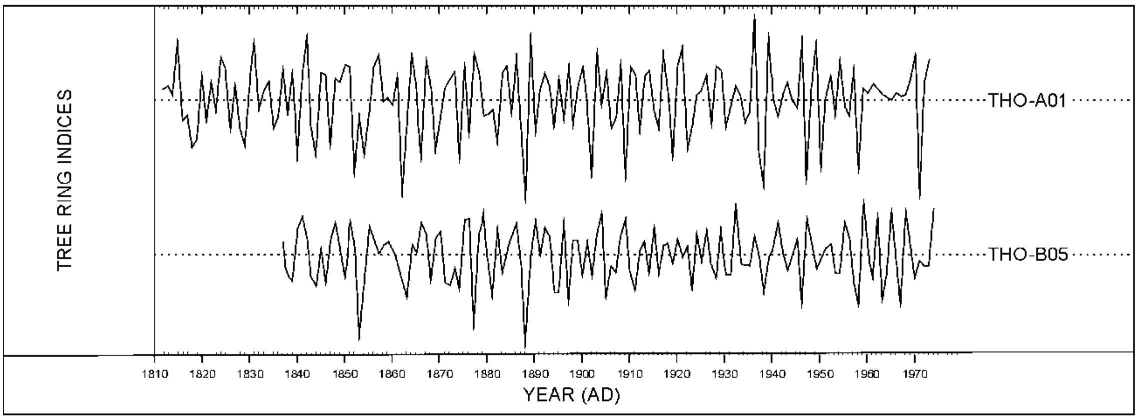


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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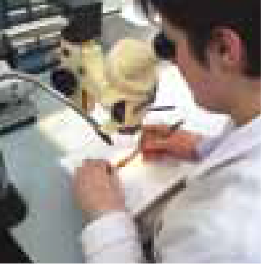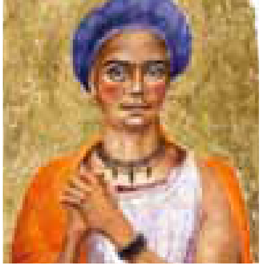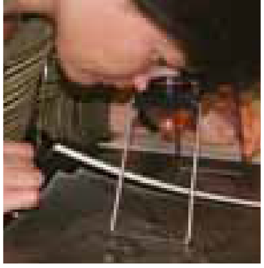

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