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Lowfield Hall, Poles Lane, Lowfield Heath, Crawley, West Sussex

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

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LOWFIELD HALL,
POLES LANE,
LOWFIELD HEATH,
CRAWLEY, WEST SUSSEX

TREE-RING ANALYSIS OF OAK TIMBERS

Alison Arnold, Robert Howard and Cathy Tyers

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SUMMARY

Dendrochronological analysis was undertaken on 17 core samples obtained from both the primary and reused timbers associated with the initial construction of the north-south barn range of Lowfield Hall. This analysis produced a single dated site chronology comprising nine samples, with an overall length of 114 rings. These rings were dated as spanning the years AD 1484–1597. Interpretation of the sapwood on the dated samples, which are all from the primary timbers, suggests that the trees used for these beams were cut as part of a single episode of felling at some point in the period AD 1604–29. Another two samples from the primary timbers remain ungrouped and undated, as do all six samples from the reused timbers.

CONTRIBUTORS

Alison Arnold, Robert Howard and Cathy Tyers

ACKNOWLEDGEMENTS

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ARCHIVE LOCATION

West Sussex County Council Historic Environment Record
West Sussex County Council Environment and Development
Environment and Economic Policy Service
The Grange
Tower Street
Chichester
West Sussex PO19 1RH

DATE OF INVESTIGATION

2016

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INTRODUCTION

Lowfield Hall, Lowfield Heath, lies just north of Crawley (Figs 1a–c). It comprises of two ranges, the north-south range being the primary structure with an east-west extension at its northern end (Fig 2). The north-south range was originally a three-bay barn with a central threshing bay and storage bays to either side. The original barn is currently not listed in its own right but comes under the curtilage of Charlwood House, a Grade II* listed building, which lies approximately 15m to the north-east.

The following information is summarised from Thompson (2016). The original barn is believed to date to between the mid-sixteenth to early-seventeenth century and comprises of four principal rafters with tiebeam trusses, the trusses at either end having high collars and the roof being half-hipped. Slightly curved braces run from the wall posts to the tiebeams, and raking queen posts (curving concavely) rise from tiebeams to principal rafters. There are straight windbraces between principal rafters and purlins at trusses 1 and 4 only. The trusses support single clasped purlins, these in turn supporting common rafters (Fig 3a). The common rafters show clear evidence of extensive reuse with redundant lap joints on the sides of many of them (Fig 3b) and it is thought that they may potentially originate from a domestic cross-wing or agricultural building. The extant roof, with its combination of primary and reused timber, is thought to represent a single phase of construction and it remains substantially in the form it was when first built.

During the eighteenth century the barn underwent extensive alterations with the fixing of additional studs within the wall frames and the replacement of some of the original curved down-braces with straight raking struts to enable the barn to be re-clad with feather-edged weather-boarding. The doors to either side were also altered at this time. It is believed that, at the same time, a single-storey extension was erected running eastwards across the northern external cross-frame of the original north-south barn, possibly as stabling or shelter for horses or oxen. This extension was constructed of stud framing on a low brick wall. Subsequently in the nineteenth century the feather-edged weather-boarding was removed from the external elevations of the barn and extension and replaced by brick infill panels (Figs 3c–d). During the late-1960s/early-1970s the barn was converted to a domestic dwelling.

SAMPLING

Although within the curtilage of Charlwood House, Historic England has received an application from the owner of Lowfield Hall for the listing of the building on its own merits. Dendrochronological analysis was requested by Simon Hawkins in order to inform the assessment of the listing application. It was hoped that tree-ring analysis would provide independent dating evidence for the primary and reused timbers associated with the initial construction of the north-south barn, secondary alterations/modifications to the barn, and the initial construction of the east-west extension.

The initial assessment of dendrochronological potential found that the timbers associated with the secondary alterations/modifications to the north-south barn and the initial construction of the east-west extension generally contained far too few rings for successful analysis, with only one or two timbers potentially being borderline with respect to suitability. Thus, following further discussions, it was agreed to confine the dendrochronological analysis to the primary and reused timbers associated with the initial construction of the north-south barn.

A total of 17 samples were obtained by coring. Each sample was given the code LFH-A (for Lowfield Heath, site 'A') and numbered 01–17 (Table 1). Of this total number, 11 samples (LFH-A01–LFH-A11) were obtained from what appeared to be primary use timbers, with the remaining samples (LFH-A12–LFH-A17) being obtained from common rafters that appeared to be reused within the initial construction phase. The trusses, bays, and individual timbers in the barn have been numbered from north to south, being then identified on an east-west basis as appropriate. The sampled timbers have been located on Figures 4a–c.

ANALYSIS AND RESULTS

Each of the 17 samples obtained from the timbers of the north-south barn was prepared by sanding and polishing, the annual growth ring widths of each sample then being measured. The data of the measurements were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process showing that nine of the 17 samples cross-matched with each other at positions as shown in Figure 5. All nine cross-matching samples are from the primary use timbers.

These nine cross-matching samples were combined at their indicated offset positions to form site chronology LFHASQ01, this having an overall length of 114 rings. Site chronology LFHASQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a series of reference chronologies when the date of its first ring is AD 1484 and the date of its last ring is AD 1597 (Table 2).

Site chronology LFHASQ01 was then compared with the remaining eight ungrouped samples, but there was no further conclusive cross-matching. The eight remaining samples were, therefore, compared individually with the full corpus of reference data for oak. There was again no conclusive cross-matching, and these eight individual samples remain undated.

INTERPRETATION

None of the nine dated samples in site chronology LFHASQ01 retain sapwood complete to the bark and it is thus not possible to determine precisely when any individual tree was cut. However, seven of the dated samples retain some sapwood, or at least the heartwood/sapwood boundary, this latter indicating that it is only the sapwood rings that have been lost (Table 1; Fig 5). The average date of the heartwood/sapwood boundary of these seven samples is AD 1589. Using the sapwood estimate of 15–40 rings (the 95% confidence interval) gives the seven timbers represented an estimated felling date in the range AD 1604–29. The remaining two dated samples, LFH-A06 and LFH-A10, with no trace of sapwood have lost not only all their sapwood rings but an unknown number of heartwood rings as well. Thus, using the minimum number of expected sapwood rings, the two timbers represented can be said to have been felled after AD 1558 and AD 1598 respectively.

Given the overall level of cross-matching between all nine dated samples, combined with the heartwood/sapwood boundary varying by only six years, it is likely that the trees represented were all part of a single programme of felling at some point during AD 1604–29. It should also be noted that LFH-A04 (with an h/s boundary) and LFH-A10 (without h/s) cross-match with a value of *t*=10.4 suggesting that it is possible that the two timbers represented have been derived from a single tree.

DISCUSSION AND CONCLUSION

The analysis undertaken here thus indicates that a number of primary use timbers associated with the initial construction of the north-south barn were felled at the same time at some point in the period AD 1604–29 with construction following on shortly after felling. As such the tree-ring analysis supports but refines the mid-sixteenth to early-seventeenth century date postulated on the basis of architectural evidence.

The overall level of cross-matching between the dated samples also indicates that the timbers represented are all likely to have been sourced from a single woodland. As may be seen from Table 2, although site chronology LFHASQ01 has been compared with reference material from all over England, the highest levels of similarity are to be found with reference chronologies from sites in the surrounding counties in the south-east region. This suggests that the dated timbers at Lowfield Hall were derived from a relatively local woodland source.

It has unfortunately not been possible to provide any dating evidence for the six samples from the timbers reused as common rafters. The ring sequences show no major growth disturbances which would potentially hamper successful analysis but they are towards the lower limit with respect to numbers of rings and the lack of cross-matching in effect makes each sample a ‘singleton’. While such individual samples can on occasion be dated, it usually requires them to have higher numbers of rings, and the chances of success are far less than with a group of cross-matched samples that produce a replicated site chronology. The lack of cross-matching could be a result of these reused timbers being salvaged from different buildings of different dates but this analysis can neither prove nor disprove this, and it should be noted that the similarities in physical characteristics of these timbers suggests that this may not be the case.

The two ungrouped and undated samples from the primary use timbers again show no major growth disturbances but both do have ring sequences towards the lower limit of suitability. It is, however, a frequent feature of tree-ring analysis to find that some samples will not group or date for no apparent reason, and with nine of the 11 samples from the primary use timbers in the north-south barn dated, the success rate is within normal limits.

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TABLES

Table 1: Details of tree-ring samples from the original north-south barn range of Lowfield Hall, Lowfield Heath, Crawley, West Sussex

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Primary timbers					
LFH-A01	Sill beam, truss 1	67	h/s	1523	1589	1589
LFH-A02	East main wall post, truss 2	53	h/s	------	------	------
LFH-A03	East principal rafter, truss 2	51	h/s	1538	1588	1588
LFH-A04	East queen post, truss 2	103	h/s	1490	1592	1592
LFH-A05	West principal rafter, truss 2	74	6	1520	1587	1593
LFH-A06	West queen post, truss 2	90	no h/s	1484	------	1573
LFH-A07	East principal rafter, truss 3	76	h/s	1511	1586	1586
LFH-A08	East queen post, truss 3	76	h/s	1515	1590	1590
LFH-A09	West main wall post, truss 3	58	h/s	------	------	------
LFH-A10	West principal rafter, truss 3	67	no h/s	1517	------	1583
LFH-A11	West queen post, truss 3	105	7	1493	1590	1597
	Reused timbers					
LFH-A12	East common rafter 2, bay 2	55	h/s	------	------	------
LFH-A13	East common rafter 3, bay 2	54	15	------	------	------
LFH-A14	West common rafter 5, bay 2	54	h/s	------	------	------
LFH-A15	East common rafter 5, bay 3	47	13	------	------	------
LFH-A16	East common rafter 6, bay 3	47	h/s	------	------	------
LFH-A17	East common rafter 7, bay 3	45	8	------	------	------

h/s = the heartwood/sapwood ring is the last ring on the sample

Table 2: Results of the cross-matching of site sequence LFHASQ01 and relevant reference chronologies when the first-ring date is AD 1484 and the last-ring date is AD 1597

Reference chronology	Span of chronology	*t*-value	Reference
Chiddingly Place, Chiddingly, East Sussex	AD 1324–1576	7.0	(Arnold and Litton 2003)
49/50 Quarry Street, Guildford, Surrey	AD 1341–1583	6.7	(Arnold and Howard 2005 unpubl)
Ightham Mote, Ivy Hatch, Kent	AD 1276–1648	6.5	(Howard *et al* 2002 unpubl)
Cobham Hall, Cobham, Kent	AD 1317–1662	6.4	(Arnold *et al* 2003)
Deal Castle, Deal, Kent	AD 1465–1601	6.2	(Arnold and Howard 2015)
Abbey Road Barrels, Barking, London	AD 1314–1599	6.1	(Tyers 2001)
Goddington House, Goddington, Kent	AD 1544–1621	6.0	(Arnold *et al* 2008)
Causeway Farmhouse, Pirbright, Surrey	AD 1403–1557	5.6	(Miles and Worthington 2000)

FIGURES

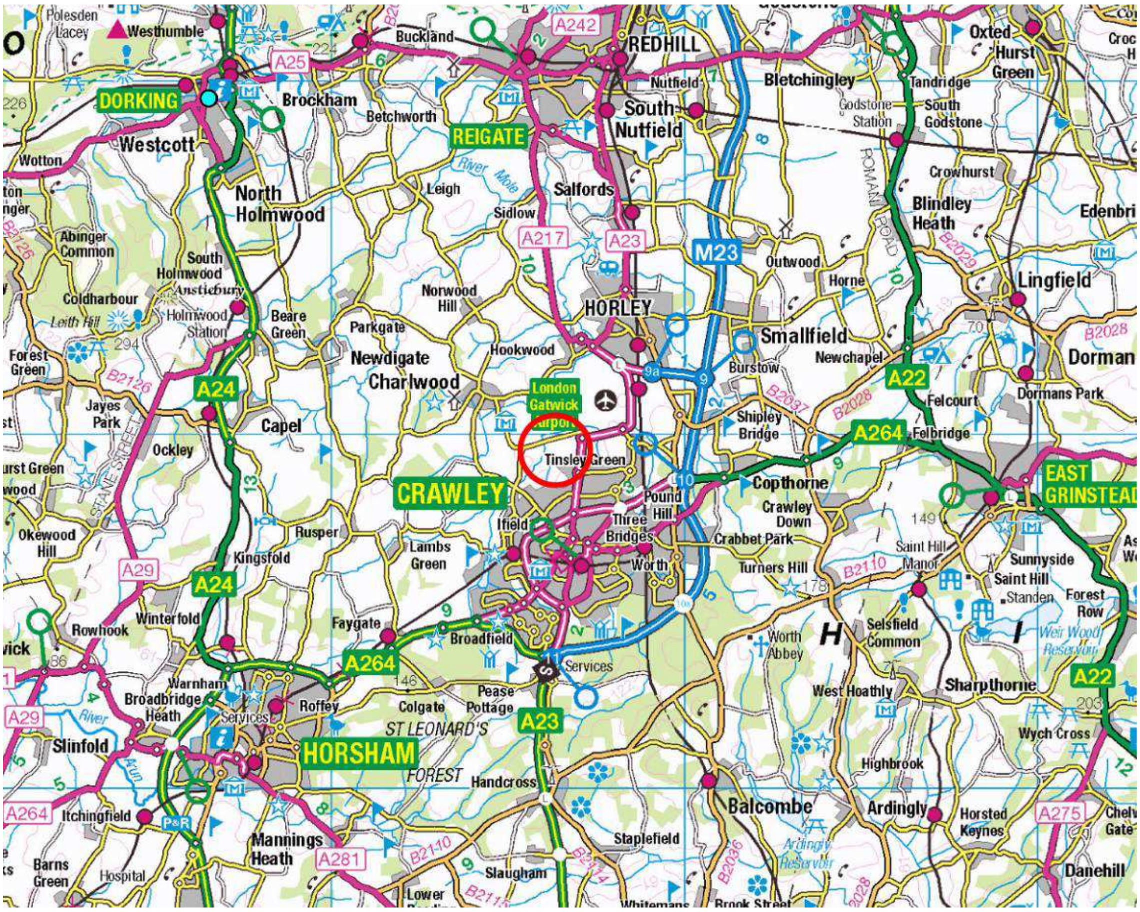


Figure 1a: Map to show the general location of Lowfield Heath, immediately north of Crawley. © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

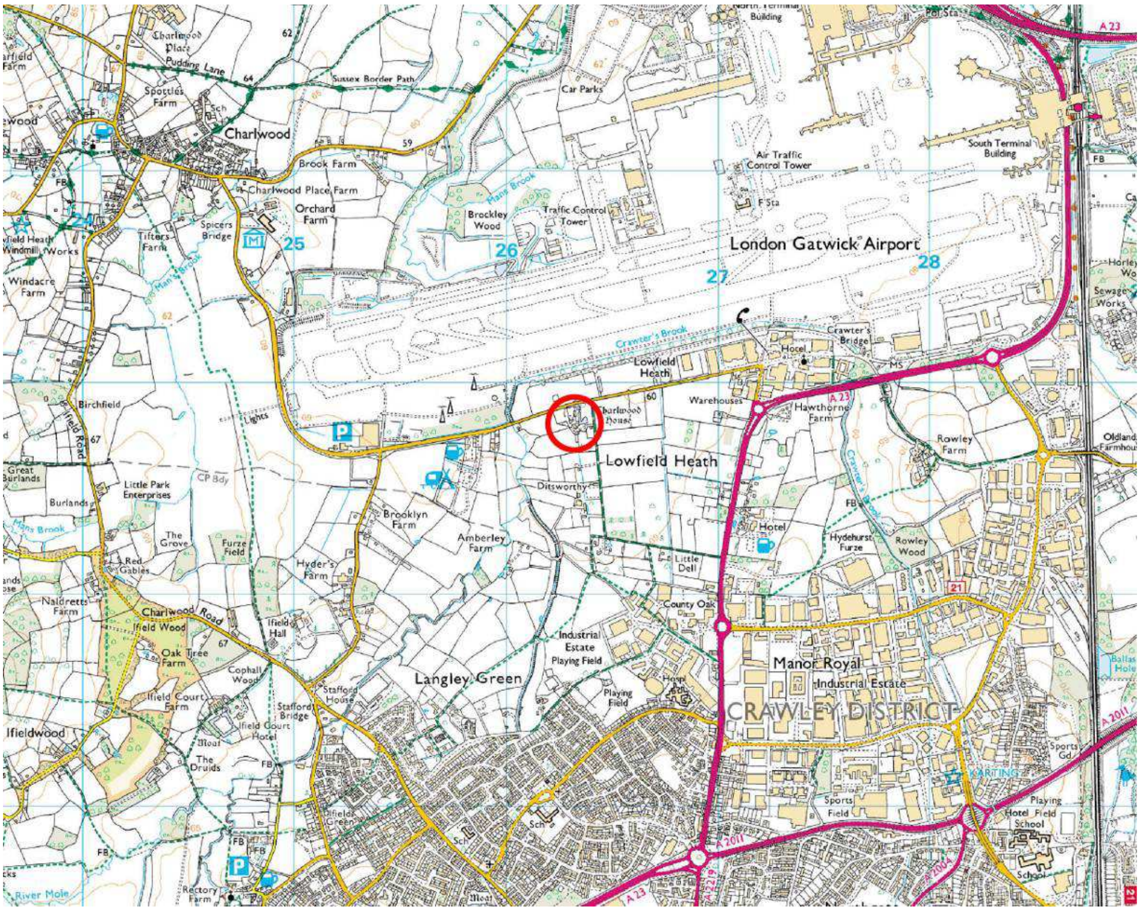


Figure 1b: Map to show the location of Lowfield Hall, Lowfield Heath. © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

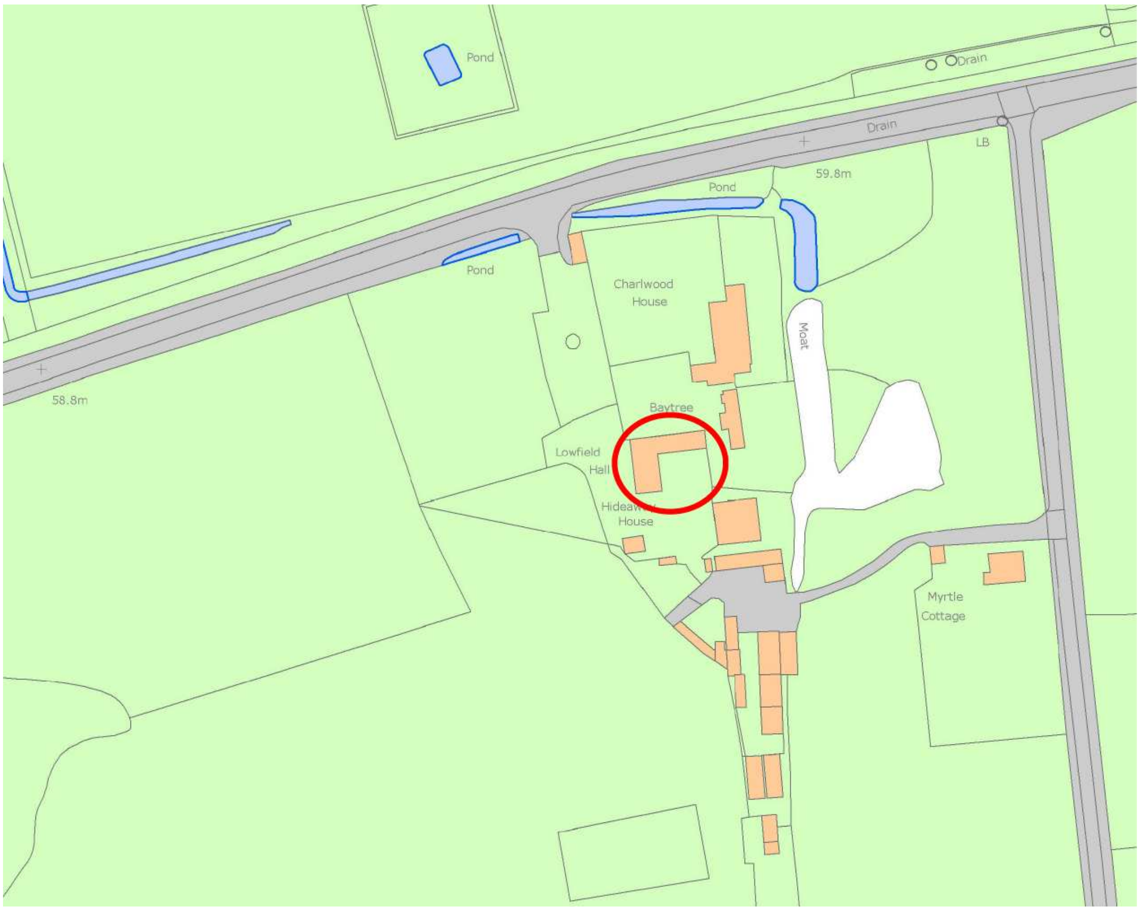


Figure 1c: Map to show the detailed location of Lowfield Hall. © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

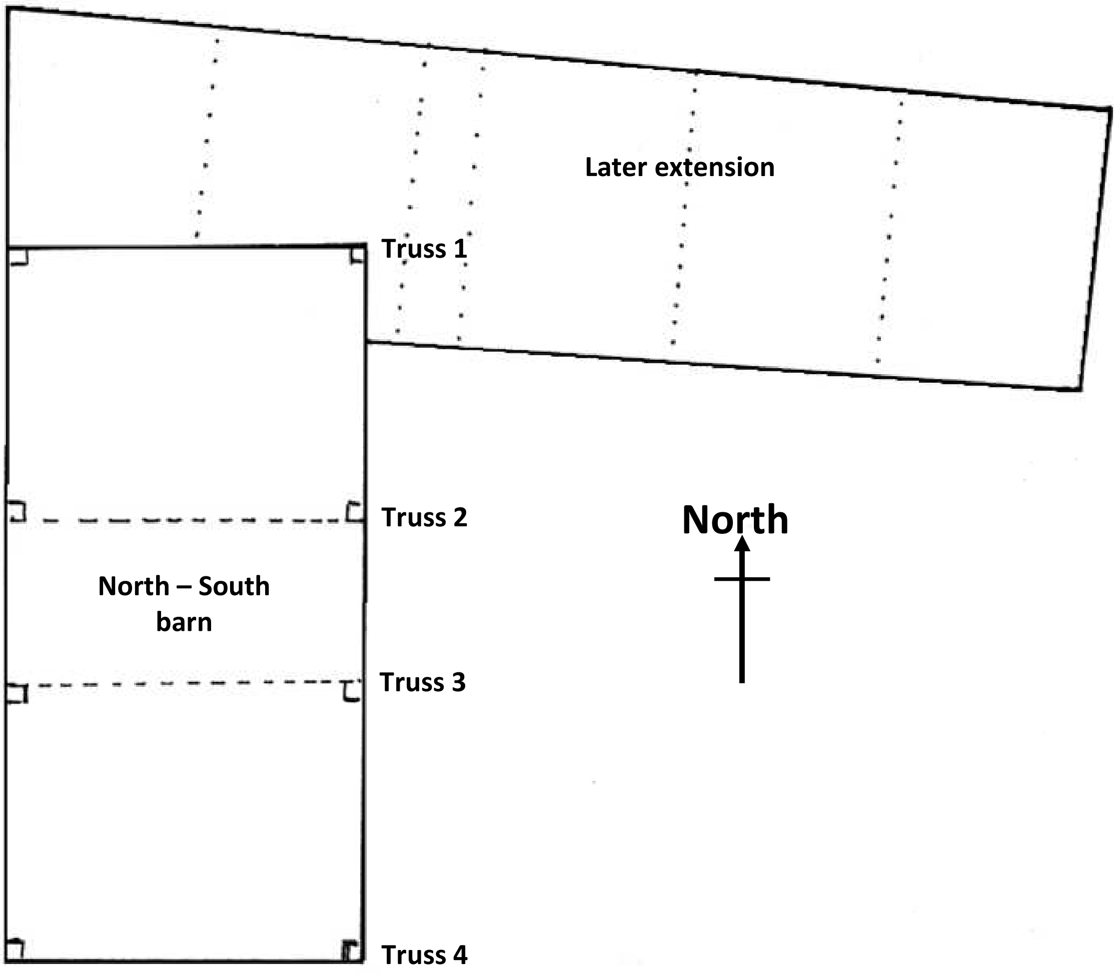


Figure 2: Plan of Lowfield Hall to show layout of the two ranges and the position of the trusses which are numbered from 1–4 from north to south in the original barn (after Thompson 2016)

Figure 3a–b: Views of the timber framing to the north-south barn (photographs Robert Howard)

Figure 3c–d: Views of the framing to the west wall of the north-south barn (top) and the north wall of the later extension (bottom) (photographs Robert Howard)

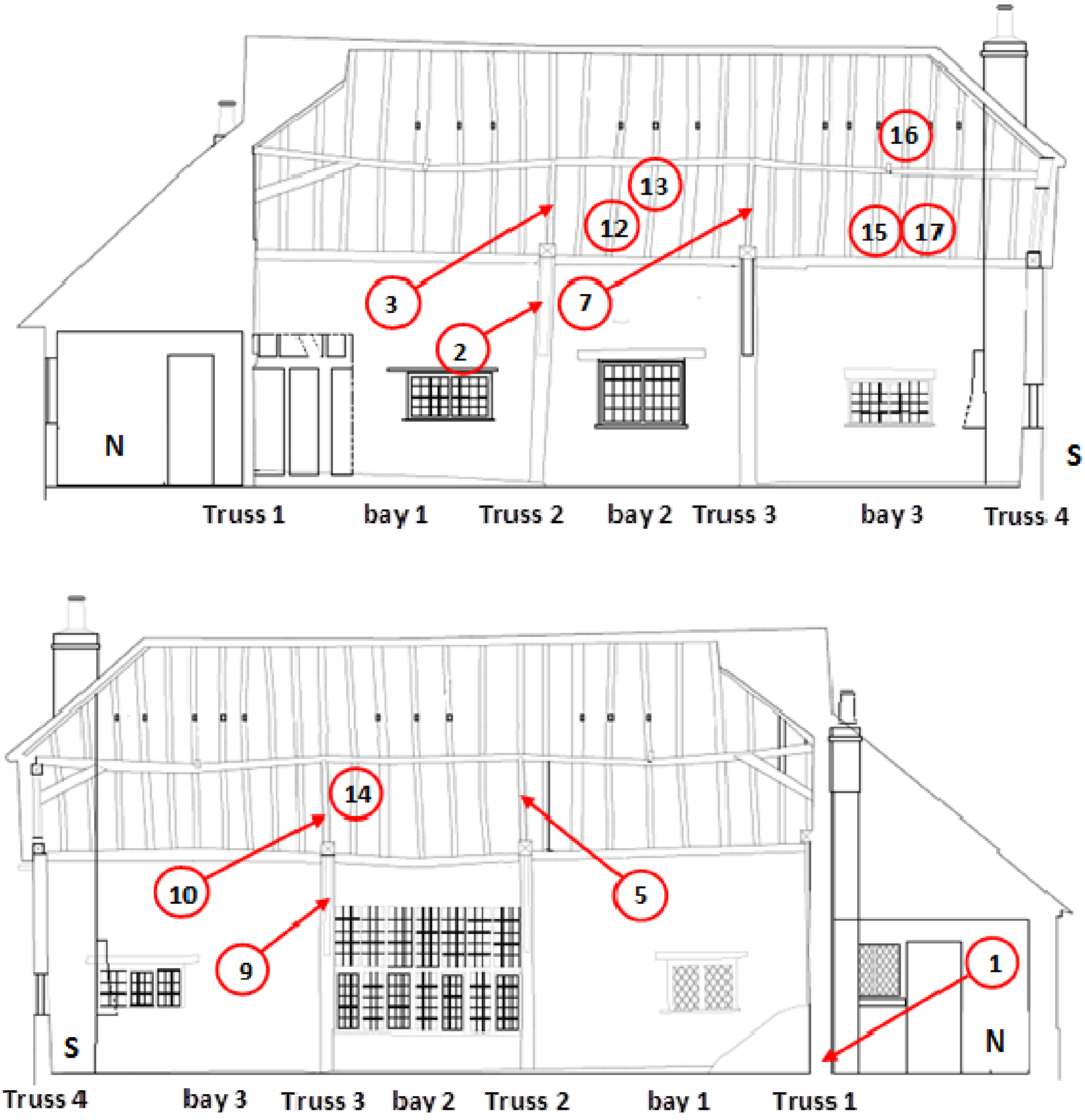
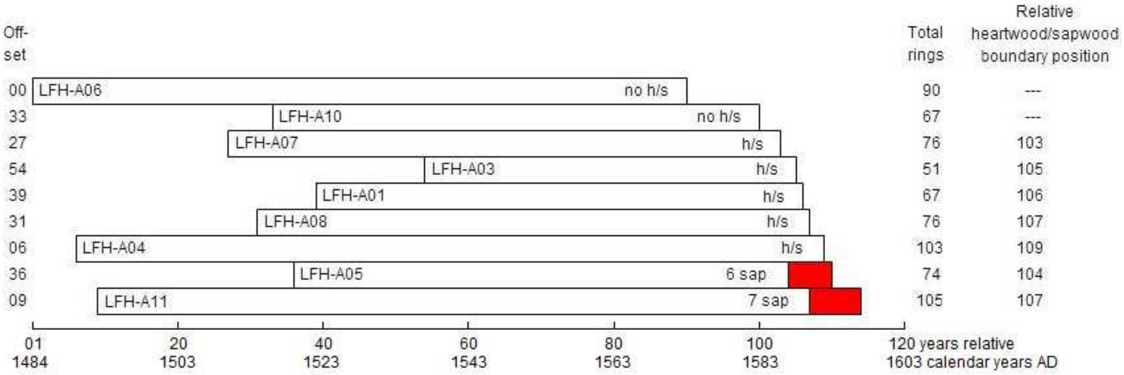


Figure 4a–b: Sections to help locate sampled timbers (after Hockley and Dawson Consulting Engineers Ltd August 2015)

Figure 4c: Annotated photograph to help locate sampled timbers (photograph Robert Howard)



white bars = heartwood rings
red bars = sapwood rings
h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the dated samples in site chronology LFHASQ01 in last measured ring date order

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LFH-A01A 67
294 311 253 301 217 232 159 107 269 187 221 219 171 201 233 164 146 111 153 50
112 79 75 85 67 124 137 142 126 119 120 108 171 102 78 139 120 165 139 207
176 138 128 76 98 179 164 221 187 148 220 167 135 106 92 115 152 213 169 182
167 196 183 184 174 119 131
LFH-A01B 67
300 307 251 287 226 230 163 105 264 189 230 219 171 200 234 163 153 110 139 64
103 78 71 98 71 112 98 105 124 103 127 111 159 97 86 119 117 174 141 192
180 132 118 73 101 188 163 226 189 148 212 167 134 108 89 110 169 200 178 187
156 191 182 200 158 116 153
LFH-A02A 53
397 517 396 475 421 655 453 444 379 219 375 251 314 240 380 282 85 95 68 90
112 131 139 177 166 177 92 160 226 310 431 328 128 194 162 181 176 210 168 240
154 159 145 137 143 107 121 159 126 181 150 177 205
LFH-A02B 52
379 513 377 480 418 628 456 458 378 231 378 289 345 258 402 273 82 97 61 95
96 128 128 182 159 165 94 150 221 358 489 304 126 200 151 182 203 238 168 256
164 160 157 137 146 104 133 148 151 176 160 203
LFH-A03A 51
111 125 111 98 70 56 47 55 77 82 98 142 99 165 387 474 422 650 455 445
248 253 222 219 306 298 332 266 160 241 265 309 235 604 518 336 396 214 137 162
155 258 285 218 262 257 193 223 242 212 283
LFH-A03B 51
113 128 106 101 67 53 48 57 73 86 102 135 101 183 390 481 417 633 454 457
252 252 199 234 315 277 327 255 159 236 247 293 337 528 514 393 359 212 143 150
160 235 308 225 256 257 206 181 200 215 245
LFH-A04A 103
68 41 58 61 60 85 76 77 58 46 46 72 65 66 45 58 70 116 137 101
54 104 52 34 67 71 117 51 25 28 57 61 119 98 88 60 82 135 137 25
24 19 12 17 21 20 11 28 30 32 27 41 20 27 20 40 37 58 87 87
94 91 141 148 108 120 118 94 92 103 93 120 124 130 137 100 77 118 141 141
160 132 103 139 133 99 110 178 139 217 175 92 96 114 148 144 149 75 71 121
106 182 185
LFH-A04B 103
69 43 56 56 63 87 81 78 50 53 43 64 67 67 46 46 80 118 130 104
58 91 58 32 62 83 119 48 30 23 53 78 134 98 98 57 83 159 137 29
20 14 18 19 19 21 23 16 33 29 23 46 18 25 27 38 29 62 75 91
96 91 147 134 120 125 108 88 94 104 90 128 117 131 137 94 75 126 139 139
167 130 102 134 139 109 107 185 135 240 185 93 95 108 158 119 144 82 53 118
100 178 190
LFH-A05A 74
233 217 249 190 206 150 198 180 187 118 78 178 126 137 110 166 111 122 112 127
110 96 71 105 53 85 69 83 105 104 96 164 305 362 385 323 258 174 225 184
216 179 214 218 309 231 139 206 159 95 128 126 164 146 150 113 70 125 100 170
204 199 161 131 132 145 140 134 132 184 153 193 204 213
LFH-A05B 74
229 224 238 189 214 142 197 181 185 114 78 185 121 139 107 162 101 125 112 126
107 103 66 109 46 89 77 95 108 121 85 161 239 375 372 392 253 185 208 183
231 182 214 210 315 239 137 235 161 93 123 130 160 134 151 106 67 111 118 170

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215 189 153 146 120 157 155 176 120 180 145 204 200 218
LFH-A06A 90
50 37 37 59 39 63 102 57 108 60 64 89 110 116 80 60 64 100 114 113
60 71 157 117 165 141 95 154 106 114 101 135 159 96 79 66 35 46 92 83
92 53 67 130 152 113 105 167 106 98 95 76 87 101 121 93 87 96 57 60
53 101 54 77 139 152 92 87 117 148 120 115 93 64 58 89 112 103 105 139
172 117 78 182 186 210 258 229 218 243
LFH-A06B 90
52 41 34 62 38 56 108 57 85 62 67 85 105 126 73 60 64 102 104 110
62 72 148 141 145 128 96 138 107 116 110 141 173 94 67 58 42 60 79 86
82 68 70 98 132 132 95 163 92 103 89 76 92 96 132 85 89 103 60 65
43 96 60 85 150 128 67 82 121 137 118 114 97 67 64 93 126 103 98 118
164 110 96 171 192 207 252 236 218 238
LFH-A07A 76
401 306 469 457 373 279 173 137 205 166 167 144 82 114 109 117 125 133 92 35
71 53 76 84 105 71 67 78 89 68 49 35 64 39 69 69 75 96 145 96
160 377 457 431 454 316 203 231 221 173 214 245 264 207 140 106 182 251 198 281
296 245 228 184 150 109 160 153 230 276 233 270 234 202 234 259
LFH-A07B 76
408 304 479 455 380 287 153 139 176 171 164 123 95 98 103 113 110 112 78 32
80 43 67 67 86 67 69 81 90 71 45 35 67 36 68 76 75 104 132 104
188 400 474 418 462 320 206 235 217 164 212 245 267 215 137 96 190 254 201 292
292 245 228 181 153 104 159 160 225 290 223 266 249 190 230 269
LFH-A08A 76
166 186 85 70 68 57 61 119 98 88 60 82 135 137 119 119 166 107 108 67
80 66 94 103 89 87 92 64 58 44 80 55 64 65 65 67 70 75 100 114
128 86 73 69 122 66 77 93 80 103 67 53 121 160 153 203 200 165 182 164
138 103 117 91 113 131 90 97 126 121 132 115 135 143 179 130
LFH-A08B 76
167 190 87 67 78 52 67 111 95 92 50 81 149 134 106 117 167 105 98 71
66 71 96 95 84 101 91 60 62 51 82 60 64 65 60 71 70 75 109 120
125 78 82 56 103 68 78 93 78 101 80 57 134 150 168 196 178 186 152 147
138 100 110 80 115 126 82 98 140 126 114 131 137 146 179 134
LFH-A09A 58
550 544 507 490 506 534 309 262 304 391 443 313 281 411 257 364 403 317 176 183
203 435 343 301 276 191 262 203 200 276 296 193 109 78 131 170 174 92 94 141
92 75 101 103 117 161 189 207 146 81 59 84 116 148 126 133 137 147
LFH-A09B 58
550 527 508 462 494 544 280 278 296 382 381 325 283 438 229 346 393 330 168 200
225 429 342 303 279 190 255 214 201 270 309 193 104 76 143 157 179 90 107 128
95 76 94 125 147 129 203 198 134 100 80 79 106 162 131 153 120 150
LFH-A10A 67
459 393 429 338 349 357 194 255 223 241 240 230 121 60 137 112 135 102 152 107
105 89 100 92 89 53 55 47 55 76 80 117 121 110 253 462 350 414 413 317
216 234 190 150 182 218 159 185 140 72 150 104 79 98 100 110 107 142 70 54
73 93 143 209 153 84 120
LFH-A10B 67
462 396 433 332 348 364 197 251 223 250 228 213 125 57 143 110 128 106 151 103
108 89 100 90 85 54 54 48 57 74 88 114 121 110 253 453 378 406 385 317
222 240 187 154 173 215 151 187 140 73 145 101 73 90 92 96 115 128 83 46
81 90 127 206 143 101 129
LFH-A11A 105
56 57 74 93 69 62 59 33 37 38 40 28 41 58 89 102 67 64 95 65
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51 59 78 73 43 47 33 19 32 40 31 25 31 28 46 41 32 21 30 24
19 26 22 22 27 22 25 29 52 26 44 21 50 73 73 89 96 100 105 151
161 128 130 121 83 84 126 109 126 132 132 153 103 99 181 167 165 163 163 123
142 185 132 109 182 120 148 170 115 104 100 89 118 133 115 112 175 152 175 121
121 158 153 123 187
LFH-A11B 105
55 58 75 94 75 64 62 33 36 39 42 30 44 53 88 108 74 62 97 62
51 60 77 82 43 49 33 22 32 41 30 27 33 21 53 42 26 20 26 22
15 17 21 21 21 26 26 27 51 27 45 28 46 72 68 86 92 94 99 151
163 128 135 125 82 90 132 121 110 135 125 158 103 99 178 146 157 173 162 128
141 178 123 109 188 117 154 169 155 108 99 89 124 142 118 111 178 154 176 122
120 162 157 129 188
LFH-A12A 55
191 97 140 151 134 119 163 129 127 275 263 313 279 322 278 286 339 285 243 192
210 235 269 133 134 157 136 151 142 192 178 125 165 122 143 165 153 109 114 110
94 96 113 144 107 103 65 73 88 53 62 57 68 54 95
LFH-A12B 55
198 94 146 145 133 127 156 134 125 282 257 318 285 309 294 278 421 285 250 187
225 233 242 153 145 157 136 161 146 188 169 132 163 125 139 171 154 114 118 104
95 89 112 142 106 110 76 61 98 57 61 60 69 51 96
LFH-A13A 54
268 261 281 257 282 191 262 298 246 284 202 189 206 271 232 167 78 121 222 278
203 234 172 182 206 151 203 192 178 121 143 219 232 131 162 134 128 97 88 142
107 130 100 162 90 120 150 78 103 56 76 95 109 126
LFH-A13B 54
261 264 292 263 299 188 265 293 249 275 204 182 219 286 239 165 84 120 213 298
223 236 175 220 207 164 219 162 168 109 132 210 237 132 185 156 123 91 80 132
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LFH-A14A 54
107 170 285 204 217 153 159 190 175 160 115 134 124 116 116 100 123 94 102 78
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LFH-A14B 54
102 185 292 205 176 146 156 184 171 165 113 130 128 116 121 98 114 99 107 72
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284 305 329 343 282 232 285 300 293 278 247 233 264 165 117 147 181 197 140 130
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LFH-A15B 47
287 307 327 361 293 229 285 282 301 275 242 224 252 164 122 131 189 192 142 135
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177 219 229 184 178 176 218
LFH-A16A 47
308 361 376 281 325 369 401 376 312 355 319 277 316 337 350 253 367 333 303 393
148 126 132 150 229 201 293 290 290 217 190 204 231 202 192 201 309 218 173 167
170 186 218 153 147 178 215
LFH-A16B 47
312 363 387 270 334 360 387 389 318 346 332 279 329 318 347 260 375 333 289 393
151 126 128 157 242 200 287 292 270 215 200 235 221 211 189 212 298 213 170 158
168 185 221 155 148 176 210
LFH-A17A 45
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361 447 301 332 311 317 326 269 144 294 332 273 309 308 246 257 238 175 214 214
192 258 104 168 207 195 207 195 160 140 170 159 214 213 179 192 159 185 184 145
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LFH-A17B 45
362 468 294 332 318 335 371 257 155 303 327 273 306 306 266 251 232 174 196 193
200 246 120 173 210 182 209 201 156 138 172 167 212 225 181 193 159 198 178 140
143 99 129 161 199

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 Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can

sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings — the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

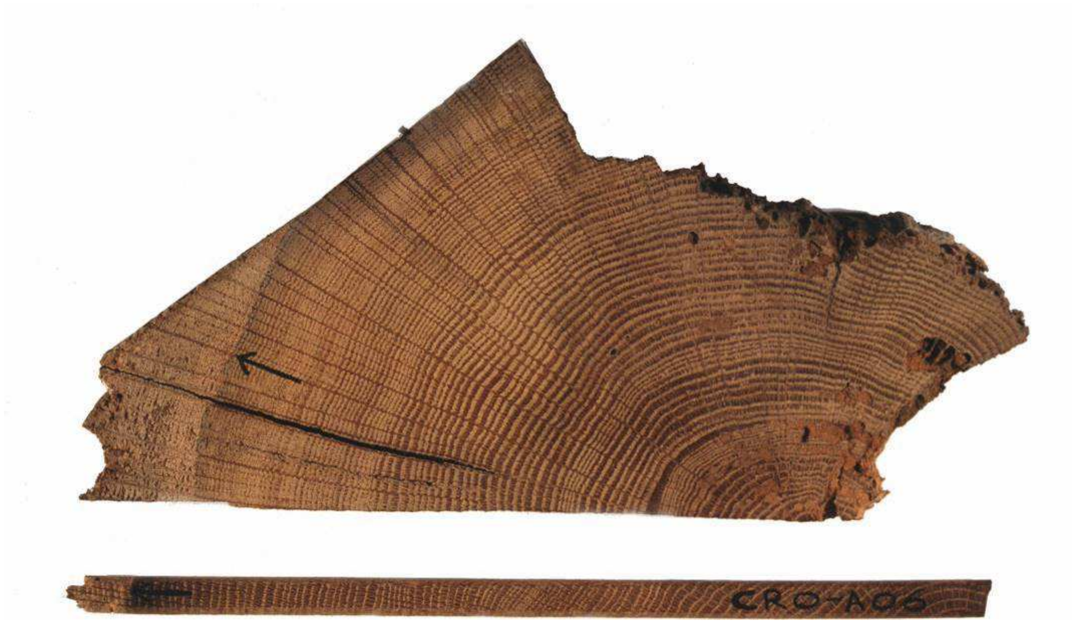


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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 Figure 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 complement 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

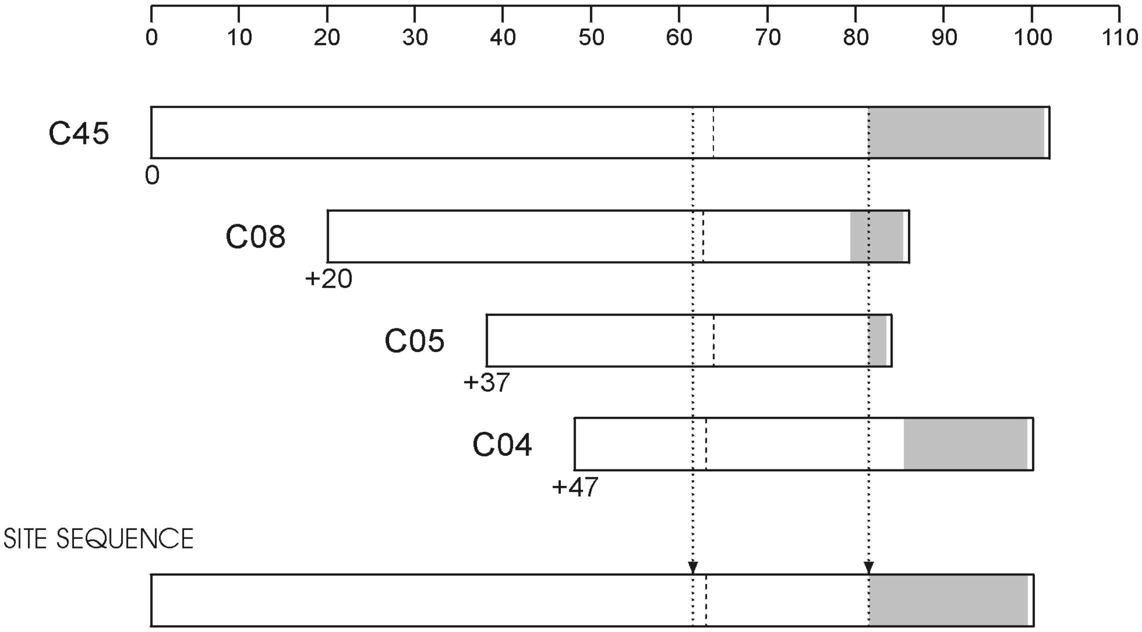


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

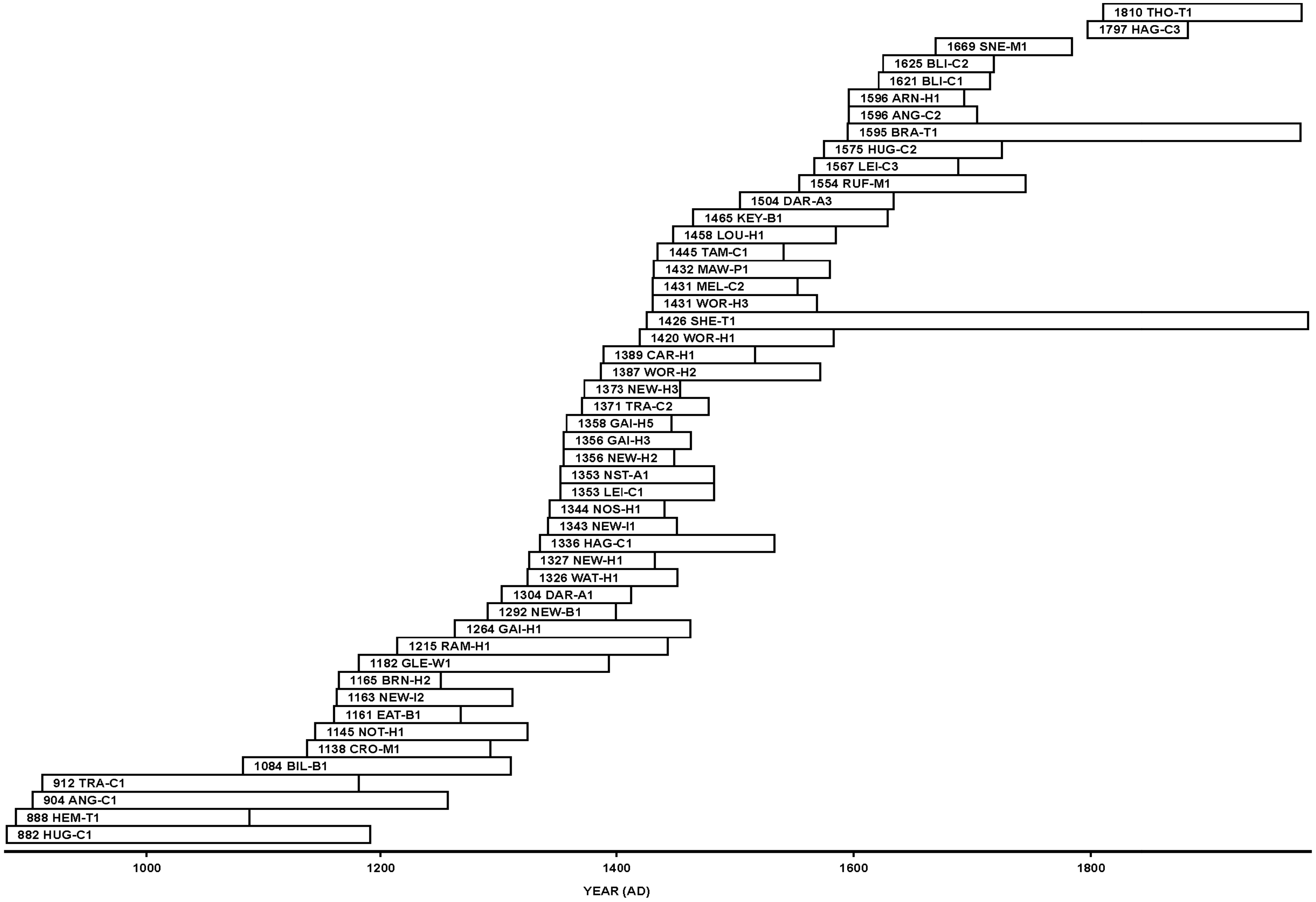
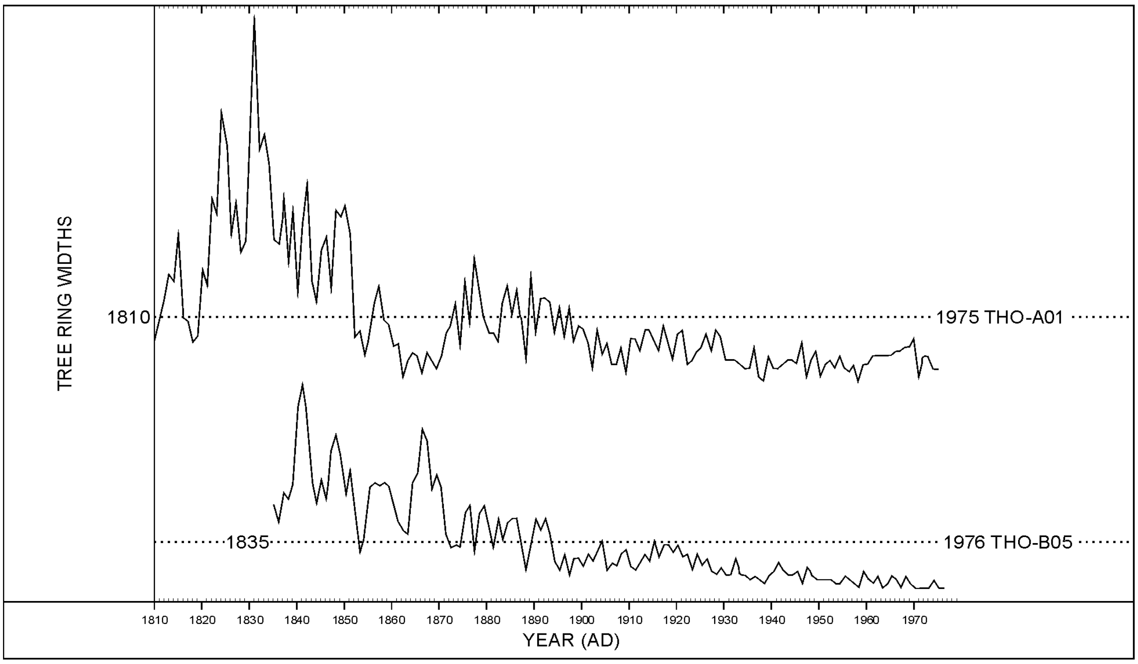


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

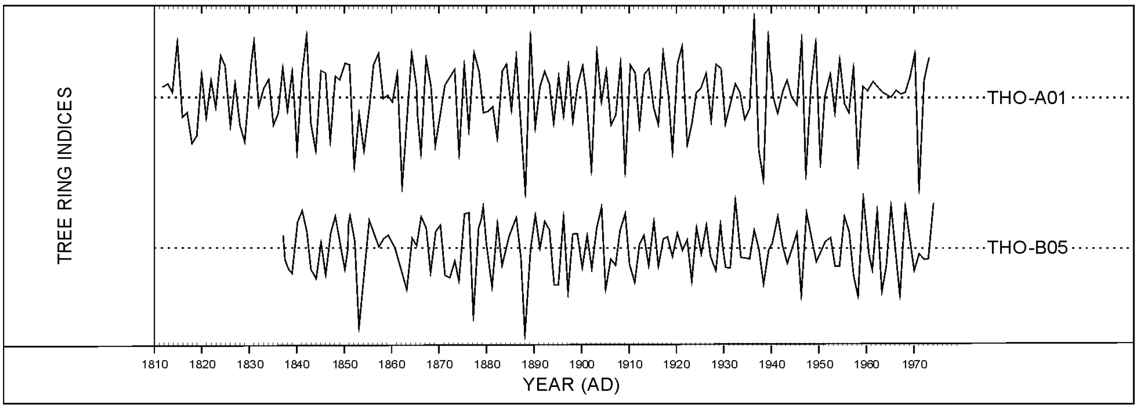


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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