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THE TITHE BARN, ELVETHALL MANOR, HALLGARTH STREET, DURHAM
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Analysis of samples from the timbers associated with two trusses of the Tithe Barn at Elvethall Manor resulted in the production of a single site chronology comprising eight of the 10 samples obtained. This site chronology is 118 years long and is dated as spanning the years AD 1331–1448. Interpretation of the sapwood indicates that all the dated timbers are likely to have been cut as part of a single phase of felling which took place between the summer of AD 1448 and before the spring of AD 1449.

CONTRIBUTORS

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DATE OF INVESTIGATION

2010

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INTRODUCTION

In AD 1083, Bishop Carileph gave Elvet, then called the Barony of Elvet, to the Priory of Durham Cathedral, a bridge of AD 1160 linking the Barony with the Durham peninsula. Hallgarth Street was closely associated with this priory and was the site of Elvethall Manor House or 'Hall Garth', which was the home farm for the Priory.

Of this manorial complex, the only medieval remains still extant are a very rare stone and timber-framed granary which underwent tree-ring analysis in 1995 but failed to date (Howard *et al* 1995 unpubl), and two large barns (NZ 278 419, Figs 1 and 2). The eastern of the two large barns is believed to be that identified in the documentary sources as the 'Great Barn' constructed in AD 1446–7, which was severely damaged by a fire in the twentieth century. The Tithe Barn, the focus of this report, is the western of these two barns.

Medieval barns as a whole are rare in north-eastern England, although recent research by the North East Vernacular Architecture Group (NEVAG) has enlarged the group of known examples (Roberts 2008). The Tithe Barn at Elvethall, however, is worthy of particular mention, not only because of its size and its significance in the development of regional roof structures, but especially for being the only building in the North East which still supports its roof on raised aisle trusses. The barn is of stone to its ground floor, with a vertically studded timber and brick upper floor, beneath a pantiled roof. It is of six bays formed by seven substantial principal-rafter trusses with tiebeams and collars (Fig 3), and is believed to be of a single phase of construction, all trusses and bays being of a similar design, all the timbers being integral to the building and jointed and pegged. The manor house itself was replaced by the present brick and stone-built Hallgarth House in *c.* AD 1700. Unlike many other parts of Elvet, these buildings avoided demolition in the 1970s. Believed, on the basis of stylistic evidence, to date to the fifteenth century, the barn it is now used as a social club by Durham prison officers.

SAMPLING

Sampling and analysis by tree-ring dating of the timbers of Elvethall Tithe Barn were originally undertaken in 1994 as part of a joint project between the Tree-ring Dating Laboratory and the North East Vernacular Architecture Group to study the buildings of the religious estates in medieval Durham (Howard *et al* 1995). Unfortunately, primarily because of the limited nature of the regional reference data available at that time, the timbers were not conclusively dated. However, because of the increased strength of the regional reference chronologies due to subsequent casework funded by English Heritage, it was felt that a reanalysis of the original data may be worthwhile. This was requested by Martin Roberts, Historic Buildings Inspector based at English Heritage's Newcastle office, because of the significance of the building in the typological development of regional roof structures. It was hoped that tree-ring analysis would establish with greater reliability and accuracy the probable construction date of the barn.

At the time of the original programme of sampling in 1994, an examination was made of all the visible timbers within the accessible part of the building, although it should be noted that access was severely restricted as a consequence of being part of the prison complex. However, although inspection and potential sampling was limited to a small part of the building, it was felt that the two trusses at the west end were representative of the structure as a whole, and that dating these would provide a date for the primary phase of construction. It was seen at this time that the majority of available timbers were of a character suitable for tree-ring analysis, ie, were of oak, were integral and primary to the phase under consideration, and were likely to have the minimum number of rings required for reliable analysis (at least 54). Thus, from the oak timbers available, a total of 10 samples was obtained by coring, each sample being given the code DUR-J (for Durham, site 'J') and numbered 01–10. The positions of the timbers sampled have been subsequently marked on drawings made by the North East Vernacular Architecture Group, and provided by English Heritage. These are reproduced here as Figure 4a/b. Further details of the samples are given in Table 1. In this table, and on the plans, the trusses have been identified and numbered from west to east, or from left to right, as the barn is viewed from its present frontage.

ANALYSIS

For the purposes of this programme of dating, the ring-widths of the 10 samples originally obtained in 1994 were reanalysed without the samples themselves being remeasured. The data for these measurements are given at the end of this report. The data of these 10 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

At a minimum value of t=4.2, a single group comprising eight samples could be formed, the samples cross-matching with each other at the offset position shown in the bar diagram, Figure 5. The samples were combined at their respective offset positions to form site chronology DURJSQ01, this having an overall length of 118 rings. Site chronology DURJSQ01 was then compared with an extensive series of reference chronologies for oak, this indicating a satisfactory cross-match when the date of its first ring is AD 1331 and a last measured ring date of AD 1448. The evidence for this dating is given in the t-values of Table 2.

The two remaining ungrouped samples were also compared with a full series of reference chronologies, but there was no further satisfactory cross-matching and both samples remain ungrouped and undated.

INTERPRETATION AND CONCLUSION

One of the eight dated samples in site chronology DURJSQ01, DUR-J02, retains complete sapwood, with a last measured ring date of AD 1448. This last ring, however, appears to comprise a proportionately large amount of summer cell growth, which may or may not have finished, but no sign of any spring growth for the following year. It is possible, therefore, that the tree represented by this sample was cut down between, say, the summer of AD 1448 but before the spring of AD 1449.

It is likely that the other the dated timbers from the barn were also felled at this, or a very similar, time. As may be seen from Table 1 and Figure 5, the relative position of the heartwood/sapwood boundary on all eight samples is similar, the boundary varying by 17 years from relative position 87 (AD 1417) on sample DUR-J10, to relative position 104 (AD 1434) on sample J06. Such consistency is indicative of a single period of felling, and although the dated timbers are from only two trusses at one end of the building, given the integral nature of the framing, it is likely to represent the construction date of the building as a whole.

The interpretation that all the dated timbers from the two analysed trusses are very likely to have been cut as part of a single programme of felling, in the middle of the fifteenth century, is further supported by the fact that the samples generally cross-match with each other very well, with a number of values in excess of t=7.0 being seen. This would suggest that the trees grew close to each other in the same wood. Indeed, given that a value of t=13.2 is indicated between samples DUR-J05 and J07, it is likely that the two timbers represented, the north principal rafters of trusses 1 and 2 respectively (both probably half-trees), have been derived from the same tree. Had these timbers been felled at different times, it is very unlikely that they would become incorporated in the same building.

The values of the cross-matching between site chronology DURJSQ01 and the reference chronologies used to date it, and particularly the localised and limited nature of these reference data, all of which are only from County Durham and the north-east (Table 2), suggests that the timber used in the construction of the barn was of very local origin. Supporting evidence for this dating, moreover, is found in the high t-values obtained between the individuals from the Tithe Barn and 14 The College, Durham (Table 3).

Two samples, DUR-J01 and J03, remain ungrouped and undated. Both samples have sufficient rings for cross-matching, and neither sample shows any particular problems, such as bands of compressed or distorted rings.

The mid fifteenth-century felling date identified for the timbers from two of the trusses in the Tithe Barn are very much in keeping with that suggested by the stylistic interpretation. This phase of constructional activity may represent part of a major improvement of the overall 'Hall Garth' site at this time, as indicated by the construction of the 'Great Barn' documented to AD 1446–7.

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TABLES

Table 1: Details of tree-ring samples from the Tithe Barn, Elvethall Manor, Durham

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
DUR-J01	Tiebeam, truss 1	66	h/s	------	------	------
DUR-J02	Tiebeam, truss 2	87	26C	1362	1422	1448
DUR-J03	South main wall post, truss 2	63	26	------	------	------
DUR-J04	Collar, truss 1	85	h/s	1346	1430	1430
DUR-J05	North principal rafter, truss 1	91	h/s	1333	1423	1423
DUR-J06	Collar, truss 2	84	h/s	1351	1434	1434
DUR-J07	North principal rafter, truss 2	96	h/s	1331	1426	1426
DUR-J08	South principal rafter, truss 2	94	7	1336	1422	1429
DUR-J09	North purlin, truss 1–2	73	h/s	1351	1423	1423
DUR-J10	South purlin, truss 1–2	63	h/s	1355	1417	1417

*h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample

Table 2: Results of the cross-matching of site sequence DURJSQ01 and relevant reference chronologies when first ring date is AD 1331 and last ring date is AD 1448

Reference chronology	Span of chronology	*t*-value	Reference
14 The College, Durham	AD 1349–1463	7.0	(Arnold and Howard 2009)
Byers Garth Barn, Sherburn, Durham	AD 1339–1448	6.7	(Howard *et al* 1995)
Hallgarth, HM Prison, Durham	AD 1349–1464	6.5	(Howard *et al* 1992)
Williamoteswick, Bardon Mill, Northumbs	AD 1330–1575	5.3	(Arnold and Howard 2009)
4 The College, Durham	AD 1336–1442	5.1	(Howard *et al* 1995)
Tunstall Hall Farm, Hartlepool	AD 1316–1484	4.7	(Howard *et al* 2002)
Choir roof, Durham Cathedral	AD 1346–1458	4.7	(Howard *et al* 1992)
Moot Hall, Hexham, Northumberland	AD 1341–1539	4.6	(Arnold *et al* 2004)

Table 3: t-value matrix showing the cross-matches between individual samples from the Tithe Barn (DUR-J) and 14 The College, Durham (DUR-R)

Filenames	dur-j02	dur-j04	dur-j05	dur-j06	dur-j07	dur-j08	dur-j09	dur-j10
dur-r01	5.99	3.89	4.24	3.61	4.88	-	3.96	-
dur-r02	4.43	3.77	3.29	4.63	4.21	-	3.85	3.17
dur-r03	3.79	3.24	3.49	3.50	3.62	3.69	3.44	3.58
dur-r04	4.74	-	-	3.11	-	-	-	-
dur-r06	5.74	4.20	3.98	4.19	3.71	3.17	5.02	3.72
dur-r09	3.20	3.72	3.05	7.04	3.36	3.30	-	-
dur-r10	4.17	-	-	-	4.00	-	4.23	3.01
dur-r11	-	4.22	3.47	5.25	4.77	4.38	3.10	-
dur-r12	-	3.23	3.02	4.17	4.26	-	3.95	3.25

- = *t*-values less than 3.00

FIGURES

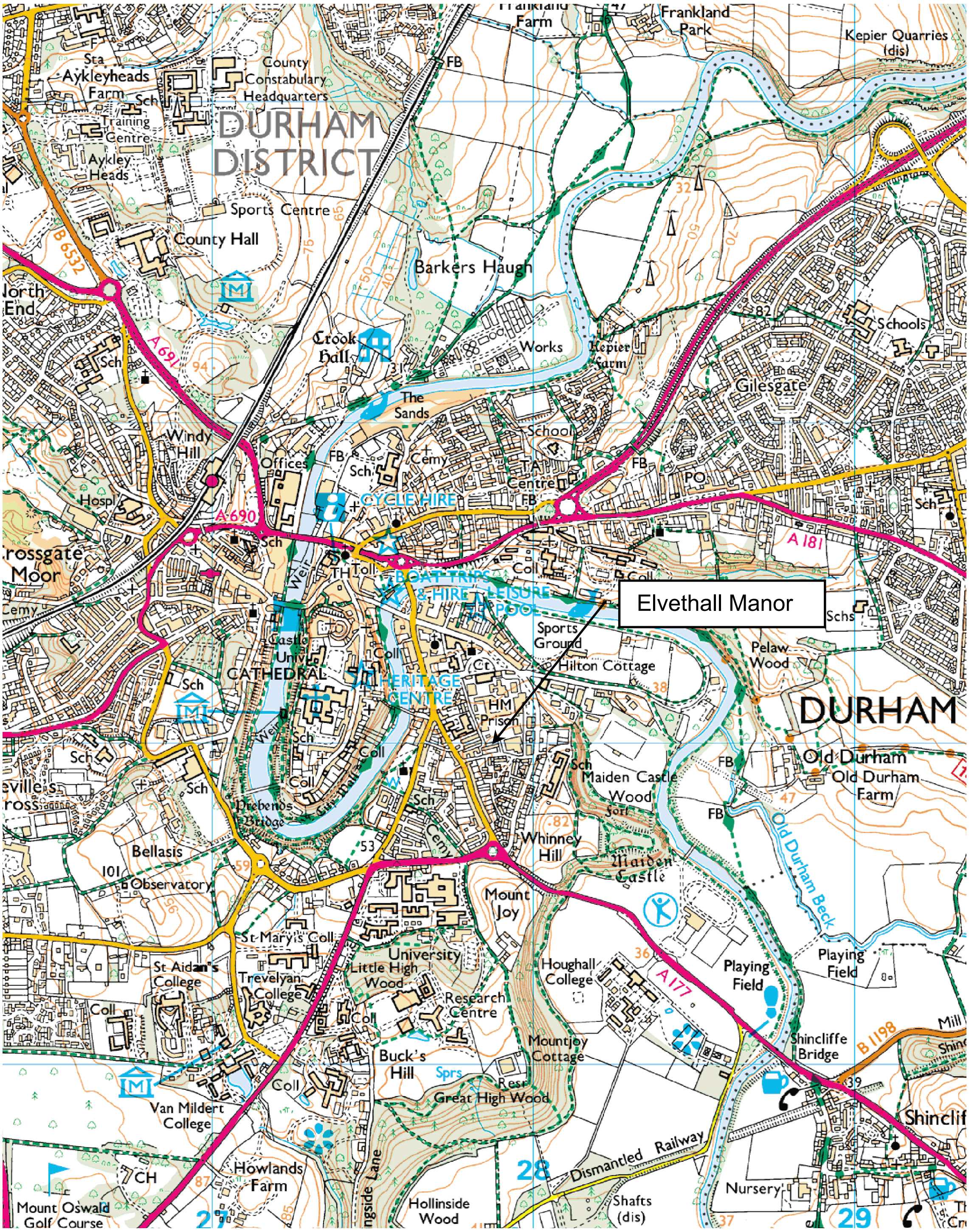

Figure 1: location of Elvethall Manor

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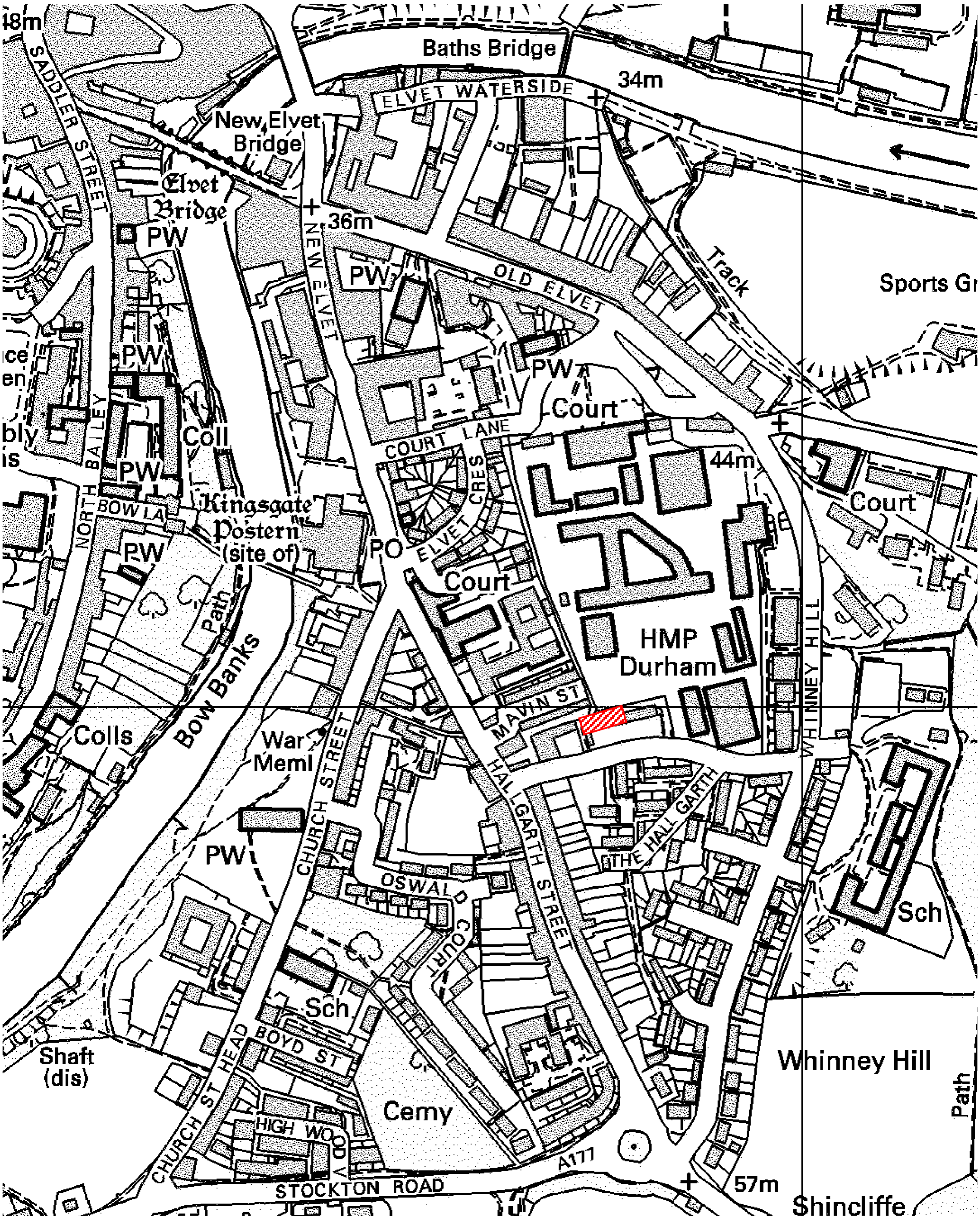


Figure 2: location of the buildings (tithe barn shaded red)

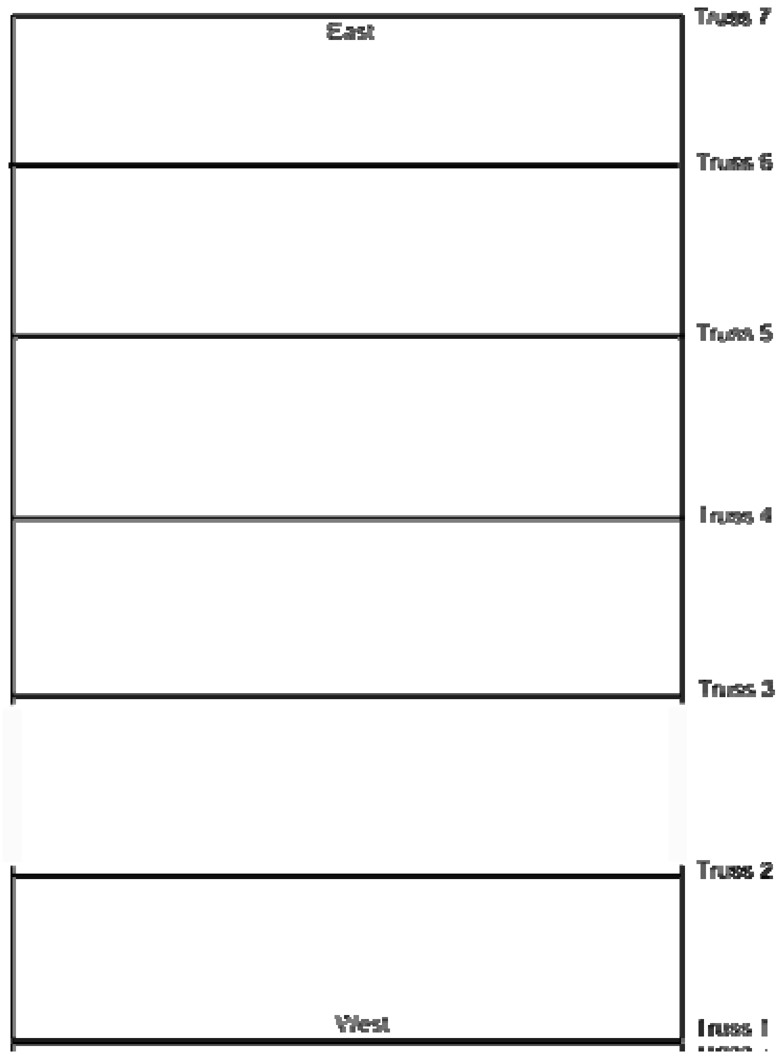


Figure 3: Simple schematic plan of Elvethall Tithe Barn (after Martin Roberts, NEVAG)

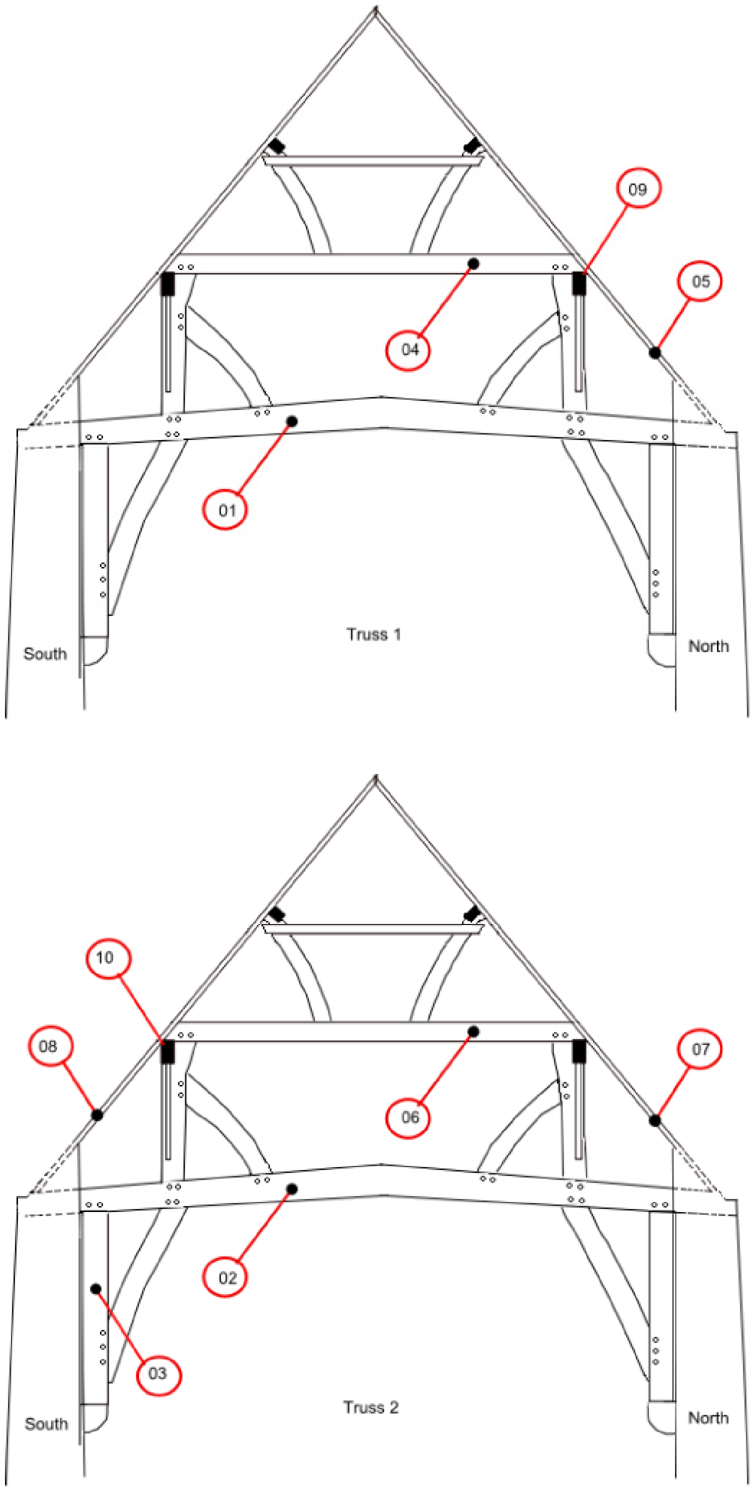
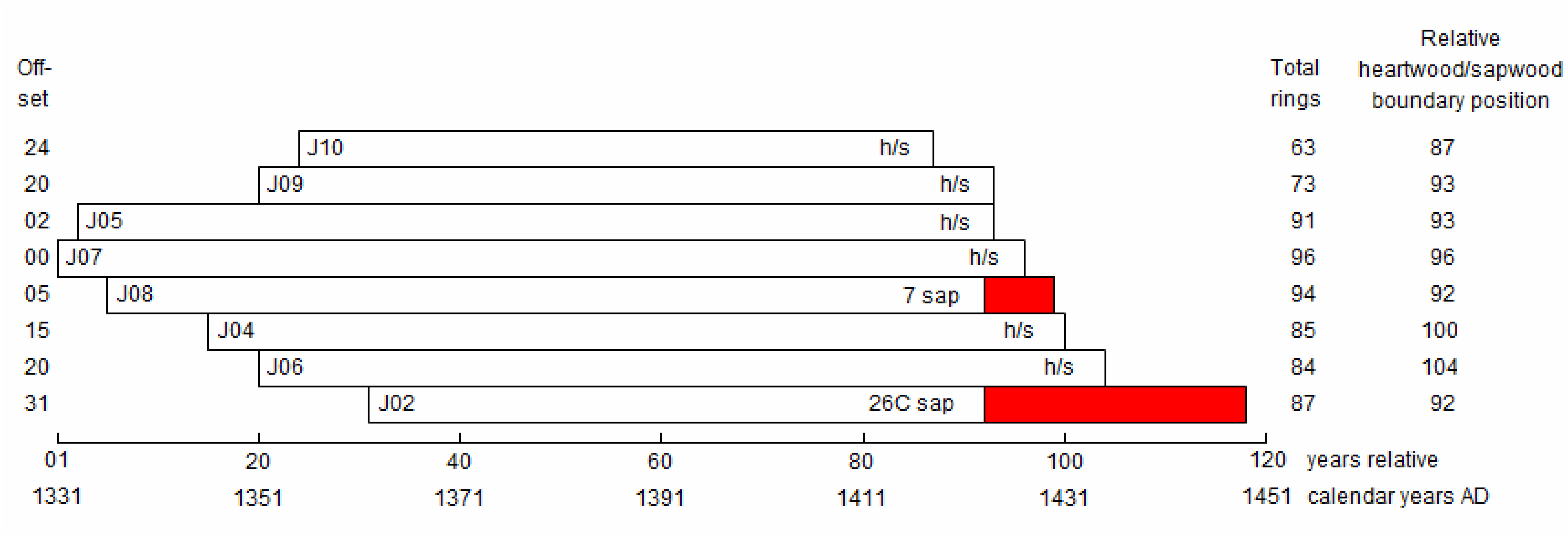


Figure 4a/b: Cross-section through trusses 1 and 2 to show sampled timbers (after Martin Roberts, NEVAG)



White bars = heartwood rings, shaded bars = sapwood rings
h/s = the last ring of the sample is at the heartwood/sapwood boundary
C= complete sapwood is retained on the sample

Figure 5: Bar diagram of the samples in site chronologies DURJSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

DUR-J01A 66
184 215 232 238 242 174 127 113 123 123 205 122 116 117 130 124 87 104 163 178
176 184 294 260 193 131 75 75 111 129 130 89 152 157 204 191 259 201 251 251
199 205 216 188 240 181 216 187 123 122 87 98 108 175 197 147 209 197 245 230
163 119 125 168 234 179
DUR-J01B 66
185 217 225 225 242 175 136 106 132 104 205 148 124 116 125 118 93 106 165 193
179 173 280 251 196 113 80 71 108 117 135 81 153 165 187 205 254 221 246 242
193 213 208 190 233 185 222 182 115 124 90 93 108 172 199 153 199 201 246 226
168 108 127 175 238 190
DUR-J02A 87
131 228 271 217 199 186 171 209 129 142 134 91 133 114 114 96 110 162 135 140
155 184 197 183 181 179 196 192 84 80 155 157 146 155 212 176 144 170 165 170
178 213 156 146 159 148 179 193 193 129 131 147 102 136 146 136 164 124 163 151
167 118 120 108 85 106 111 154 163 150 142 133 136 115 148 129 106 110 138 178
147 161 144 191 184 222 197
DUR-J02B 87
151 219 249 220 190 211 130 147 118 132 145 92 116 111 113 104 127 166 125 130
168 175 213 188 187 189 197 195 88 96 135 154 147 147 184 168 153 177 173 183
159 200 150 150 142 158 178 186 203 137 136 148 102 138 144 129 164 122 168 145
162 129 123 102 77 118 104 147 158 158 132 145 125 123 142 129 108 104 143 178
151 153 190 160 192 203 217
DUR-J03A 63
177 134 141 238 257 261 307 283 244 287 213 147 80 97 77 136 187 174 139 213
144 160 155 175 159 159 142 171 115 108 98 131 181 151 106 108 144 91 131 100
93 113 97 121 93 127 106 121 42 122 145 141 195 221 175 215 157 148 153 118
119 114 194
DUR-J03B 63
183 125 146 236 246 270 286 267 247 282 201 149 95 84 83 145 190 203 133 190
153 165 151 177 152 155 154 173 108 108 110 130 177 143 104 106 125 94 121 110
95 104 92 121 104 122 117 122 51 123 140 138 185 205 146 245 150 150 142 125
125 133 127
DUR-J04A 85
253 233 300 195 213 305 234 263 222 122 113 98 77 45 62 89 76 167 142 143
113 119 106 49 121 142 127 120 136 123 57 55 71 96 108 139 160 119 130 144
136 153 176 87 53 46 94 75 140 98 211 154 122 104 137 134 211 217 229 179
151 146 108 135 120 69 47 59 52 89 73 137 143 108 55 143 162 170 104 63
72 98 135 217 145
DUR-J04B 85
233 236 299 163 213 298 226 194 217 127 121 95 75 45 53 93 67 175 150 137
116 125 102 52 119 137 125 130 132 133 41 51 69 102 108 137 158 104 142 140
143 147 176 89 66 37 94 76 139 100 211 150 122 117 137 127 212 215 213 193
148 147 117 127 112 72 42 72 43 87 78 133 153 104 53 148 157 149 119 74
59 102 143 205 156
DUR-J05A 91
370 444 387 357 383 439 267 273 211 108 117 167 150 139 138 191 192 145 226 237
257 299 163 201 117 62 49 65 95 95 122 141 125 111 114 58 46 47 123 127
130 222 242 154 124 144 179 238 241 307 264 255 255 278 267 195 100 97 99 151

186 199 226 302 217 140 127 189 201 194 201 171 142 129 181 182 314 216 104 115
123 62 131 80 88 143 108 93 211 251 217
DUR-J05B 91
354 402 390 351 407 446 269 261 216 116 115 160 160 137 143 197 188 161 212 228
248 293 152 201 115 60 55 69 104 97 116 143 129 108 110 58 45 60 118 124
127 236 238 172 102 130 185 254 238 288 280 288 255 272 287 221 100 104 100 152
189 189 223 291 211 141 119 191 192 194 195 176 144 131 175 181 334 207 106 125
130 64 127 100 90 139 99 99 243 302 215
DUR-J06A 84
213 234 226 264 172 216 86 104 45 49 90 83 155 161 166 129 139 84 51 102
125 173 171 213 242 100 90 106 212 165 132 209 147 179 130 130 159 171 90 70
57 84 79 119 100 184 175 92 83 168 154 234 213 169 242 191 179 167 131 80
72 62 88 69 71 96 117 143 92 90 108 175 208 123 67 86 106 170 241 175
155 132 145 153
DUR-J06B 84
220 230 221 270 187 217 95 90 42 47 92 86 151 170 157 136 140 83 51 104
138 165 161 216 234 99 88 129 242 159 130 207 151 164 136 130 169 152 88 68
58 75 79 115 94 199 179 89 83 174 156 240 200 175 251 182 170 177 129 76
67 59 94 65 73 95 115 149 95 73 120 178 201 125 65 74 118 164 241 174
165 131 138 178
DUR-J07A 96
345 322 364 392 500 465 407 626 452 463 318 250 257 340 208 232 187 270 291 209
339 343 347 341 236 279 167 82 75 67 148 104 141 167 135 87 94 53 45 74
136 198 150 287 238 140 145 173 199 269 350 272 176 191 220 264 258 251 153 151
92 170 221 238 163 242 201 122 135 190 134 180 192 177 149 166 145 160 242 224
141 172 178 95 169 102 118 146 99 84 209 207 161 89 83 87
DUR-J07B 96
373 320 389 384 484 485 432 617 438 434 323 259 255 339 223 238 195 263 300 217
339 348 354 327 211 291 160 69 61 69 148 118 150 164 121 87 99 52 43 73
136 197 153 282 242 138 141 180 198 270 356 270 167 193 229 275 238 253 133 174
92 178 223 226 167 255 194 134 137 192 154 172 188 173 132 156 150 146 241 205
136 172 180 91 163 116 116 159 99 83 207 207 160 93 67 115
DUR-J08A 94
367 285 377 327 291 195 135 171 184 196 272 253 334 317 196 276 251 297 226 171
194 92 46 48 48 108 181 125 158 147 151 117 100 55 102 180 281 164 213 177
112 110 147 174 238 215 160 164 190 203 242 201 185 104 124 86 94 213 189 184
187 136 85 110 110 104 151 120 102 111 104 180 144 175 111 79 70 63 49 70
68 71 141 116 104 131 154 143 104 79 65 92 123 150
DUR-J08B 94
374 300 378 314 286 201 129 178 175 196 255 254 345 283 215 301 264 283 211 189
195 91 52 46 44 111 176 131 159 150 162 100 93 60 98 186 273 175 220 187
102 114 140 179 236 216 157 158 194 204 236 205 185 106 121 88 99 209 195 187
180 139 82 104 100 99 146 130 90 121 108 174 145 181 118 76 70 68 49 65
69 67 144 100 106 129 150 140 100 80 90 88 96 188
DUR-A09A 73
166 196 233 158 230 264 213 174 104 89 94 93 156 160 145 162 172 172 156 145
187 151 135 182 176 124 108 131 142 142 162 185 147 144 142 161 163 159 87 102
69 83 99 135 95 131 98 87 93 137 102 100 146 99 119 89 118 104 135 134
79 88 108 69 118 92 99 116 98 104 116 115 108
DUR-A09B 73
142 190 238 170 241 272 207 176 98 82 88 91 133 158 138 148 165 170 162 176
188 153 141 174 184 134 121 117 129 138 156 195 151 138 140 176 164 164 95 105
75 95 93 141 100 163 97 82 85 130 100 113 151 101 119 96 119 115 126 126

95 86 115 79 111 83 106 117 98 102 114 112 106
DUR-J10A 63
262 259 193 182 117 63 111 77 151 229 188 181 207 207 140 196 203 183 158 233
201 150 135 136 187 169 186 211 179 186 137 177 201 200 144 106 116 104 104 123
96 110 94 69 95 116 104 100 125 87 77 75 102 98 123 120 62 190 113 80
93 82 125
DUR-J10B 63
250 246 185 194 108 69 111 86 137 226 175 179 212 204 135 196 201 176 173 240
209 147 123 147 184 173 172 208 174 193 133 179 208 195 134 119 112 100 106 119
93 113 99 69 92 119 104 98 133 72 87 78 100 95 123 113 68 94 76 83
78 84 95

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the 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, 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

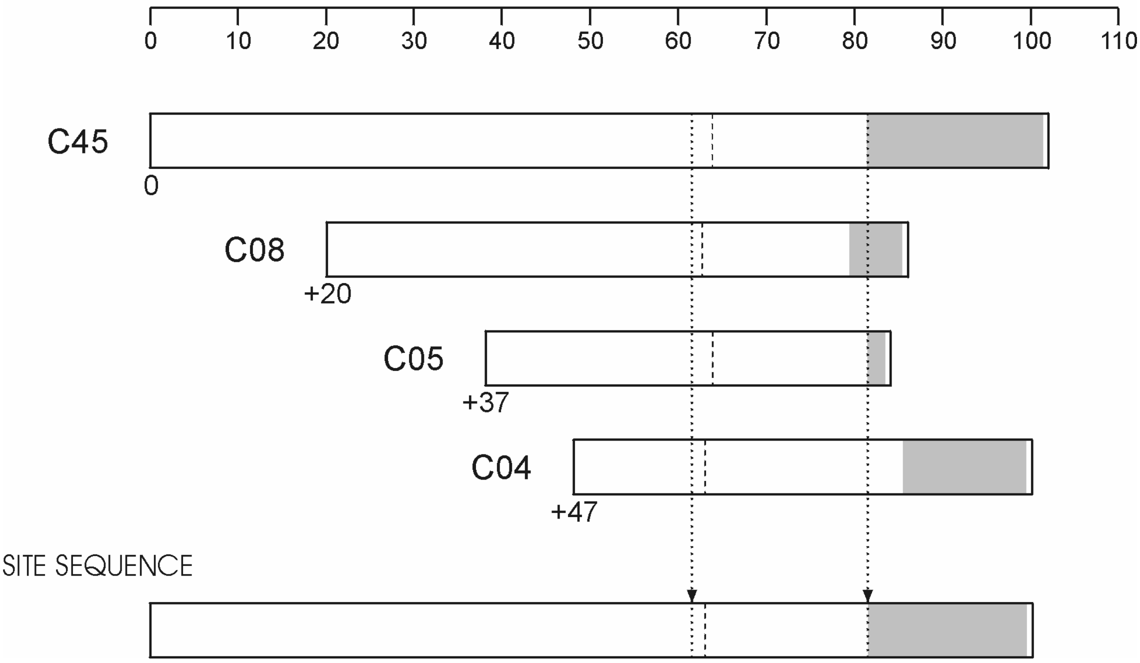


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

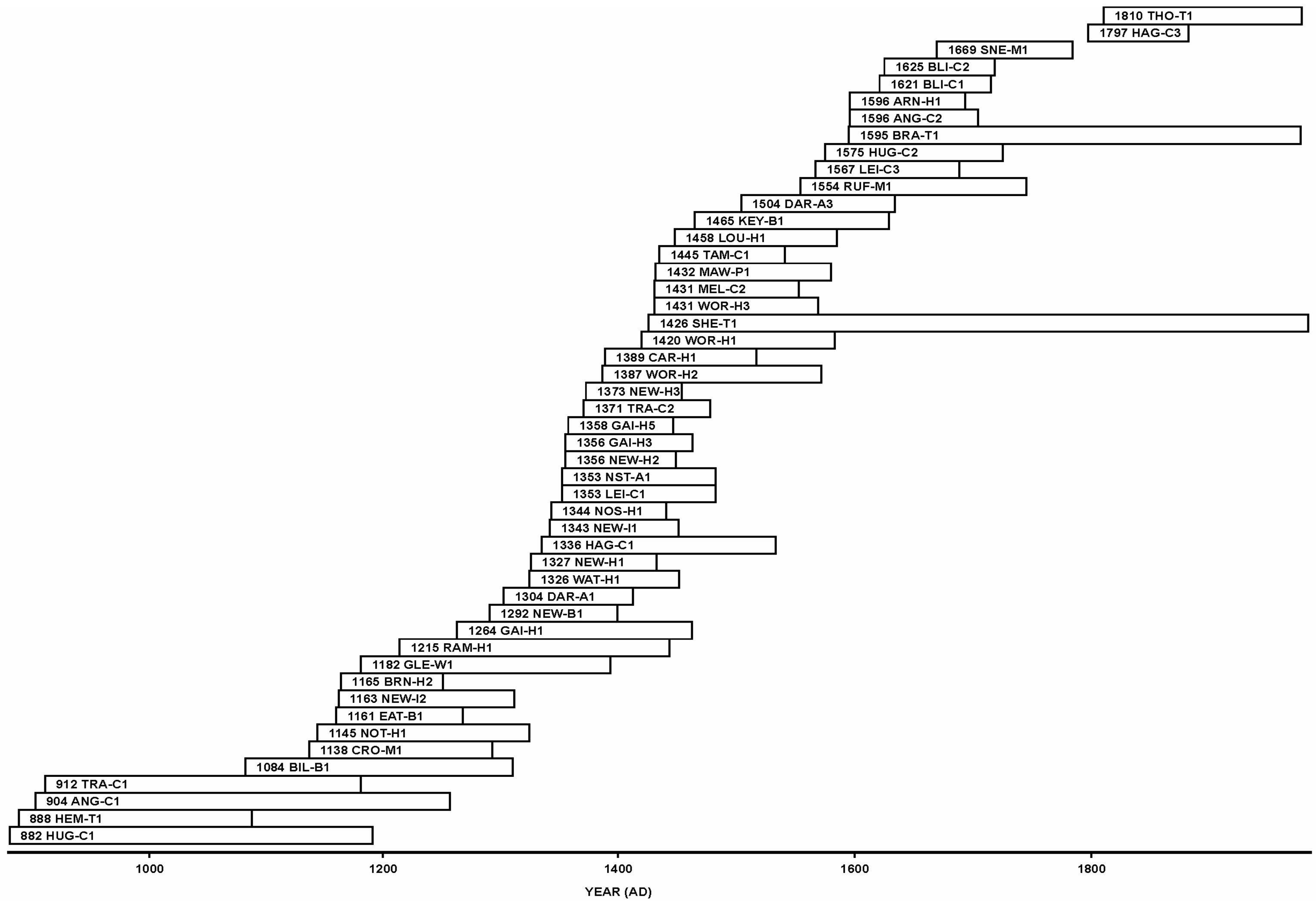
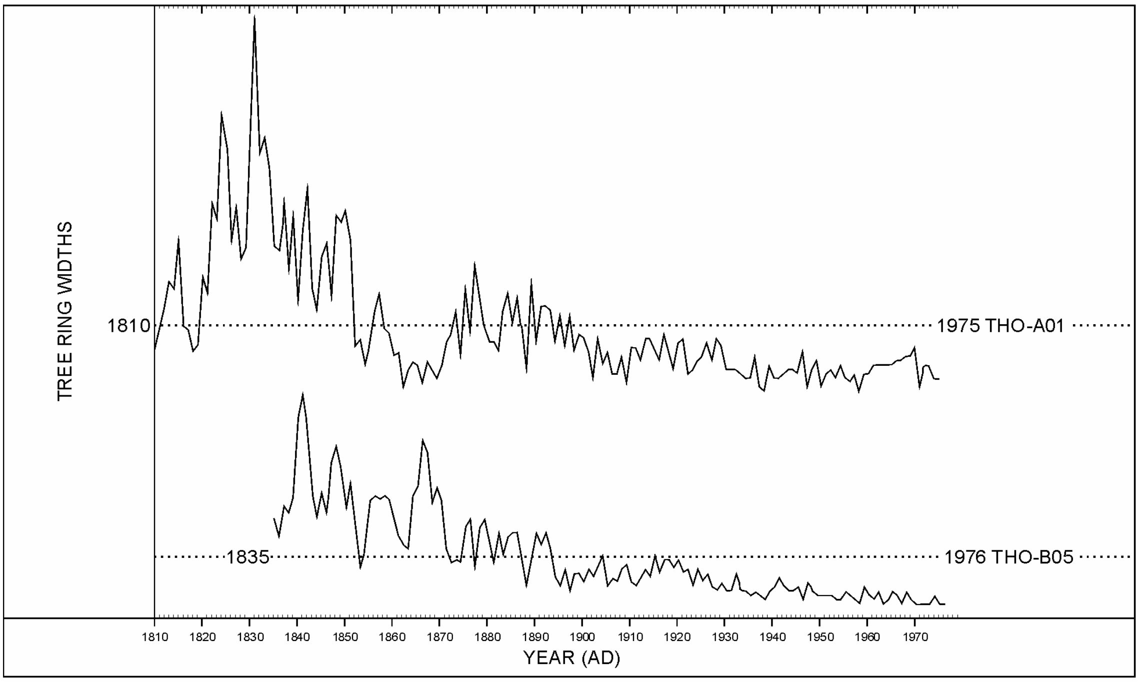


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

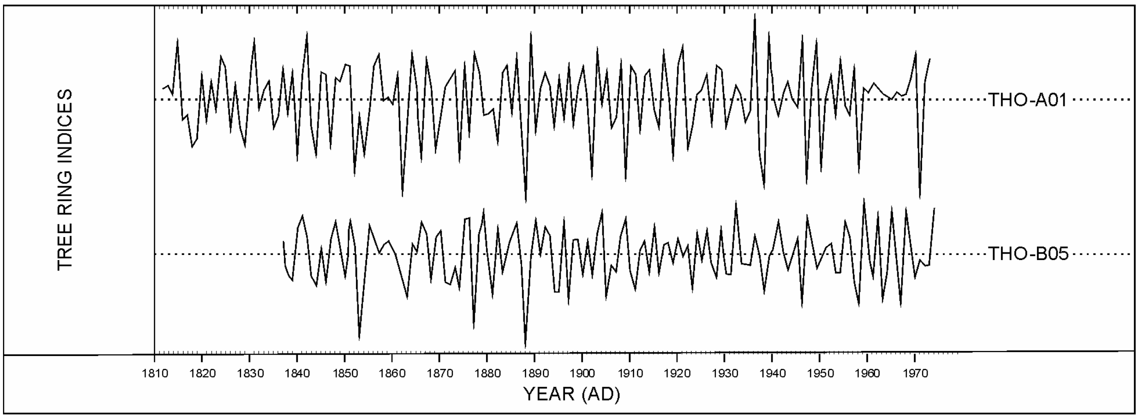


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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