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CHURCH OF ST MICHAEL, CHURCH STREET, APPLEBY MAGNA, LEICESTERSHIRE
TREE-RING ANALYSIS AND RADIOCARBON WIGGLE-MATCHING OF THE LADDER IN THE TOWER

SCIENTIFIC DATING REPORT

Alison Arnold, Alex Bayliss, Gordon Cook, Robert Howard and Peter Marshall

INTERVENTION
AND ANALYSIS

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SUMMARY
Dendrochronological analysis was undertaken on five oak samples from the rungs and stringers of a wooden ladder in the tower of St Michael's Church, Appleby Magna, Leicestershire. This analysis produced a single dated site chronology, APMBSQ01, comprising two samples, and having an overall length of 120 rings. These rings were dated as spanning the years AD 1461–1580. Interpretation of the sapwood on the two dated samples, both from rungs, indicates that one timber was felled in the period AD 1545–70, while the other timber was felled in AD 1580. The three remaining oak timbers are undated. Samples were also obtained from three further rungs, but these were of elm and had too few rings for analysis and hence were not measured.

Three single-year samples of oak from wall stringer APM-B07, which had not been dated by dendrochronology, were subsequently sent for radiocarbon dating and wiggle-matching. This analysis suggests that this timber was felled in the early fifteenth century cal AD.

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INTRODUCTION

The Church of St Michael stands near the centre of Appleby Magna, itself approximately 20 miles north-west of Leicester (SK 31502 09850, Figs 1 and 2). According to the listing description, from which this introduction is taken, St Michael's Church is grade II* listed with stonework mainly of the fourteenth century. The church has a nave of five bays with identical north and south aisles, the large reticulated aisle windows separated by buttresses. It also has a chancel with a chapel to its north side. The interior is dominated by its west gallery and an elaborate Gothic plaster rib vault, which formed part of the restoration work completed in 1832. The church also contains a fine series of contemporary box pews. The tower has Perpendicular details with angle buttresses, and carries battlements and a recessed spire.

Within the tower, between the ringing chamber and the chamber above, there runs an unusual wooden ladder comprising two stringers, or basal support rails, and 14 rungs made from solid blocks or baulks of timber (Figs 3a/b). In the main, these rungs are pegged to the stringers, although some large supplementary nails are used as well. It would appear possible that at least one stringer, that to the wall, and some of the rungs, may have been reused. This stringer contains at least one redundant mortice and, along with some of the rungs, redundant peg holes as well (Figs 3c/d). It is possible, however, that these redundancies are not evidence of use in an earlier feature as such, but may simply be as a result of the re-setting of the rungs to the stringers at slightly different positions during repairs due to wear and tear.

SAMPLING

Sampling and analysis by dendrochronology of the timbers of the ladder were requested by Amanda White, English Heritage Heritage at Risk Architect/Surveyor, this programme of dating being undertaken to inform grant-aided repairs and to better understand the history of the church. While wooden ladders are not unknown (another example being found at St Margaret's Church at Wetton in Staffordshire), they are not common, and there is virtually no documentary or stylistic evidence as to their dates. The example seen at St Michael's offered a rare possibility of obtaining a definitive date for such a feature.

A pre-sampling assessment of the ladder showed that the majority of timbers were derived from fast-grown trees, and were thus likely to have low numbers of rings. It was seen, however, that a few timbers could possibly have higher numbers of rings, and were thus potentially suitable for tree-ring analysis. In this instance, given the comparative rarity of wooden ladders, it was decided that tree-ring dating should be attempted.

Thus, from the likely suitable timbers available, a total of eight samples was obtained by coring. Each sample was given the code APM-B (for Appleby magna, site 'B') and numbered 01–08. The positions of the sampled timbers are shown on two photographs taken at the time of sampling, shown here as Figures 4a/b. Details of the samples are given in Table 1. In this table the rungs have been numbered from bottom to top, with the stringers described as being either the wall stringer or the hanging stringer.

TREE-RING ANALYSIS

Each of the eight samples obtained in this programme of tree-ring dating was initially prepared by sanding and polishing. It was confirmed at this time that three samples were of elm (*Ulmus* spp) and, in also having between only 15–30 rings, were unsuitable for tree-ring dating and hence rejected from this programme of analysis. The annual growth-ring widths of the remaining five oak samples were however measured, the data of these measurements being given at the end of this report. The data of the measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

This comparative process indicated a low, though still significant, cross-match between two samples only, APM-B02 and APM-B03, at the off-set positions shown in the bar diagram Figure 5. The value of the cross-match at this position is t=3.5. When combined at these off-set positions the two samples form a site chronology APMBSQ01, 120 rings long which, when compared to the reference chronologies produces a satisfactory series of cross-matches with a first-ring date of AD 1461 and a last-ring date of AD 1580. The evidence for this dating is given in Table 2.

As a check of this cross-matching and dating, because of the low cross-matching between the samples and because sample APM-B02 is only 52 rings long, each of the two samples was then compared individually with the reference chronologies. This process also indicated a series of satisfactory cross-matches for each sample at the dates expected from their analysis when combined, thus lending confidence to the original dating.

Site chronology APMBSQ01 was then compared with the three remaining measured but ungrouped single samples, but there was no further satisfactory cross-matching. Each of the three remaining samples was then compared individually with the full range of reference chronologies for oak but there was no satisfactory cross-matching and these three samples must remain undated.

RADIOCARBON DATING

Following the tree-ring dating described above, a series of three single-year tree-rings were sub-sampled from the oak wall stringer APM-B07, which retained complete sapwood but remained undated by dendrochronology. This timber appeared to have been reused on the basis of at least one redundant mortice and a number of redundant peg holes, although it is possible that these redundancies are not evidence of use in an earlier feature as such, but rather the result of the re-setting of the rungs to the stringers at slightly different positions during repair. Further dating was required to determine whether elements of an earlier structure are present in the extant ladder.

The samples were dated at the Scottish Environmental Research Centre (SUERC). They were pretreated as described by Stenhouse and Baxter (1983), graphatised (Vanderputte *et al* 1996), and measured by Accelerator Mass Spectrometry (Xu *et al* 2004; Freeman *et al* 2007).

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Table 3), and are quoted according to the international standard known as the Tronheim convention (Stuiver and Kra 1986). They have been calibrated using the atmospheric data for the northern hemisphere (Reimer *et al* 2009), the probability method (Stuiver and Reimer 1993), and the computer program OxCal v4.1 (Bronk Ramsey 1995; 1998; 2001; 2009). The probability distributions of the calibrated dates are shown in Figure 6.

BAYESIAN WIGGLE-MATCHING

Wiggle-matching is the process of matching a series of radiocarbon determinations which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of different blocks of wood submitted for dating is known precisely by counting the rings in the timber. An excellent summary of the history and variety of approaches employed for wiggle-matching is provided by Galimberti *et al* (2004).

A Bayesian approach to wiggle-matching has been adopted here (Christen and Litton 1995; Bronk Ramsey *et al* 2001). This combines the calibrated radiocarbon dates with the order of the dated samples, and intervals between dated samples provided by the tree-ring analysis. This highly informative additional information constrains the calibrated radiocarbon dates (which are shown in outline in Figure 7), and so the model outputs are more precise probability distributions known as posterior density estimates. These posterior density estimates are shown in black in Figure 7 and the resultant date ranges are quoted in italics in the text. A general introduction to Bayesian wiggle-matching as it applies to historic buildings is provided by Bayliss (2007).

The technique used is a form of numerical integration and has been applied using the program OxCal v4.1 (http://www.rlaha.ox.ac.uk/orau/). Details of the algorithms employed for this application are available from the on-line manual or in Bronk Ramsey (1995; 1998; 2001; 2009). The specific algorithm used for the model shown in Figure 7 is defined by the large square brackets down the left-hand side of the diagram along with the OxCal CQL2 keywords.

The chronological model shown in Figure 7 includes the radiocarbon measurements on the three single-year tree-ring samples with the information that there were 28 rings between the earlier pair of samples and 19 rings between the later pair, and the information that there was another ring to complete the sapwood of the sampled timber. This analysis suggests that the timber used for the wall stringer was felled in *cal AD 1400–*

1450 (95% probability; APM-B07 felling; Fig 7) or *cal AD 1410–1440 (68% probability)*. This model has good overall agreement (Acomb= 78.2, An=48.8, n=3). This means that the radiocarbon measurements are compatible with the evidence from the tree-ring analysis.

INTERPRETATION

Analysis of five-oak samples from the ladder in the tower of St Michael's Church has produced a single site chronology comprising two samples, its 120 rings dated as spanning the years AD 1461–1580. As may be seen from Table 1 and the bar diagram Figure 5, one of these samples, APM-B03, retains complete sapwood, this being indicated by upper case 'C'. This means that the sample has the last ring produced by the tree from which the timber has been derived before it was cut down and thus the felling of the tree represented being dated to AD 1580.

The other dated sample, APM-B02 in site chronology APMBSQ01, has a last measured ring date of AD 1530. This last ring however, is at the heartwood/sapwood boundary, meaning that the sample has lost all of its sapwood rings, though *only* its sapwood rings. This is indicated by h/s in Table 1 and the bar diagram. Because of this a precise felling date for the timber cannot be given. However, using a 95% confidence interval of 15–40 for the number of sapwood rings this sample would give the timber represented an estimated felling date in the range AD 1545–70.

A third sample, APM-B07, has been dated by wiggle-matching. It was felled in *cal AD 1400–1450 (95% probability; APM-B07 felling*; Fig 7) or *cal AD 1410–1440 (68% probability)*. It is clear that this timber is reused in its current position. It is possible that the extant ladder at Appleby Magna has its origins in the first half of the fifteenth century, and was reconfigured in the Elizabethan period.

CONCLUSION

On the basis of this analysis, therefore, it would appear probable that at least three different felling dates are represented amongst the timbers of this ladder, the wall stringer in the first half of the fifteenth century, a rung in the period AD 1545–70, and another rung in AD 1580. Two other sampled oak timbers, a rung and the hanging stringer, are undated, both with fewer than the 50 rings generally deemed necessary for reliable analysis (Table 1). Three further timbers, all rungs, are of elm and with only 15–30 rings were also deemed unsuitable for analysis.

Given the variation in the dates of at least three of the timbers contained in this ladder, the use of different species of timber in the same construction and structural evidence that some of the rungs and the dated stringer show evidence for possible reuse or later insertion, it seems probable that the existing structure is made up of timbers of various periods. It does however contain timbers that were felled in the early fifteenth century and the later-sixteenth century.

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TABLES

Table 1: Details of tree-ring samples from the Church of St Michael, Appleby Magna, Leicestershire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
APM-B01	Rung 14 (from bottom)	42	h/s	------	------	------
APM-B02	Rung 13	52	h/s	1479	1530	1530
APM-B03	Rung 11	120	22C	1461	1558	1580
APM-B04	Rung 5 (elm)	nm	---	------	------	------
APM-B05	Rung 4 (elm)	nm	---	------	------	------
APM-B06	Rung 2 (elm)	nm	---	------	------	------
APM-B07	Wall stringer	50	18C	------	------	------
APM-B08	Hanging stringer	48	h/s	------	------	------

nm = sample not measured
h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the timber, the last measured ring date is the felling date of the tree

Table 2: Results of the cross-matching of site chronology APMBSQ01 and relevant reference chronologies when first-ring date is AD 1461 and last-ring date is AD 1580

Reference chronology	Span of chronology	*t*-value	Reference
Church Farm House, Ockbrook, Derbyshire	AD 1491–1631	8.2	(Arnold and Howard 2009)
Low Farmhouse, Maplebeck, Nottinghamshire	AD 1385–587	6.4	(Arnold *et al* 2008)
Gotham Manor, Gotham, Nottinghamshire	AD 1391–1590	6.2	(Howard *et al* 1991)
101 Meeting Street, Quorn, Leicestershire	AD 1489–1658	6.1	(Arnold *et al* 2008 unpubl)
Flore's House, Oakham, Rutland	AD 1570–1659	6.1	(Hurford *et al* 2008)
Ravens Farm, Misterton, Nottinghamshire	AD 1482–1634	6.0	(Arnold *et al* 2002)
St Stephen's Church, Sneinton, Nottingham	AD 1484–1654	5.9	(Arnold and Howard 2007)
Old Hall Farmhouse, Mayfield, Staffordshire	AD 1414–1558	5.5	(Arnold and Howard 2006 unpubl)

Table 3: Radiocarbon determinations from single-year sample from core APM-B07

Laboratory Number	Sample	Radiocarbon Age (BP)	δ^{13}C (‰)	*Highest Posterior Density Interval (95% probability)*	*Highest Posterior Density Interval (68% probability)*
SUERC-40204	Oak heartwood, ring 2 from core APM-B07	590±30	−24.0	*cal AD 1355–1400*	*cal AD 1360–1395*
SUERC-40208	Oak heartwood, ring 30 from core APM-B07	555±30	−24.4	*cal AD 1380–1430*	*cal AD 1390–1420*
SUERC-40209	Oak sapwood, ring 49 from core APM-B07	520±30	−25.3	*cal AD 1400–1450*	*cal AD 1410–1440*

FIGURES

Figure 1: Map to show the general location of Appleby Magna. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location of the Church of St Michael, Appleby Magna. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3a/b: General views of the wooden ladder

Figure 3c/d: Views of the ladder showing redundant mortice and peg holes in the wall stringer (left), and redundant peg holes in rung 11 (right)

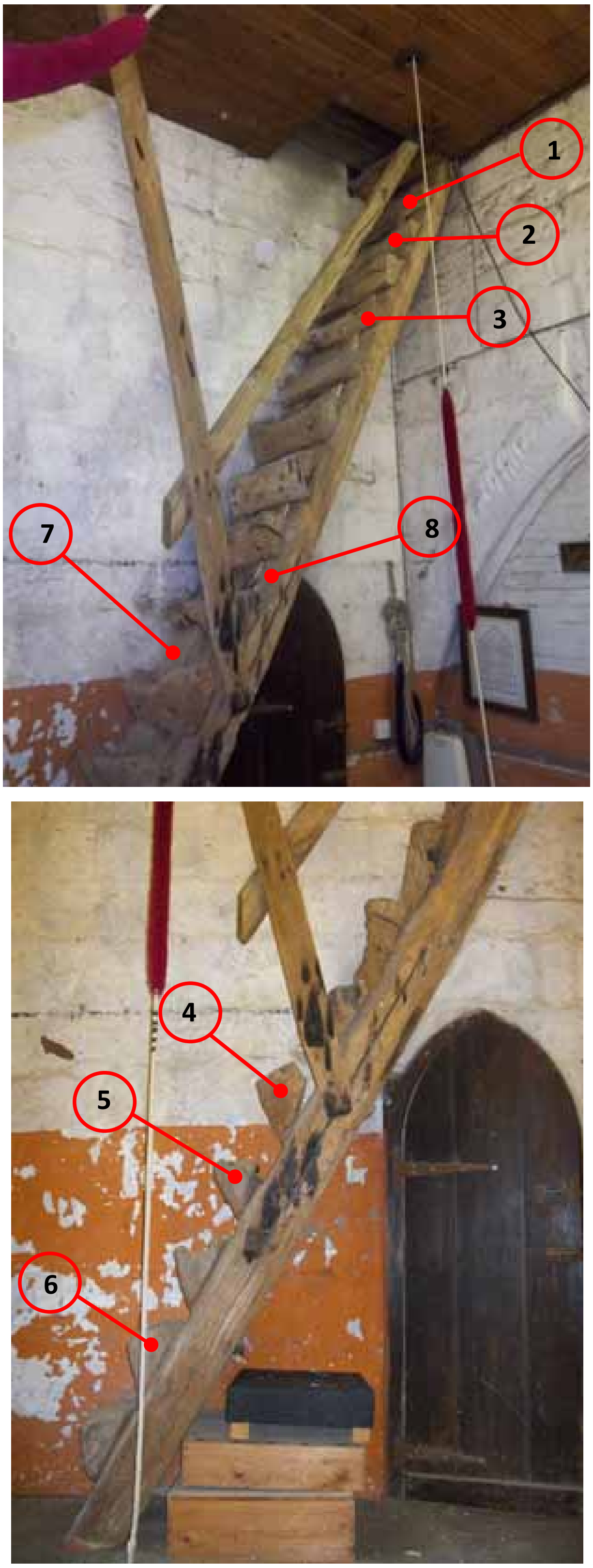
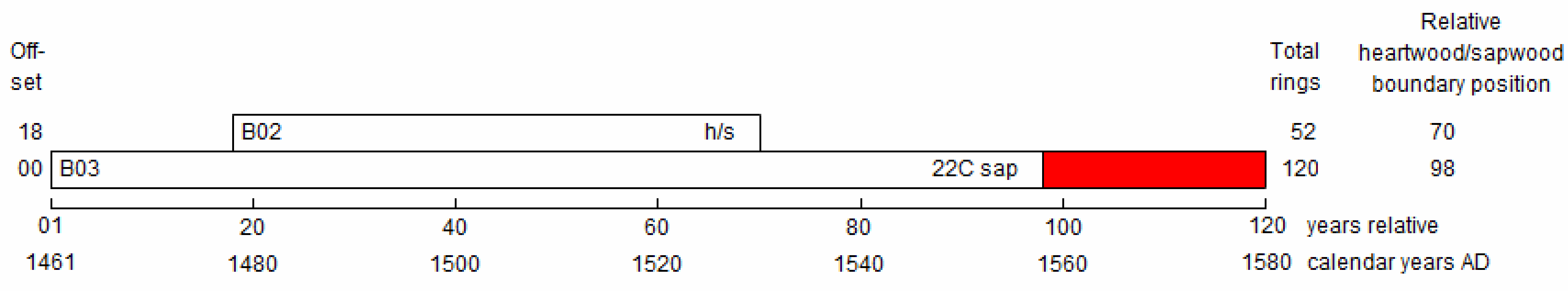


Figure 4a/b: Photographs to show the sampled timbers



White bars =heartwood rings, shaded area = sapwood rings.
h/s = the last measured ring is at the heartwood/sapwood boundary
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented

Figure 5: Bar diagram of samples in site sequence APMBSQ01

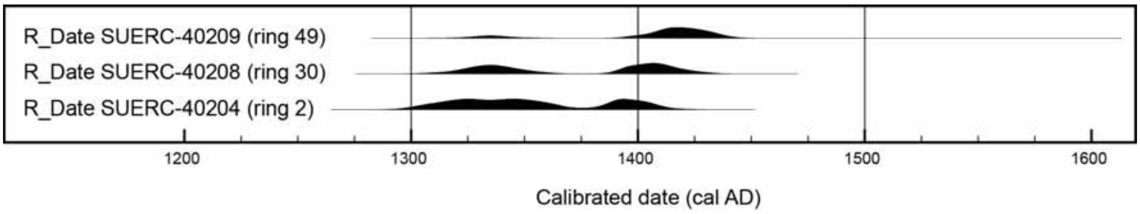


Figure 6: Calibrated radiocarbon dates from timber APM-B07

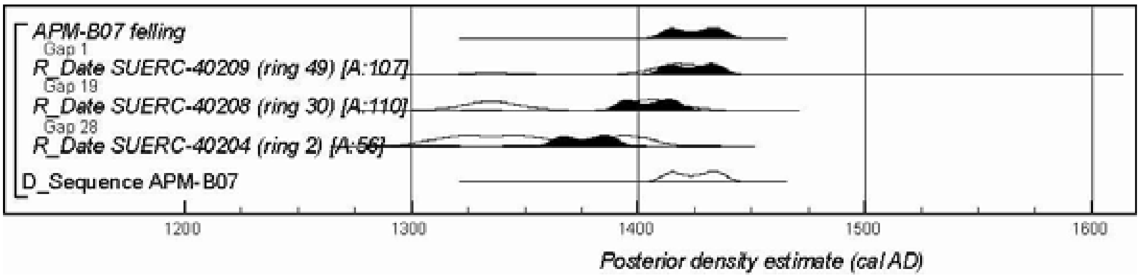


Figure 7: Probability distributions of dates from the timber APM-B07. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'APM-B07 felling' is the estimated date when the timber was felled. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

APM-B01A 42
553 338 253 410 350 239 181 191 139 153 103 103 69 60 67 95 120 126 96 49
51 35 27 53 79 80 58 50 49 44 73 46 42 70 71 132 232 146 78 83
65 88
APM-B01B 42
553 305 264 404 228 276 203 184 114 142 107 107 73 60 69 89 123 117 99 51
59 32 31 57 78 75 64 48 43 34 82 42 46 73 72 130 228 152 81 78
71 103
APM-B02A 52
244 234 250 319 238 263 219 134 178 132 151 98 91 83 87 83 91 100 100 55
77 75 78 91 82 89 80 90 85 64 92 75 85 82 54 42 74 72 50 85
79 50 56 57 79 67 49 85 115 102 92 75
APM-B02B 52
224 220 257 291 274 259 210 142 176 132 142 100 94 81 88 87 87 96 108 53
73 81 82 78 85 86 81 92 79 67 82 83 89 71 60 39 68 63 43 84
85 50 42 61 74 75 68 70 97 103 85 78
APM-B03A 120
122 141 177 214 161 224 268 209 149 101 75 57 69 114 126 190 185 114 78 57
61 57 53 53 89 91 96 78 73 87 51 70 98 121 107 157 118 84 117 135
103 67 81 63 50 78 71 66 87 103 126 134 121 104 70 83 53 102 85 63
81 87 67 74 46 76 103 120 91 78 68 56 47 51 109 88 104 98 79 57
84 52 93 98 101 100 142 151 187 176 162 140 157 103 123 100 68 101 164 109
96 97 93 79 84 82 95 112 101 150 132 92 96 79 104 120 106 84 89 112
APM-B03B 120
116 139 171 212 147 221 250 209 154 104 60 58 69 114 133 195 218 117 66 55
62 67 50 52 90 75 82 80 73 73 51 75 92 117 117 144 112 83 125 133
98 76 73 66 55 75 69 66 89 110 121 130 127 100 75 74 57 103 82 61
83 84 62 78 40 77 108 117 95 75 87 66 40 52 117 89 103 99 86 49
83 48 86 83 110 100 145 143 182 165 164 146 154 102 127 90 65 103 168 115
93 95 93 84 85 81 94 123 98 132 123 98 96 75 113 114 107 90 87 123
APM-B07A 50
281 511 289 156 192 172 144 189 146 217 155 214 226 250 244 220 233 314 271 321
278 306 272 260 378 289 238 307 392 326 223 130 108 116 166 136 131 140 148 145
117 162 164 257 275 282 194 215 210 251
APM-B07B 50
284 514 294 155 187 175 151 198 158 207 155 219 218 260 234 229 228 308 255 330
271 318 285 254 370 279 251 296 386 289 213 156 125 117 146 126 142 135 146 140
137 142 142 270 264 287 182 204 190 233
APM-B08A 48
122 177 181 249 446 484 425 335 332 275 250 225 183 198 171 192 114 100 125 123
133 125 147 164 165 185 164 139 135 125 132 113 120 138 111 115 125 134 171 160
131 85 100 154 169 178 251 253
APM-B08B 48
123 186 179 248 431 469 416 338 339 285 249 225 199 210 183 217 128 112 143 114
140 119 148 178 150 184 181 140 142 120 125 126 117 142 116 115 131 147 170 162
120 94 101 150 160 184 244 260

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 Laboratory's Monograph, An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building (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

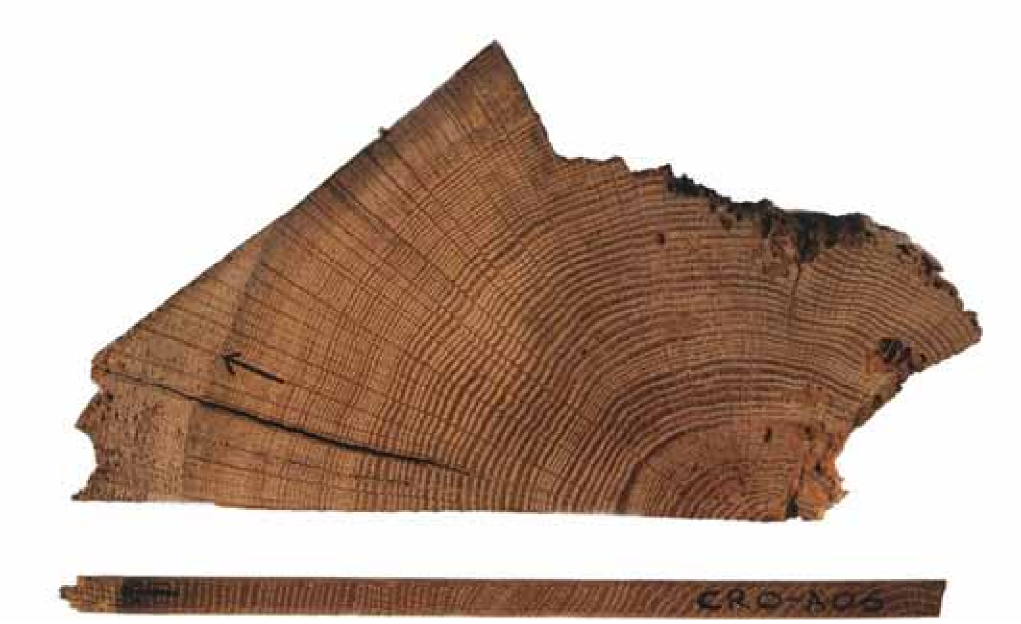


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

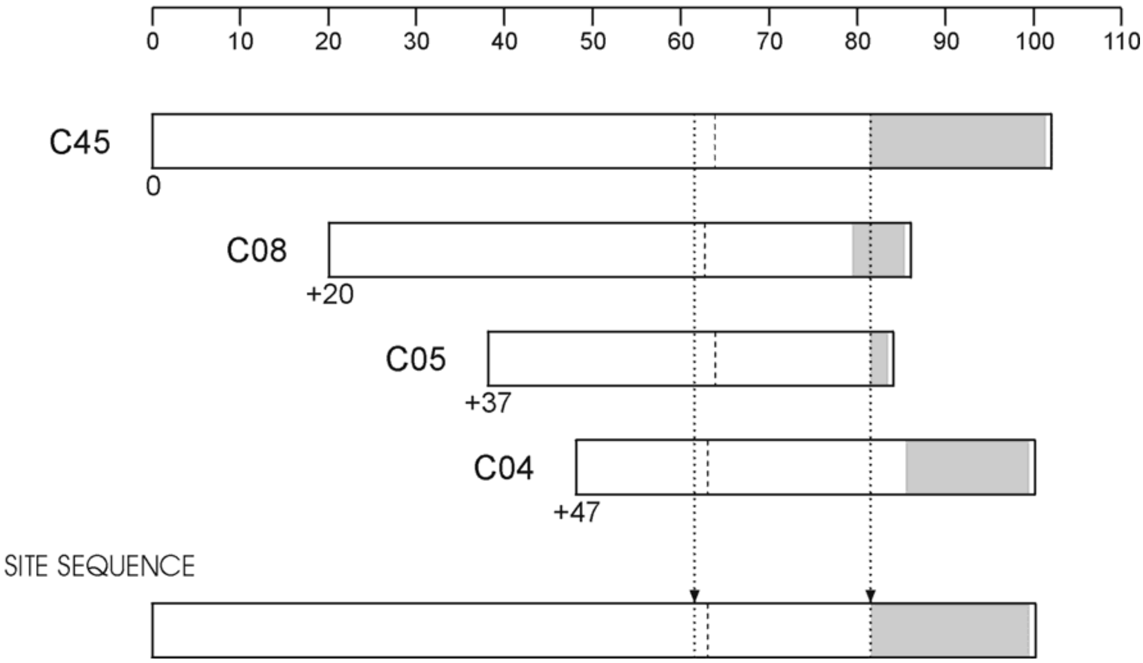


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

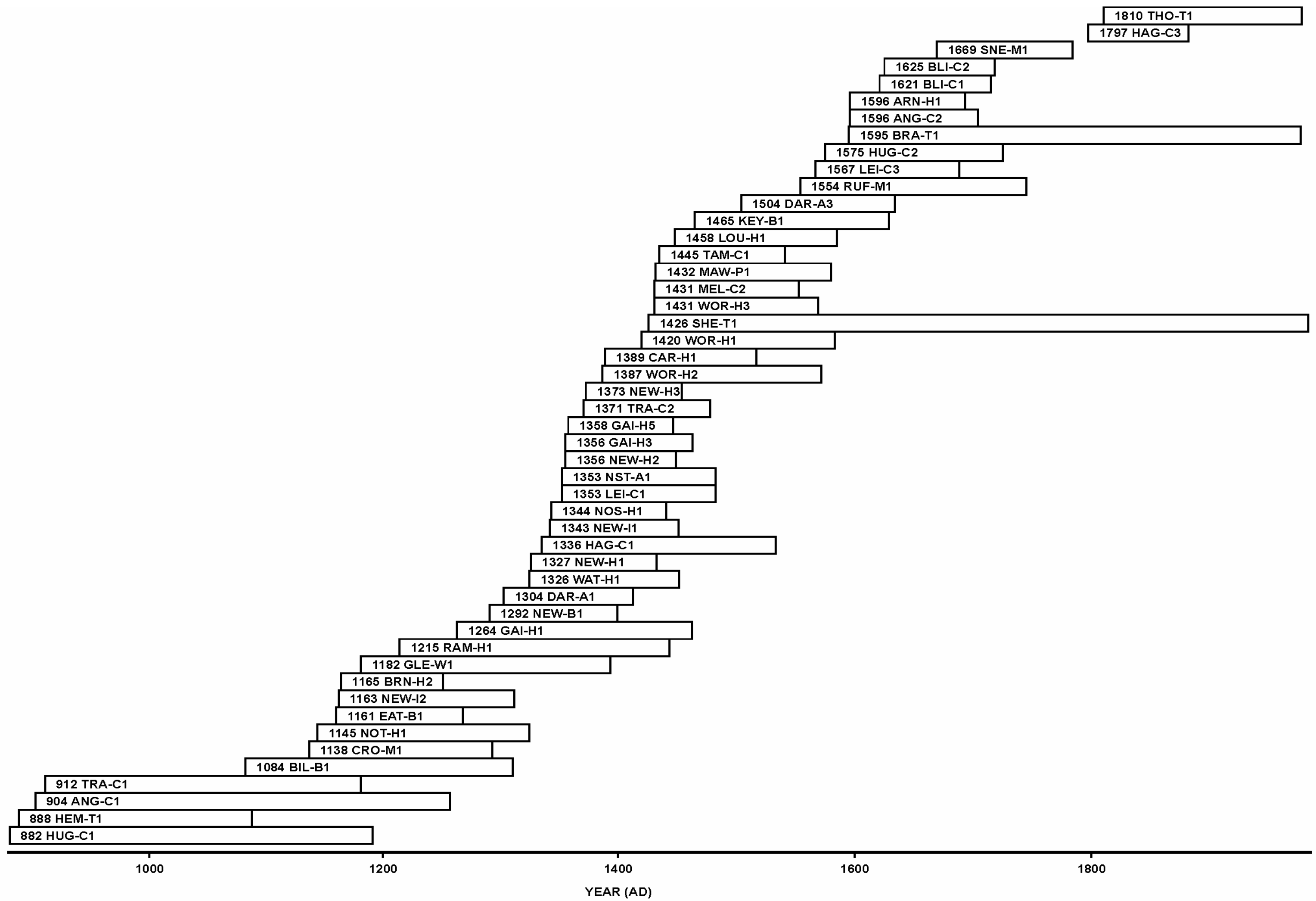
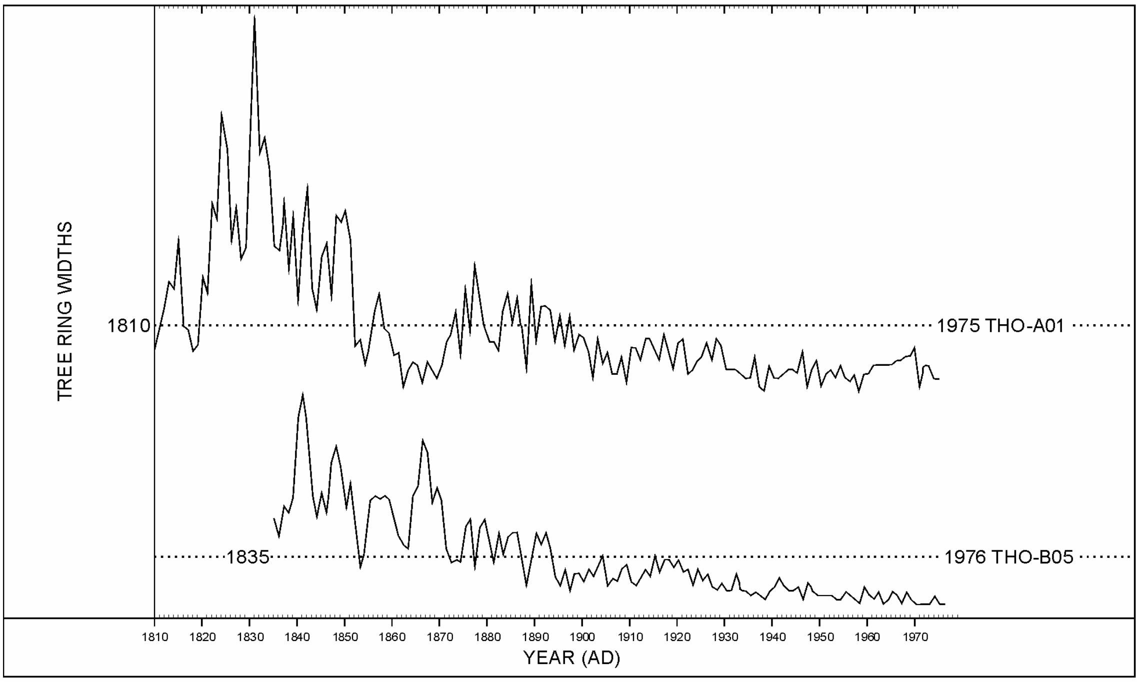


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

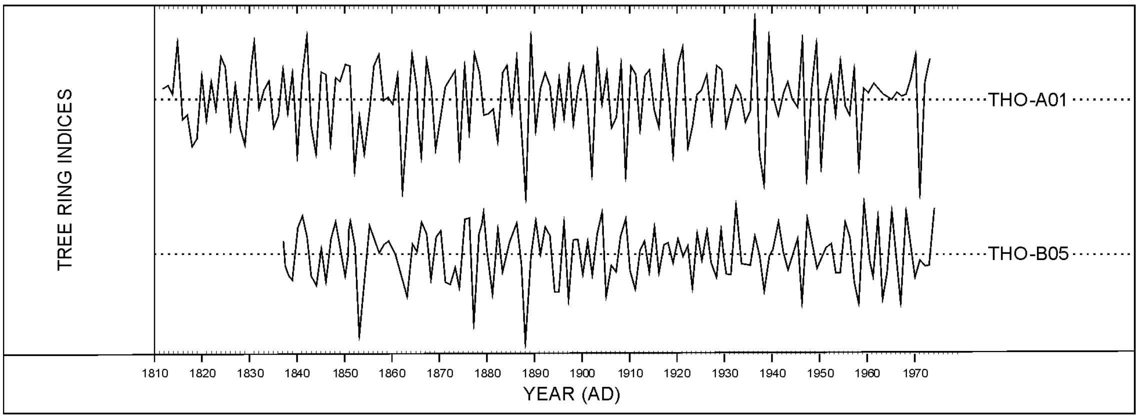


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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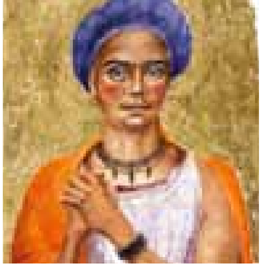


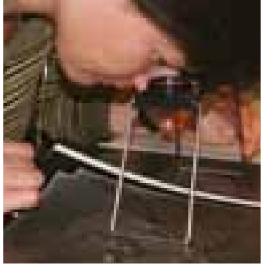


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