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10 Church Street (Jennings Carpets), Tewkesbury, Gloucestershire

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

Scientific Dating

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Summary

Dendrochronological analysis was undertaken on samples from 22 timbers from the roofs over both the central and southern bays of this building, as well as an attic floor beam in the central bay and timbers accessible at second floor/attic level in the southern bay. This analysis produced a single site chronology comprising 20 samples from both bays. This site chronology is 203 rings long, these rings dated as spanning the years AD 1265–1467. Interpretation of the sapwood on the dated samples would indicate that the timbers to the southern bay are derived from trees felled in AD 1467. The timbers used in the central bay were felled at some point during the AD 1450s–60s, possibly slightly earlier than those in the southern bay. Thus, from a dendrochronological perspective, timbers from both bays appear essentially coeval, in spite of there being some constructional differences between the roof structures.

Contributors

Alison Arnold, Robert Howard and Cathy Tyers

Acknowledgements

We would firstly like to thank the owners and residents of 10 Church Street for their enthusiasm and support for this programme of analysis, and particularly for their cooperation on the day of sampling. We would also like to thank Rebecca Lane, Historic England Senior Architectural Investigator, and Johanna Roethe, Historic England Architectural Investigator, for not only promoting this programme of tree-ring analysis, but also for their help in arranging access to this building and ensuring that the description of the building provided below is in accordance with their investigations. Thanks also to Julian Baggs, the Conservation Officer at Tewkesbury Borough Council, and Amanda Hooper, Senior Listing Adviser at Historic England. Finally, we would like to thank Shahina Farid, Historic England Scientific Dating Coordinator, for commissioning this programme of tree-ring dating and for her valuable contributions to this report.

Archive location

Historic England Archive, The Engine House, Fire Fly Avenue, Swindon, Wiltshire SN2 2EH.

Historic Environment Record

Gloucestershire County Council Archaeology Service, Shire Hall, Westgate Street, Gloucester GL1 2TH.

Date of investigation

2022

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Contents

Introduction

Tewkesbury High Street Heritage Action Zone

In 2019 Tewkesbury (Fig 1) was selected as one of over 60 successful High Street Heritage Action Zone (HSHAZ) bids; a government funded programme delivered by Historic England, in partnership with local bodies, devised to unlock the potential of high streets across England, fuelling economic, social and cultural recovery. Tewkesbury's HSHAZ area encompasses much of the town centre, extending from the Abbey to the south to Healing's Mill to the northwest. It centres on High Street, Barton Street and Church Street. The area is part of the Tewkesbury Conservation Area and contains many listed buildings.

It is hoped that such works will increase the use of the High Street area by conserving and restoring buildings, improving the public realm, and increasing public access and awareness. As part of this process, it was proposed that Historic England Architectural Investigators, Rebecca Lane (Senior Architectural Investigator), and Johanna Roethe (Architectural Investigator), would undertake research on a small number of buildings selected in consultation with Julian Baggs, the Conservation Officer at Tewkesbury Borough Council, and Amanda Hooper, Senior Listing Adviser at Historic England, with dendrochronology being one of the supporting elements to the work were considered appropriate. It was hoped that such research would help towards delivery of the overall objectives of the HSHAZ programme by improving understanding of the town centre area and providing a good evidence base for future planning and improvement decisions. Number 10 Church Street was selected as being a building of particular merit.

10 Church Street

This Grade II* building (List Entry Number: 1282789) comprises three single-bay elements, each structurally distinct from the others. There is a three-storey front block to the north fronting on to the south-east side of Church Street, a three-storey central bay, and a two-storey (with attic) rear bay to the south. The building is aligned broadly north-west to south-east but for the purposes of this report is deemed to be aligned north to south. The northernmost bay, fronting on to Church Street, appears almost entirely late-eighteenth century or early-nineteenth century in date, although with some possibly reused medieval timbers inserted into its ground floor. The central bay retains timbering to its roof comprising a principal rafter truss to the south with tiebeam and collar, the truss supporting single purlins to each pitch of the roof. There is a single main beam to the floor of the attic. To the north, in the junction between the central bay and the later front bay, further elements of a truss, of the same form as that to the south survive, including a tiebeam.

The first-floor bay has a moulded ceiling beam and hollow chamfered joists. On the second floor the external wall to the east has closely spaced timber studs, and timber-framing with up-bracing is visible in the north and south walls.

In the southern bay the northern wall abuts directly up against the central bay. The walls in the attic in this bay are formed of main posts and close-set vertical studs, the roof formed of a north truss with two principal rafters with tiebeam and collar, with queen struts between tiebeam and collar. The south truss has been rebuilt in brick above and below the tiebeam. The trusses support single purlins to each pitch of the roof, these in turn supporting common rafters. There are curved up-braces from the main posts of the trusses to the tiebeams, and windbraces from the principal rafters to the purlins (Fig 2a/b). Thus, there are differences between the roofs of the southern and central bays, particularly in the use of windbraces.

Sampling

Dendrochronological investigation was requested by Johanna Roethe and Rebecca Lane as a supporting element to the research being undertaken within the HSHAZ programme, in order to provide independent dating evidence, thereby enhancing understanding of the building.

An initial survey of the timbers to the roof and attic floor of the central bay, and of the timbers to the roof and first floor walls of the southern bay, showed that, in being of oak (*Quercus* spp) and having adequate numbers of annual growth rings, timbers from both bays had potential for dendrochronology analysis.

Thus, from the various timbers available, a total of 22 timbers were sampled by coring. Each sample was given the code TWK-B (for Tewkesbury, site 'B') and numbered 01–22. Of this number, nine samples, TWK-B01–09, were obtained from the roof and attic floor of the central bay, with a further 13 samples, TWB-A10–22, being taken from the roof and first floor timbers of the southern bay. Details of the samples are given in Table 1, with the sampled timbers also being identified in a series of annotated photographs in Figures 3a–4b.

Analysis and Results

Each of the samples obtained was prepared by sanding and polishing. The widths of the annual growth rings of the samples from all 22 timbers were then measured, these measured data being given at the end of this report. The 22 measured series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix 1). This comparative process resulted in the production of a single group comprising seven samples from the central bay, and 13 samples from the southern bay. These 20 samples combine at a minimum value of t=3.7, cross-matching with each other at the positions illustrated in Figure 5.

These 20 series were combined at their indicated offset positions to form TWKBSQ01, a site chronology with an overall length of 203 rings. This site chronology was then compared with an extensive range of oak reference chronologies, this indicating a repeated series of strong cross-matches when the first ring of the site chronology dates to AD 1265 and the date of its latest ring is AD 1467 (Table 2).

Site chronology TWKBSQ01 was then compared with the two remaining but ungrouped samples, TWK-B04 and TWK-B05, both from the roof to the central bay, but there was no satisfactory cross-matching. These two samples were, therefore, compared individually with the full corpus of reference material for oaks, but again there was no secure cross-matching identified and both samples must remain undated for the moment.

Interpretation

Dendrochronological analysis has successfully dated 20 of the 22 timbers from which samples were obtained, these timbers being to both the roof and attic floor of the central bay and to the roof and second floor of the southern bay (Table 1; Fig 5).

Southern bay (rear block)

Five of the dated samples, all from common rafters, retain complete sapwood. This means that they each have the last growth ring produced by the tree represented before it was cut. In each case, this last growth ring, and thus the felling of the trees represented, is the same, being dated to AD 1467, with some of these samples indicating a felling in the early summer of that year.

Five further samples from the southern bay retain some sapwood or at least the heartwood/sapwood boundary, this last meaning that although a sample may have lost all of its sapwood rings (the most recent growth of the tree) it is *only* the sapwood rings that have been lost. The amount of sapwood, and particularly the relative position and date of the heartwood/sapwood boundary on these five remaining samples, is very similar to those on the timbers whose precise felling date is known - the average heartwood/sapwood boundary date of the five samples with complete sapwood is AD 1444, while that on the five samples with incomplete sapwood, but with the heartwood/sapwood boundary, is dated AD 1442. Such similarity is indicative of a group of timbers having a very similar, if indeed not identical, felling date.

The three remaining dated samples from the southern bay, TWK-B11, TWK-B12, and TWK-B13, do not retain the heartwood/sapwood boundary, and, in having lost not only all their sapwood rings, but an unknown number of heartwood rings as well, it is in theory impossible to say when they were felled. These three samples match very strongly with each other, producing *t*-values of 9.1, 11.2, and 8.8 and match sufficiently well with the 10 other south bay samples, discussed above, to suggest that all the source trees are likely to have been growing in the same woodland. As such, it is perhaps more likely than not, that all the trees used were felled at, or at least about, the same time as each other (it being considered something of a coincidence that trees, once growing adjacent to a number of others, but felled at quite different times, should come to be used in the same building as former neighbours). Thus, taken overall, it is very likely that all the trees used in the southern bay were felled at, or at least about, the same time in AD 1467.

Central bay

None of the seven dated samples retains sapwood complete to the bark (i.e. none have the last growth ring produced by the tree represented before it was cut down), and it is thus not possible to say precisely when any of the trees represented were felled. All seven samples do again, though, retain some sapwood or at least the heartwood/sapwood boundary, the average heartwood/sapwood boundary date of these seven samples being dated to AD 1438. Allowing for a minimum of 15 sapwood rings, and a maximum of 40 sapwood rings (the 95% confidence interval for the number of sapwood rings on oak trees), would give these timbers an estimated felling date of some point between AD 1453 at the earliest and AD 1478 at the latest.

In order to attempt to further refine the estimated felling date range for this group of timbers from the central bay, the material was assessed for its suitability with respect to using the methodology developed by Miles (2005) and implemented in OxCal v4.4 (Bronk Ramsey 2009; Miles 2006). Following the methodology described by Millard (2002), Bayesian statistical models are used to provide individual sapwood estimates for each timber using the variables of the number of heartwood rings present, the mean ring-width of those heartwood rings, the heartwood/sapwood boundary date, and the number of any surviving sapwood rings (including those that can only be counted, not measured, or those lost on sampling). Miles (2005) developed several such models, of which the one that is considered most appropriate for the timbers in this case is that for ‘England & Wales AD’ (EnglandWales). This model is based on data from timbers throughout this area, although there is a bias towards data from Shropshire, Somerset, Hampshire, Oxfordshire, and Kent. This model is generally considered appropriate geographically for historic timbers from buildings in Gloucestershire, as well as being compatible with the growth characteristics of this particular assemblage.

Using the above methodology, we have therefore combined the probability distributions for the felling dates of these seven timbers that retain their heartwood/sapwood boundaries and estimate that this felling episode occurred in AD 1456–1465 (95.4% probability; central; Fig 6; see Appendix 2). The distributions have good agreement with the interpretation that these timbers represent a single felling episode (Acomb: 85.7, An: 26.7, n: 7). The individual felling date ranges (95.4% probability) are listed in Table 3.

Discussion and Conclusion

Tree-ring analysis of timbers from this site has successfully dated 20 of the 22 timbers from which samples were obtained. Interpretation of the sapwood on the dated samples would indicate that the timbers to the southern bay are derived from trees felled in AD 1467, whilst those used in the central bay were felled at some point during the period AD 1453–78 or, using the refined estimated felling date range derived through OxCal (see above), *AD 1456–1465* (*95% probability; central;* Fig 6).

Thus, from a purely dendrochronological perspective both bays appear to be essentially coeval, with the central bay timbers possibly felled slightly earlier based on the refined estimated felling date range obtained through OxCal. The slightly earlier average heartwood/sapwood boundary date of the samples from the central bay, AD 1438 (heartwood/sapwood boundary dates range from AD 1427 to AD 1445), as compared to the overall average for the southern bay timbers, AD 1443 (heartwood/sapwood boundary dates range from AD 1436 to AD 1452), could also be taken to suggest this as a possibility. Structural evidence, however, intriguingly suggests that the southern bay roof was pre-existing at the time that the central bay roof was built (Lane and Roethe pers. comm.). Bearing this in mind, it is worth noting that the precise felling date of AD 1467 for the southern bay is derived from a single element type, namely five common rafters. It should also be noted that the precise felling date for the southern bay of AD 1467 lies within 99.7% probability range of *AD 1456–1469* for the central bay (*central*, Fig 6), a fact that has been previously observed in relation to some groups of timbers when using the 'England & Wales AD' sapwood model (Tyers 2008).

Woodland sources

As may be seen from Table 2, although site chronology TWKBSQ01 has been compared with reference material from all over the British Isles, there is a distinct trend for it to match best with reference chronologies made up of timbers from other buildings in the South West and Midlands regions of England, as well as adjacent counties in Wales. The highest levels of similarity are, however, found with other sites in Gloucestershire and the two counties immediately to the north, Herefordshire and Worcestershire. While the sources of the timbers used at these particular reference sites are themselves unknown, such cross-matching would suggest that the dated trees used at 10 Church Street are from a similar relatively local source.

Wherever the source woodland(s), it may be of interest to note that some timbers may have been derived from the same tree. Samples TWK-B17, TWK-B19, and TWK-B22 (all common rafters to the roof of the southern bay) for example cross-match with each other with values ranging from t=9.2 to as high as t=14.1, this indicating a possible same-tree source. Further common rafters, represented by samples TWK-B18, TWK-B20, and TWK-B21, may have come from a tree, or trees, growing virtually adjacent. It is also possible that the timbers represented by samples TWK-B11 and TWK-B13, respectively a wall post and a purlin in the southern bay, are also derived from a single tree, these two samples cross-matching with each other with a value of t=11.2.

The cross-matching between samples from each area of sampling, the central bay and the southern bay, is not as good as it is between samples within each area. That is, the samples from the central bay match better with each other, as do the samples from the southern bay, but the matching between the two locations is not quite so good. This might be taken as evidence that the timbers for each bay were sourced from potentially different woodland areas, although probably not far removed from one another, which in turn might suggest that the two groups of timbers were felled at slightly different times, and that there was at least a small period of time between the building of what is now the central bay, and what is now the southern bay.

Undated samples

As may also be seen in Table 1, two samples, TWK-B04 and TWK-B05, both from the central bay roof, remain undated, despite, with respectively 50 and 74 rings, having sufficient number for reliable dating. Neither sample shows any features such as distortion or compression which might cause problems with cross-matching. It is possible that these undated timbers grew somewhere for which there is currently insufficient reference data available to provide secure cross-matching, although this seems relatively unlikely. However, for whatever reason, it is a very common, if inexplicable, feature of tree-ring analysis to find that some samples will not date. This undated material will be reviewed periodically as further reference chronologies for the locality become available and these timbers may, in due course, also be dated.

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Tables

Table 1: Details of tree-ring samples from 10 Church Street (Jennings Carpets), Tewkesbury, Gloucestershire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Central bay roof and attic floor					
TWK-B01	Tiebeam	69	16	1389	1441	1457
TWK-B02	Collar	90	10	1363	1442	1452
TWK-B03	East queen strut	90	18	1362	1433	1451
TWK-B04	West queen strut	50	no h/s	------	------	------
TWK-B05	East principal rafter	74	8	------	------	------
TWK-B06	West principal rafter	82	h/s	1361	1442	1442
TWK-B07	East purlin	84	7	1357	1433	1440
TWK-B08	West purlin	87	11	1352	1427	1438
TWK-B09	Attic floor beam	116	h/s	1330	1445	1445
	Southern bay roof and second floor timbers					
TWK-B10	Tiebeam, north truss	130	21	1330	1438	1459
TWK-B11	West wall post	126	no h/s	1296	------	1421
TWK-B12	East purlin	75	no h/s	1265	------	1339
TWK-B13	West purlin	141	no h/s	1295	------	1435
TWK-B14	East wall plate	58	17	1402	1442	1459
TWK-B15	East common rafter 1 (from north)	105	15C	1363	1452	1467
TWK-B16	East common rafter 5	41	28C	1427	1439	1467
TWK-B17	West common rafter 3	91	3	1353	1440	1443
TWK-B18	West common rafter 4	64	16	1393	1440	1456
TWK-B19	West common rafter 5	107	31C	1361	1436	1467
TWK-B20	West common rafter 6	115	3	1340	1451	1454

Table 1: cont.

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
TWK-B21	West common rafter 7	74	15C	1394	1452	1467
TWK-B22	West common rafter 8	104	28C	1364	1439	1467

*h/s = the heartwood/sapwood ring is the last ring on the sample; C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Table 2: Results of the cross-matching of site sequence TWKBSQ01 and relevant reference chronologies when the first-ring date is AD 1265 and the last-ring date is AD 1467

Reference chronology	Span of chronology	t-value	Reference
St Mary Magdalene’s Church, Twyning, Gloucestershire	AD 1251–1452	13.0	Tyers 1996
24 High Street, Droitwich, Worcestershire	AD 1313–1455	12.0	Tyers 2017
The Master’s House, Ledbury, Herefordshire	AD 1330–1488	11.8	Arnold and Howard 2009 unpubl
The Kennetts, Whitbourne, Herefordshire	AD 1349–1458	10.7	Tyers 2008
St Peter’s Church, Pirton, Worcestershire	AD 1347–1507	10.7	Arnold and Howard 2013 unpubl
St Leonard’s Church (tower), Cotheridge, Worcestershire	AD 1264–1426	10.5	Arnold and Howard 2019 unpubl
Mucknell Farm, Stoulton, nr Pershore, Worcestershire	AD 1193–1438	10.3	Arnold *et al* 2008
Brockworth Court House, Brockworth, Gloucestershire	AD 1281–1447	10.1	Howard 2000 unpubl
Tithe Barn, Ashleworth, Gloucestershire	AD 1319–1475	9.8	Bridge 2002
Abbey Gatehouse, Kingswood, Gloucestershire	AD 1307–1428	9.6	Arnold *et al* 2003

Table 3: The individual OxCal derived felling date range (95.4% probability) for the seven dated samples from the central bay

Sample number	OxCal derived felling date range (95.4% probability)
TWK-B01	AD 1456–1475
TWK-B02	AD 1452–1480
TWK-B03	AD 1450–1473
TWK-B06	AD 1452–1480
TWK-B07	AD 1444–1474
TWK-B08	AD 1438–1469
TWK-B09	AD 1458–1492

Figures

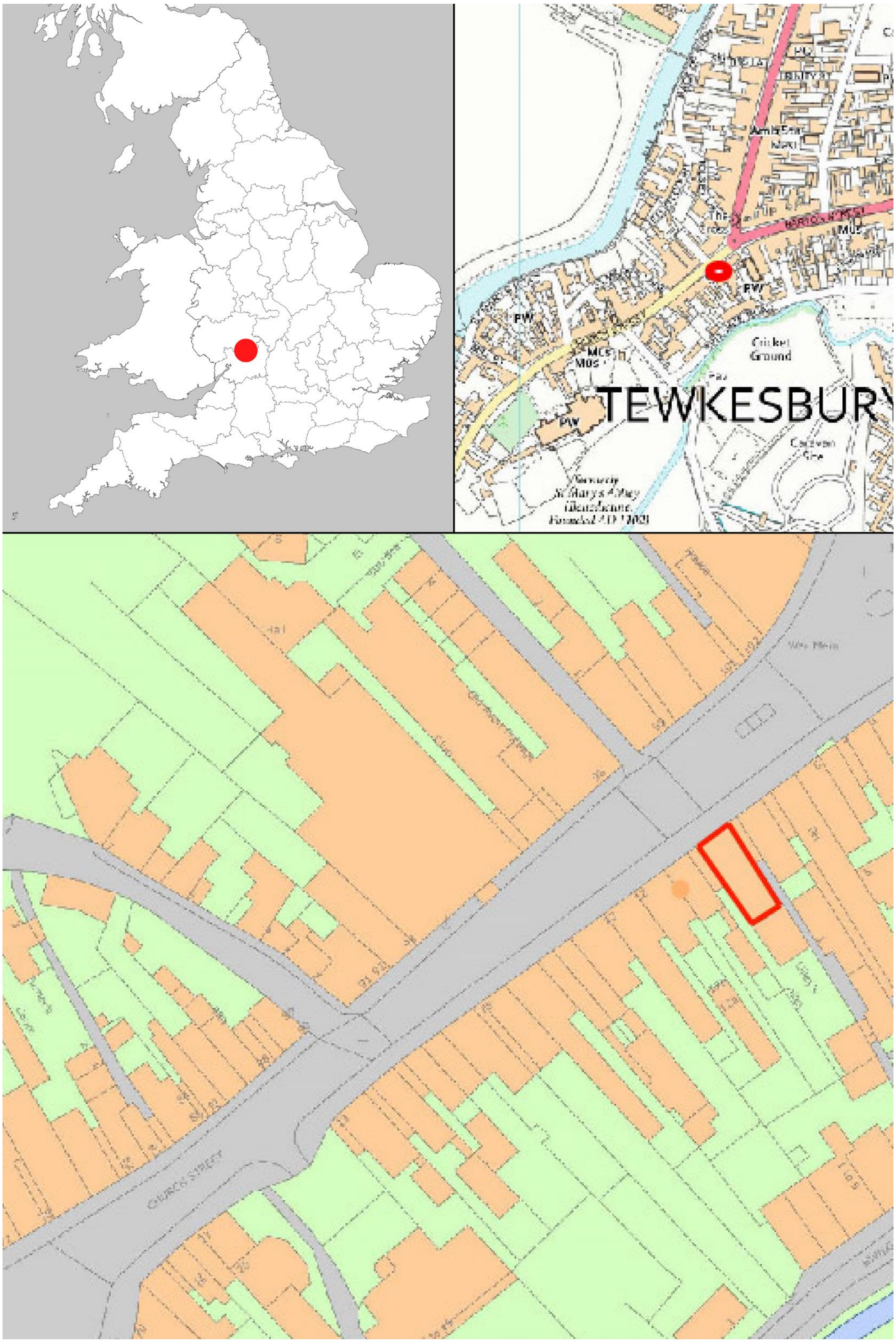


Figure 1: Map to show the location of 10 Church Street in Tewkesbury. Marked in red - top left map of England; top right scale: 1:6500; bottom scale 1:800. [© Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900]

Figure 2a/b: General views of the timbers to the roof of the southern bay, looking north-east (top) and north-west (bottom). [photographs Robert Howard]

Figure 3a/b: Annotated photographs of the roof over the central bay to help identify sampled timbers, looking south-east (top) and south (bottom). [photographs Robert Howard]

Figure 3c: Annotated photograph of the roof over the central bay to help identify the sampled timber, looking south. [photograph Robert Howard]

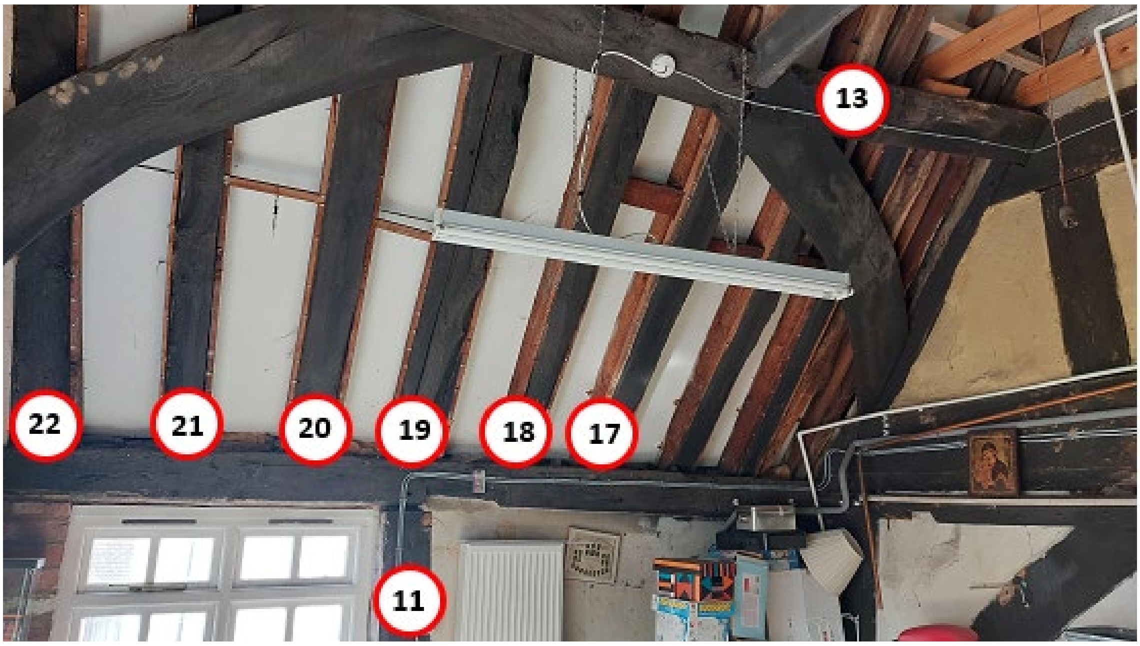
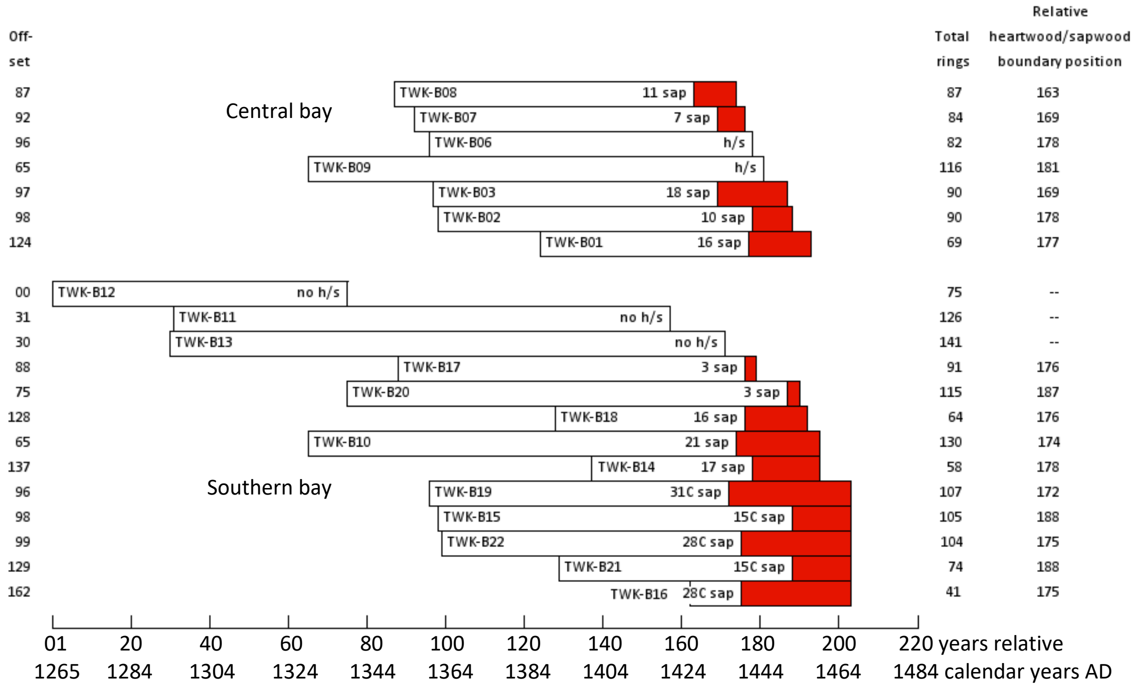


Figure 4a/b: Annotated photographs of the roof over the south bay to help identify sampled timbers, looking east (top) and west (bottom). [photographs Robert Howard]



Key:
White bars = heartwood rings; red bars = sapwood rings.
h/s = the heartwood/sapwood ring is the last ring on the sample.
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree.

Figure 5: Bar diagram of the 20 dated samples of site chronology TWKBSQ01 grouped by roof location and arranged in last measured ring date order.

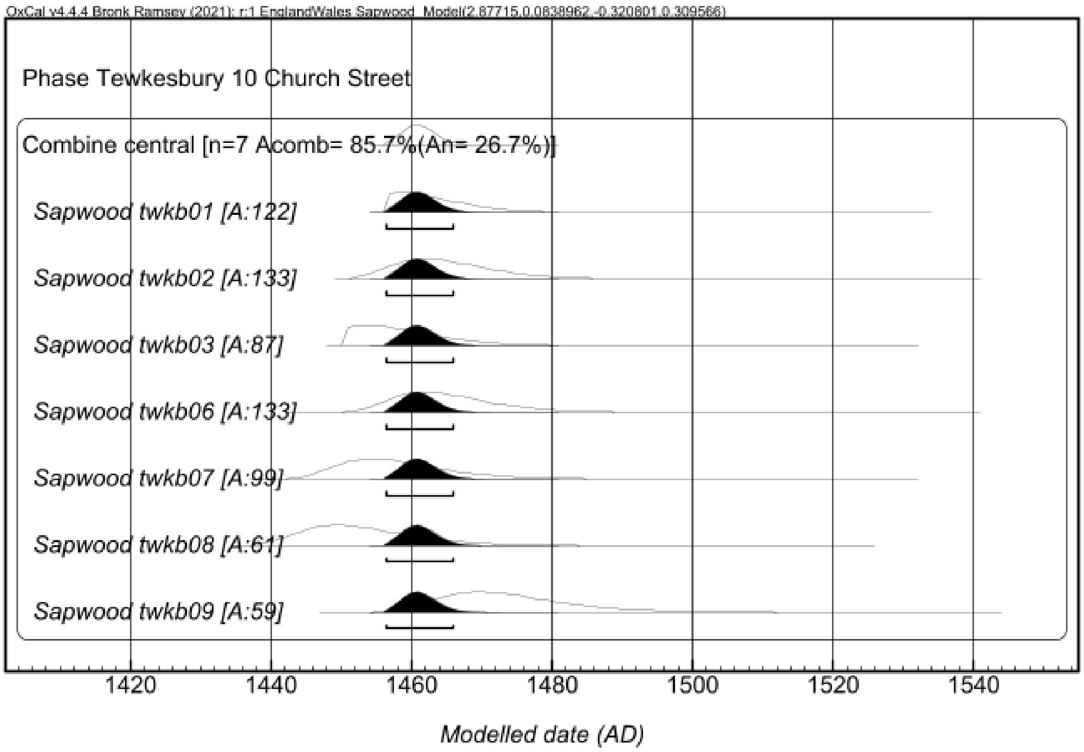


Figure 6: Probability distributions for the date of the felling of timbers from the central bay. Individual felling date distributions are shown in outline and the combined felling date distribution is shown in black with the 95.4% probability range bar below.

Data of Measured Samples

Measurements in 0.01mm units
TWK-B01A 69
227 189 279 164 195 219 208 371 234 196 250 308 286 212 321 218 167 192 207 382
546 350 217 224 155 152 221 157 231 309 137 201 140 140 384 209 135 84 129 240
185 174 233 322 170 118 110 107 89 108 109 93 192 173 128 134 123 165 101 118
109 125 179 196 168 160 205 150 248
TWK-B01B 69
246 188 280 170 200 221 224 366 234 194 268 305 284 216 327 232 175 181 192 362
546 364 228 211 175 168 240 141 225 296 151 187 135 145 375 203 137 92 139 221
174 181 225 306 171 121 113 104 101 103 114 81 213 168 126 151 114 160 115 125
95 128 175 209 179 151 212 163 230
TWK-B02A 90
147 192 199 226 183 176 216 189 100 155 141 176 144 180 159 150 176 132 160 161
145 162 133 262 235 198 164 146 190 145 164 160 118 182 114 216 235 253 243 151
210 197 129 151 143 164 182 164 153 190 162 114 179 100 101 162 121 185 123 135
192 151 185 147 114 116 117 127 127 186 107 101 123 151 184 117 76 143 127 144
128 121 154 116 122 115 120 112 162 152
TWK-B02B 90
160 196 202 227 182 169 225 194 93 154 130 187 152 172 167 135 176 141 159 168
142 160 132 264 235 200 157 137 200 146 157 165 119 182 115 218 244 242 235 162
213 192 126 145 160 150 201 137 157 198 148 112 182 106 101 162 110 189 125 130
195 146 192 157 113 111 98 126 143 172 115 118 128 140 184 96 78 154 132 137
156 134 159 115 125 118 116 114 163 173
TWK-B03A 90
409 191 100 54 113 148 151 295 237 144 200 242 255 162 232 216 223 270 140 163
182 131 187 201 305 245 254 148 121 243 119 170 125 96 178 98 131 153 183 129
101 107 117 78 76 67 76 143 76 70 90 92 92 73 81 70 96 61 87 54
58 94 57 75 48 54 70 60 75 65 120 89 75 93 65 98 64 93 81 131
110 140 106 90 91 85 78 83 91 98
TWK-B03B 90
371 190 98 54 113 140 156 301 228 144 196 243 239 165 229 224 228 246 135 160
185 139 190 190 307 253 257 161 142 246 107 169 125 105 178 99 134 162 182 143
98 104 112 90 77 75 64 140 87 72 78 87 101 66 81 73 100 50 87 60
61 98 62 67 54 53 64 68 59 65 132 81 76 85 76 92 84 68 90 129
90 140 114 95 77 91 103 80 76 140
TWK-B04A 50
151 151 208 223 193 212 309 209 230 180 212 160 213 281 193 142 182 159 114 262
269 223 176 217 141 140 129 188 128 100 159 160 178 141 114 129 103 90 67 57
65 73 76 62 43 40 59 48 31 20
TWK-B04B 50
159 151 202 227 200 192 309 217 232 167 223 162 216 277 177 140 164 164 125 252
282 223 184 207 177 171 132 216 122 103 159 127 178 142 111 140 110 96 73 57
75 70 84 65 48 40 60 56 37 18
TWK-B05A 74
190 223 217 164 244 187 130 112 125 223 126 118 162 169 151 205 200 180 153 201
193 203 196 260 194 139 167 192 153 111 110 114 128 128 81 71 86 93 97 110
108 160 127 139 109 140 150 145 200 179 198 178 184 214 178 129 125 87 112 106
110 156 140 145 107 139 120 157 116 130 146 107 156 191
TWK-B05B 74
178 225 213 169 242 187 124 118 115 224 114 131 173 167 164 196 193 186 152 200
184 200 202 224 203 143 163 192 161 107 108 122 122 137 85 67 86 89 85 117
118 155 124 153 103 133 157 141 195 174 202 185 182 206 182 140 141 85 125 107

120 170 150 140 116 122 146 136 117 138 146 96 153 198
TWK-B06A 82
73 334 401 324 204 245 234 146 264 280 246 276 233 271 213 250 250 260 250 236
174 204 164 207 109 185 175 140 181 130 160 128 170 124 155 158 150 168 170 198
213 135 204 157 149 151 101 103 146 101 71 87 93 139 104 109 54 81 79 85
106 93 133 107 117 93 103 135 131 107 97 140 104 120 140 175 126 133 104 120
87 149
TWK-B06B 82
81 332 389 324 205 249 233 150 262 278 246 280 218 260 210 246 242 260 259 237
187 205 157 214 117 182 158 158 183 115 160 131 157 129 153 161 144 168 170 206
215 130 196 165 143 159 107 106 140 98 72 87 103 126 107 105 61 84 68 80
112 96 137 114 114 89 98 157 125 107 103 143 96 103 153 163 128 133 113 112
89 135
TWK-B07A 84
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118 153 138 145 141 160 155 110 121 142 132 118 160 80 128 112 85 82 85 96
102 103 108 127 140 114 141 143 115 125 118 95 112 96 98 117 90 110 118 118
88 96 67 95 120 79 121 95 96 65 85 109 92 117 118 137 106 101 106 76
118 110 114 148
TWK-B07B 84
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123 150 154 135 141 155 147 116 125 139 120 114 160 83 120 121 86 85 75 103
113 99 105 142 143 95 159 154 110 131 104 104 107 98 96 107 95 115 114 117
68 95 73 82 107 88 112 96 89 67 98 109 89 118 118 115 104 117 95 87
107 117 128 143
TWK-B08A 87
215 215 221 195 125 170 175 181 117 128 143 156 178 128 134 128 117 212 125 125
112 113 128 128 136 109 111 117 109 105 99 99 110 89 97 93 80 78 78 95
74 68 71 57 70 50 82 78 82 103 67 98 104 95 92 65 84 103 95 106
113 81 103 110 92 89 95 68 79 89 65 101 76 60 75 75 83 73 87 73
78 77 79 87 42 68 135
TWK-B08B 87
162 217 222 193 127 179 172 177 113 143 146 146 185 120 128 135 128 194 134 141
119 103 124 128 128 117 108 108 121 76 91 91 111 85 97 100 78 81 80 94
67 68 71 61 67 49 77 71 85 96 76 115 114 96 88 78 81 107 107 98
90 90 84 103 88 81 93 75 84 87 78 97 76 60 79 62 71 76 71 88
95 71 75 70 53 67 144
TWK-B09A 116
105 82 81 83 92 96 107 109 107 101 68 88 75 90 85 114 104 117 137 166
155 139 150 144 110 80 75 97 78 89 76 67 62 91 103 93 92 92 71 71
62 55 60 60 55 60 67 78 72 81 53 56 48 51 66 58 64 75 64 72
57 82 53 52 68 64 60 71 78 92 103 103 89 132 99 87 98 78 81 82
76 76 89 73 81 98 126 89 85 62 70 91 69 116 94 98 84 121 129 107
110 118 103 106 118 142 125 126 125 117 103 110 84 92 125 204
TWK-B09B 116
113 78 82 84 91 94 109 108 105 110 70 83 75 92 86 108 109 116 141 157
169 147 150 139 112 91 76 94 85 103 93 66 78 90 110 96 96 78 75 77
68 56 62 60 63 72 64 74 81 73 52 56 50 51 64 60 63 75 66 71
46 89 58 49 70 57 57 71 84 95 92 110 85 128 101 92 98 87 82 82
71 79 81 76 85 92 129 90 82 65 76 95 64 110 101 87 87 124 129 106
104 122 102 106 118 146 123 118 126 114 107 112 96 90 129 194
TWK-B10A 130
175 244 184 212 232 291 165 208 312 319 318 307 194 249 181 160 243 263 203 200
299 271 167 190 190 164 50 64 34 50 46 36 62 82 117 81 69 90 101 119
103 74 70 76 78 87 96 112 118 162 115 101 98 117 134 181 162 166 139 142

118 135 88 127 99 148 178 115 175 204 125 181 150 205 155 133 189 150 190 231
142 112 166 174 178 153 140 153 192 128 212 155 122 280 147 220 90 128 156 156
120 137 230 159 134 109 115 101 96 130 107 174 116 133 118 157 124 132 123 93
134 134 131 148 114 168 137 169 190 181
TWK-B10B 130
179 238 193 210 232 287 174 204 310 325 316 307 194 251 174 163 252 261 192 196
294 257 170 171 201 175 51 64 32 57 34 33 60 85 117 81 66 90 95 128
109 73 76 75 71 90 99 112 118 160 121 89 98 109 135 167 164 178 146 130
125 132 75 123 106 149 167 126 159 198 129 179 159 211 174 131 192 165 189 218
164 120 166 173 172 162 102 165 212 139 216 153 131 253 142 180 106 127 162 131
131 133 213 162 136 122 115 112 99 109 109 182 110 126 131 141 106 134 125 84
121 141 137 128 121 178 134 178 158 203
TWK-B11A 126
270 230 123 212 247 384 275 196 218 196 337 259 232 164 241 173 213 196 303 306
297 293 162 386 235 299 381 343 264 189 141 248 204 198 175 142 100 179 156 241
185 237 170 301 197 270 170 214 168 212 267 218 225 237 226 248 184 225 190 117
109 112 78 102 100 101 109 159 168 110 108 102 98 95 93 93 104 99 111 131
193 144 136 177 85 67 62 76 66 75 103 106 131 121 93 102 99 141 106 114
156 128 143 173 178 148 107 133 103 100 138 117 188 218 150 152 134 118 122 136
151 143 154 110 175 112
TWK-B11B 126
286 236 128 217 255 385 293 207 221 206 335 262 214 157 247 171 221 196 295 289
335 293 164 378 260 303 423 329 268 182 126 251 216 173 179 142 95 187 170 242
188 220 166 307 195 260 182 231 166 207 267 209 240 248 221 240 160 224 218 127
112 94 84 106 103 93 111 163 146 121 109 95 88 100 96 94 103 99 112 128
176 153 126 166 75 75 59 77 70 75 99 109 125 119 95 101 103 151 90 118
159 140 137 174 172 158 103 123 110 94 138 120 194 220 142 146 137 126 115 117
161 150 153 117 175 140
TWK-B12A 75
355 394 218 307 193 143 117 176 278 246 346 262 281 196 264 325 276 192 143 308
335 391 165 162 467 385 387 443 461 629 478 420 392 160 196 296 293 305 123 192
173 209 217 225 140 223 187 257 193 300 406 374 250 143 381 271 356 357 211 262
148 102 212 203 162 146 101 71 106 131 196 172 225 191 307
TWK-B12B 75
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321 390 152 171 418 382 403 446 432 595 468 414 354 151 190 262 328 306 128 187
176 210 217 218 161 217 178 250 192 296 387 403 228 153 390 270 340 373 228 259
152 93 224 208 166 138 130 78 97 141 174 175 222 193 314
TWK-B13A 141
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191 199 168 98 178 225 235 235 196 186 129 92 159 132 103 71 71 50 77 97
141 107 118 88 133 110 153 124 161 97 144 238 146 177 184 216 284 137 191 171
85 74 127 173 187 157 141 148 133 128 124 111 91 125 127 105 121 96 75 60
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58 93 61 71 84 126 121 71 126 93 117 88 78 109 126 106 173 154 128 117
126 148 134 129 74 164 110 115 278 142 142 61 83 103 81 67 98 130 70 67
90
TWK-B13B 141
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193 199 166 98 199 214 233 217 200 200 124 85 183 125 103 75 71 55 73 94
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89 83 128 176 178 148 126 138 115 125 114 109 107 119 128 98 119 110 81 57
64 77 57 76 83 52 63 67 84 48 41 43 49 46 39 50 70 50 64 54
64 92 56 79 85 110 123 70 122 99 101 101 67 117 131 106 170 163 128 117
131 148 126 128 73 162 100 112 267 145 137 65 84 101 73 84 93 134 74 61

94
TWK-B14A 58
289 561 530 436 438 382 438 427 316 230 219 244 214 378 259 204 414 234 350 268
296 329 272 210 112 109 165 220 163 153 194 175 151 134 109 109 160 152 151 189
125 115 90 73 121 115 110 106 101 129 109 123 100 118 114 114 115 81
TWK-B14B 58
264 515 513 427 396 382 434 430 322 210 230 232 211 388 243 196 413 240 350 260
295 320 273 192 126 106 165 224 154 160 207 168 153 130 124 106 164 138 157 192
131 110 98 78 118 109 110 117 107 126 109 124 92 107 109 134 106 96
TWK-B15A 105
144 144 74 57 56 75 78 66 46 55 47 29 24 29 24 36 41 33 26 76
85 77 80 98 100 71 53 39 51 34 35 39 44 33 35 53 33 30 34 21
25 27 32 23 22 33 25 17 16 27 35 59 94 80 71 87 83 180 148 113
193 146 102 57 86 103 101 60 128 293 188 260 209 192 226 204 190 94 147 120
128 159 182 198 140 153 90 112 196 224 125 131 304 293 163 115 101 170 146 171
206 114 140 210 384
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21 29 30 23 27 26 21 17 19 30 46 55 94 78 76 80 82 184 153 114
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177 114 146 200 359
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92 105 57 75 82 150 115 150 145 147 125 96 111 122 88 85 128 64 154 382
380
TWK-B16B 41
38 54 44 48 57 89 72 67 100 92 162 155 117 75 130 102 110 86 89 91
80 96 61 66 90 145 113 173 137 135 132 96 108 117 84 90 117 71 152 385
381
TWK-B17A 91
110 202 154 320 308 239 303 205 283 344 271 307 206 153 111 192 246 79 82 177
204 173 225 260 236 197 229 190 128 170 126 134 134 135 96 114 76 67 60 76
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TWK-B17B 91
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211 167 235 254 238 194 221 187 135 180 132 125 129 128 103 108 85 66 57 78
80 54 48 84 57 87 78 66 89 90 101 67 65 100 79 84 83 46 49 39
48 54 50 39 43 36 41 53 50 35 73 48 35 42 25 50 49 45 54 126
126 160 164 235 248 262 173 107 150 110 168
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162 168 164 212
TWK-B18B 64
157 95 104 160 153 163 145 105 123 150 147 101 94 119 115 125 120 73 105 103
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106 72 77 82 121 160 164 128 207 168 118 130 158 178 169 178 117 168 171 203
182 146 153 234
TWK-B19A 107
132 182 191 226 176 98 90 100 136 81 50 77 91 85 101 139 103 103 132 112

86 152 91 81 88 111 125 86 71 54 42 50 53 41 47 68 53 78 74 59
73 71 85 56 45 75 71 73 59 42 37 30 39 36 40 50 31 37 24 45
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167 125 131 137 139 156 131 165 125 120 147 131 121 121 123 109 107 95 132 106
120 93 184 59 80 67 225
TWK-B19B 107
152 184 197 229 169 104 80 110 128 76 41 73 89 91 96 139 104 104 126 111
89 153 98 76 94 107 119 90 69 60 37 51 50 43 43 67 56 75 77 60
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67 62 64 93 67 33 36 33 43 49 35 37 70 48 82 70 55 66 71 84
58 103 101 45 79 53 50 55 46 44 41 50 282 200 181
TWK-B20B 115
313 337 276 337 268 231 248 251 198 228 128 174 116 121 145 64 44 116 161 200
137 112 110 217 186 105 67 55 105 171 108 104 58 76 57 77 75 84 68 97
77 68 69 88 70 81 120 123 121 121 104 76 62 64 50 40 54 59 64 93
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68 59 65 90 65 35 32 31 43 50 31 40 69 52 75 68 59 60 80 81
37 110 103 55 71 59 53 48 54 43 43 50 256 170 213
TWK-B21A 74
85 56 68 73 109 118 67 100 78 84 65 58 135 139 197 169 112 119 88 91
54 100 93 81 63 57 75 67 49 114 101 54 35 44 41 42 33 62 197 138
148 172 134 133 146 134 104 242 151 110 162 125 132 130 142 103 139 154 114 141
64 116 110 141 185 162 200 140 123 188 105 124 215 260
TWK-B21B 74
83 63 71 77 117 104 70 90 87 87 57 58 118 138 197 170 110 126 82 90
54 99 100 82 65 51 75 64 55 117 92 57 37 34 46 50 29 57 176 132
148 168 137 125 144 142 113 241 145 120 160 121 139 132 141 100 132 164 103 134
63 117 116 142 164 164 191 139 117 194 110 128 210 258
TWK-B22A 104
215 169 91 78 139 175 50 60 77 132 102 171 180 123 103 121 68 46 78 75
58 62 75 73 82 56 50 35 48 76 54 41 72 57 69 78 46 63 49 64
47 27 51 42 46 39 31 26 21 29 32 31 38 32 32 31 50 41 32 60
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137 130 139 166 175 137 84 126 175 168 226 164 193 171 135 206 192 154 154 176
82 221 412 306
TWK-B22B 104
219 176 87 77 149 166 56 57 85 125 106 161 183 134 105 128 67 48 75 74
71 62 79 95 80 71 50 51 48 76 57 39 77 51 59 74 63 64 60 68
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Appendix 1: 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

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 AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 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

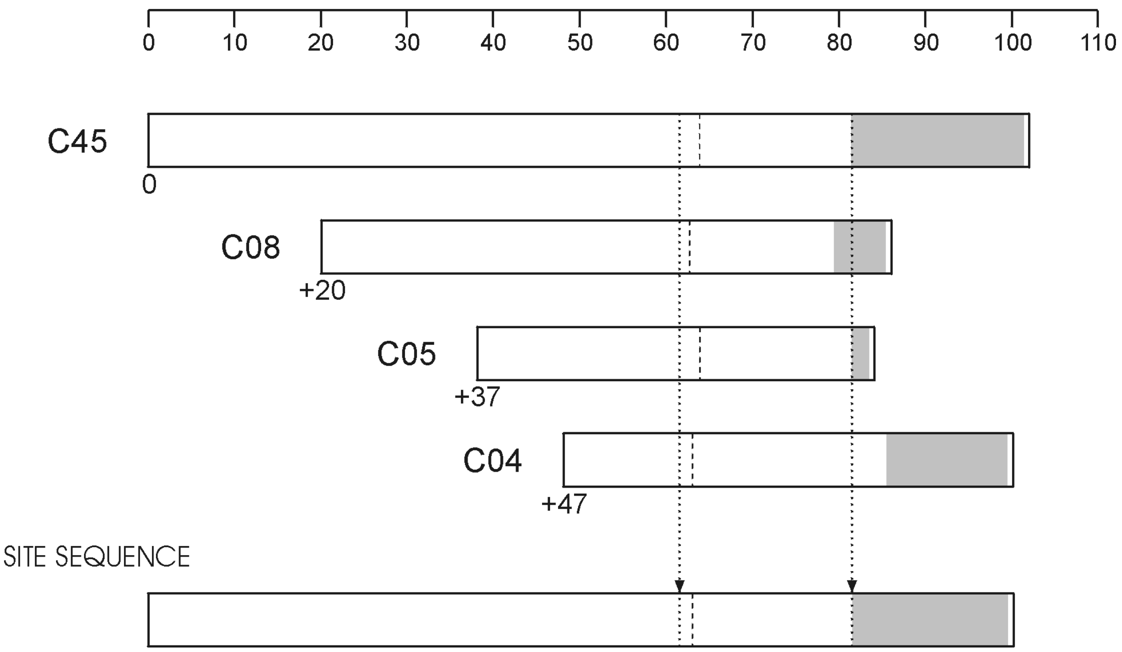


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

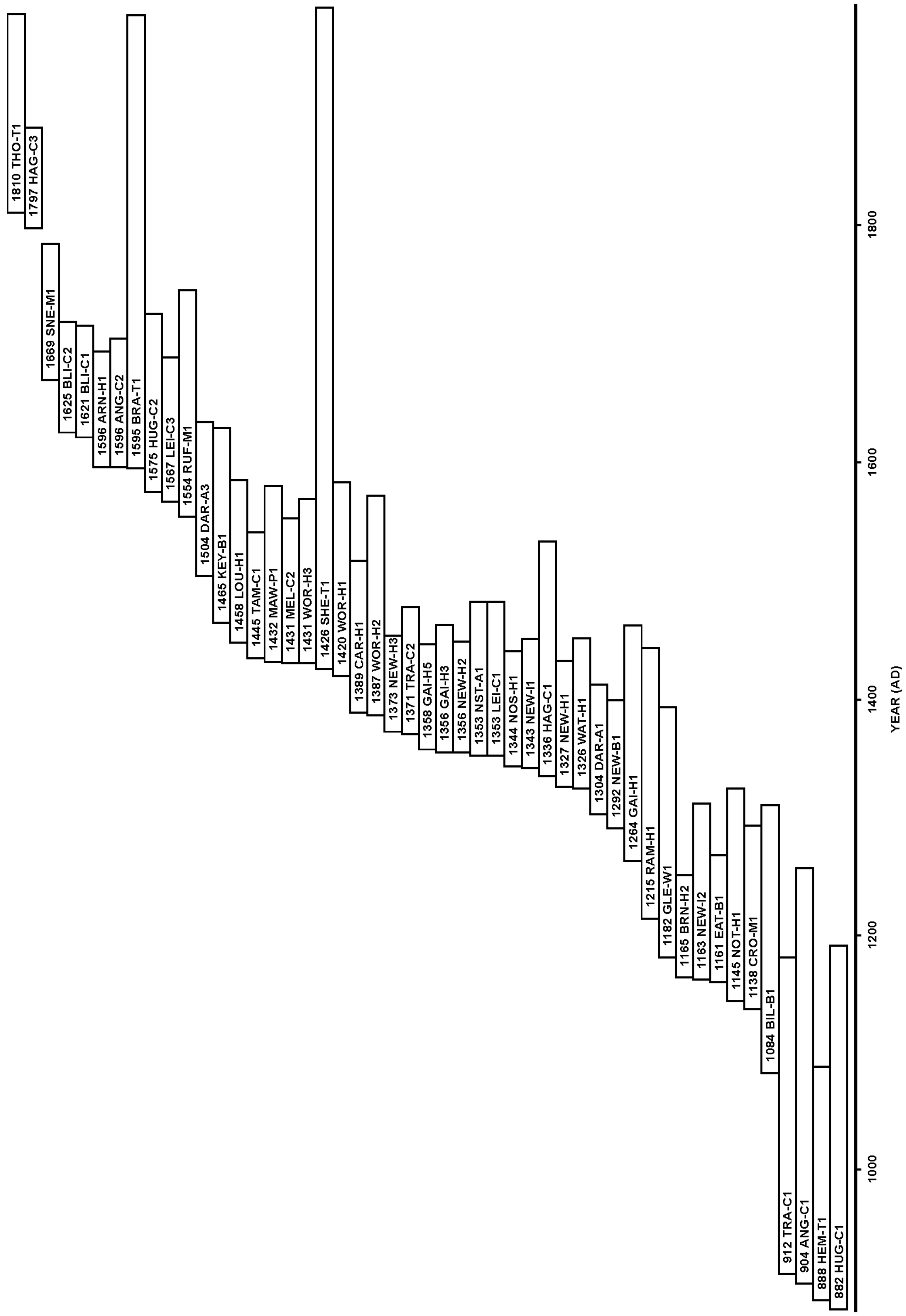
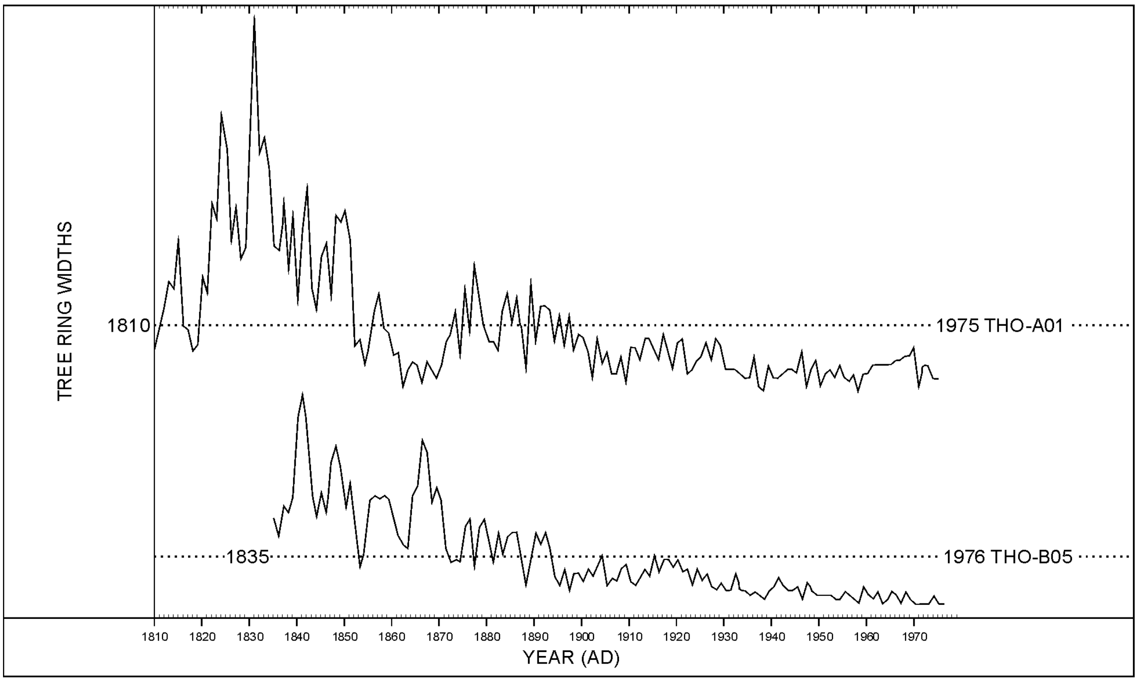


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

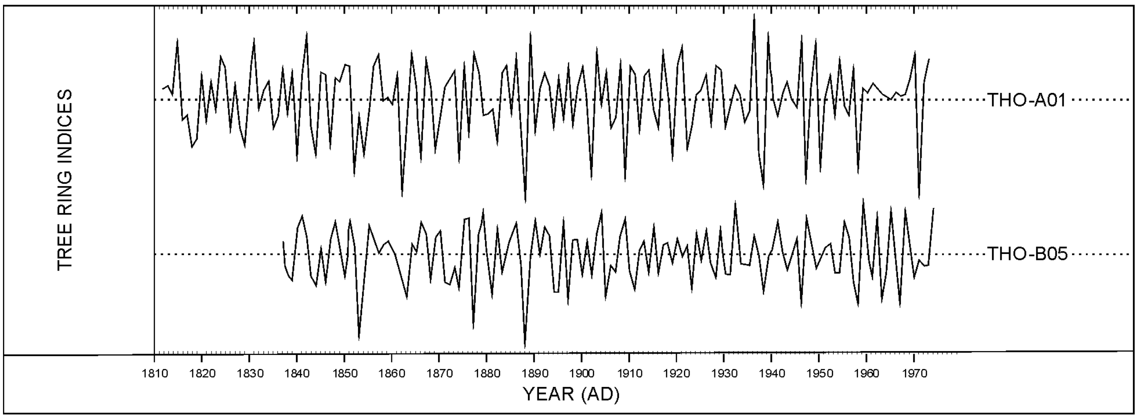


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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Appendix 2: OxCal Code

Central bay timbers (Fig 6)

```
Options()
 {
  Resolution=1;
 };
 Plot()
 {
  Sapwood_Model("EnglandWales", 2.877146, 0.0838962, -0.3208009, 0.3095663);
  Phase("Tewkesbury 10 Church Street");
  Combine(central bay)
  {
   Sapwood("twkb01", 1441, 53, 16, 2.12);
   Sapwood("twkb02", 1442, 80, 10, 1.59);
   Sapwood("twkb03", 1433, 72, 18, 1.37);
   Sapwood("twkb06", 1442, 82, 0, 1.61);
   Sapwood("twkb07", 1433, 77, 7, 1.26);
   Sapwood("twkb08", 1427, 76, 11, 1.08);
   Sapwood("twkb09", 1445, 116, 0, 0.91);
  };
 };
```

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