Historic England

Scientific Dating

Westgate End House, Kemps Bridge, Wakefield, West Yorkshire

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 28-2015

Research Report Series 28-2015

WESTGATE END HOUSE, KEMPS BRIDGE, WAKEFIELD, WEST YORKSHIRE

TREE-RING ANALYSIS OF TIMBERS

Alison Arnold and Robert Howard

NGR: SE 32233 20540

ISSN 2059-4453 (Online)

SUMMARY

Dendrochronological analysis was undertaken on samples from 19 timbers removed from this building during demolition and subsequently stored off-site. This analysis produced a single-dated site chronology, WKFBSQ01, comprising 14 samples with an overall length of 191 rings. These rings were dated as spanning the years AD 1377–1567. Interpretation of the sapwood clearly shows that there are different phases of felling. These felling dates follow the general pattern of the listing description. One of these phases dates to the earlier sixteenth century, perhaps representing the construction of the primary central hall range, with a further phase of felling around the mid-sixteenth century, perhaps representing the construction of a later cross-wing. There is then a potential modification in the very late-sixteenth century, perhaps for the flooring-in of the earlier ranges. A second site chronology, WKFBSQ02, was also created comprising three samples and being 86 rings long. This site chronology cannot be dated, but it is almost certain that the timbers are coeval. Two further samples, both with distorted growth rings, remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would firstly like to thank Elizabeth Chamberlain of West Yorkshire Archaeology Advisory Service for her unstinting efforts in arranging storage and care of these timbers, then arranging access for sampling, and for making a drawn survey and record of the timbers. We must also thank Elizabeth for much useful information in identifying individual timbers. The Laboratory would also like to thank Andrew Schoolar and the other staff of the local authority storage depot for their cooperation and help at the time of sampling. Finally we would like to thank Shahina Farid and Cathy Tyers (English Heritage Scientific Dating Team) for commissioning this programme of tree-ring dating, and for the help and assistance provided during analysis and reporting.

ARCHIVE LOCATION

West Yorkshire Historic Environment Record
Registry of Deeds, Newstead Road
Wakefield, West Yorkshire WF1 2DE

DATE OF INVESTIGATION

2014

CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

CONTENTS

INTRODUCTION

Westgate End House was a Grade II listed building comprising a large central hall range with cross wings, which once stood at Kemps Bridge off Westgate End Road in Wakefield (Figs 1a/b). Externally, the central portion was described in the listing description as seventeenth or early eighteenth century but internal inspection indicated that the central hall range was an earlier, formerly timber-framed building, possibly of sixteenth-century date or earlier, with two complete truss frames and plaster clad posts with jowel-heads. These supported deep tiebeams of oak and king-post roof trusses, one of these with applied lath-and-plaster suggestive of the remnants of a firehood. At first-floor level, the north wing had a fully exposed raised cruck frame of unusual type, the curved blades tied together by a collar from which sprang a diminutive king-post that carried a diamond-set ridge beam. In the central hall range the principal dining room had a heavily beamed ceiling with stop-chamfered oak joists that probably dated from the seventeenth century, perhaps when the former open hall was floored over. Given its form and structure, Westgate End House was considered an unusual survival for West Yorkshire.

In recent years the building had fallen into a state of considerable decay, and was in a very poor state prior to its demolition by the current owners in November 2013. However, although raised to the ground, a number of substantial timbers associated with the early timber framed building were rescued from the debris and temporarily set aside for this dendrochronological analysis in an off-site council owned open air storage unit in Wakefield.

SAMPLING

A retrospective dendrochronological survey of Westgate End House was requested by Kathryn Gibson, English Heritage Inspector of Historic Buildings and Areas. It was commissioned to obtain as much information as possible about the now demolished structure. The aim was to obtain independent dating evidence for the primary construction of the hall and to demonstrate, if possible, its ensuing chronological development. The information obtained here may inform future ground and below-ground investigations.

In the first instance it was necessary to undertake a detailed assessment of dendrochronological potential of the salvaged timbers and attempt to identify what elements of the framing they might be (it not having been possible to survey or record the timbers prior to demolition). This assessment and survey was undertaken with Elizabeth Chamberlain of West Yorkshire Archaeological Advisory Service.

This process identified approximately 25 timbers of potential interest. However, it was not always certain what element of the framing the timbers represented, and there was no indication as to which part of the building they had originally come, this leading to some uncertainty in the description of each timber. Despite this, a total of 19 samples were obtained from the most appropriate timbers. Samples were taken by slicing with a chainsaw as the timbers were not required for reuse (Fig 2a/b), Each sample was given the code WKF-B (for Wakefield, site 'B') and numbered 01–19 (Table 1).

ANALYSIS AND RESULTS

Each of the 19 samples obtained from Westgate End House was prepared by sanding and polishing, and its annual growth ring widths were measured. The data of these measurements are given at the end of this report. The data of the 19 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this resulting in the production of two separate groups of cross-matching samples.

The first group comprises 14 samples, these cross-matching with each other as shown in Figure 3a. These 14 samples were combined at their indicated offset positions to form site chronology WKFBSQ01, this having an overall length of 191 rings. Site chronology WKFBSQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a series of these when the date of its first ring is AD 1377 and the date of its last measured ring is AD 1567 (Table 2).

The second group comprises three samples, these cross-matching with each other as shown in Figure 3b. These three samples were also combined at their indicated offset positions to form site chronology WKFBSQ02, this, having an overall length of 86 rings. Site chronology WKFBSQ02 was also compared to an extensive corpus of reference material for oak, but there was no satisfactory cross-matching. The three samples must, therefore, remain undated.

Each of the two site chronologies, WKFBSQ01 and WKFBSQ02 were then compared with the two remaining ungrouped samples. There was however, no cross-matching. The two ungrouped samples were also compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and they too are undated.

INTERPRETATION

Interpretation of the sapwood on the 14 dated samples from Westgate End House suggests that at least three, and possibly more, phases of felling are represented amongst its timbers (Fig 3a). The earliest definite phase of felling appears to be represented by samples WKF-B09, B11, and B19. None of these three retains complete sapwood (the last growth ring produced by the tree before it was felled), and it is, thus, not possible to determine a precise felling date for the timbers. The samples do, though, have some sapwood, and retain the heartwood/sapwood boundary, the average date of this being AD 1497. Using a sapwood estimate of 15–40 rings (the usual 95% confidence interval), and allowing that the latest sapwood ring on any of the three samples (WKF-B09) is dated to AD 1512, this would give these timbers an estimated felling date in the range AD 1513–37.

A later phase of felling is represented by samples WKF-B03, B04, B05, B07, B08, and B16. Again, none of these six has complete sapwood, and the exact felling date of any of the timbers is unknown, but the samples do again have some sapwood, and retain the heartwood/sapwood boundary. In this case the average date of this boundary is AD 1512. Using the same sapwood estimate as above, 15–40 rings, and again allowing that the latest sapwood ring on any of these (WKF-B03) is dated to AD 1533, this would give these timbers an estimated felling date in the range AD 1534–52.

The latest phase of felling is represented by sample WKF-B02. This sample has a heartwood/sapwood boundary date of AD 1567, plus a further 25–30 unmeasured sapwood rings (this portion of the wood being too decayed and indistinct to reliably measure), which is believed to be complete to the bark edge. As such, this would give the timber represented an estimated felling date of *c* AD 1592–97.

By contrast, it is not possible to estimate the felling date ranges of the timbers represented by samples WKF-B17 and B18, and samples WKF-B01 and B06. These four timbers are missing all their sapwood rings as well as an unknown number of heartwood rings. It is likely, however, given the high level of cross-matching between the samples in each pair that they are coeval. It is, in theory, possible that either pair, or both pairs, of timbers belong with the early sixteenth century phase of felling, or that either pair, or both pairs, belong with the mid-sixteenth century phase. It is of course also possible that the pairs represent entirely separate phases of felling, or that they belong with the late-sixteenth century phase, although this latter interpretation is somewhat less likely given the size and age the parent trees might have grown to had they been felled this late.

The second site chronology, comprising three samples, and having an overall length of 86 rings cannot be dated. However, given the virtually identical position of the heartwood/sapwood boundary on them, and the fact that they cross-match very well with each other, would suggest that the timbers are coeval and that they represent a single phase of felling, albeit of unknown date.

CONCLUSION

Although, due to the lack of recording before demolition, it is not possible to marry up the timbers and their felling dates with specific parts of the building tree-ring analysis has clearly shown that there are several different phases of felling and that sixteenth century material certainly existed in the building. One of these phases is in the earlier sixteenth century, perhaps representing the construction of a primary central hall range, with a further phase of felling around the mid-sixteenth century, perhaps representing the construction of a later cross-wing. There is then a potential modification of some sort in the very late-sixteenth century, perhaps for a further cross-wing, or the flooring-in of the earlier ranges. As such, these dates appear to follow the general pattern as suggested in the description in the Historic Environment Record from West Yorkshire Archaeology Advisory Service.

The overall cross-matching between the 14 dated samples in site chronology WKFBSQ01 is somewhat variable, which would suggest that the utilised trees were sourced from different areas of woodland reflecting the fact that they were felled at different times (had they all been felled at the same time it is more likely that they would have come from a single woodland and thus cross-matching more highly with each other). Despite this, however, it is likely that some beams have been derived from a single tree. Samples WKF-B03 and B08, for example, cross-match with a value of t=12.1, while samples WKF-B09 and B19 cross-match with a value of t=12.5. Indeed it is possible that one tree has provided the timbers represented by three samples, WKF-B10, B13, and B15, which, although undated, again cross-match with high t-values, again, supporting the interpretation that the three timbers represented are coeval.

In respect of the location of the source woodland, it may be noted from Table 2 that, although site chronology WKFBSQ01 has been compared to reference chronologies from all parts of England the highest levels of similarity (as indicated by the t-values) are found with other sites in northern England. It will be seen that most of these sites are in Yorkshire, and some are relatively close by, Kirkburton and Liversedge for example. This would suggest that the dated timbers used at Westgate End House are from relatively local woodland sources.

Despite having sufficient rings for reliable dating, two samples, WKF-B12 and B14, remain ungrouped and undated. Both samples show some distortion and disturbance to their growth, and it is almost certainly this, which prevents them from grouping and dating. The presence of undated samples is, however, a frequent feature of tree-ring analysis, and in this respect Westgate End House is a good example in having almost 74% of its samples successfully dated.

BIBLIOGRAPHY

Arnold, A J, and Howard, R E, 2007 *Tree-ring analysis of timbers from All Hallows Church, Kirkburton, West Yorkshire*, English Heritage Res Dept Rep Ser, 49/2007

Arnold, A J, and Howard, R E, 2008 unpubl Norton Conyers Hall, Wath, North Yorkshire, Nottingham Tree-ring Dating Laboratory unpubl computer file *NRCASQ01*

Arnold, A J, and Howard, R E, 2014 *7–12 Church Street, Dronfleld, Derbyshire, Tree-ring analysis of timbers,* English Heritage Res Rep Ser, 55-2014

Hillam, J, 1984 *Tree-ring analysis of timbers from Elland Old Hall, West Yorkshire,* Anc Mon Lab Rep, 4165

Howard, R E, Laxton, R R, Litton, C D, Morrison A, Sewell, J, and Hook, R, 1994 List 58 no 11, Nottingham University Tree-Ring Dating Laboratory, Derbyshire, Peak Park and RCHME dendrochronological Survey 1992–93, *Vernacular Architect*, 25, 41–3

Howard, R E, Laxton, R R, and Litton, C D, 2003 *Tree-ring analysis of timbers from Combermere Abbey, Whitchurch, Cheshire*, Centre for Archaeol Rep, 83/2003

Tyers, I, 1998 *Tree-ring analysis of oak timbers from the "Brewhouse" and "Refectory" at Nostell Priory, near Wakefield, West Yorkshire,* Anc Mon Lab Rep, 20/98

Tyers, I, 2001 *Dendrochronological analysis of timbers from Headlands Hall, Liversedge, West Yorkshire,* ARCUS Rep, 574c

TABLES

Table 1: Details of tree-ring samples from Westgate End House, Wakefield, West Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
WKF-B01	Possible brace	89	no h/s	1395	------	1483
WKF-B02	Possible collar	120(+25-30 nm)	h/s (+25-30nm C)	1448	1567	1567
WKF-B03	Uncertain (fire-damaged)	113	26	1421	1507	1533
WKF-B04	Post	122	h/s	1389	1510	1510
WKF-B05	Post	125	9	1399	1514	1523
WKF-B06	Uncertain	107	no h/s	1377	------	1483
WKF-B07	Uncertain	80	7	1445	1517	1524
WKF-B08	Possible tie-beam	119	18	1412	1512	1530
WKF-B09	Post	94	15	1419	1497	1512
WKF-B10	Uncertain (one side badly charred)	86	18	------	------	------
WKF-B11	Uncertain	95	h/s	1404	1498	1498
WKF-B12	Uncertain (distorted)	90	no h/s	------	------	------
WKF-B13	Uncertain	66	15	------	------	------
WKF-B14	Possible collar (distorted)	83	no h/s	------	------	------
WKF-B15	Uncertain	80	11	------	------	------
WKF-B16	Possible brace	81	h/s	1432	1512	1512
WKF-B17	King Post - central range	76	no h/s	1379	------	1454
WKF-B18	King Post - central range	74	no h/s	1380	------	1453
WKF-B19	Uncertain	125	4	1377	1497	1501

h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample
nm = rings not measured

Table 2: Results of the cross-matching of site sequence WKFBSQ01 and relevant reference chronologies when the first-ring date is AD 1377 and the last-ring date is AD 1567

Reference chronology	Span of chronology	*t*-value	Reference
All Hallow's Church, Kirkburton, West Yorkshire	AD 1306–1633	9.5	(Arnold and Howard 2007)
Norton Conyers Hall, West Yorkshire	AD 1448–1609	8.7	(Arnold and Howard 2008 unpubl)
Elland Old Hall, West Yorkshire	AD 1372–1574	8.5	(Hillam 1984)
Nostell Priory, near Wakefield, West Yorkshire	AD 1263–1536	8.3	(Tyers 1998)
Headlands Hall, Liversedge, West Yorkshire	AD 1388–1487	8.0	(Tyers 2001)
7–12 Church Street, Dronfield, Derbyshire	AD 1313–1526	7.9	(Arnold and Howard 2014)
Combermere Abbey, Whitchurch, Cheshire	AD 1363–1564	7.9	(Howard *et al* 2003)
Ughill Manor, Bradfield, South Yorkshire	AD 1349–1504	7.9	(Howard *et al* 1994

FIGURES

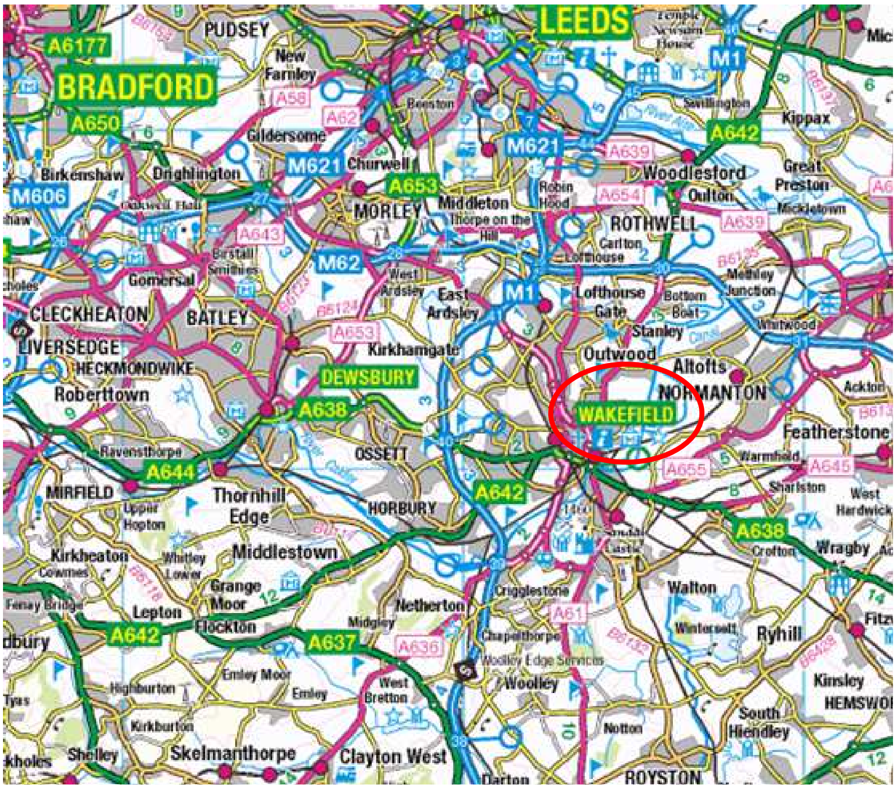
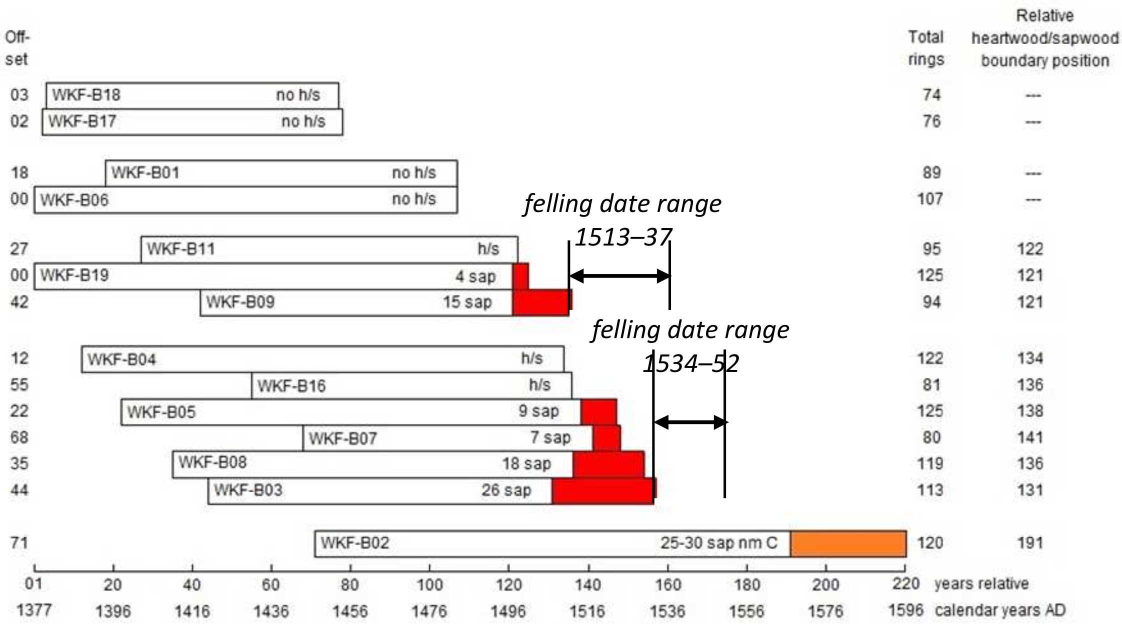
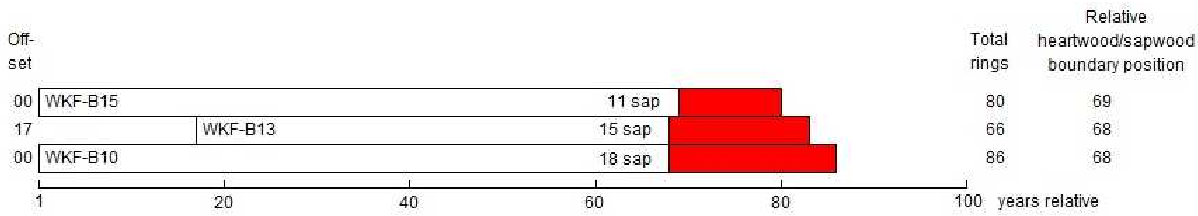


Figure 1a/b: Maps to show the location of Wakefield (top) and Westgate End House © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2a/b: Views showing the timbers (Photographs William Howard)





White bars = heartwood rings,
shaded bars (red) = measured sapwood rings;
shaded bars (orange) = unmeasured sapwood rings;
h/s = heartwood/sapwood boundary; nm = rings not measured
C = complete sapwood

Figure 3a/b: Bar diagram of the samples in site chronology WKFBSQ01 (top) and WKFBSQ02 (bottom)

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WKF-B01A 89
407 397 360 316 285 285 196 255 216 267 234 239 239 274 200 237 170 200 185 148
160 125 78 114 107 191 169 144 161 133 160 78 109 109 175 158 190 203 139 132
123 121 118 143 139 146 156 114 151 143 126 117 149 101 93 156 168 190 91 57
71 73 82 78 51 73 93 99 100 110 129 117 143 153 106 143 151 140 157 175
247 149 153 126 206 178 176 226 228
WKF-B01B 89
438 383 353 311 284 282 196 255 226 260 253 225 252 285 186 234 179 192 185 146
157 127 82 103 107 182 162 151 160 143 140 87 92 117 176 166 175 216 135 131
125 120 131 127 145 151 156 127 140 150 128 118 145 106 100 160 154 178 89 65
64 82 85 68 50 84 87 95 98 116 131 108 154 146 103 135 164 136 151 182
259 154 139 121 190 168 185 221 229
WKF-B02A 120
249 174 159 169 119 95 247 329 302 299 151 148 158 180 141 230 153 168 217 221
215 200 229 203 103 128 132 223 205 162 80 75 156 153 126 165 148 125 148 220
198 162 169 110 95 140 129 156 134 112 118 95 112 68 80 113 142 145 170 133
115 140 159 142 133 93 93 80 96 117 140 162 98 131 115 114 112 101 114 126
176 139 116 135 173 143 128 90 112 90 102 94 84 82 54 70 100 101 76 83
90 68 62 72 65 65 58 57 59 46 46 37 40 46 36 50 32 46 43 39
WKF-B02B 120
252 171 155 173 121 92 232 354 298 305 166 128 173 167 134 225 151 185 200 213
217 204 246 208 124 135 128 203 255 144 103 88 155 151 137 164 167 140 137 206
176 179 162 112 95 143 123 151 145 104 112 95 103 76 80 103 131 148 167 129
117 145 154 145 130 96 92 96 86 110 142 156 107 131 126 109 136 96 123 112
159 156 118 131 174 146 128 84 113 96 98 91 81 86 59 70 92 106 81 76
87 70 60 70 62 71 54 58 59 49 43 37 40 46 47 47 45 37 42 45
WKF-B03A 113
232 223 167 221 202 165 186 148 167 159 157 216 182 142 135 132 141 164 123 123
153 130 121 167 190 96 128 137 127 92 82 72 63 68 120 141 96 94 82 141
135 120 114 87 105 97 115 146 140 160 216 160 223 143 204 170 104 110 103 123
151 140 128 193 128 145 179 128 107 123 108 75 118 137 135 191 169 162 139 103
104 140 182 179 159 223 126 150 149 125 145 153 199 173 146 156 112 155 193 153
169 184 184 219 138 176 142 175 159 112 127 100 145
WKF-B03B 113
235 219 169 225 206 147 202 134 175 157 150 209 176 160 148 128 142 166 116 134
130 135 128 167 167 103 145 128 125 91 89 71 60 75 114 135 103 96 77 149
147 113 114 83 114 89 111 143 146 164 214 173 232 170 217 156 119 101 92 134
156 156 165 150 134 143 164 131 114 118 106 75 121 140 137 203 171 148 135 95
106 149 189 175 140 237 114 161 143 135 134 174 175 186 132 162 105 153 193 159
162 191 185 206 138 180 146 169 158 115 137 95 151
WKF-B04A 122
236 142 106 108 107 149 127 167 192 233 257 301 217 348 244 361 245 268 257 244
250 329 235 287 267 257 207 191 226 213 122 277 205 172 323 217 281 275 123 190
183 182 221 185 112 182 197 185 98 96 126 137 154 125 207 205 140 118 114 128
145 146 223 237 75 80 59 81 77 59 90 118 115 128 136 128 169 203 166 170
175 165 128 129 143 166 225 195 128 150 229 182 196 188 234 201 210 228 246 119
117 143 96 126 134 133 125 231 143 81 128 189 125 190 155 157 152 165 196 185
212 230

WKF-B04B 122
234 136 120 93 124 145 126 175 183 206 276 294 214 350 242 398 232 282 262 244
235 316 221 284 243 253 211 179 225 198 129 257 210 178 329 211 281 296 122 176
164 182 217 187 128 173 190 198 96 96 150 148 156 121 214 191 123 126 115 123
154 153 221 234 89 81 55 82 76 62 84 110 105 115 115 128 159 199 150 165
171 166 121 136 134 170 233 196 126 164 212 191 187 200 227 199 222 212 255 128
125 139 104 127 126 133 125 240 136 100 121 191 109 206 142 153 127 203 193 197
203 225
WKF-B05A 125
288 322 259 278 308 331 289 263 207 192 258 98 67 88 54 99 133 67 78 100
114 139 121 110 153 168 155 141 149 182 235 162 203 247 207 165 222 185 191 142
139 159 228 157 209 189 182 95 162 118 165 178 110 129 140 126 157 127 108 146
112 195 157 175 221 146 200 262 154 208 126 212 257 209 237 203 321 259 157 145
128 240 295 290 309 251 222 263 249 187 159 155 119 134 196 219 228 351 250 231
243 309 169 188 235 217 215 278 175 174 189 159 206 213 212 189 157 167 136 217
171 182 162 237 251
WKF-B05B 125
292 320 263 282 308 324 289 269 216 181 268 100 65 91 51 94 130 67 77 107
115 139 117 110 150 166 158 146 149 178 232 167 205 250 214 152 225 188 200 150
131 157 232 141 220 199 167 90 171 112 171 173 114 129 135 118 164 129 103 151
112 195 150 193 192 140 218 257 151 212 117 220 254 205 229 212 307 255 161 146
128 230 303 310 296 246 245 260 246 168 183 168 136 126 206 215 240 378 266 221
228 314 172 181 240 228 215 281 178 164 180 168 221 211 181 196 162 176 139 215
163 182 158 220 253
WKF-B06A 107
206 259 267 196 279 291 254 241 229 277 325 266 269 407 481 424 303 278 225 379
303 259 230 352 216 264 240 243 204 213 198 217 143 173 159 201 239 140 156 127
92 127 122 210 218 160 223 142 162 87 95 120 178 231 196 271 183 151 137 120
100 143 103 150 126 114 131 120 101 112 124 92 86 125 143 180 141 112 90 114
87 71 53 103 101 137 134 117 118 144 141 150 162 145 151 116 146 159 184 187
190 156 206 196 224 225 296
WKF-B06B 107
236 269 263 249 267 285 269 232 239 269 294 251 269 423 494 459 335 310 233 362
314 262 218 346 218 259 242 237 219 210 195 204 143 164 157 196 217 145 163 117
102 123 114 206 217 175 215 145 159 89 93 115 175 243 198 276 183 151 140 112
106 143 125 150 137 125 114 118 104 110 126 93 78 137 129 184 116 106 98 104
84 71 50 98 103 146 129 125 127 161 156 166 133 141 152 118 143 165 165 215
175 170 210 209 225 221 284
WKF-B07A 80
258 146 283 207 258 261 92 74 89 85 108 141 117 131 123 132 138 144 155 184
175 188 192 250 265 285 242 152 165 172 336 293 209 192 194 189 271 237 292 273
261 240 335 234 230 214 159 176 292 395 315 438 267 268 260 320 238 244 231 281
292 359 221 247 221 264 313 209 240 215 161 202 224 254 221 277 165 240 237 282
WKF-B07B 80
227 160 272 213 259 262 95 68 87 91 100 135 119 128 130 128 139 144 164 181
169 205 179 242 268 284 239 155 175 185 324 307 207 185 189 182 270 237 308 275
228 232 336 279 234 233 195 168 276 409 340 431 273 275 251 324 231 259 223 283
281 353 218 259 218 275 283 206 234 224 156 200 215 259 231 280 171 223 235 290

WKF-B08A 119
393 345 285 344 225 261 273 196 223 291 263 237 289 230 246 232 167 188 197 175
260 192 175 155 117 152 190 124 164 166 159 160 253 203 164 173 168 182 121 120
70 54 89 81 109 84 78 68 93 125 141 142 137 146 135 154 162 173 206 232
175 196 151 262 236 152 109 123 189 283 241 183 204 175 212 320 172 162 162 121
93 128 164 175 262 196 188 152 108 115 184 209 200 168 259 150 137 178 165 194
245 253 239 204 194 175 193 262 221 213 266 275 326 190 178 178 243 203 184
WKF-B08B 119
323 382 279 343 266 236 281 212 221 282 257 234 284 240 259 231 178 196 184 161
247 201 171 143 125 129 203 128 157 176 167 151 265 196 159 171 176 171 123 134
67 51 83 85 100 84 78 79 89 118 144 143 129 154 140 140 164 165 206 216
170 209 159 246 248 143 101 135 200 280 228 199 190 184 191 320 171 168 158 128
92 134 157 181 255 228 171 157 95 118 206 225 192 181 219 146 162 165 178 181
228 240 234 202 221 181 174 262 234 205 303 278 340 179 205 173 225 197 205
WKF-B09A 94
165 298 183 197 241 147 159 93 100 181 230 155 184 258 200 173 187 127 140 152
154 244 241 180 221 338 251 185 204 185 214 184 179 228 274 238 172 189 123 101
90 146 153 162 131 115 129 162 145 140 162 219 190 145 160 137 223 109 98 112
195 160 195 193 229 221 197 160 176 181 123 89 88 56 76 133 156 206 134 112
113 95 81 62 93 96 70 88 81 87 135 109 128 146
WKF-B09B 94
130 314 186 200 235 169 151 105 84 203 233 151 200 269 207 173 197 124 150 157
167 249 245 183 223 337 229 187 214 184 209 198 173 218 298 243 165 168 123 84
89 143 149 168 117 110 134 179 136 131 185 239 188 144 157 142 245 131 103 98
171 154 176 195 228 210 209 150 194 164 132 84 82 59 80 112 156 210 140 106
96 109 81 75 83 87 71 91 81 89 119 121 122 146
WKF-B10A 86
160 156 64 33 35 56 68 132 180 192 150 105 51 59 137 203 207 263 273 198
307 285 175 152 151 193 114 78 84 89 108 115 135 185 205 285 228 200 116 104
196 221 200 196 203 229 266 345 435 343 249 243 153 159 173 267 180 178 157 171
186 156 164 204 231 190 220 190 334 322 243 247 203 115 125 111 112 134 163 167
126 126 126 106 165 179
WKF-B10B 86
158 148 64 37 40 52 70 132 179 201 147 98 44 64 151 193 201 253 278 206
325 306 199 153 146 192 122 70 89 88 107 114 149 171 213 282 240 181 133 102
185 218 192 192 203 218 275 345 429 357 277 240 164 175 181 264 183 174 173 182
175 170 165 206 210 207 232 193 339 331 235 245 204 105 133 105 109 154 164 162
153 126 109 163 149 190
WKF-B11A 95
369 448 463 279 279 194 194 157 266 239 173 156 124 135 209 227 192 257 203 225
182 167 139 120 120 245 271 321 414 260 184 218 160 173 218 190 243 192 152 133
146 159 139 132 106 109 109 155 206 173 351 184 198 204 96 70 96 105 151 123
87 82 79 115 143 139 135 93 102 112 118 184 96 96 99 96 126 125 109 146
131 112 114 135 146 103 104 65 83 91 90 96 87 87 96
WKF-B11B 95
394 442 456 271 268 196 216 153 264 234 157 169 131 142 225 230 191 251 203 225
199 157 138 100 117 215 269 307 402 249 178 218 151 164 237 188 239 197 160 134
133 153 143 135 108 108 107 153 206 186 350 196 197 187 93 71 101 110 148 118
92 81 78 119 128 142 143 92 100 125 130 165 112 100 96 97 123 123 109 148
129 103 120 131 151 105 104 79 88 90 96 100 96 87 105

WKF-B12A 90
279 211 285 399 301 517 326 287 200 266 266 241 132 134 242 403 248 432 396 292
188 235 158 276 214 200 203 174 292 229 168 173 107 104 112 125 254 334 430 443
337 333 320 579 677 631 500 402 521 600 423 338 219 341 296 331 267 282 306 293
214 260 135 66 53 46 40 40 33 68 97 78 70 65 48 52 127 197 266 196
148 134 51 37 29 46 38 31 46 40
WKF-B12B 90
301 202 273 395 304 503 311 301 207 321 286 279 134 169 228 450 249 475 396 247
164 225 157 248 212 191 193 181 279 225 185 187 101 104 110 109 240 360 439 426
338 358 328 557 637 636 493 383 534 607 450 331 235 365 309 325 296 277 314 293
212 257 135 65 53 52 40 36 36 71 93 73 73 65 52 50 124 197 272 190
150 140 43 40 26 50 36 39 46 38
WKF-B13A 66
301 297 203 316 232 210 192 187 294 173 162 138 141 155 143 155 193 150 188 203
139 92 90 175 250 227 178 167 218 253 294 429 318 337 257 167 100 171 252 179
142 138 189 190 162 131 168 169 165 206 210 234 210 218 225 209 111 109 89 106
116 137 120 160 153 178
WKF-B13B 66
288 297 207 306 242 209 222 196 284 185 147 95 124 160 140 169 168 154 188 189
139 81 103 185 233 216 182 175 217 260 321 432 287 323 257 173 99 175 240 162
151 143 184 193 167 148 153 174 164 214 232 233 221 209 232 203 117 115 98 110
136 143 123 156 164 167
WKF-B14A 83
128 143 125 148 305 475 417 310 409 426 144 50 41 41 35 34 48 52 64 64
102 172 160 129 60 39 45 76 156 218 113 88 88 88 125 207 239 108 100 106
77 109 140 131 155 196 117 98 170 135 146 125 159 169 187 270 214 75 66 69
83 103 112 114 78 78 82 91 104 90 90 114 70 46 77 62 50 65 98 139
131 92 110
WKF-B14B 83
152 165 121 143 309 490 451 298 389 430 144 53 51 34 39 42 51 59 75 78
110 190 146 153 52 33 39 56 125 182 107 73 75 67 100 160 171 85 61 81
52 71 91 82 88 104 69 57 98 89 110 100 139 132 171 248 191 59 63 75
79 121 100 123 90 79 76 101 128 89 103 110 59 53 70 59 57 59 104 140
157 87 104
WKF-B15A 80
95 107 55 31 35 51 64 96 209 202 165 113 52 79 121 200 203 284 285 212
330 337 239 239 261 259 125 96 92 103 135 127 169 208 215 234 215 185 100 102
206 233 278 226 218 231 344 456 418 279 295 196 173 146 182 282 234 198 192 200
195 212 179 257 311 291 344 309 656 572 343 358 243 109 106 135 118 146 159 212
WKF-B15B 80
109 109 58 31 33 52 64 108 204 200 177 108 58 71 122 194 187 262 291 187
312 334 239 247 260 265 146 87 94 92 132 128 181 226 199 264 229 207 97 100
206 253 267 228 223 234 376 457 384 284 264 223 151 139 185 290 216 196 189 194
204 200 196 265 303 274 329 308 650 542 337 350 246 104 111 134 115 159 166 220
WKF-B16A 81
297 189 131 254 178 141 192 159 163 152 138 159 228 196 160 189 121 206 155 183
178 164 172 143 200 157 125 150 191 164 162 119 153 151 181 146 131 200 193 151
128 126 103 170 204 121 123 132 146 197 178 184 129 100 99 126 76 94 75 79
78 92 88 89 115 75 90 86 53 82 75 80 98 78 81 59 162 123 150 108
140

WKF-B16B 81
316 196 134 266 173 131 192 163 164 156 126 167 225 191 161 191 128 205 155 185
178 160 171 147 200 154 139 150 180 167 168 139 144 166 173 160 126 189 168 160
131 121 103 182 206 110 125 139 135 204 173 170 135 106 100 120 90 73 82 70
79 89 88 104 112 84 81 71 76 73 77 86 89 82 66 61 160 127 145 105
132
WKF-B17A 76
331 364 306 363 411 368 410 448 473 458 363 380 299 436 332 363 282 441 295 290
345 343 270 470 384 498 362 426 279 397 393 256 198 300 356 337 321 190 184 339
52 62 80 113 228 168 190 169 225 257 359 324 343 453 269 343 346 411 201 336
268 290 240 178 277 326 204 112 137 79 162 174 156 193 203 252
WKF-B17B 76
316 368 319 360 437 412 368 462 462 454 360 374 282 446 335 360 273 453 300 273
296 317 273 472 383 500 357 425 275 403 388 242 217 298 360 299 337 196 188 311
50 65 77 123 221 175 181 176 215 259 309 331 315 440 265 338 343 400 218 331
281 291 246 163 275 344 188 116 128 78 187 146 159 211 185 240
WKF-B18A 74
472 523 535 657 503 382 526 535 535 497 516 321 492 429 506 370 624 501 282 364
300 464 421 292 517 392 690 356 499 484 259 193 284 328 349 429 271 218 559 228
390 168 284 444 189 146 160 149 250 299 162 265 340 156 208 297 253 150 254 193
262 243 144 250 219 130 90 124 74 150 169 160 175 180
WKF-B18B 74
480 497 540 661 495 378 527 534 540 489 538 314 488 421 509 382 636 501 265 365
314 455 443 284 529 401 690 346 499 474 263 196 306 324 341 443 256 230 560 239
360 153 228 389 188 150 160 145 251 291 174 270 351 153 204 296 253 148 256 203
253 246 150 253 199 138 74 112 72 159 166 153 190 162
WKF-B19A 125
377 299 298 232 229 255 246 233 192 330 278 296 203 497 271 222 228 183 157 268
228 268 176 246 206 187 224 240 235 225 193 229 226 204 228 256 228 191 190 178
117 193 154 270 194 181 242 181 146 131 106 196 235 189 232 289 217 192 246 134
171 148 155 230 247 171 192 244 214 159 196 159 184 117 70 113 150 125 109 125
93 71 82 109 112 123 115 87 123 128 141 143 169 228 145 140 160 158 204 153
140 123 181 134 178 201 171 139 133 125 153 97 96 62 65 66 101 104 131 175
94 96 103 107 133
WKF-B19B 125
387 287 295 231 229 255 252 235 193 330 275 294 210 500 267 228 219 182 164 276
228 261 185 248 201 189 222 231 243 223 190 217 222 213 228 224 236 227 218 189
125 194 142 268 206 185 240 174 144 135 96 204 224 186 221 302 217 177 260 140
175 146 150 236 237 179 185 236 190 146 187 153 193 94 79 91 131 139 96 128
90 60 81 124 89 129 112 97 107 142 129 134 167 225 148 148 153 170 204 154
140 125 178 140 187 190 176 146 144 128 145 106 96 56 81 52 103 106 143 143
102 89 90 124 178

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular 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

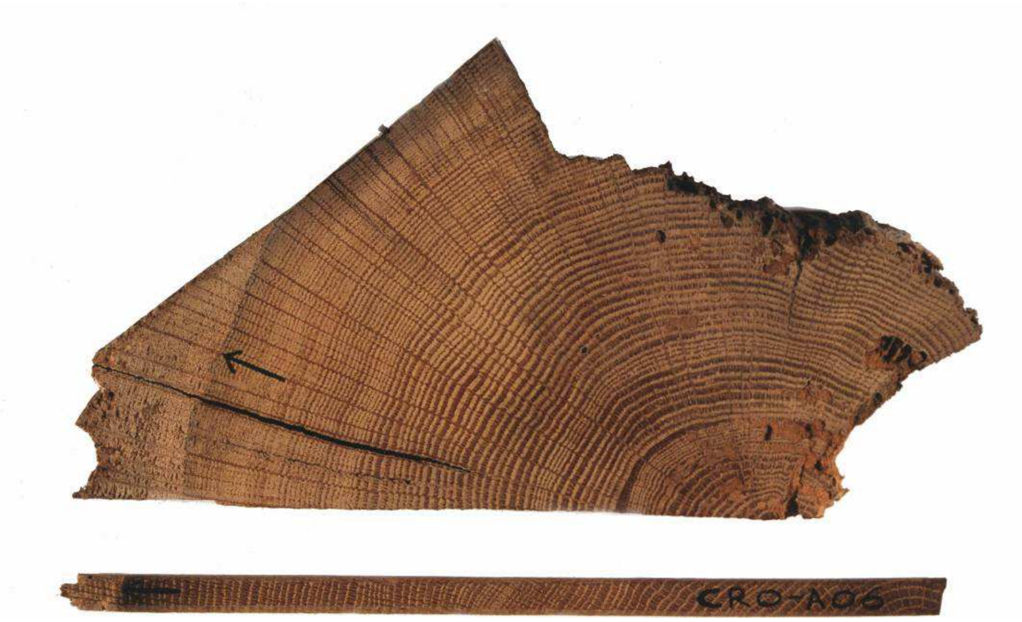


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

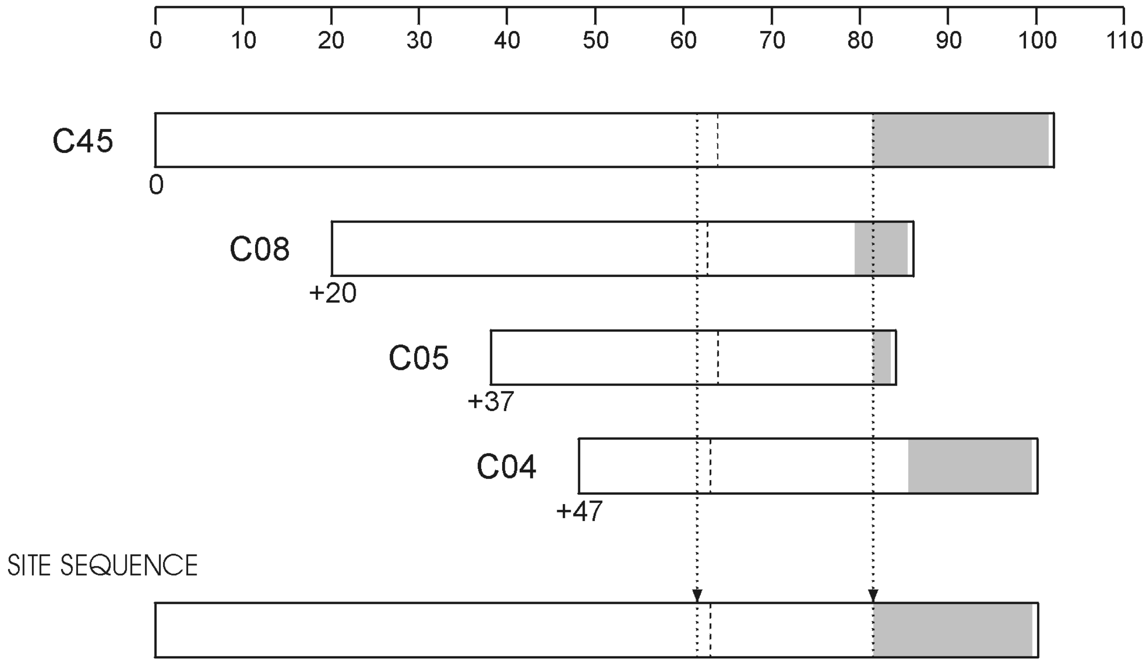


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

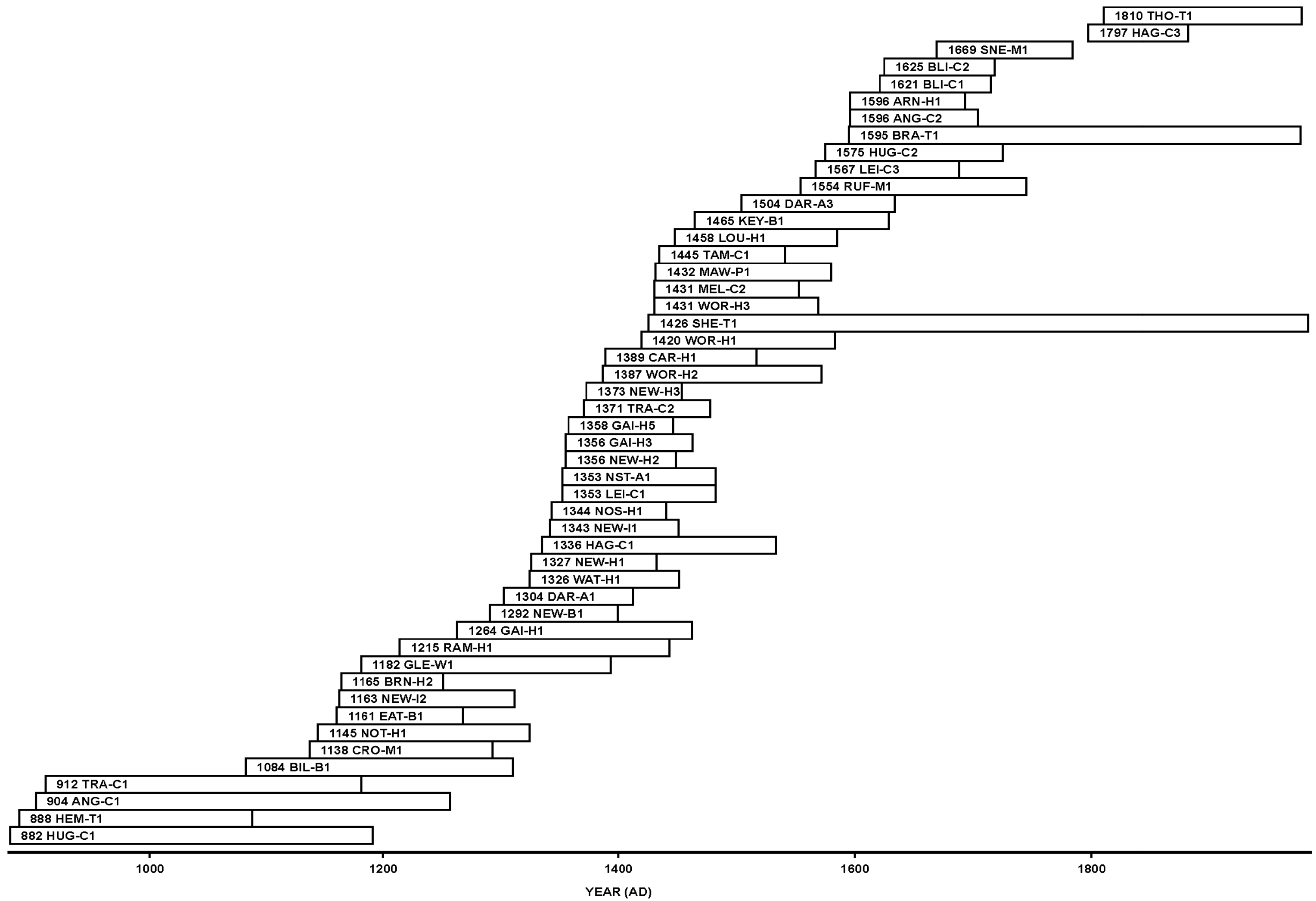
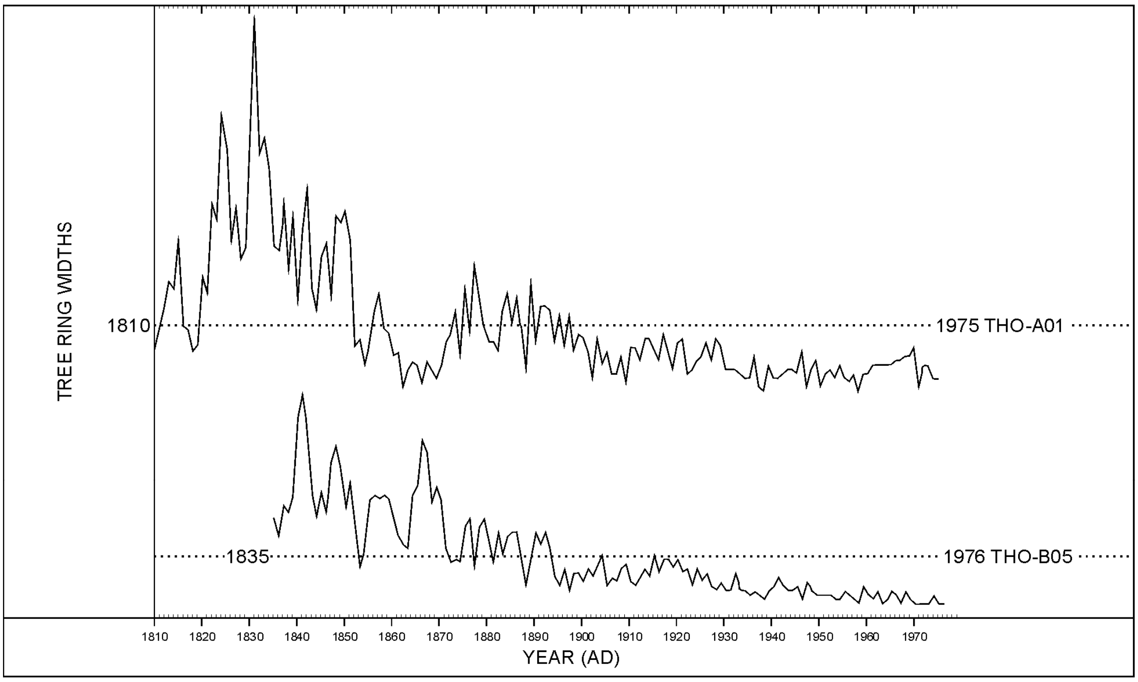


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

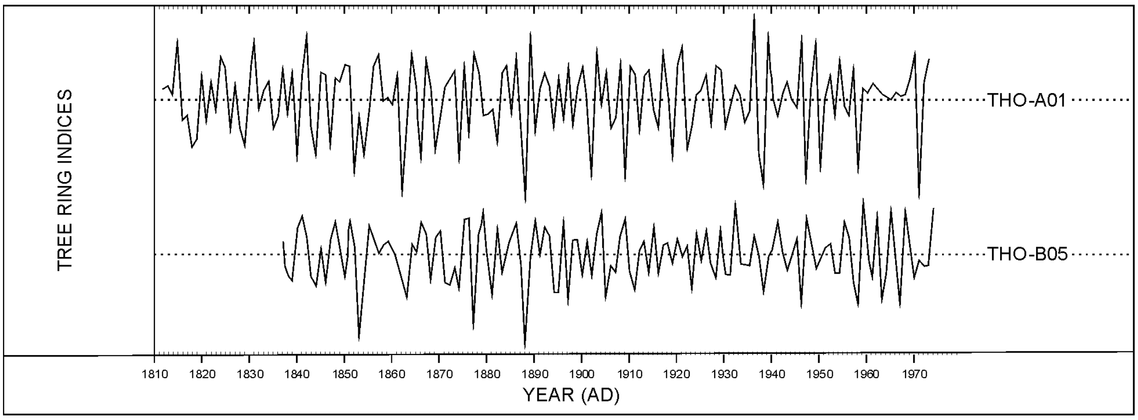


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

References

Baillie, M G L, and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-Ring Bull*, **33**, 7–14

English Heritage, 1998 *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*, London

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95 Nottingham University Tree-Ring Dating Laboratory results, Vernacular Architect, 15–26

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, **23**, 51–6.

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series **III**

Laxton, R R, and Litton, C D, 1989 Construction of a Kent master dendrochronological sequence for oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90–8

Laxton, R R, Litton, C D, and Howard, R E, 2001 *Timber: Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, **7**

Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*, **18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architect*, **28**, 40–56

Pearson, S, 1995 *The Medieval Houses of Kent, an Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London






Historic England Research and the Historic Environment

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

Historic England works to improve care, understanding and public enjoyment of the historic environment. We undertake and sponsor authoritative research. We develop new approaches to interpreting and protecting heritage and provide high quality expert advice and training.

We make the results of our work available through the Historic England Research Report Series, and through journal publications and monographs. Our online magazine Historic England Research which appears twice a year, aims to keep our partners within and outside Historic England up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.HistoricEngland.org.uk/researchreports

Some of these reports are interim reports, making the results of specialist investigations available in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation.

Where no final project report is available, you should consult the author before citing these reports in any publication. Opinions expressed in these reports are those of the author(s) and are not necessarily those of Historic England.

The Research Report Series incorporates reports by the expert teams within the Investigation& Analysis Division of the Heritage Protection Department of Historic England, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series

ISSN 2059-4453 (Online)