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ST MARTIN'S CHURCH, ALFRETON, DERBYSHIRE
TREE RING ANALYSIS OF TIMBERS FROM THE BELFRY FLOOR

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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A J Arnold and R E Howard

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SUMMARY

Dendrochronological analysis undertaken on samples from the belfry floor has resulted in the construction and dating of two site sequences.

The first contains two samples and spans the period AD 1413–1560. Interpretation of the heartwood/sapwood boundary ring date of these two samples suggests they were both felled in AD 1575–95.

The second again contains two samples, and spans the period AD 1546–1607, with the two timbers represented likely to have been felled in AD 1619–39.

CONTRIBUTORS

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ACKNOWLEDGEMENTS

Thanks are given to Mr Eric Sterland, the technical manager of the restoration project, for arranging access to the church and his helpful on-site discussions. The English Heritage Scientific Dating team and Cathy Tyers of the Sheffield Dendrochronology Laboratory have, as always, provided invaluable support and advice during the production of this report. The plan of the belfry floor (Fig 6) was provided by English Heritage.

ARCHIVE LOCATION

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DATE OF INVESTIGATION

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INTRODUCTION

The parish church of St Martin is located in the town of Alfreton in Derbyshire, on the north side of Church Street (Figs 1–3; SK 407 559). The church consists of western tower, nave with clerestory to the south side, south gabled aisle, large gabled north aisle, and lower chancel with north vestry. Some of these elements date from the thirteenth, fourteenth, and fifteenth centuries, whilst the north and south chancel bays were added in AD 1868 by T C Hine. The chancel was further enlarged in AD 1899–1901 and a hall was added to the north of the north aisle in AD 1930.

The three-stage, western tower is fifteenth century in date. It contains a bellframe which dates to the nineteenth century. This belfry floor upon which this frame sits is supported by six large beams. These run north-south and rest on corbels (Figs 4–6). The building description above is based on its Listing description (www.imagesofengland.co.uk).

AIMS AND OBJECTIVES

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage; Graham Pledger and Dr Valerie Scott, both English Heritage, requested the work be undertaken to assist with the interpretation of the belfry floor in the context of current repairs. Providing dating for these beams would greatly assist in defining their importance within the church fabric.

SAMPLING

Inspection of the six large timbers of the belfry floor showed two of these to be unsuitable for analysis. Beams 2 and 5 could be seen to be derived from very fast-grown trees, unlikely to have sufficient number of growth rings to make secure tree-ring dating a possibility. Core samples were taken from the other four timbers. Each sample was given the code ALF-B and numbered 01–04. The location of these samples has been noted on Figure 6. Further details relating to the samples can be found in Table 1. Beams have been numbered from west to east.

ANALYSIS, RESULTS, AND INTERPRETATION

All four samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. All samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

Two samples matched each other and were combined at the relevant offset positions to form ALFBSQ01, a site sequence of 148 rings (Fig 7). This site sequence was then compared with a large number of relevant reference chronologies for oak indicating a consistent match when the date of its first ring is AD 1413 and of its last measured ring is AD 1560. The evidence for this dating is given by the t-values in Table 2. Both of these samples have the heartwood/sapwood boundary ring, the dates of which are suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1560, which allows an estimated felling date to be calculated for the two timbers represented to within the range AD 1575–95.

The other two samples matched each other and were combined at the relevant offset positions to form ALFBSQ02, a site sequence of 62 rings (Fig 8). This site sequence was compared against the reference chronologies where it was found to match at a first-ring date of AD 1546 and a last-ring date of AD 1607. The evidence for this dating is given by the t-values in Table 3. Again, both these samples have the broadly contemporary heartwood/sapwood boundary ring dates. The average of which is AD 1604, allowing an estimated felling date range to be calculated for the two timbers represented to within the range AD 1619–39.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees from this area have 15–35 sapwood rings.

DISCUSSION AND CONCLUSION

Tree-ring research undertaken on the timbers of the belfry floor has succeeded in dating four of them; the only other two being unsuitable for analysis. Two of the timbers are now known to have been felled in AD 1575–95 with a further two felled in AD 1619–39. These results indicate a difference in felling date of several decades between the two sets of beams.

The two seventeenth-century timbers (beams 1 and 6) are the farthest west and east, with the late-sixteenth century timbers (beams 3 and 4) being the two middle beams. The dates gained could suggest that the belfry floor was inserted in the last quarter of the sixteenth century, soon after the felling of earlier beams, with beams 3 and 4 being added some years later, to strengthen the floor or perhaps to replace beams which had failed. The fact that these two beams are located immediately adjacent to the unsampled beams 2 and 5 (Fig 9) could lend support to the possibility that they were a later addition to strengthen the floor. Alternatively, it might be that the two earlier beams are reused from another structure and that the floor as a whole dates to the second quarter of the sixteenth century.

The tree-ring dating has demonstrated this floor to be more complex than might have been thought. No obvious signs of reuse and/or later insertion were noted at the time of sampling but in view of these results further structural survey may be required to determine the construction sequence of this floor.

It is perhaps of interest to note the disparate nature of the timber utilised in this structure. Beams 3 and 4 were derived from long-lived, slow-grown trees that had been quartered whereas beams 1 and 6 were derived from significantly younger, faster-grown trees that had been halved. Additionally, although beams 2 and 5 were unsuitable for analysis and so could not be dated dendrochronologically a visual inspection showed them to be similar in appearance, both very wide ringed and quartered.

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TABLES

Table 1: Details of tree-ring samples from the belfry floor, St Martin's Church, Alfreton, Derbyshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
ALF-B01	Beam 1	50	h/s	1551	1600	1600
ALF-B02	Beam 3	137	h/s	1423	1559	1559
ALF-B03	Beam 4	148	h/s	1413	1560	1560
ALF-B04	Beam 6	62	h/s	1546	1607	1607

h/s = the heartwood/sapwood boundary ring date is the last-measured ring on the sample.

Table 2: Results of the cross-matching of site sequence ALFBSQ01 and relevant reference chronologies when the first-ring date is AD 1413 and the last-ring date is AD 1560

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	7.9	AD 882–1981	Laxton and Litton 1988
Moor Farm Cottage, Shardlow, Derbyshire	8.5	AD 1434–1614	Howard *et al* 1994
Old Manor House, Hartshorne, Derbyshire	7.7	AD 1448–1611	Arnold and Howard 2007a unpubl
Wakelyn Old Hall, Hilton, Derbyshire	7.7	AD 1415–1573	Arnold and Howard 2007b unpubl
Melbourne Church, Derbyshire	7.1	AD 1431–1569	Laxton *et al* 1984
All Hallows' Church, Kirkburton	7.1	AD 1306–1633	Arnold and Howard 2007
Offerton Hall, Offerton, Derbyshire	7.3	AD 1401–1592	Howard *et al* 1995
21 Church St, Mansfield, Nottinghamshire	7.0	AD 1439–1584	Howard *et al* 1994

Table 3: Results of the cross-matching of site sequence ALFBSQ02 and relevant reference chronologies when the first-ring date is AD 1546 and the last-ring date is AD 1607

Reference chronology	*t*-value	Span of chronology	Reference
Bolsover Castle (Riding house), Derbyshire	7.1	AD 1494–1744	Howard *et al* 2005
Hipper Hall, Walton, Derbyshire	6.0	AD 1454–1615	Howard *et al* 1995
Cromford Bridge Hall, Cromford, Derbyshire	6.4	AD 1550–1662	Arnold and Howard 2007c unpubl
Moat House, Appleby Magna, Leicestershire	5.7	AD 1449–1621	Howard *et al* 1998 unpubl
Old Hall Farmhouse, Mayfield, Derbyshire	5.6	AD 1437–1622	Arnold and Howard 2006 unpubl
St Andrew's Owston, Leicestershire	5.6	AD 1485–1611	Howard *et al* 1998
Brewhouse Yard Museum, Nottinghamshire	5.6	AD 1544–1701	Howard *et al* 1994

FIGURES

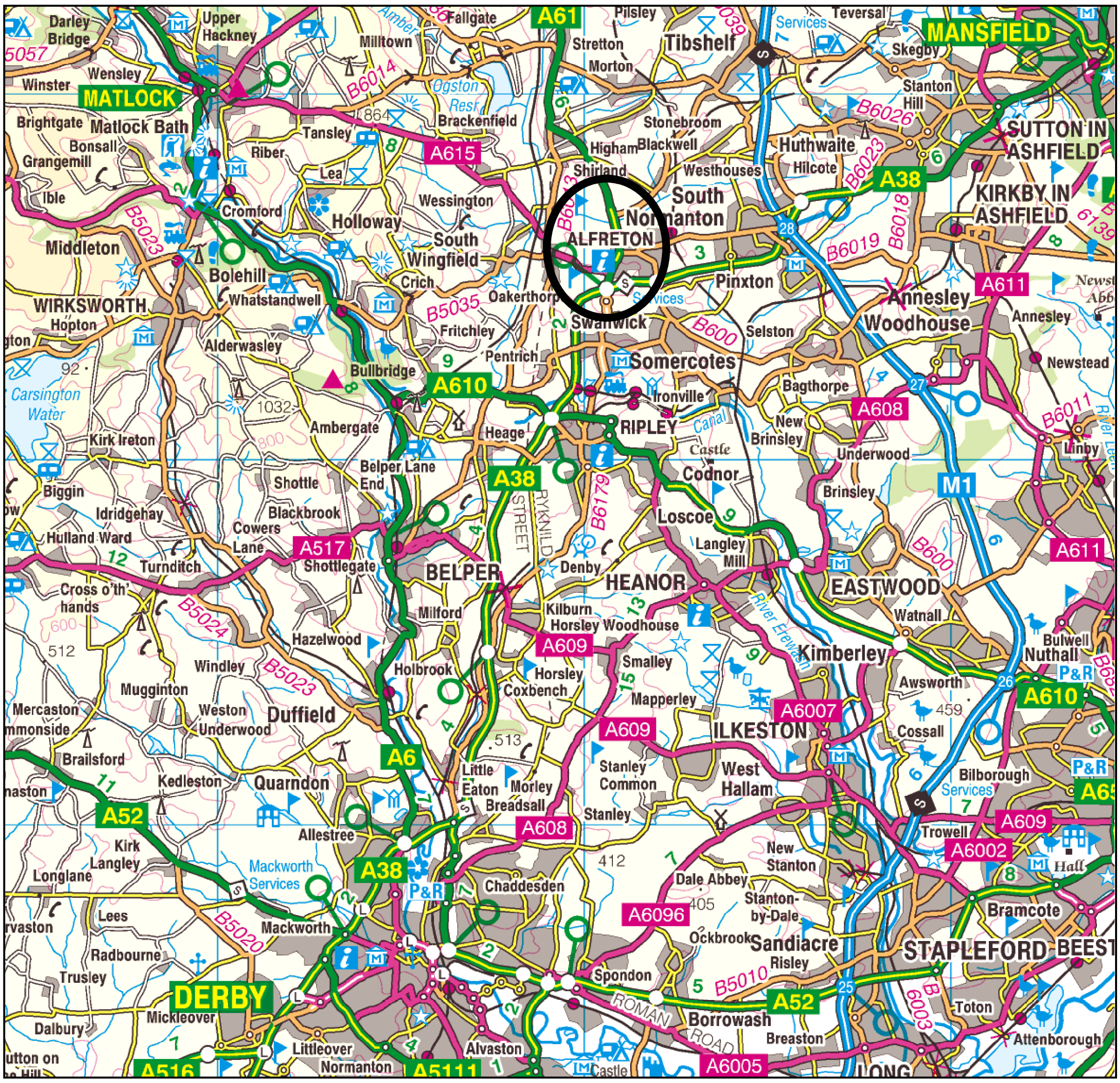


Figure 1: Map to show the location of Alfreton

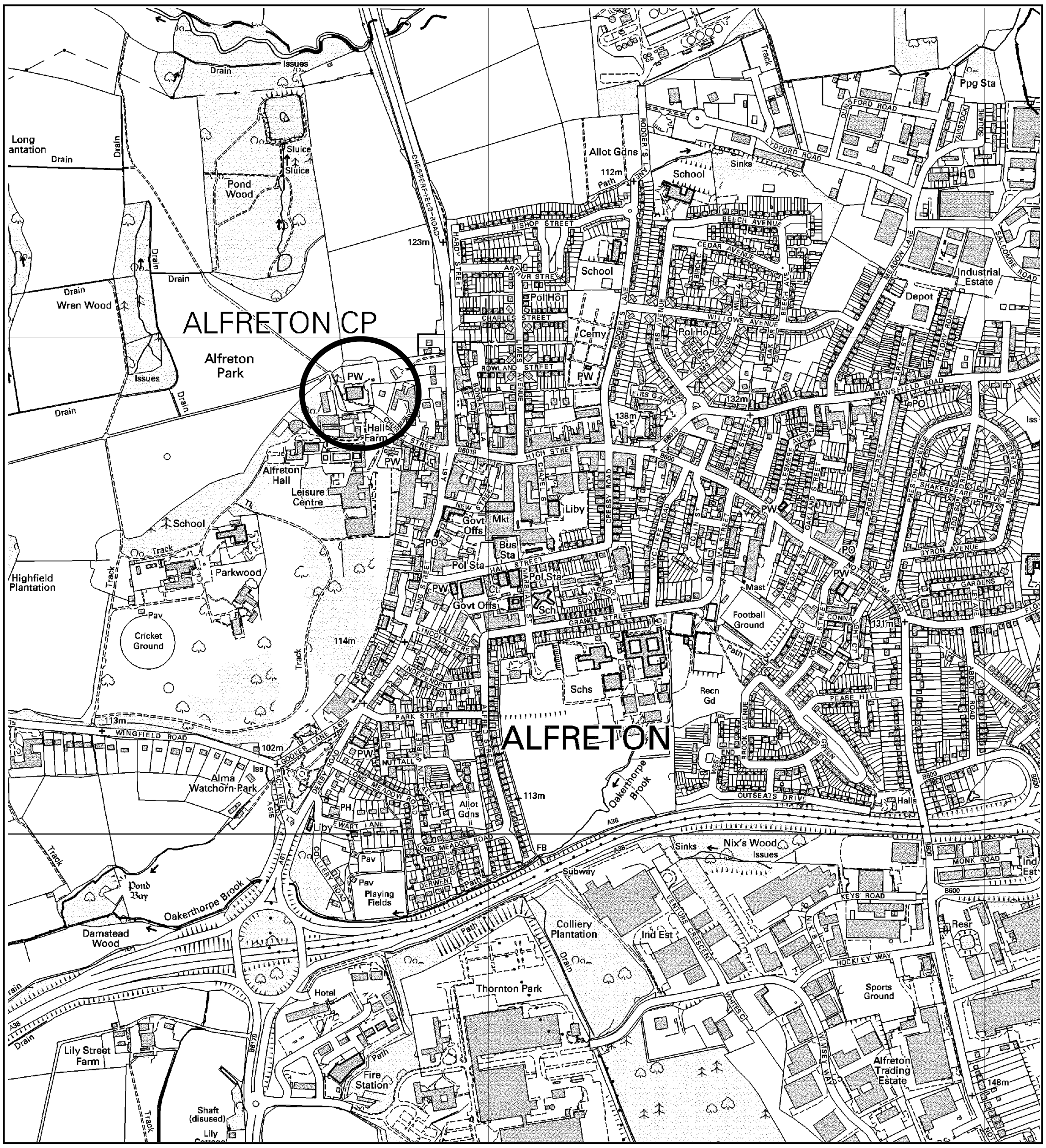


Figure 2: Map to show the general location of St Martin's Church, Alfreton

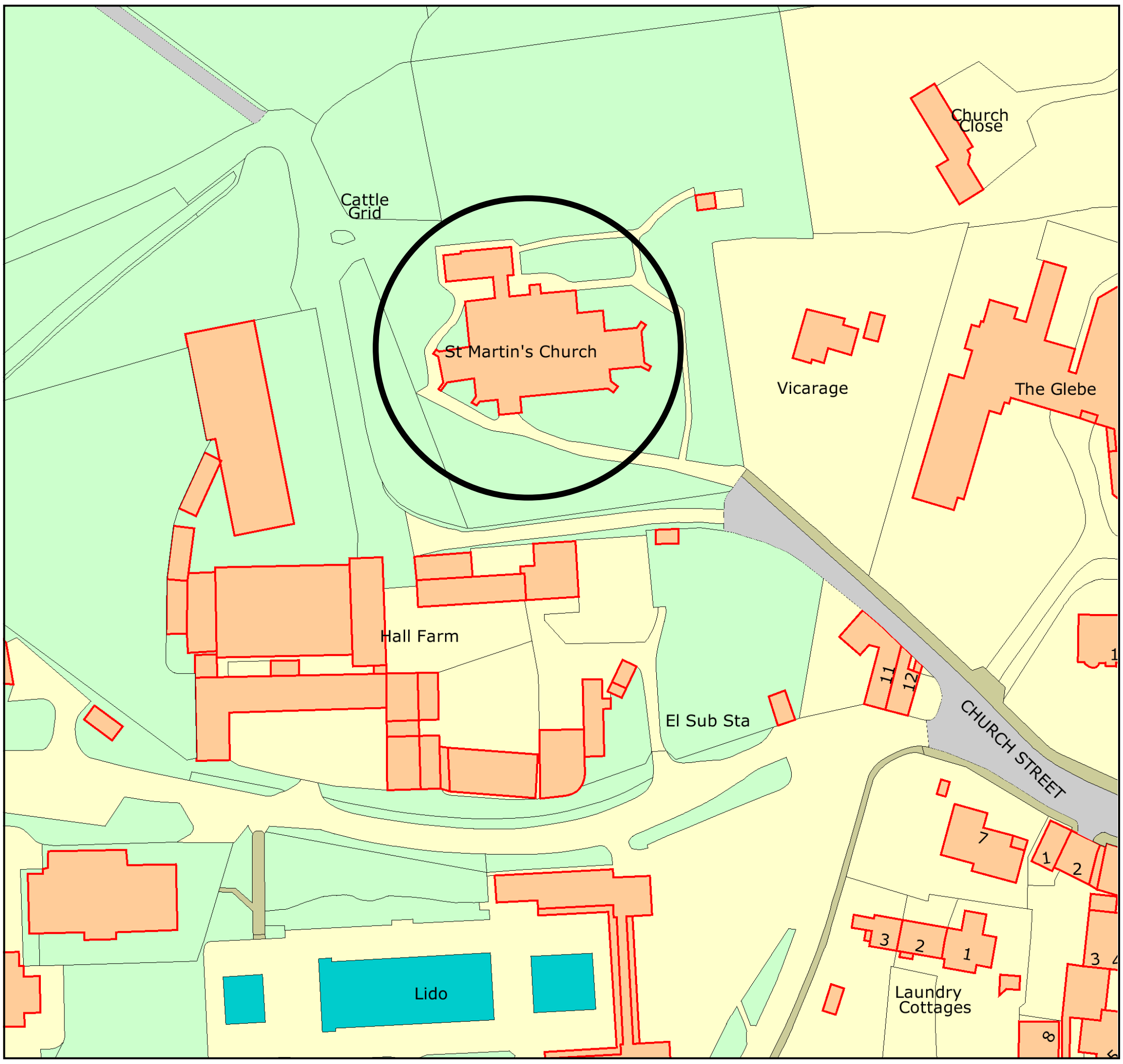


Figure 3: Map to show the location of St Martin's Church

Figure 4: The underside of the belfry floor

Figure 5: The underside of the belfry floor

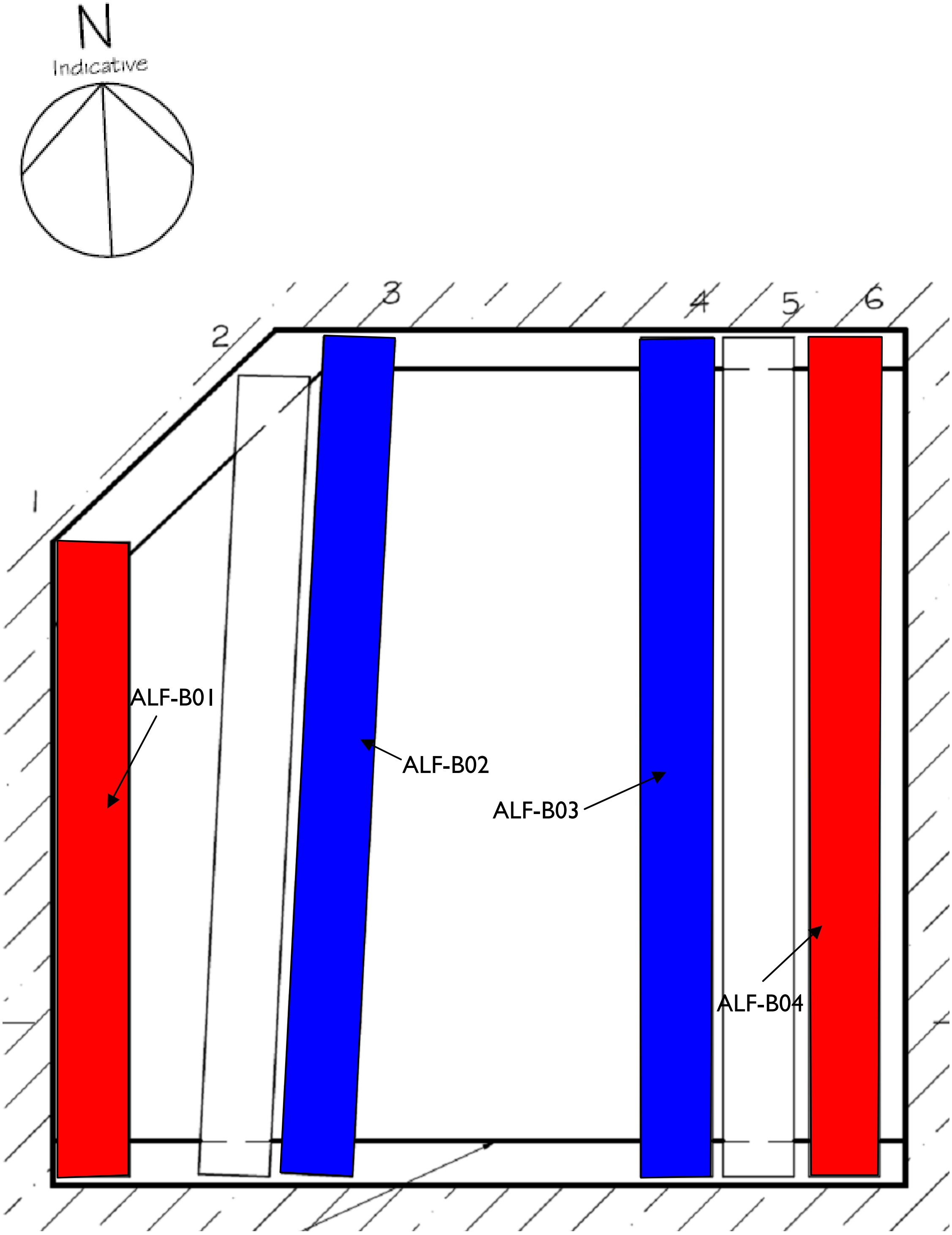
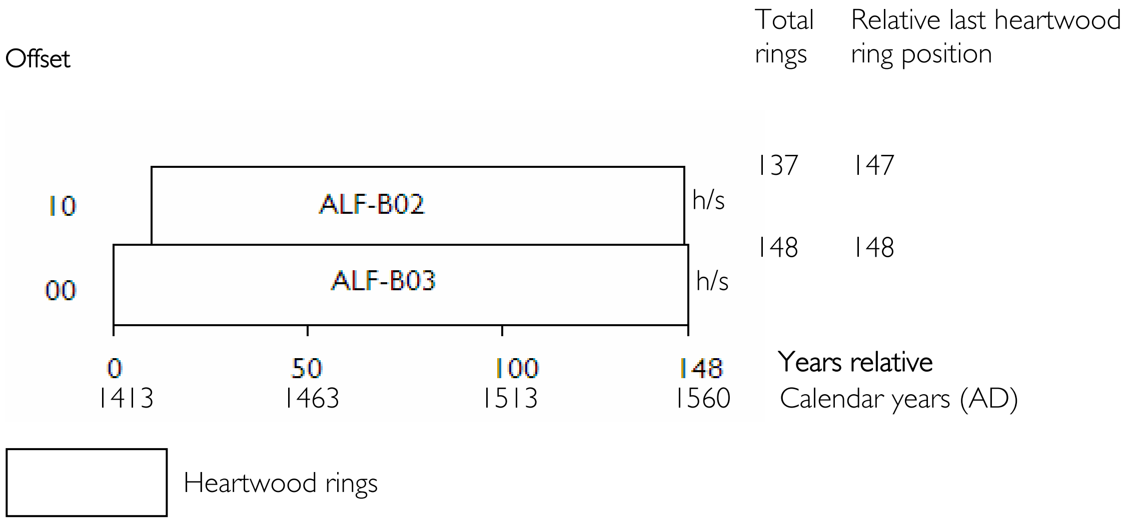


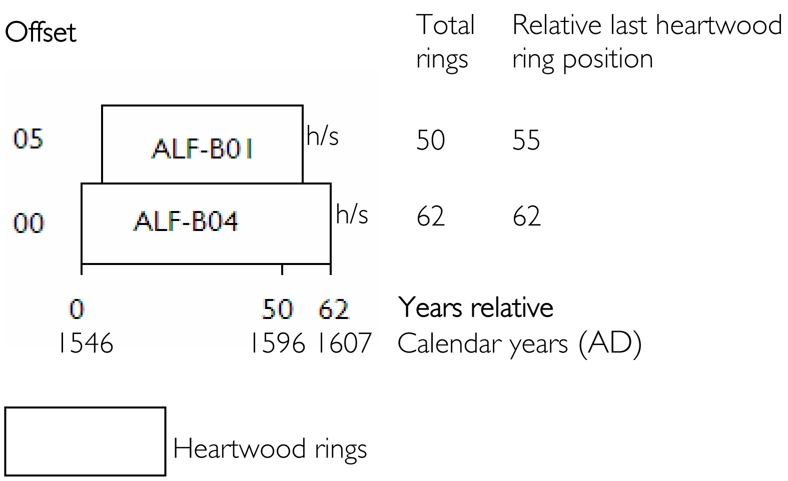
Figure 6: Plan showing the location of samples ALF-B01–04

Sixteenth-century beams in blue and seventeenth-century beams in red (English Heritage, amended)



h/s = the heartwoods/sapwood boundary ring is the last ring on the sample

Figure 7: Bar diagram of samples in site sequences ALFBSQ01



h/s = the heartwoods/sapwood boundary ring is the last ring on the sample

Figure 8: Bar diagram of samples in site sequence ALFBSQ02

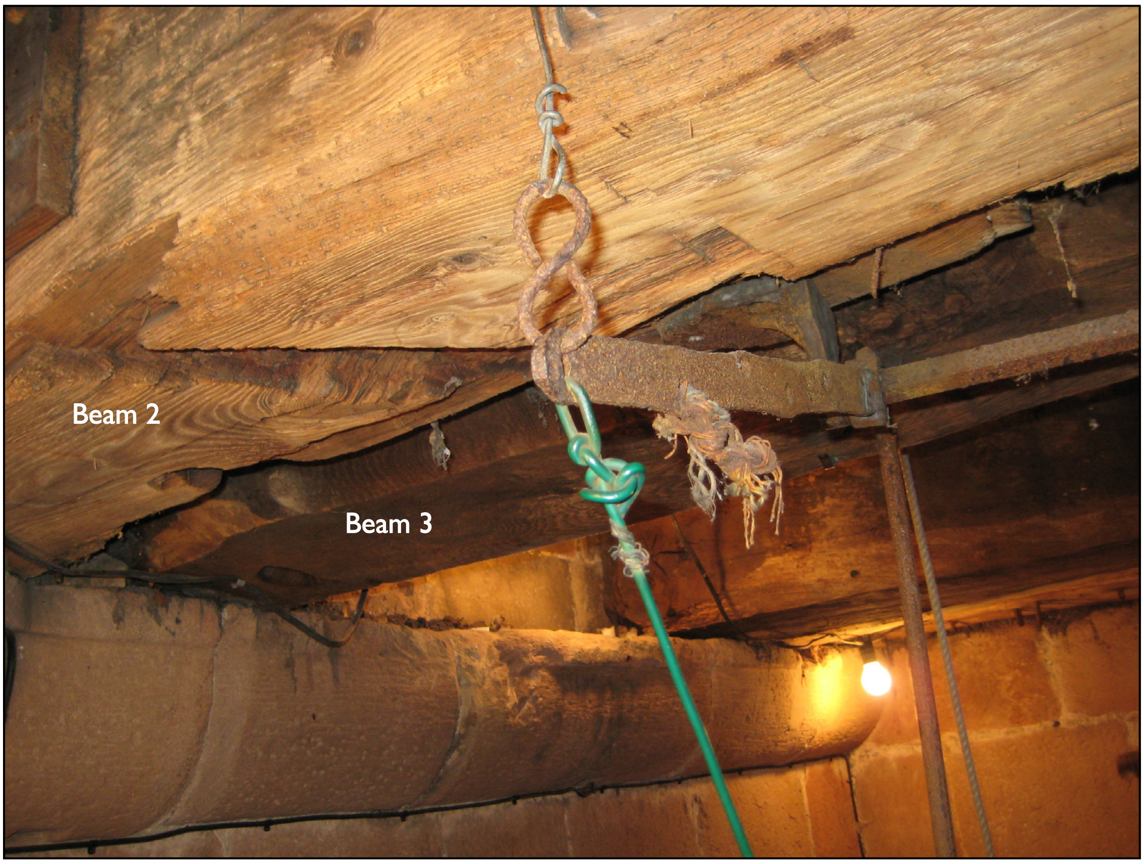


Figure 9: Beams 2 and 3 located immediately adjacent to each other

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

ALF-B01A 49
173 335 374 234 176 81 64 148 232 178 233 253 368 452 274 305 214 266 210 274
230 247 246 239 178 200 207 220 242 265 189 223 212 265 219 322 366 265 269 205
260 358 458 293 259 212 198 209 166
ALF-B01B 40
233 234 411 518 291 336 237 266 208 315 196 212 194 200 119 167 168 177 214 250
132 151 171 238 184 264 310 215 261 177 218 265 394 240 233 185 168 176 125 112
ALF-B02A 137
291 239 216 181 204 155 208 202 195 301 159 219 186 195 151 123 173 203 255 212
222 243 231 139 195 238 218 228 222 224 179 221 202 219 190 140 117 144 203 206
188 175 144 189 203 190 202 155 164 132 131 162 228 191 170 120 159 146 154 150
177 174 173 146 173 118 122 113 108 129 115 138 127 148 130 113 87 96 117 144
152 151 135 120 109 124 142 120 153 138 147 118 108 108 136 147 125 115 141 135
108 144 159 157 208 127 121 117 169 144 121 154 120 184 146 189 186 213 133 143
146 181 235 175 199 191 182 200 221 181 183 117 155 140 116 165 181
ALF-B02B 137
280 241 206 183 203 155 201 210 195 310 153 215 181 197 150 124 173 200 241 215
221 246 226 140 194 245 217 228 228 219 177 217 208 222 189 142 109 146 195 206
182 174 140 182 212 191 203 155 163 124 132 162 222 197 166 123 159 138 173 153
179 167 171 139 171 124 125 109 104 132 120 133 137 150 127 113 88 94 118 143
159 144 130 129 116 118 137 119 152 140 138 111 127 112 146 152 138 115 138 135
112 139 162 155 202 139 120 104 173 144 126 149 127 195 146 173 193 211 118 140
145 186 233 185 195 197 173 192 222 179 184 121 149 148 113 156 180
ALF-B03A 147
250 238 326 282 304 191 125 200 178 154 155 161 225 273 236 233 251 184 311 232
176 288 331 305 226 271 180 225 190 128 177 195 183 156 189 243 226 173 172 201
132 131 155 178 174 137 97 152 151 169 120 101 119 140 170 220 126 145 167 161
138 152 186 180 152 197 199 185 233 180 181 194 180 150 208 203 179 200 172 164
150 143 168 183 165 139 151 106 68 79 54 64 69 77 78 89 97 90 120 106
113 120 116 109 118 136 131 103 152 143 113 132 123 133 157 122 119 91 175 119
129 129 152 143 110 157 135 146 96 93 110 118 117 113 132 133 133 138 172 163
154 103 140 98 75 104 139
ALF-B03B 148
236 230 316 287 246 201 146 192 166 169 166 161 212 282 238 228 258 193 305 252
174 281 287 300 234 268 191 232 173 133 178 192 181 159 191 254 226 182 162 199
140 127 154 180 175 130 102 150 148 169 118 110 113 138 171 222 127 143 160 157
145 156 187 172 165 196 201 199 233 201 187 195 178 148 196 198 173 195 178 150
144 147 166 195 157 141 147 105 73 80 53 61 61 83 86 92 104 93 118 108
117 121 111 113 115 134 132 104 157 136 114 131 125 133 150 125 123 86 171 128
135 133 155 141 112 155 133 146 98 96 113 109 122 118 139 128 127 135 166 168
150 101 140 103 68 101 143 113
ALF-B04A 62
121 167 157 159 142 145 92 137 111 113 54 42 90 115 101 75 119 101 93 58
56 86 81 111 246 202 175 118 210 134 166 218 200 212 351 302 353 363 377 299
319 265 154 224 154 225 274 311 295 258 165 208 200 231 180 167 189 262 290 190
197 233
ALF-B04B 62
126 161 159 148 133 132 99 129 108 116 48 46 89 116 88 79 115 104 86 60
50 85 82 109 240 197 170 148 216 143 170 228 188 222 361 307 332 358 368 300
315 267 163 237 150 227 262 306 301 260 164 197 201 230 190 185 182 270 283 192
200 227

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 1988). 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,

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

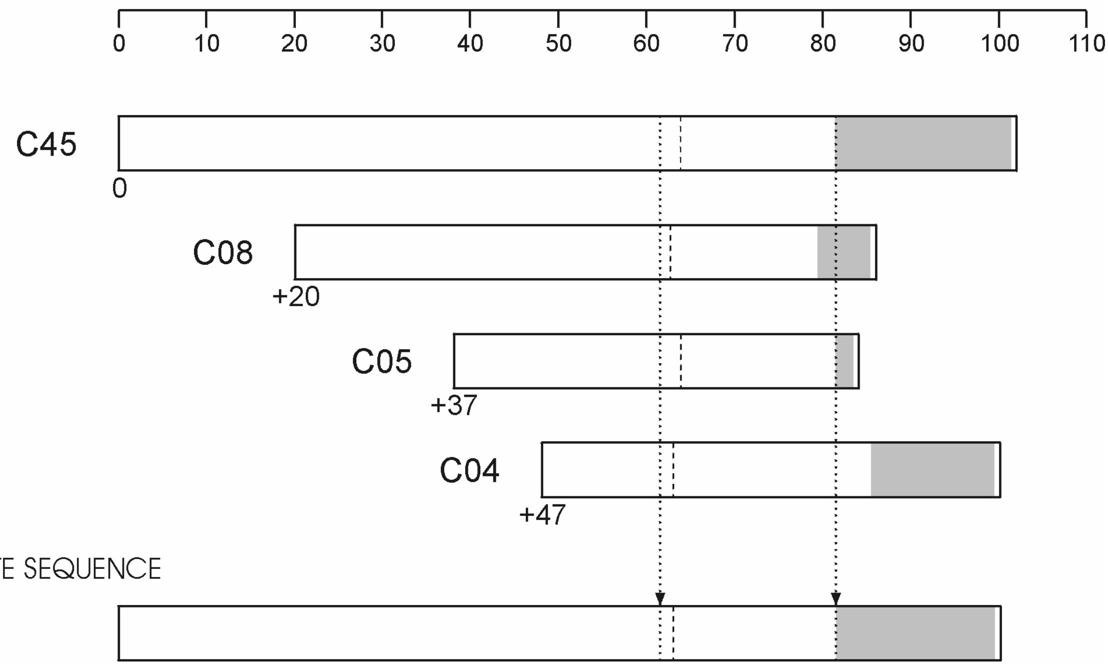


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

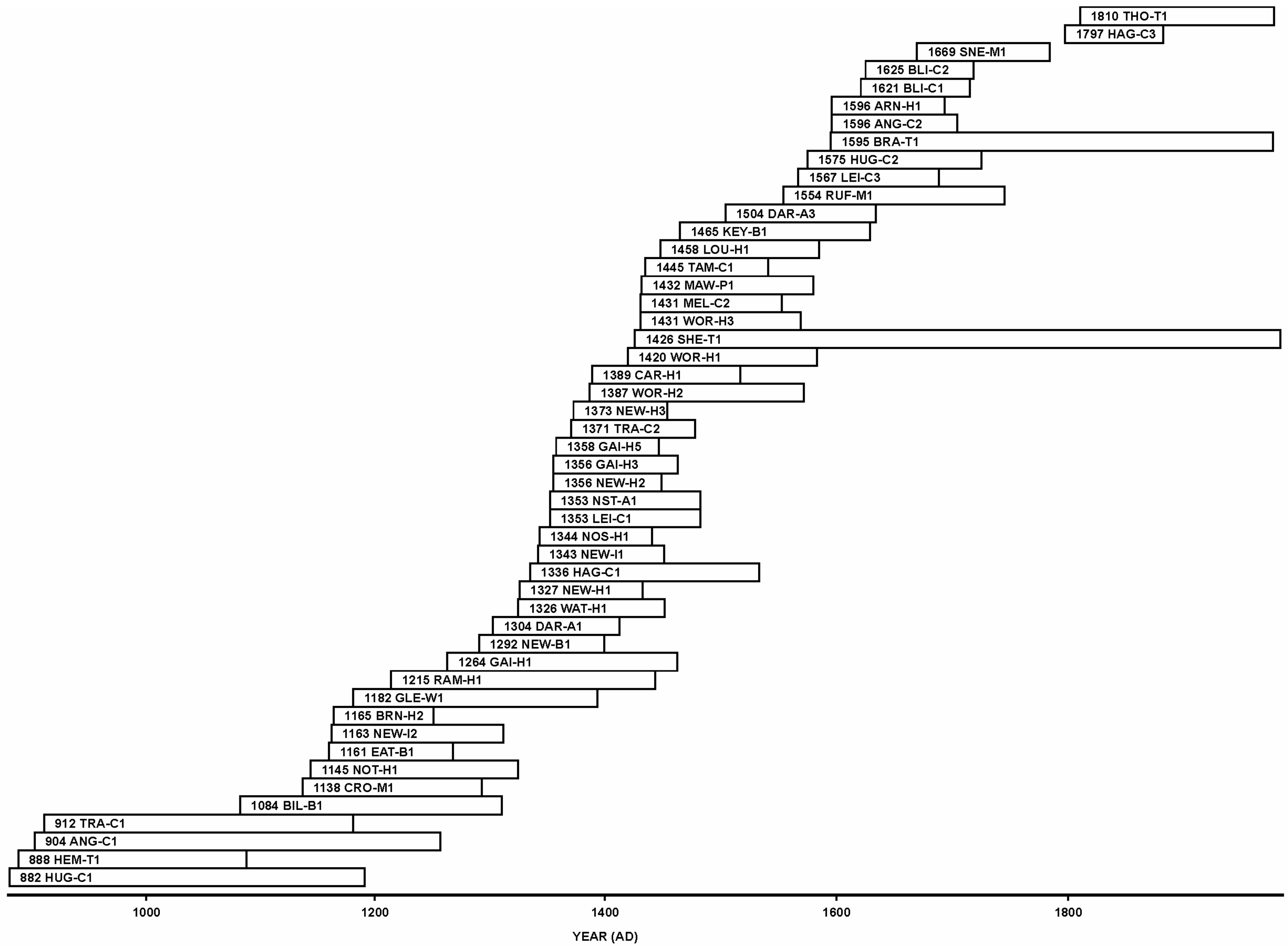
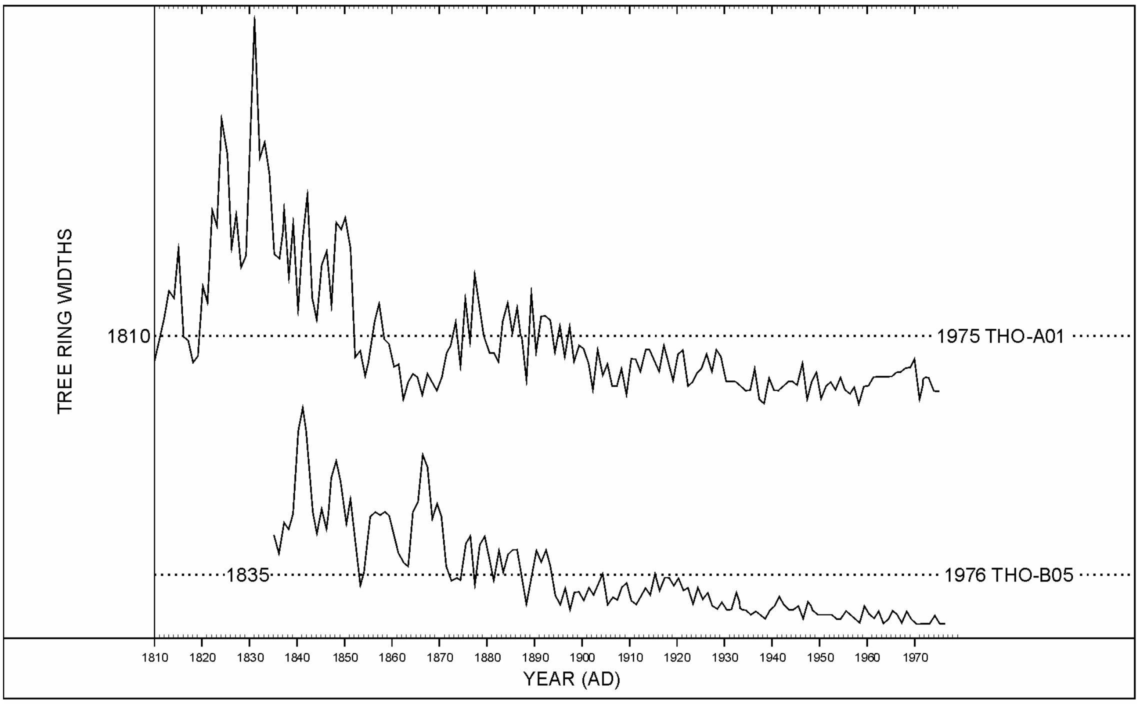


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

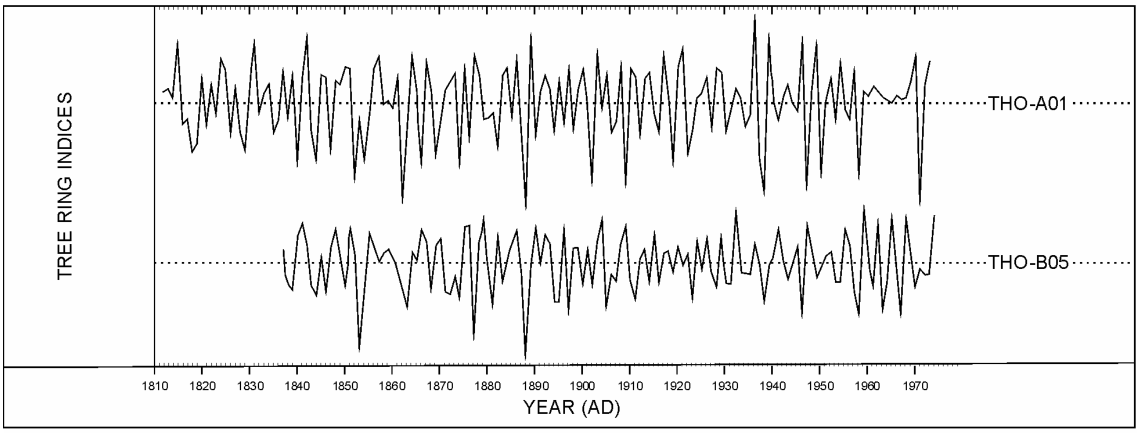


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

(i)

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

The growth trends have been removed completely

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