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St Mary's Church, Portchester, Fareham, Hampshire

Tree-ring Analysis of Oak Timbers from the Bellframe

Alison Arnold and Robert Howard

Scientific Dating

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Summary

Dendrochronology analysis has demonstrated that the church bellframe at St Mary Portchester is mostly constructed with timber felled in, or around, AD 1624–47 but also incorporates at least three (and most likely four) timbers felled somewhat earlier in AD 1504–24.

Contributors

Alison Arnold and Robert Howard

Acknowledgements

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Front cover image

St Mary's Church, Portchester in Fareham [photograph by Alison Arnold]

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Introduction

The Grade I-listed Church of St Mary (List Entry Number: 1339235 https://historicengland.org.uk/listing/the-list/list-entry/1339235?section=official-list-entry) is located within the walls of Roman Portchester Castle, thought to date to *c*. AD 1133, which lies approximately 6.4km northwest of Portsmouth and around 29km east of Southampton (Fig 1). The church was originally of cruciform plan, although the south transept is now missing, and it has a short tower with pyramidal roof at the crossing. At second-floor level of this tower is the belfry.

The oak bellframe is of long-headed type with three parallel pits (Fig 2). Each truss has a king post, end posts, braces from king post to cill, and further braces from head to posts and posts to return. There are also outrigger' type braces from each corner (Figs 3 and 4) and, unusually, the posts of the outer trusses (1 and 4) are moulded (Fig 5). The three bells are dated 1633, 1632, and 1589, whilst the bellframe itself is thought to date to the late-sixteenth century.

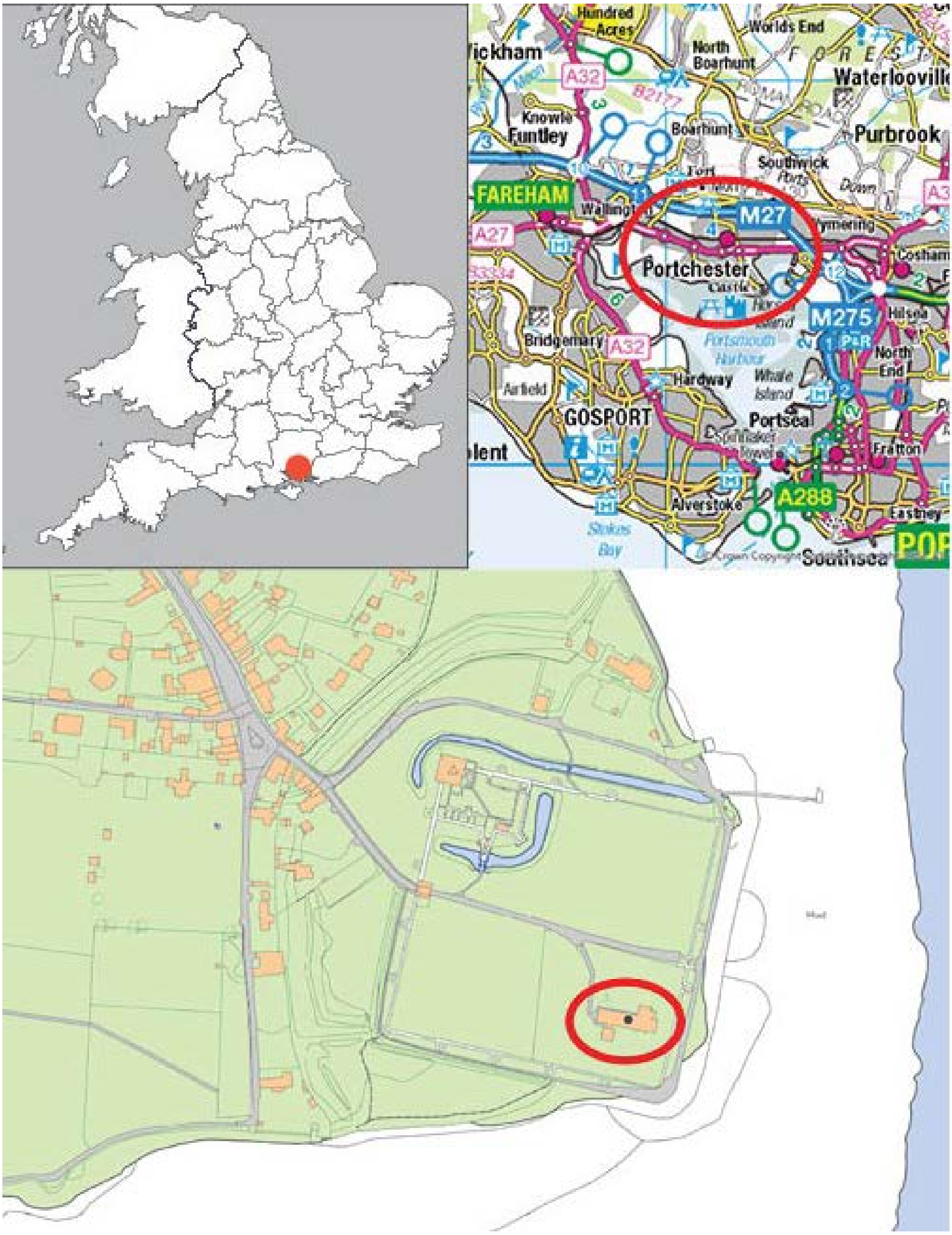

Figure 1: Maps to show the location of St Mary's Church, Portchester in Fareham, Hampshire marked in red. Scale: top right 1:105,000; bottom: 1:3000. [© Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900]

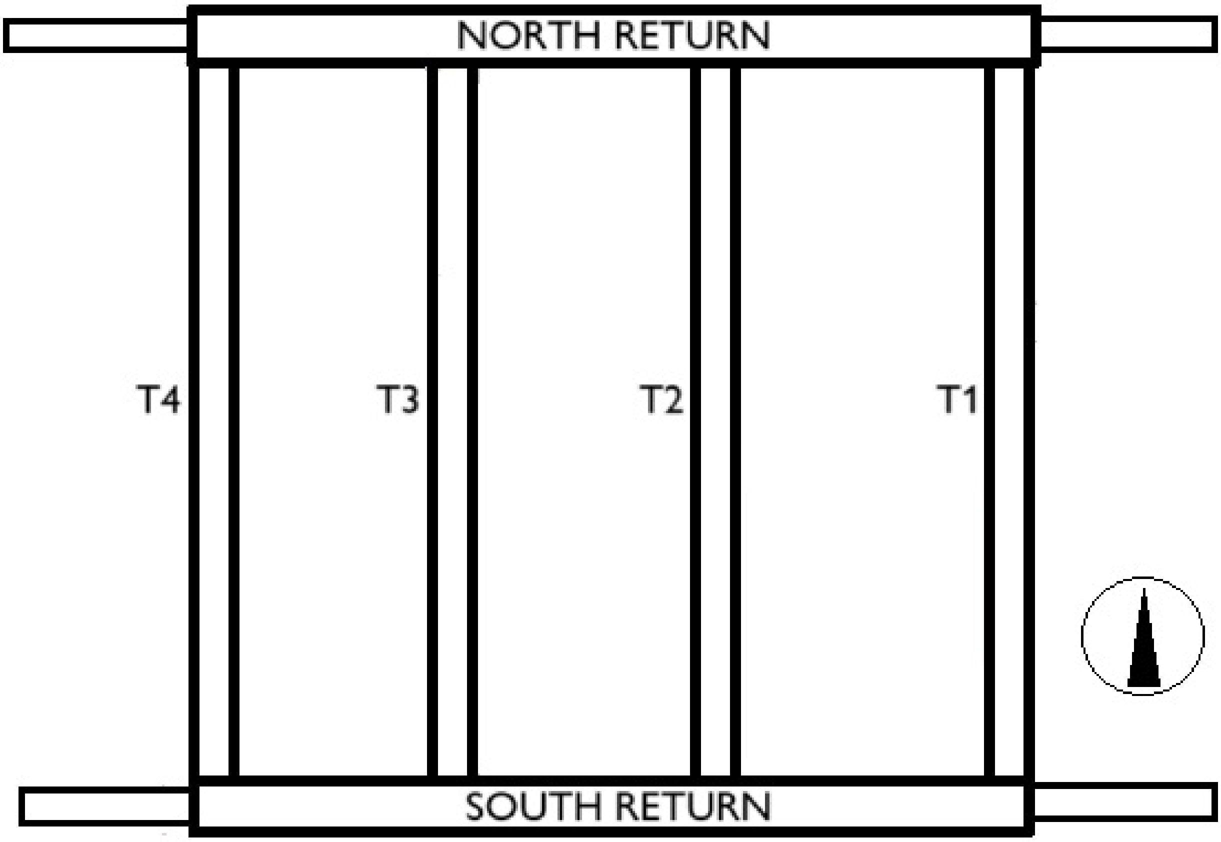

Figure 2: Sketch plan of bellframe

Figure 3: North return, photograph taken from the north [Alison Arnold]

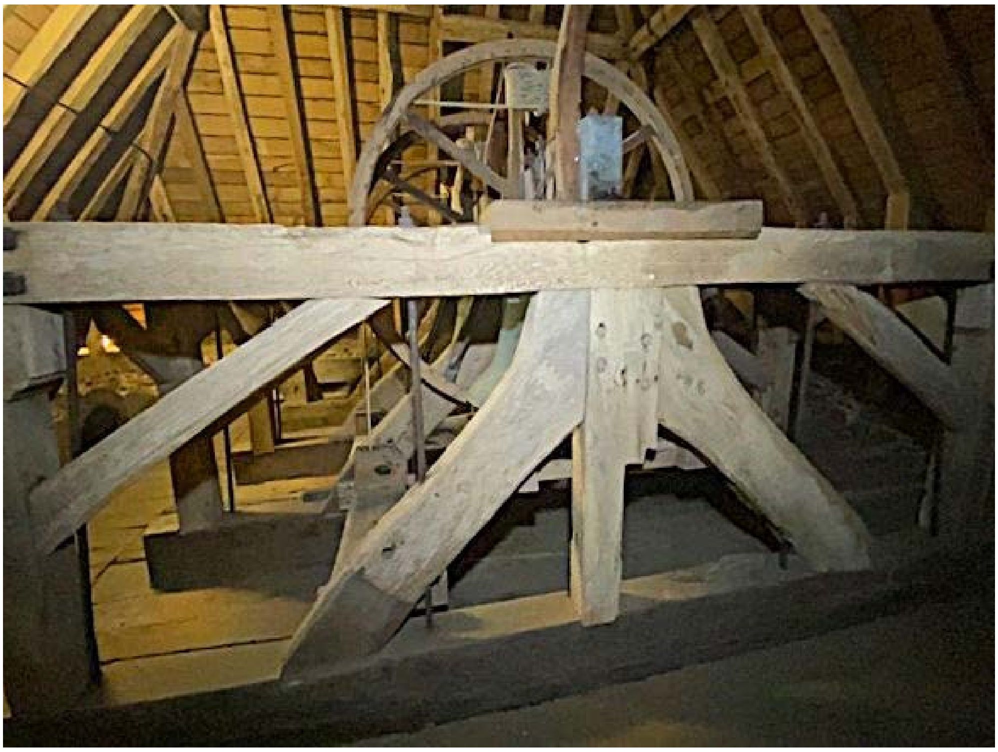

Figure 4: Truss 4, photograph taken from the west [Alison Arnold]

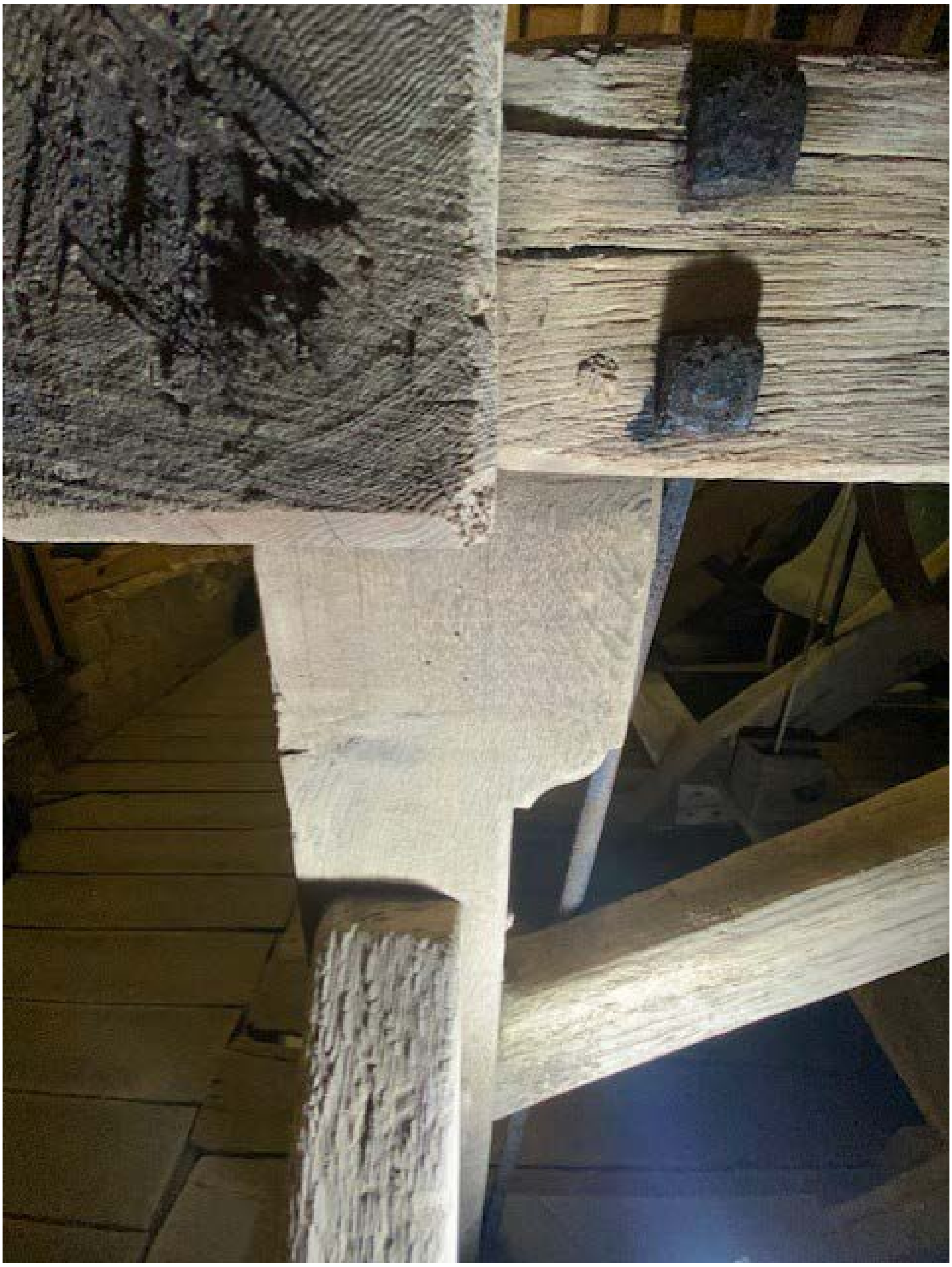

Figure 5: North post of truss 4 showing moulding, photograph taken from the north-west [Alison Arnold]

Sampling

A dendrochronological survey was requested by Rachel Fletcher, Inspector of Historic Buildings and Areas in London and the South East region, for independent dating evidence to inform understanding, and hence significance, of the bellframe in relation to decision making on whether the installation of a different set of bells is viable.

A total of 12 oak timbers of the bellframe was sampled, with each sample being given the code FAR-B and numbered 01–12. with duplicate core samples being taken from three of the timbers (samples FAR-B02, FAR-B09, and FAR-B12) in order to maximise the measurable ring series. Details relating to the samples can be found in Table 1, with sample locations marked on Figures 6–11.

Table 1: Details of samples taken from the bellframe, St Mary's Church, Portchester, Fareham, Hampshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
FAR-B01	King post, truss 1	148	--	1290	----	1437
FAR-B02	Frame head, truss 2	97	--	1467	----	1563
FAR-B03	North post, truss 2	144	02	1470	1611	1613
FAR-B04	South post, truss 2	113	h/s	1495	1607	1607
FAR-B05	Frame head, truss 3	127	h/s	1479	1605	1605
FAR-B06	North post, truss 4	112	h/s	1496	1607	1607
FAR-B07	North brace, truss 4	75	h/s	1409	1483	1483
FAR-B08	South post, truss 4	137	15	1487	1608	1623
FAR-B09	Frame head, north return side	100	--	1497	----	1596
FAR-B10	Frame head, south return side	97	07	1515	1604	1611
FAR-B11	North-east 'outrigger' brace	92	h/s	1392	1483	1483
FAR-B12	South-east 'outrigger' brace	83	18	1421	1485	1503

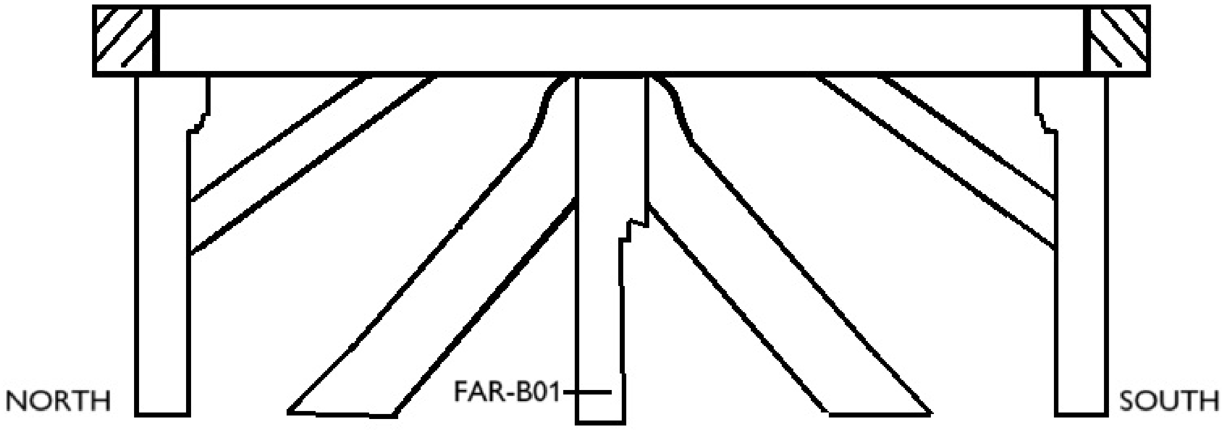

Figure 6: Sketch of truss 1, showing sampled timbers

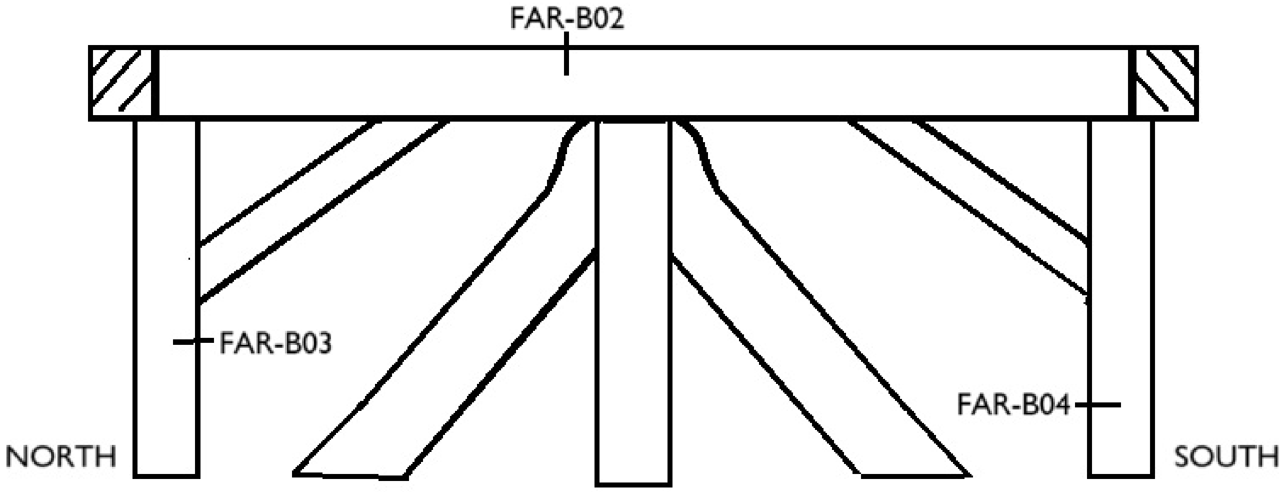

Figure 7: Sketch of truss 2, showing sampled timbers

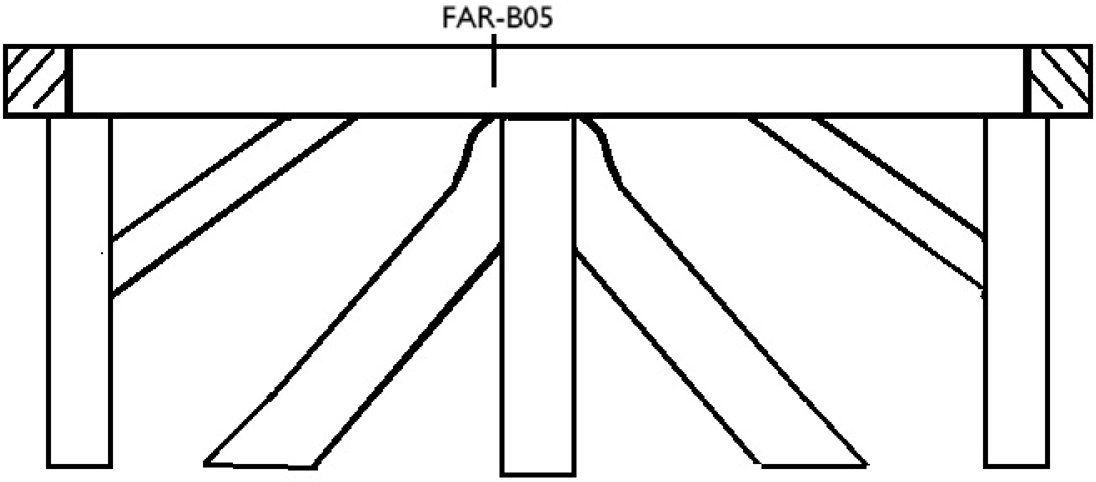

Figure 8: Sketch of truss 3, showing sampled timbers

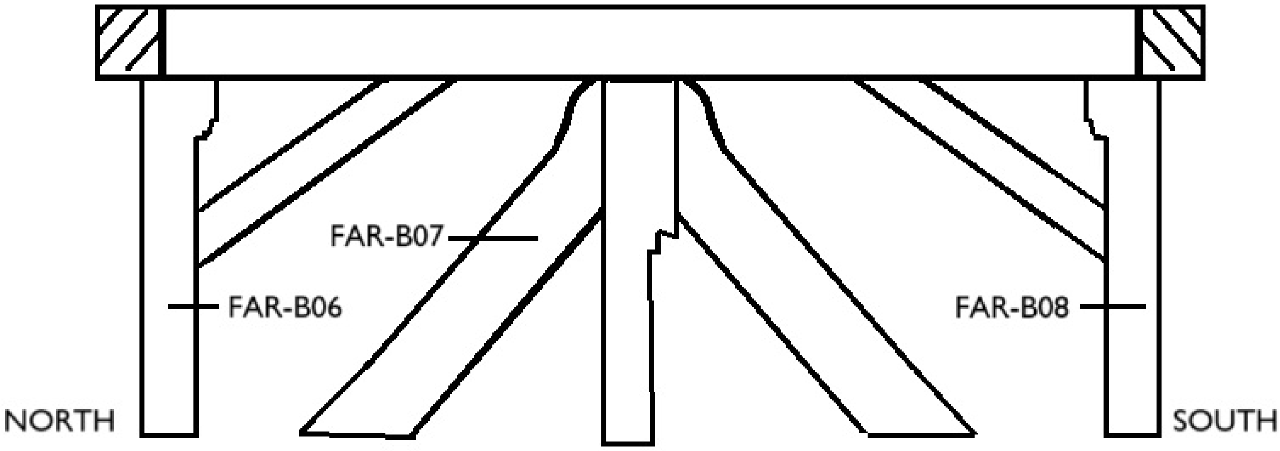

Figure 9: Sketch of truss 4, showing sampled timbers

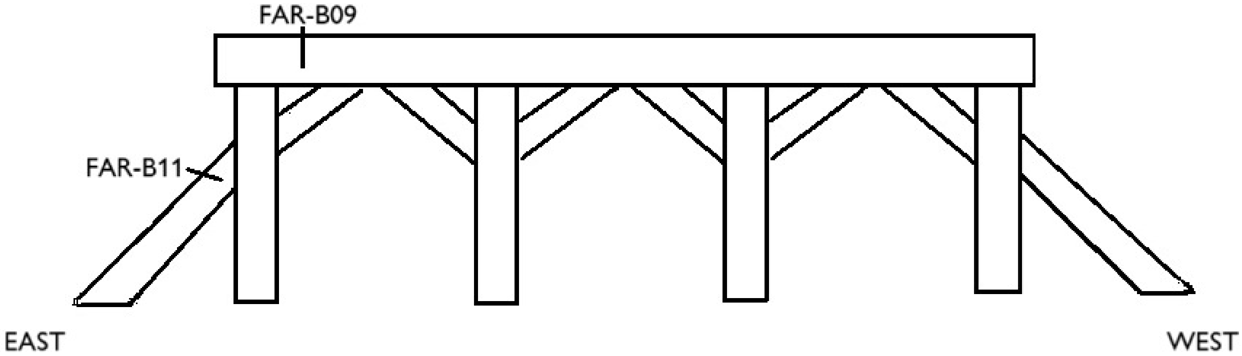

Figure 10: Sketch of north return, showing sampled timbers

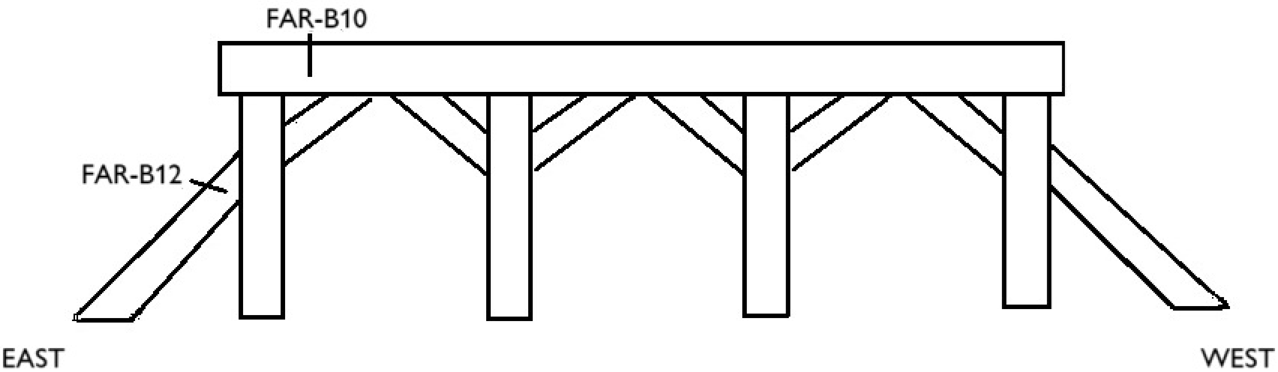

Figure 11: Sketch of south return, showing sampled timbers

Analysis and results

All 12 samples were prepared by sanding and polishing and their growth-ring widths measured. The data of these measurements are given at the end of this report. Firstly, the duplicate samples (FAR-B02, FAR-B09, and FAR-B12) were averaged to form a single sample series before all samples were compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 10 samples matching to form two groups.

Firstly, eight samples matched each other at a minimum value of *t* = 10.7 and were combined at the relevant offset positions to form FARBSQ01, a site sequence of 157 rings (Fig 12). This site sequence was then compared against a series of relevant oak reference chronologies where it was found to span the period AD 1467–1623. The evidence for this dating is given by the *t* – values in Table 2.

Two other samples grouped at a value of *t* = 9.3 were combined at the relevant offset positions to form FARBSQ02, a site sequence of 112 rings (Fig 13). Comparison with the oak chronologies identified a consistent and secure match at a first-ring date of AD 1392 and a last-measured ring date of AD 1503. The evidence for this dating is given by the *t* – values in Table 3.

The remaining ungrouped samples were then compared individually against the reference chronologies where sample FAR-B01 was found to match consistently at AD 1290–1437 (Table 4) and sample FAR-B07 matched the period AD 1409–1483 (Table 5).

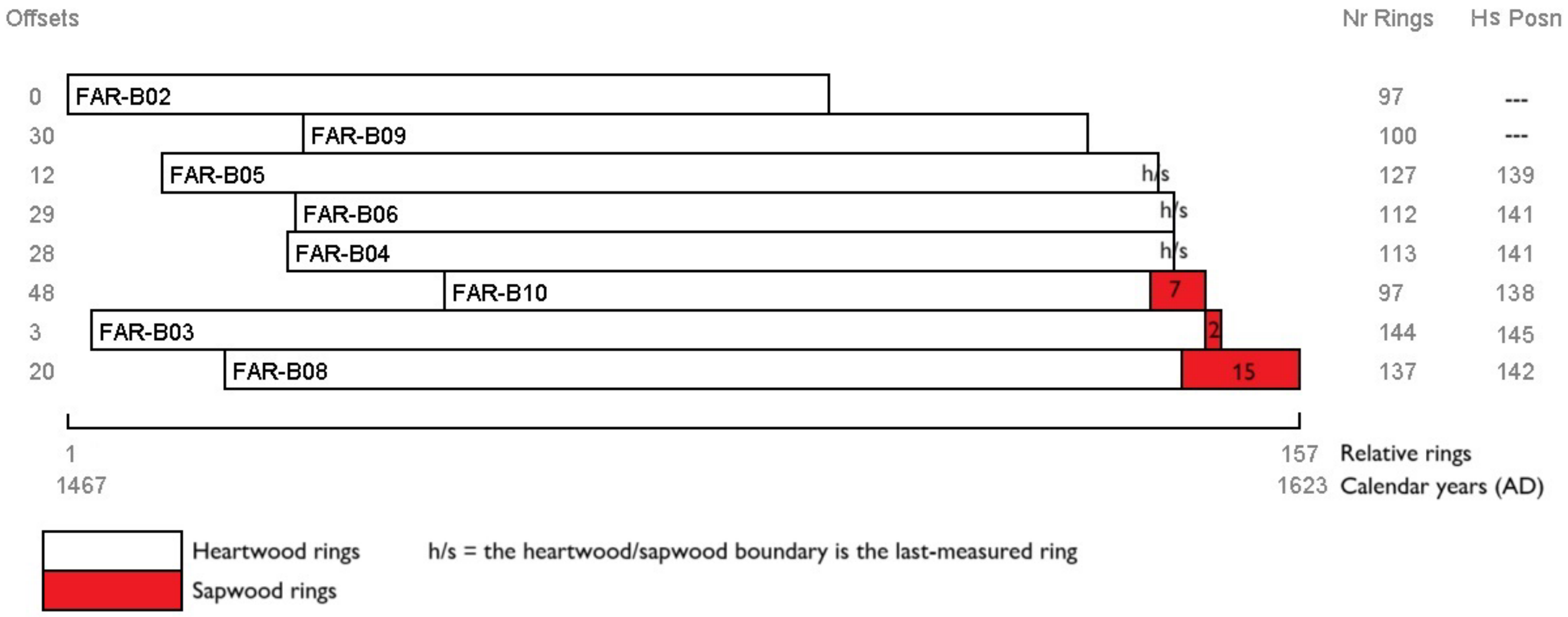

Figure 12: Bar diagram of samples in site sequence FARBSQ01

Table 2: Results of the cross-matching of site sequence FARBSQ01 and relevant reference chronologies when the first-ring date is AD 1467 and the last-measured ring date is AD 1623

Reference chronology	*t* - value	Span of chronology (AD)	Reference
Apethorpe Hall, Northamptonshire	8.5	1292–1639	Arnold and Howard 2008a
Home Farm, Newdigate, Surrey	8.2	1492–1639	Bridge 1998
Knole House, Kent	7.8	1431–1605	Miles and Bridge 2010
Upper House Farm, Nuffield, Oxon	7.7	1431–1627	Haddon-Reece et al. 1989
Nyetimber Farm Barn, West Sussex	7.4	1463–1605	Arnold et al. 2010
Avebury Manor, Wiltshire	7.3	1393–1596	Arnold et al. 2012
Reigate Priory, Surrey	7.2	1384–1545	Bridge 2003
Mercer's Hall, Gloucester, Gloucestershire	7.1	1383–1545	Howard et al. 1996
Eastcote House, London	7.0	1504–1591	Arnold and Howard 2012
Hartlebury Castle, Stourport on Severn, Worcestershire	7.0	1316–1678	Tyers 2010

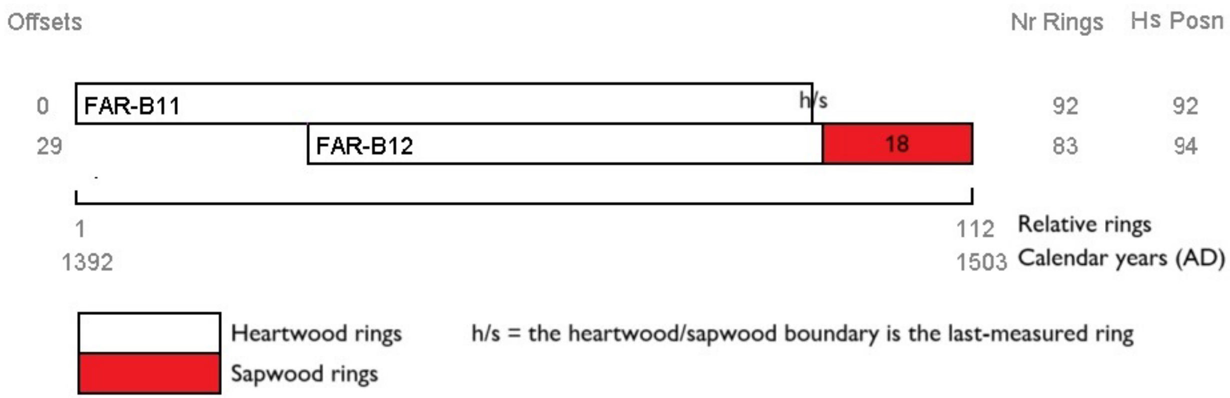

Figure 13: Bar diagram of samples in site sequence FARBSQ02

Table 3: Results of the cross-matching of site sequence FARBSQ02 and relevant reference chronologies when the first-ring date is AD 1392 and the last-measured ring date is AD 1503

Reference chronology	*t* - value	Span of chronology (AD)	Reference
Abbot's Lodging, Coggeshall Abbey, Essex	7.4	1225–1354	Arnold and Howard 2015
Danny House, West Sussex	6.9	1389–1589	Miles and Bridge 2010
Falmer Court Barn, East Sussex	6.5	1386–1497	Howard et al. 1998
Primrose Hill, Kings Norton, West Midlands	6.4	1354–1593	Arnold and Howard 2008b
Salisbury Cathedral, Wiltshire	6.1	1409–1541	Miles et al. 2005
Lower Brockhampton Manor, Herefordshire	6.0	1304–1505	Arnold and Howard 2014 unpublished
West Molesey, Elmbridge, Surrey	5.9	1382–1502	Arnold et al. 2006
Ickenham Manor, Middlesex	5.9	1374–1483	Arnold and Howard 2011
Springfield, Chard, Somerset	5.9	1366–1445	Arnold et al. 2004
Sydenham House, Devon	5.7	1266–1629	Arnold et al. 2015

Table 4: Results of the cross-matching of sample series FAR-B01 and relevant reference chronologies when the first-ring date is AD 1290 and the last-measured ring date is AD 1437

Reference chronology	*t* - value	Span of chronology (AD)	Reference
Abbot's Lodging, Coggeshall Abbey, Essex	6.4	1225–1354	Arnold and Howard 2015
Turret Close, Wittenham, Oxfordshire	6.0	1272–1351	Alcock et al. 1989
2 School Road, Wellesbourne, Warwick	5.6	1287–1429	Alcock et al. 1989
Lower Hope Farmhouse Ullingswick, Herefordshire	5.5	1292–1373	Arnold and Howard 2021
Unknown Nottingham building, Nottinghamshire	5.5	1160–1384	Arnold and Howard 2020 unpublished
Coventry Charterhouse, Warwickshire	5.5	1301–1431	Arnold et al. 2020
St Martin's Church, Colchester, Essex	5.5	1218–1349	Tyers 1998
Pendean Farm, Midhurst, West Sussex	5.4	1313–1609	Tyers pers. comm. 2000
Roundhouse, Evesham, Worcestershire	5.3	1316–1432	Arnold and Howard 2023 unpublished
Mercer's Hall, Gloucester, Gloucestershire	5.3	1289–1541	Howard et al. 1996

Table 5: Results of the cross-matching of sample series FAR-B07 and relevant reference chronologies when the first-ring date is AD 1409 and the last-measured ring date is AD 1483

Reference chronology	*t* - value	Span of chronology (AD)	Reference
Abbey Farm, Lacock, Wiltshire	6.9	1471–1569	Arnold and Howard 2022 unpublished
Manor Farm Barn, Winterborne Clenston, Dorset	6.2	1339–1515	Bridge 2014
Romsey Abbey, Hampshire	6.0	1362–1496	Hillam and Groves 1994
Priest's House Museum, Wimborne Minster, Dorset	5.7	1259–1634	Miles 1994
Falconers Hall, Good Easter, Essex	5.5	1324–1457	Bridge 1996
Kington Magna Church, Dorset	5.3	1367–1472	Bridge 2008
100 Minories, London	5.3	1313–1567	Tyers 2017
Mottisfont Abbey, Hampshire	5.2	1388–1538	Miles 1996
Wells Cathedral, Somerset	5.2	1101–1506	Arnold and Howard 2004 unpublished
12 Pickwick, nr Corsham, Wiltshire	5.1	1284–1535	Arnold and Howard 2018 unpublished

Interpretation

Tree-ring analysis has resulted in the successful dating of all 12 sampled oak timbers (Fig 14). Felling date ranges and *termini post quem* for felling dates have been calculated using the estimate that 95% of mature oak trees have 15–40 sapwood rings. The heartwood/sapwood boundary ring exists on nine of the samples with interpretation of these dates suggesting that two separate felling periods are represented.

The heartwood/sapwood boundary dates for three of these nine samples are all in the AD 1480s, and suggestive of a single phase of felling. The combined heartwood/sapwood boundary ring date for these three samples is AD 1484, allowing an estimated felling date to be calculated for the timbers represented to within the range AD 1504–24. This allows for sample FAR-B12 having a last-measured ring date of AD 1503, with incomplete sapwood.

The heartwood/sapwood boundary ring dates on six other samples are again broadly contemporary, varying by only seven years, and suggestive of a subsequent single phase of felling. The combined heartwood/sapwood boundary ring date for these six samples is AD 1607, giving an estimated felling date range for the timbers represented to within the range of AD 1624–47, allowing for sample FAR-B08 having a last-measured ring date of AD 1623, with incomplete sapwood.

The three remaining dated samples do not have the heartwood/sapwood boundary ring date and so estimated felling date ranges cannot be calculated for them. However, with last-measured ring dates of AD 1437 (FAR-B01), AD 1563 (FAR-B02), and AD 1596 (FAR-B09), would be estimated to have *termini post quem* for felling dates of AD 1452, AD 1578, and AD 1611, respectively. Additionally, the high level at which samples FAR-B02 and FAR-B09 (Table 6) match the seventeenth-century timbers, makes it very likely that these two timbers were also felled at this time (AD 1624–47).

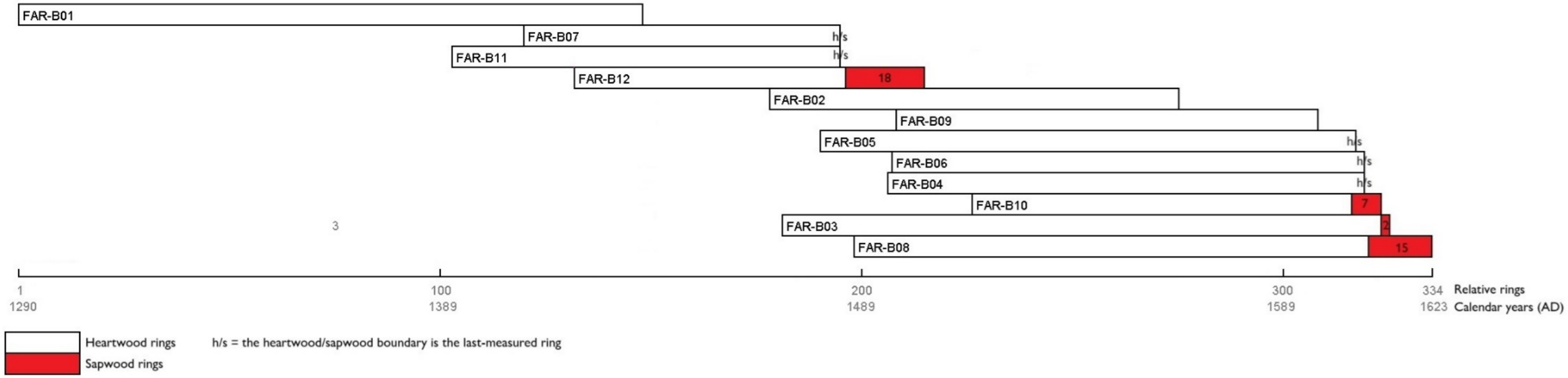

Figure 14: Bar diagram of all dated samples

		1	2	3	4	5	6	7	8
FAR-B02	1	***	-3	-28	-12	-29	-20	-30	-48
FAR-B03	2	10.1	***	-25	-9	-26	-17	-27	-45
FAR-B04	3	8.7	7.8	***	16	-1	8	-2	-20
FAR-B05	4	10.9	9.4	8.0	***	-17	-8	-18	-36
FAR-B06	5	10.4	8.8	9.9	10.8	***	9	-1	-19
FAR-B08	6	11.4	9.3	8.2	10.8	10.1	***	-10	-28
FAR-B09	7	9.7	11.6	7.3	6.7	8.1	6.9	***	-18
FAR-B10	8	7.0	8.1	6.1	6.6	10.0	9.4	7.1	***

Table 6: *t*-value matches and offsets between component samples in site sequence FARBSQ01; values of *t* = 10+ may suggest timbers cut from the same tree.

Discussion

The tree-ring analysis has identified the use of timber of at least two different dates within the bellframe. The majority of the timbers are now known to date to AD 1624–47, suggesting a construction date in the second quarter of the seventeenth century. Indeed, with two of the bells dating to 1633 and 1634, it is not unreasonable to suggest that the bellframe is of a similar date, given that these dates fall within the felling date range.

The incorporation of three (and probably four) timbers of AD 1504–24 suggests the use of reused timber, although whether from a, since demolished, sixteenth-century structure, possibly even an earlier bellframe from the church or from somewhere completely unconnected is not possible to say.

The extremely strong intra-site matching of samples in site sequence FARBSQ01 (Table 6), suggests the use of a coherent series of trees and, given the very high *t* – value matches seen between some of them, probably only two or three trees utilised in all. As to woodland source exploited in both the sixteenth and seventeenth century, this is likely to have been relatively local as the reference chronologies against which FARBSQ01 and FARBSQ02 match most highly, are generally located in the south or south-east (Tables 2 and 3).

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Data of Measured Samples

FAR-B01A 148
227 299 269 287 115 126 157 154 161 135 126 125 169 95 109 102 120 162 179 131
105 123 106 110 156 232 252 208 144 122 161 196 249 259 219 101 72 106 121 164
174 95 116 97 125 138 136 150 145 204 171 170 118 96 92 120 142 135 202 149
67 70 97 101 122 67 73 115 77 109 109 162 111 96 105 102 94 74 173 121
106 89 101 90 97 115 147 113 122 105 85 108 108 119 102 116 169 133 141 101
104 131 89 82 128 148 162 108 96 89 144 159 73 105 105 114 84 96 79 78
74 59 107 80 95 81 78 93 100 78 96 88 65 92 105 76 79 64 63 57
48 73 105 92 103 89 75 73

FAR-B01B 148
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63 78 92 100 124 63 71 115 82 104 113 159 109 98 99 98 102 72 116 115
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FAR-B02B 91
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222 227 209 143 154 192 229 126 149 204 154 205 142 141 190 205 156 142 213 176
142 132 137 142 147 136 155 137 142 89 88 84 94 93 98 133 142 100 107 83
81 91 82 63 53 76 90 133 70 66 61

FAR-B03A 144
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FAR-B03B 144
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FAR-B04A 113
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FAR-B05A 127
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FAR-B06A 112
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FAR-B07B 75
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FAR-B08A 137
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FAR-B08B 137
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FAR-B09A 96
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FAR-B09B 87
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162 105 117 127 69 56 79

FAR-B10A 97
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120 72 65 90 114 145 98 86 76 86 108 73 95 125 109 109 119 110 97 64
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FAR-B10B 97
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FAR-B11A 92
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235 242 209 167 190 213 145 145 114 132 153 222 152 284 264 232 236 227 296 278
271 205 201 241 140 140 130 112 114 139 134 155

FAR-B11B 92
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275 216 201 243 139 131 135 115 97 157 132 149

FAR-B12A 67
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FAR-B12B 69
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160 166 166 142 116 91 123 126 183 128 199 295 206 207 173 213 195 207 172 179
217 135 134 142 143 141 194 217 143 156 116 123 141 148 150 230 155 142 137 179
156 181 181 111 156 132 96 93 95

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	

Bar Diagram

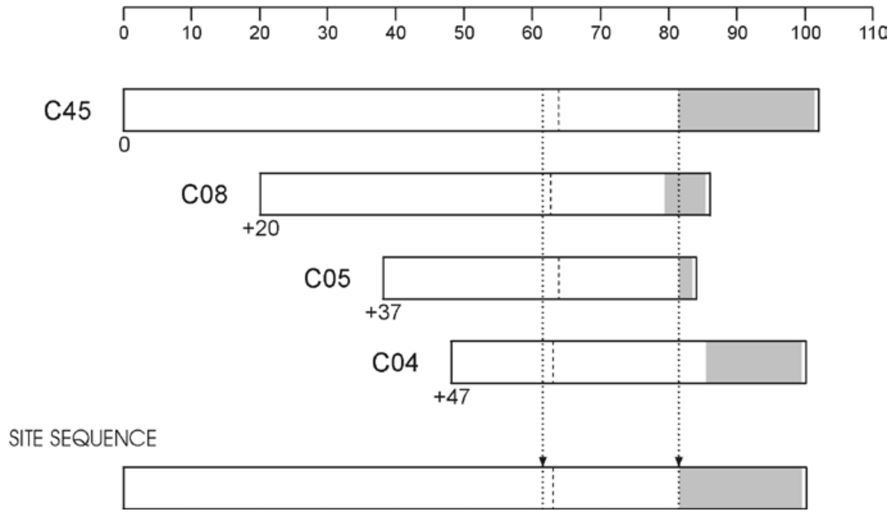


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

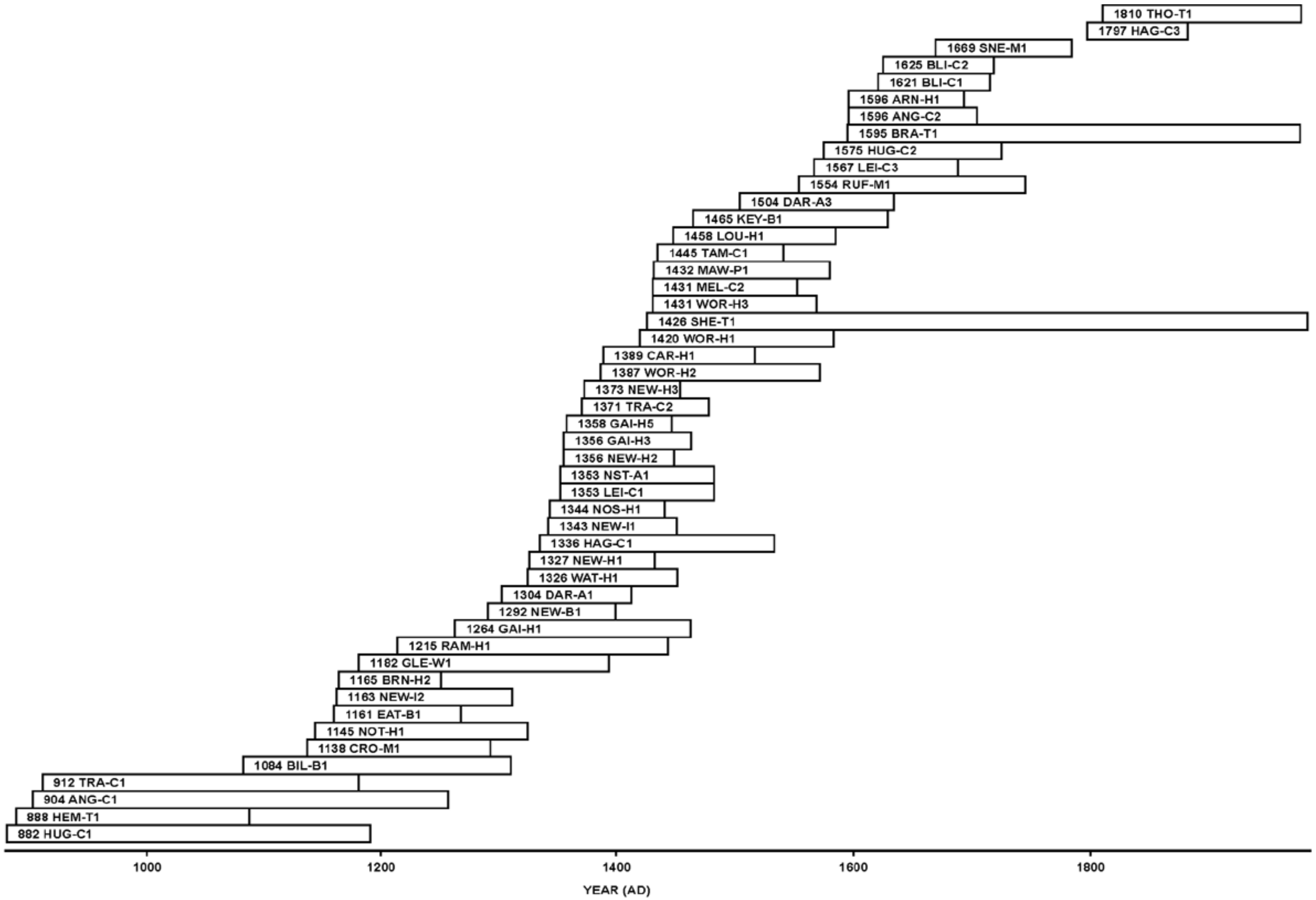
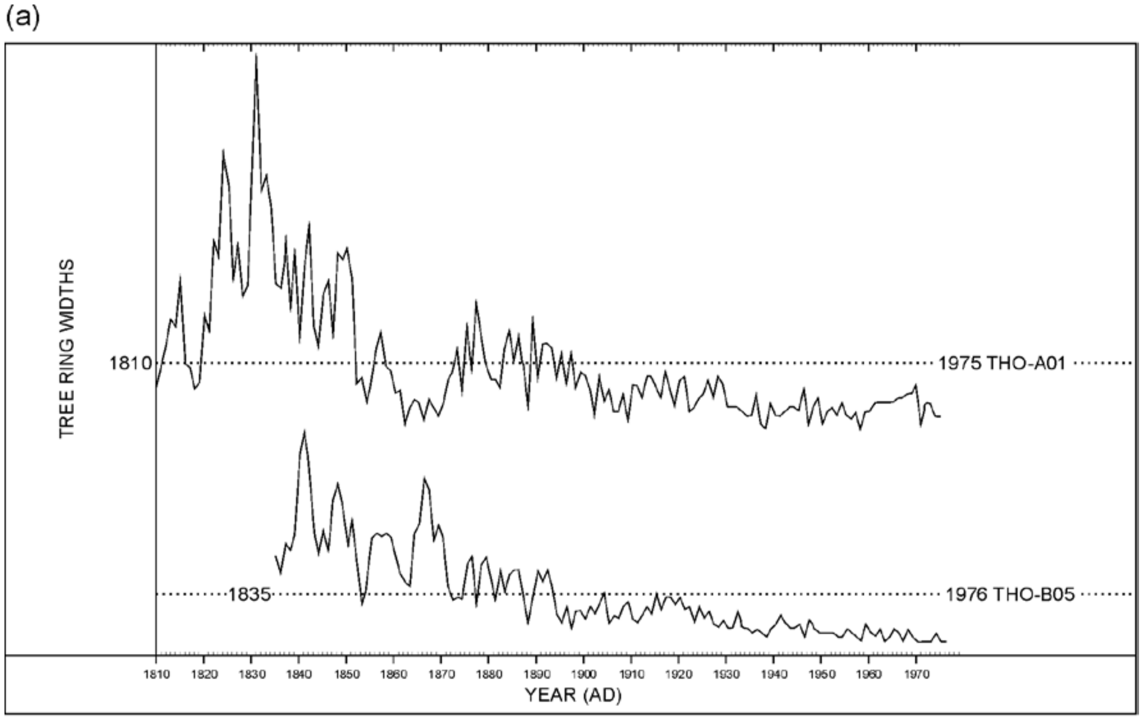


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



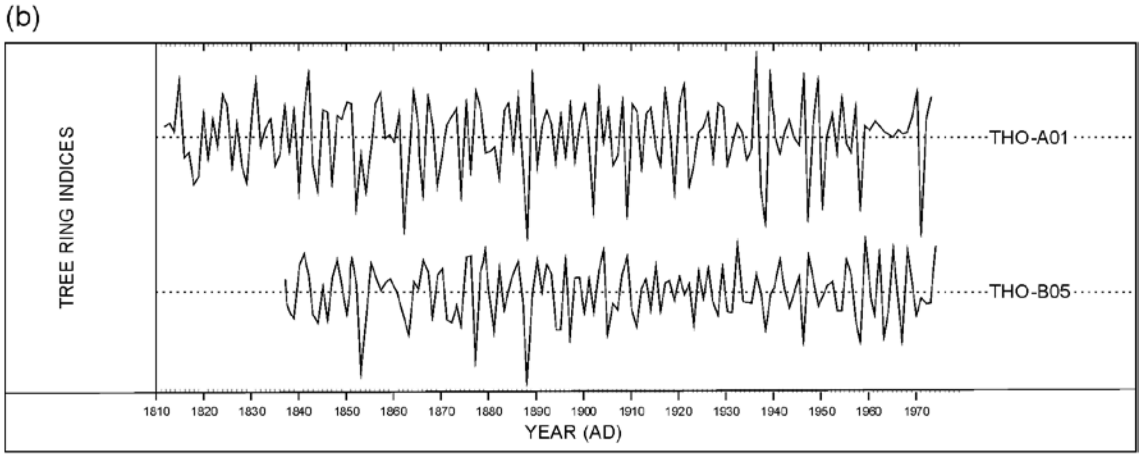


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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