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Tree-Ring Analysis of Oak Timbers from the Chapter House, Worcester Cathedral, Worcester

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Summary

Analysis undertaken on 13 samples taken from the timbers of the roof of the Chapter House resulted in the construction of a single site sequence.

Site sequence WORCSQ05 contains nine samples and spans the period AD 1558-1660. Eight of these samples have complete sapwood and a last ring date of AD 1660, the felling date of the timbers represented. The ninth sample has an estimated felling date range also entirely consistent with this felling date.

Prior to tree-ring analysis being carried out this roof was thought to date to documented renovations of the Chapter House during AD 1386-92. It is now known to be constructed from timbers felled in AD 1660.

Keywords

Dendrochronology
Standing Building
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Introduction

Worcester Cathedral, standing in a prominent position on the east bank of the River Severn (SO 850 545; Fig 1) has a long history. The bishopric was founded in the seventh century and the first Cathedral was dedicated to St Peter. Oswald, who was made bishop in AD 961, built a new cathedral, dedicated to St Mary. The presbytery of St Peter's was rebuilt following a Danish raid in AD 1041. Both early cathedrals appear to have been demolished around the time St Wulfstan started the present cathedral in AD 1084.

Surviving work of St Wulfstan's period includes the crypt, western transepts, cloisters, and Chapter House. In AD 1175 the crossing tower fell down and was rebuilt (Guy 1994). It was rebuilt again in the AD 1370s. In AD 1224 the construction of a new east end was started under bishop William of Blois. Much of the existing decorated architecture at the east end belongs to this phase, with additional work in the Perpendicular style dating from the late-fourteenth or early-fifteenth century. There was also a considerable amount of rebuilding activity in the nineteenth century.

The Chapter House is polygonal and Perpendicular on the outside (Fig 2) but circular and Norman within, and is dated to *c* AD 1120, although its timber roof is apparently not the original one, being thought to date to documented restorations carried out between AD 1386-92. The present roof concentrates most of its weight onto the central pier, from which radiate ten principals (Fig 3). There are three straight purlins between each principal and each principal is stiffened by tied straight braces at its centre and by strutted curved braces at its wallposts.

Previous work carried out at Worcester Cathedral by this Laboratory has resulted in timbers of the nave roof being dated to the early-seventeenth century, with these being thought to represent repair work undertaken at that time (Howard *et al* 1995). A much larger programme of sampling of timbers from the choir, the north-east and south-east transepts, and the crossing between them showed that major repairs took place here in the early-eighteenth century, reusing some earlier timbers (Howard *et al* 2000). A further programme of tree-ring analysis undertaken of the timbers of the roof of St John Chapel, and of the roof connecting the Chapel to the Chapter House (Howard *et al* 2001a) showed these roofs again contained much reused timber, and that the last major repair phase was in the AD 1740s. Finally, work in AD 2003 on timbers of the Lady Chapel and Choir roofs identified the latest periods of work again being in the eighteenth century (Arnold *et al* 2003).

The Laboratory would like to take this opportunity to thank all those who assisted with the sampling of the timbers. In particular thanks are due to the Chapter of Worcester Cathedral and to the Vergers' Office, whose staff assisted with access to the roof. The Laboratory would also like to thank Mr Christopher Guy, the Cathedral Archaeologist, for his advice and assistance, in particular with the descriptive introduction to the site given above.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was hoped that dendrochronological investigation would provide a precise date for the construction of the roof and hence both inform the repair programme due to take place this summer and contribute to the on-going research into the roofs of the Cathedral.

Sampling

Fourteen core samples were taken from the principal rafters, struts, and central post of this roof. The cores were taken using a 15mm diameter corer attached to an electric drill and the resulting holes filled with oak heartwood. Each sample was given the code WOR-C (for Worcester Cathedral) and numbered 201-14. The position of all samples was noted at the time of sampling and has been marked on Figure 4. Further details relating to the samples can be found in Table 1.

Analysis and Results

At this stage it was noticed that one of the samples (WOR-C207) had too few rings for secure dating, and so was rejected prior to measurement. The remaining 13 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These were then compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a value of t=4.5, nine samples matched each other and were combined at the relevant offset positions to form WORCSQ05, a site sequence of 103 rings (Fig 5). This site sequence was then compared with a large number of relevant reference chronologies for oak indicating a consistent match when the date of its first ring is AD 1558 and of its last measured ring is AD 1660. The evidence for this dating is given by the t-values in Table 2.

Attempts to date the remaining ungrouped samples by individually comparing them with the reference chronologies proved unsuccessful and these remain undated.

Interpretation and Discussion

Analysis of 13 samples taken from timbers of the roof of the Chapter House resulted in the construction and dating of a single site sequence.

Site sequence WORCSQ05, of 103 rings, contains nine samples and spans the period AD 1558-1660. Eight of the samples contained within this site sequence have complete sapwood and a last ring date of AD 1660, the felling date of the timbers represented. Interpretation of the heartwood/sapwood boundary of the ninth sample, WOR-C204, suggests the timber this is from was also felled in AD 1660.

The Chapter House was originally constructed in *c* AD 1120. Prior to this analysis, the present roof was thought to be a replacement of the original, dating to documented renovations in AD 1386-92. It can now be seen from the dendrochronological analysis that it is actually constructed from timbers felled over 250 years later in AD 1660.

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Table 1: Details of tree-ring samples from the roof of the Chapter House, Worcester Cathedral, Worcestershire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
WOR-C201	Principal rafter, number 8	86	21C	1575	1639	1660
WOR-C202	Principal rafter, number 9	73	17C	----	----	----
WOR-C203	Strut, wallpost to rafter 9	54	14	----	----	----
WOR-C204	Strut, wallpost to rafter 10	76	10	1572	1637	1647
WOR-C205	Principal rafter, number 1	84	17C	1577	1643	1660
WOR-C206	Principal rafter, number 2	95	22C	----	----	----
WOR-C207	Strut, wallpost to rafter 4	NM	--	----	----	----
WOR-C208	Strut, wallpost to rafter 5	92	23C	1569	1637	1660
WOR-C209	Tie centre post – inner strut 4	65	25C	1596	1635	1660
WOR-C210	Inner strut 10	92	25C	----	----	----
WOR-C211	Upper central post	92	19C	1569	1641	1660
WOR-C212	Inner central post	81	15C	1580	1645	1660
WOR-C213	Principal rafter 5	65	35C	1596	1625	1660
WOR-C214	Principal rafter number 7	103	23C	1558	1637	1660

*NM = not measured
C = Complete sapwood on timber, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence WORCSQ05 and relevant reference chronologies when the first-ring date is AD 1558 and the last-ring date is AD 1660

Reference chronology	t-value	Span of chronology	Reference
East Midlands	4.9	AD 882-1981	Laxton and Litton 1988
England	4.8	AD 404-1981	Baillie and Pilcher 1982 unpubl
Pembridge belltower, Hertfordshire	6.7	AD 1559-1668	Tyers 1999
Croft Castle, Herefordshire	6.4	AD 1475-1666	Tyers 2002a
Wigmore Abbey, Herefordshire	6.0	AD 1055-1729	Tyers 2002b
Gunns Mills, Glos	5.5	AD 1438-1681	Howard *et al* 2001b
Bolsover Castle (riding school), Derbys	5.5	AD 1494-1744	Howard *et al* forthcoming
Sherwood Trees, Notts	5.4	AD 1426-1981	Laxton and Litton 1988

Figure 1: Map to show the location of Worcester Cathedral

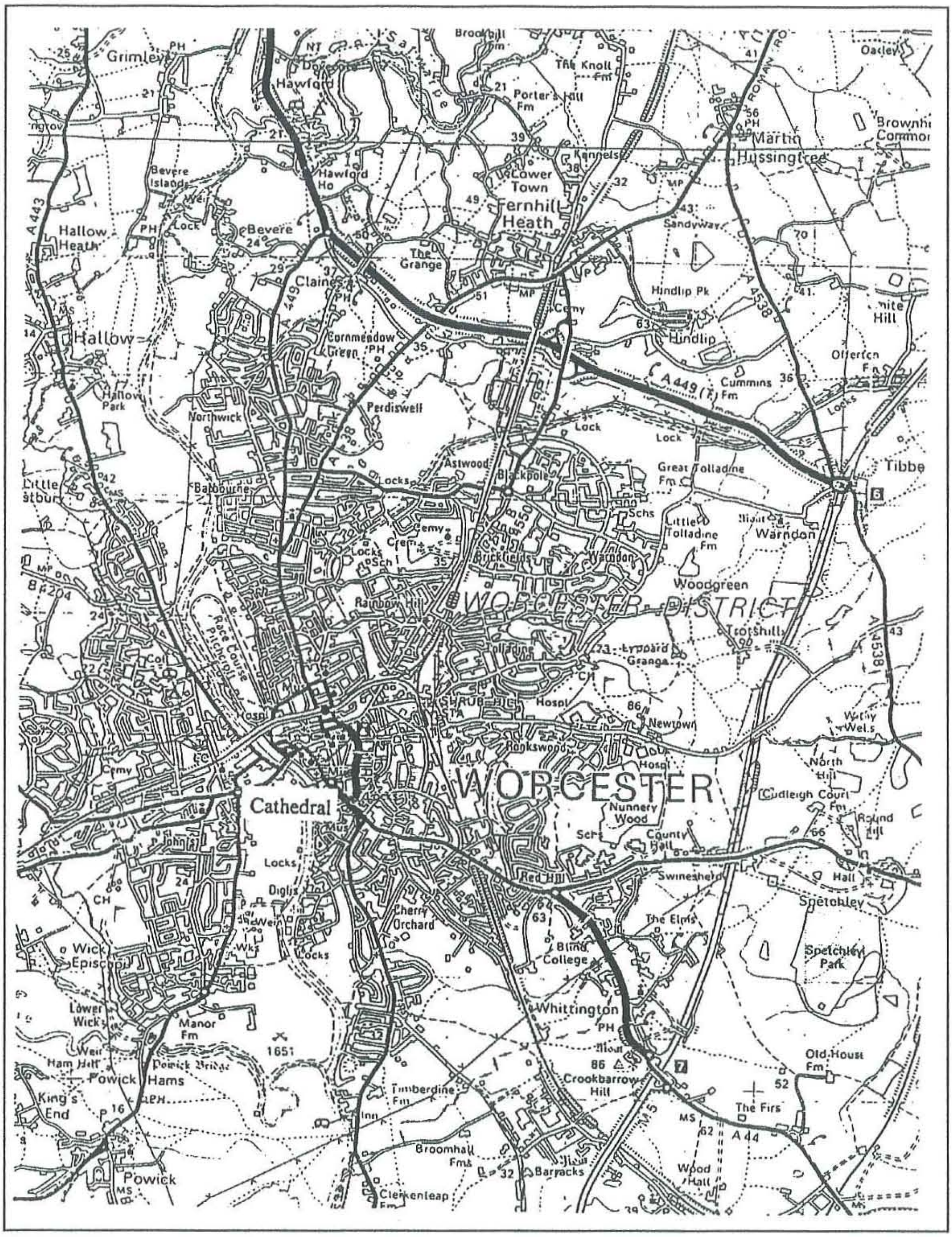


Figure 2: Worcester Cathedral, the Chapter House (provided by English Heritage)

Figure 3: Worcester Cathedral, Chapter House roof (provided by English Heritage)

Figure 4: Worcester Cathedral, the high-roof of the Chapter House, showing the location of samples WOR-C201-14 (provided by English Heritage); numbers 1-10 refer to principal rafter number used to locate the samples in Table 1

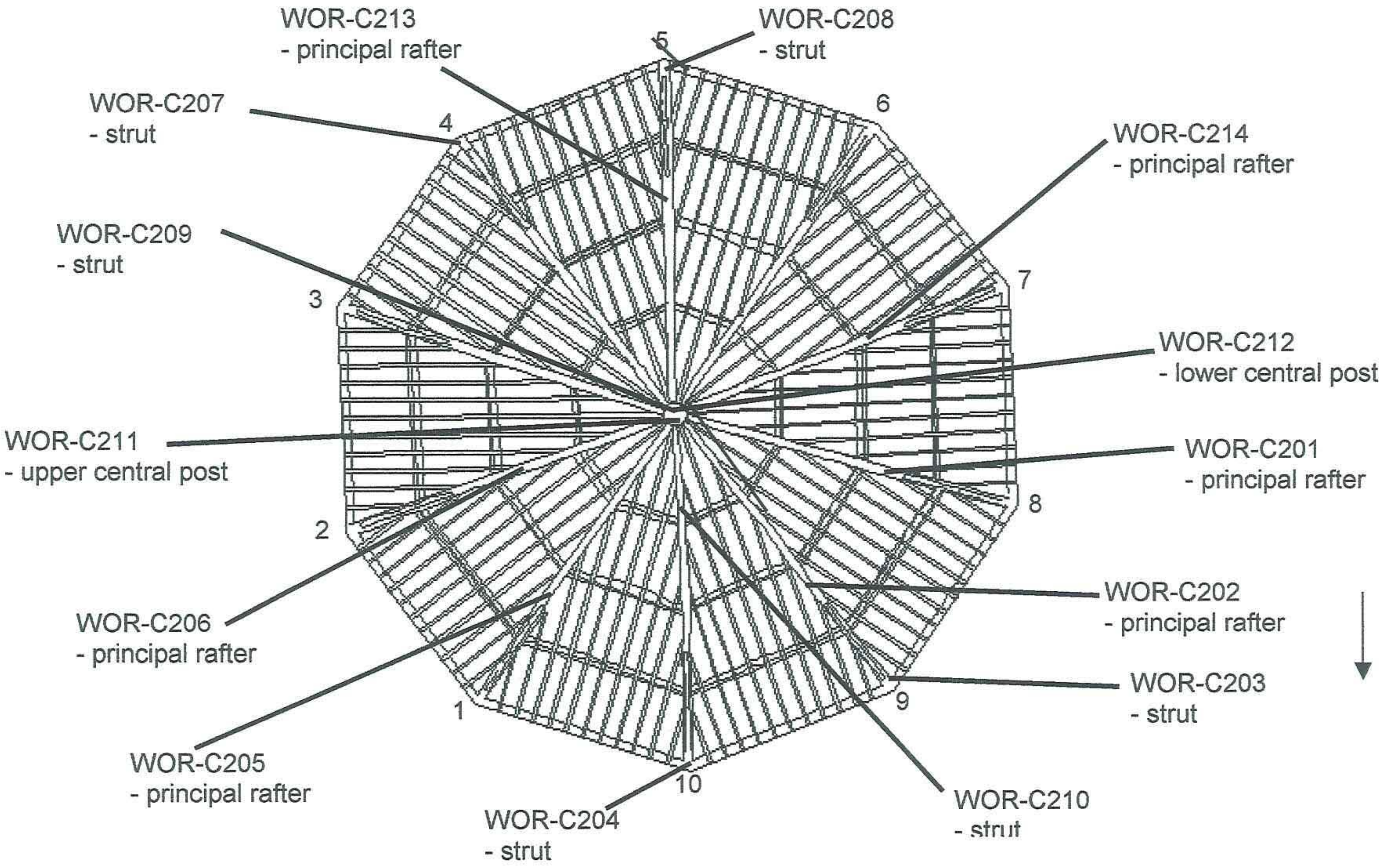
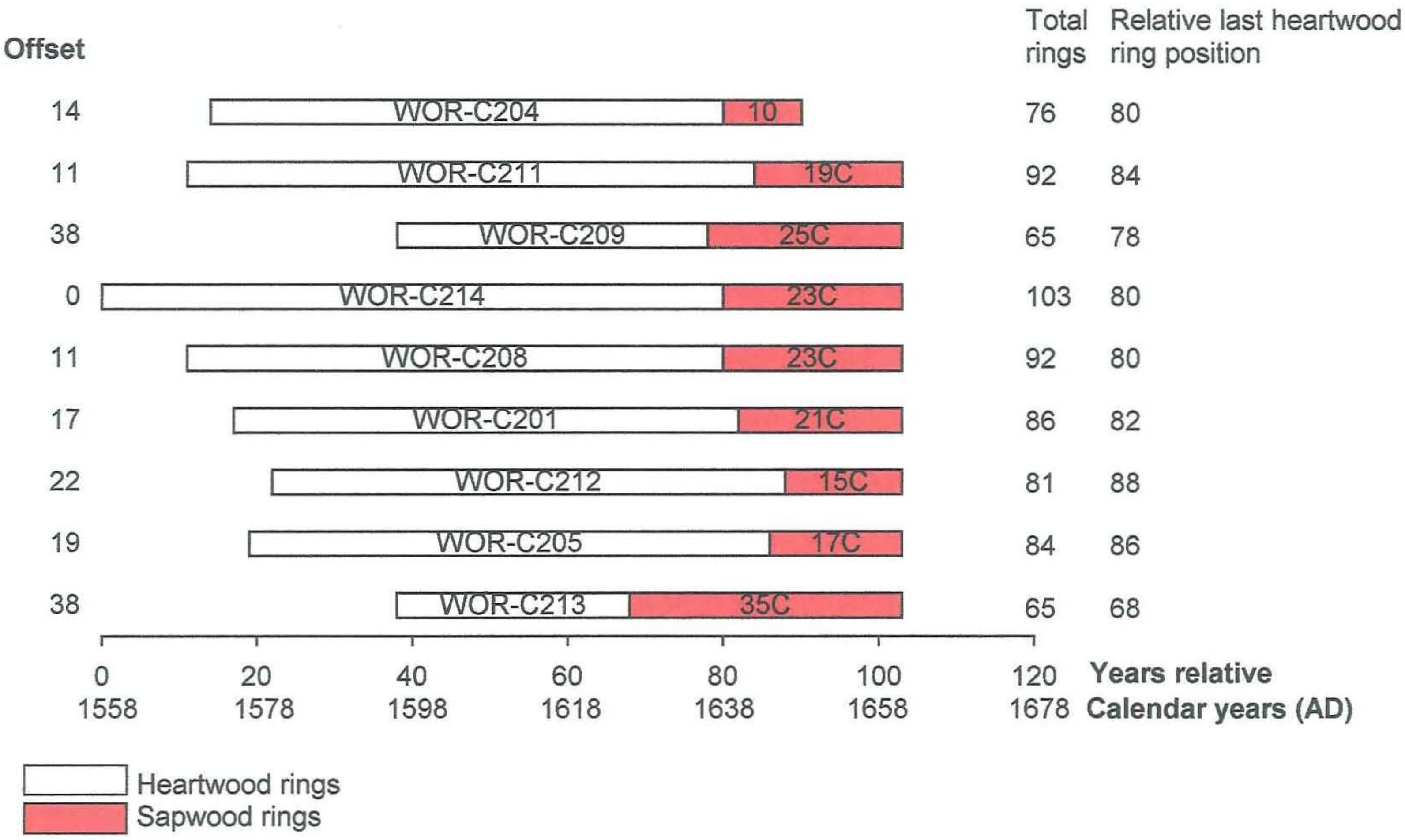


Figure 5 Bar diagram of samples in site sequence WORCSQ05



C = complete sapwood on timber, last ring is the felling date

Data of measured samples – measurements in 0.01mm units

WOR-201A 86
334 366 323 430 295 453 380 251 195 208 240 234 219 168 136 141 201 131 212 244
335 275 216 187 156 101 164 203 192 160 101 123 142 174 151 167 169 199 190 220
179 214 310 292 261 209 180 266 216 164 124 79 186 265 372 217 187 265 175 81
73 32 42 45 110 109 112 135 123 111 126 157 114 139 168 214 217 170 93 82
83 115 75 101 75 122
WOR-201B 86
355 367 343 400 285 453 377 246 204 217 226 244 219 162 154 129 228 128 215 237
338 269 231 191 154 95 161 195 190 153 102 117 149 167 144 173 175 186 191 233
183 223 300 306 266 193 182 268 222 154 116 86 171 263 374 232 180 258 168 94
59 28 40 49 95 111 109 116 118 123 130 165 108 140 163 222 235 157 84 89
92 108 72 111 68 112
WOR-202A 73
258 460 319 351 447 424 409 346 245 192 225 261 234 264 249 229 258 202 292 274
242 238 185 247 174 249 207 216 223 281 336 326 326 359 409 379 318 303 329 378
328 298 338 328 315 391 225 196 202 308 330 269 278 260 190 220 235 250 231 208
239 241 243 289 206 168 125 344 222 220 289 215 294
WOR-202B 73
340 409 364 372 416 399 425 348 242 180 219 253 249 263 261 231 264 200 252 256
249 260 195 271 154 255 207 210 215 288 328 292 330 353 443 359 318 309 339 402
318 276 356 316 333 393 221 189 194 306 338 250 283 260 224 205 255 235 235 210
250 244 249 277 205 164 117 319 226 249 248 216 281
WOR-203A 54
300 346 549 566 453 493 608 578 367 171 375 79 82 64 84 126 116 180 134 115
157 103 109 113 182 170 193 242 184 450 436 228 232 246 190 308 234 178 177 148
174 127 165 131 171 156 151 138 142 134 100 163 224 139
WOR-203B 54
350 410 540 492 500 492 541 595 373 167 374 78 81 60 85 119 127 172 152 86
166 107 114 120 181 179 196 249 183 394 438 216 214 257 200 256 188 168 167 148
160 121 158 122 183 149 160 137 154 129 105 164 201 129
WOR-204A 76
198 164 132 191 195 201 191 256 204 181 106 116 211 172 145 180 131 174 158 236
244 248 322 275 200 180 126 155 169 311 210 185 250 170 180 211 139 184 201 280
211 174 151 242 276 315 358 383 278 240 187 211 191 102 63 119 170 247 181 237
199 255 211 170 73 88 174 165 199 200 194 200 208 121 130 133
WOR-204B 76
199 163 139 187 192 207 188 264 189 188 107 126 210 176 166 175 129 173 153 241
242 246 329 271 199 171 141 162 171 331 191 178 244 171 177 209 140 180 195 277
223 195 135 242 263 333 365 378 289 234 188 210 186 101 64 115 164 248 186 232
212 233 192 172 81 86 166 175 227 212 207 212 171 121 138 128
WOR-205A 84
184 218 154 253 353 284 306 379 442 346 349 397 430 234 398 323 432 436 398 225
237 279 264 228 341 300 322 294 213 245 259 251 186 154 129 116 100 130 137 137
192 181 155 164 145 169 201 89 94 88 151 166 193 157 151 169 161 73 83 64
114 215 177 160 213 118 124 96 146 177 103 147 145 139 137 116 109 74 156 161
153 171 133 80

WOR-205B 84
287 237 169 325 335 253 315 359 448 334 349 385 418 229 396 333 430 479 364 235
229 282 262 218 375 278 309 272 230 234 245 225 198 158 120 117 112 113 140 129
175 184 134 152 150 166 190 102 87 90 155 160 190 159 141 180 155 83 84 64
131 215 158 185 195 127 111 108 140 173 111 136 147 143 121 121 116 74 158 158
150 168 144 89
WOR-206A 95
132 111 176 171 255 329 321 237 203 209 326 347 245 142 145 169 206 143 107 92
172 186 137 140 135 85 97 140 140 138 159 148 142 91 120 142 147 203 152 176
203 167 172 160 182 181 191 153 115 130 148 154 141 117 139 165 179 208 178 151
116 94 81 93 103 146 132 131 185 131 115 108 86 103 172 117 176 140 157 110
169 139 137 135 147 148 104 103 102 112 91 98 129 150 161
WOR-206B 95
86 108 179 175 285 316 323 225 199 215 318 373 253 154 128 172 191 143 110 93
176 187 140 178 119 87 91 125 134 138 153 137 135 103 117 132 145 200 151 155
196 152 193 151 173 196 186 124 116 135 138 156 133 117 138 168 166 201 173 144
117 86 73 96 98 137 147 135 166 136 99 115 85 112 174 112 163 139 159 121
167 139 133 127 158 143 98 107 105 116 76 96 130 154 173
WOR-208A 92
255 394 273 129 184 309 290 283 270 388 295 285 293 131 190 275 245 233 347 278
306 305 254 157 298 195 197 137 253 217 214 203 201 187 251 155 149 116 154 198
137 106 123 158 116 118 174 117 108 189 159 151 69 130 136 150 119 63 133 178
222 214 192 143 125 132 102 59 95 166 82 145 188 105 103 62 56 94 104 101
99 98 101 90 91 90 119 142 133 172 140 170
WOR-208B 92
295 385 299 126 191 325 289 293 255 366 311 300 278 143 186 285 237 244 348 306
293 307 264 152 297 199 184 150 233 230 178 185 183 168 230 164 150 108 160 206
125 100 110 164 117 134 182 111 117 187 157 149 78 128 138 159 112 61 121 159
216 208 177 137 145 129 112 55 91 158 89 133 179 104 94 61 60 71 102 103
119 90 104 101 97 78 130 140 132 169 151 167
WOR-209A 65
195 221 198 168 223 256 270 288 216 196 193 221 187 195 167 231 209 223 169 204
151 208 201 226 273 157 197 211 258 149 50 56 114 153 150 145 106 122 81 112
70 82 122 83 121 178 144 157 102 78 160 112 151 131 107 126 127 129 112 239
243 201 256 300 312
WOR-209B 65
175 215 218 166 225 253 273 286 221 194 186 221 190 209 163 223 225 195 178 215
151 197 212 239 242 167 188 200 272 150 56 44 99 172 137 141 107 117 101 114
67 83 132 85 125 171 163 149 96 84 130 122 147 129 111 124 122 143 101 241
242 203 258 315 359
WOR-210A 92
300 300 282 280 344 291 245 310 329 363 450 241 217 184 280 295 265 267 286 316
231 251 271 284 314 295 296 273 225 309 262 288 402 378 507 253 243 232 229 172
215 161 108 155 94 101 129 108 114 113 80 89 104 64 69 70 62 61 86 44
97 51 62 71 51 40 61 40 45 90 74 94 103 132 108 94 89 123 117 137
98 101 83 87 78 52 88 96 97 87 64 108

WOR-210B 92
338 303 282 283 346 296 246 321 334 338 444 255 186 216 266 264 272 255 294 308
338 262 253 289 312 332 302 243 235 334 273 271 403 383 502 260 242 233 226 169
218 150 114 154 99 99 123 108 107 122 86 79 74 92 70 76 49 61 82 57
83 52 60 58 52 49 50 52 37 95 78 88 107 131 102 103 85 128 112 138
85 91 78 87 73 52 91 91 107 86 76 89
WOR-211A 92
508 657 695 567 604 693 656 502 608 613 491 568 410 306 270 299 383 365 382 324
283 242 312 228 223 198 230 175 119 97 122 120 163 271 371 295 205 214 209 347
313 309 391 404 385 312 300 300 322 251 294 269 232 299 363 408 252 152 196 231
307 265 215 213 223 183 149 113 145 264 328 325 331 453 275 227 138 180 219 257
240 218 200 188 174 199 213 229 260 180 170 240
WOR-211B 92
491 652 692 568 588 684 658 498 605 608 473 556 389 311 273 286 384 348 360 327
277 233 306 214 224 244 244 164 129 84 126 122 163 271 369 300 206 219 227 318
317 308 398 405 390 296 303 302 326 256 294 265 227 322 365 374 247 166 205 221
320 239 215 223 230 181 138 105 156 264 330 320 336 455 278 221 141 182 219 250
245 239 175 190 168 194 227 228 243 199 186 234
WOR-212A 67
455 381 169 147 257 224 299 299 209 185 193 281 368 411 338 446 525 492 491 390
163 131 118 170 131 77 170 156 129 121 101 148 178 57 145 87 188 243 468 647
718 575 660 404 295 127 48 76 65 91 118 111 211 194 163 185 114 237 353 323
340 453 292 306 123 133 135
WOR-212B 51
119 163 190 75 136 94 161 237 498 623 724 563 639 402 215 113 53 70 58 97
112 103 214 213 162 206 119 231 367 324 319 394 310 271 156 120 171 165 250 216
151 128 164 114 137 317 353 401 305 257 360
WOR-213A 65
330 378 367 252 228 287 252 299 340 411 476 514 409 328 355 424 346 265 246 298
216 203 176 148 140 160 137 199 149 75 84 83 102 86 105 82 85 96 75 67
66 55 115 110 97 84 73 76 55 79 94 101 80 95 88 100 92 68 55 122
118 68 75 72 111
WOR-213B 65
361 359 353 270 218 255 292 331 358 475 458 496 413 310 355 430 360 261 248 300
212 204 176 158 128 168 145 208 140 94 88 78 87 99 102 88 89 83 89 66
63 56 105 123 81 95 69 76 58 73 91 97 95 87 79 115 80 75 48 133
114 69 76 82 113
WOR-214A 103
185 355 298 248 313 234 272 244 235 353 269 308 303 308 257 266 265 398 222 245
266 267 369 300 237 241 383 354 301 236 208 221 182 289 244 202 257 232 95 70
69 98 130 162 99 119 109 80 105 95 136 157 133 254 208 285 234 255 269 360
298 289 312 303 286 301 244 144 184 255 219 283 177 219 201 208 155 132 103 112
159 187 170 150 143 127 113 130 173 132 169 162 168 126 151 96 75 152 126 169
129 124 110

WOR-214B 103

233 419 296 287 313 250 270 221 261 355 285 315 290 287 256 275 265 379 226 237
259 281 362 308 233 228 381 350 304 238 208 217 175 307 241 200 244 244 102 78
69 91 137 152 97 121 125 71 107 91 134 160 127 252 188 301 231 277 261 344
298 294 309 307 288 304 245 148 180 250 230 275 172 228 203 212 157 134 99 127
160 194 176 153 135 142 121 115 186 144 173 171 173 116 148 101 74 146 130 170
120 116 145

APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building*' (Laxton and Litton 1988) and, *Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 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 1, 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 University of 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 2 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 to 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.

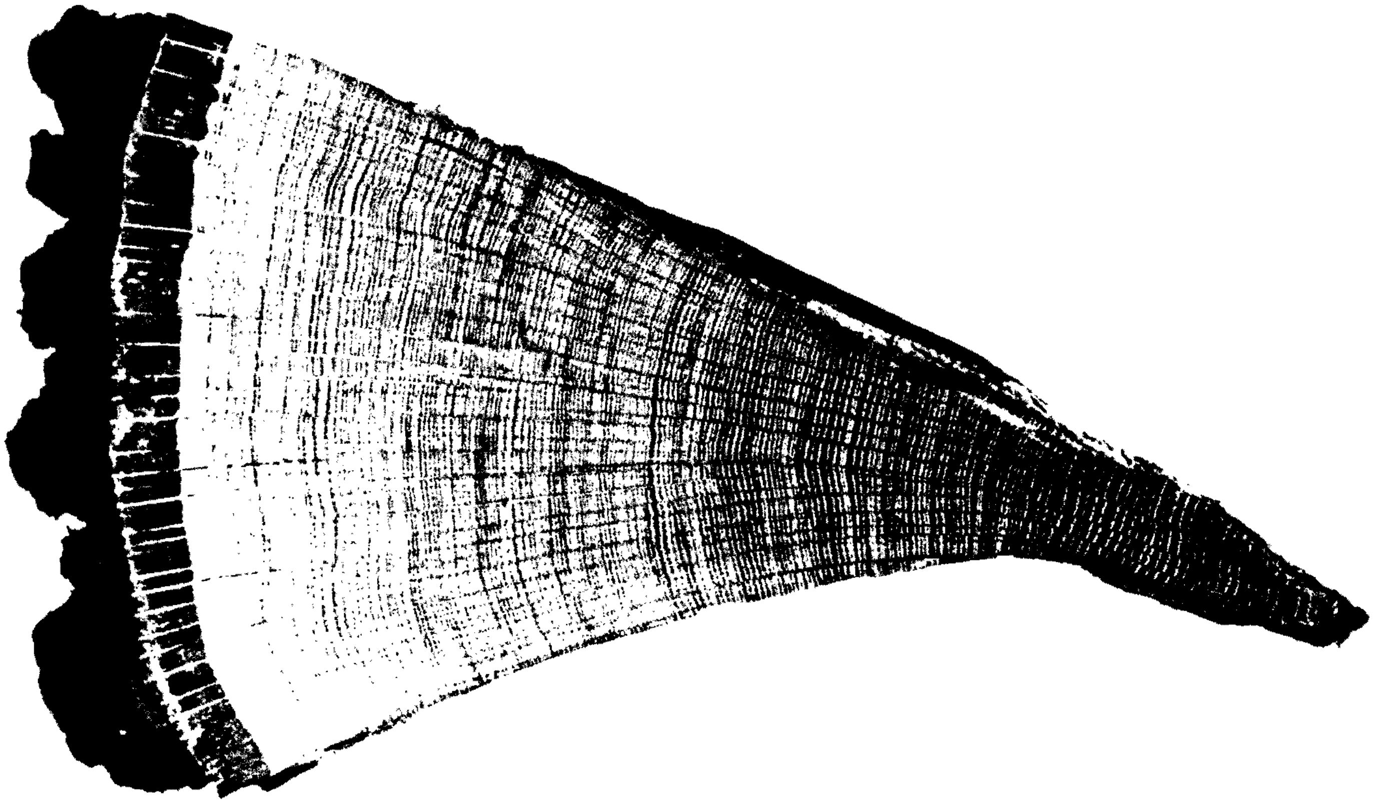


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

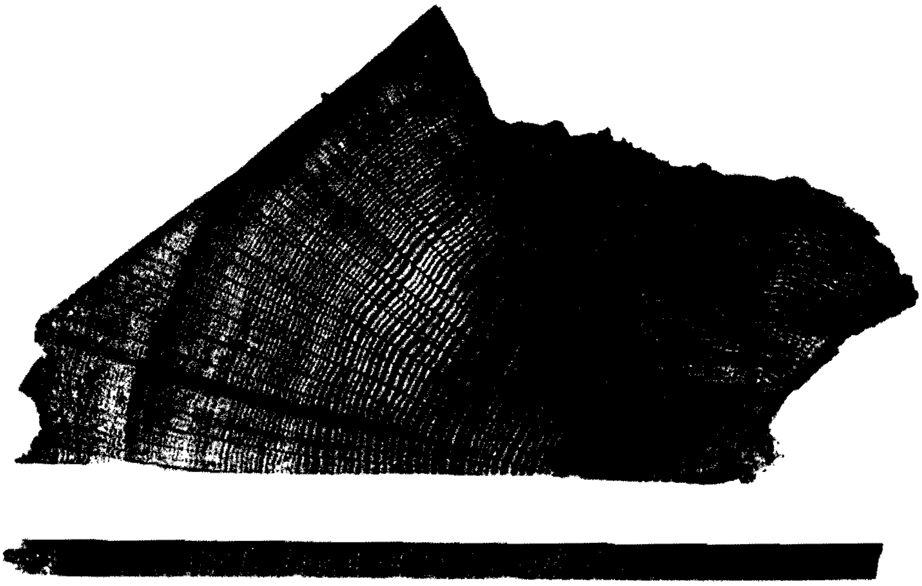


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig. 3 Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure 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.

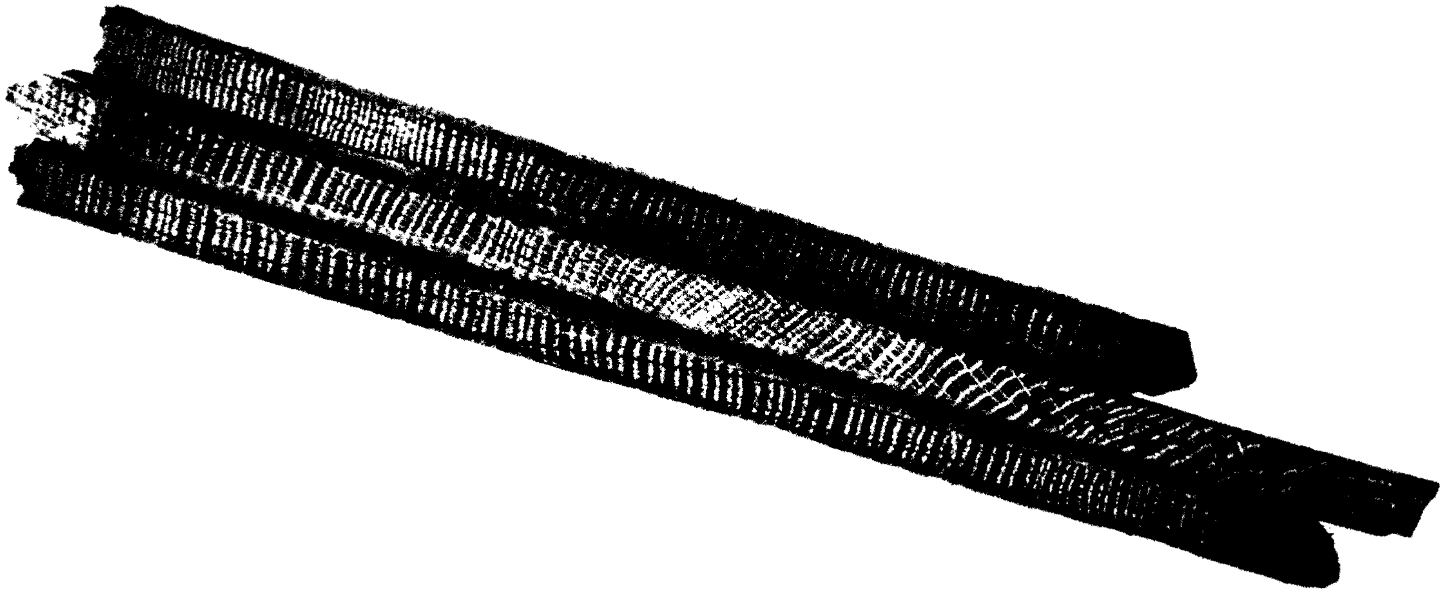


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 2; it is about 15cm long and 1cm 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.

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 2. 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 3).

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 4). 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 Fig 5 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 Fig 5. 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 5 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months 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 2, 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 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 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, 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 *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

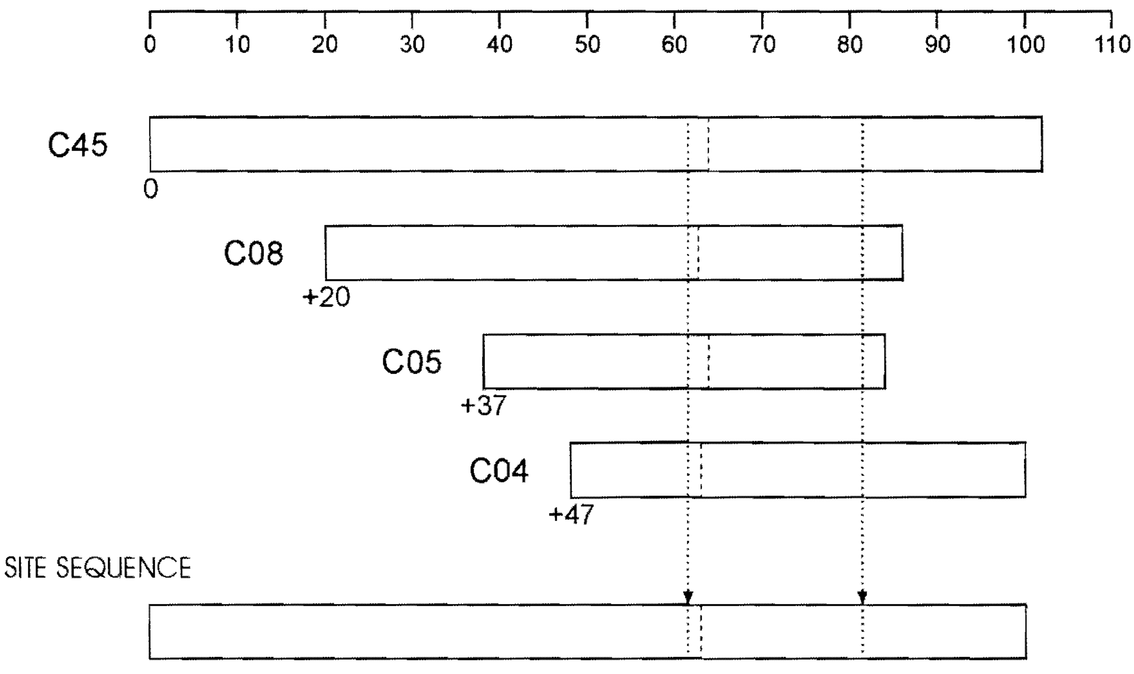


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

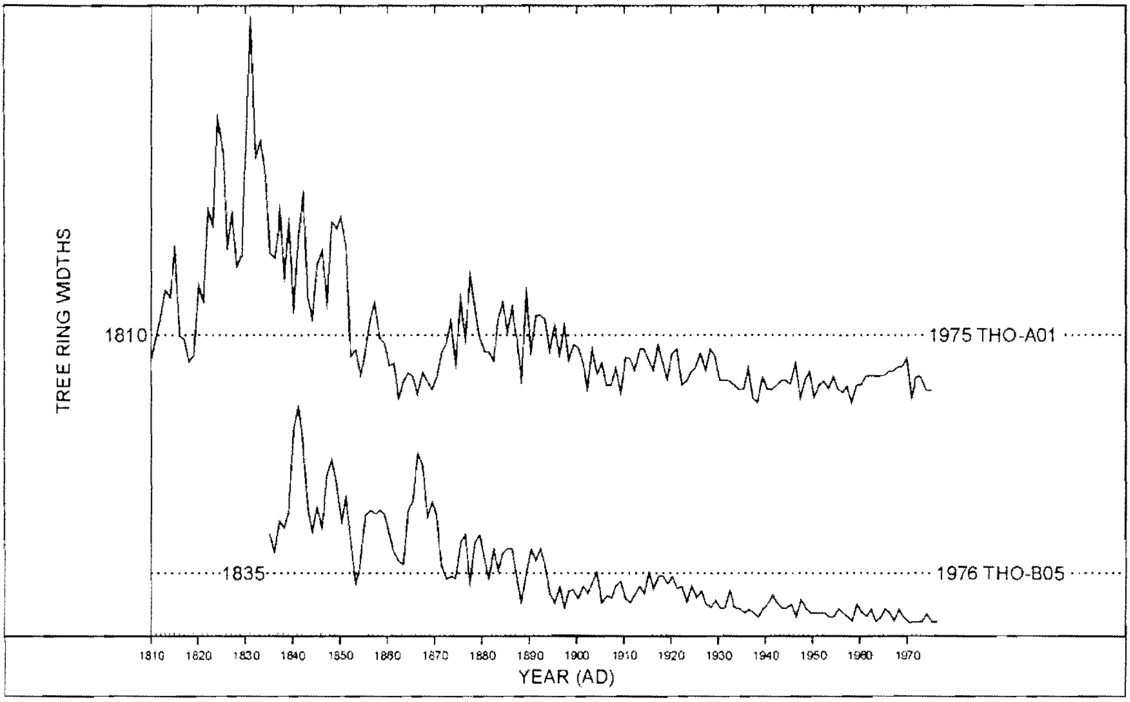
Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring 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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 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 Fig 6. 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 Fig 7. 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 phenomena 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.

(a)



(b)

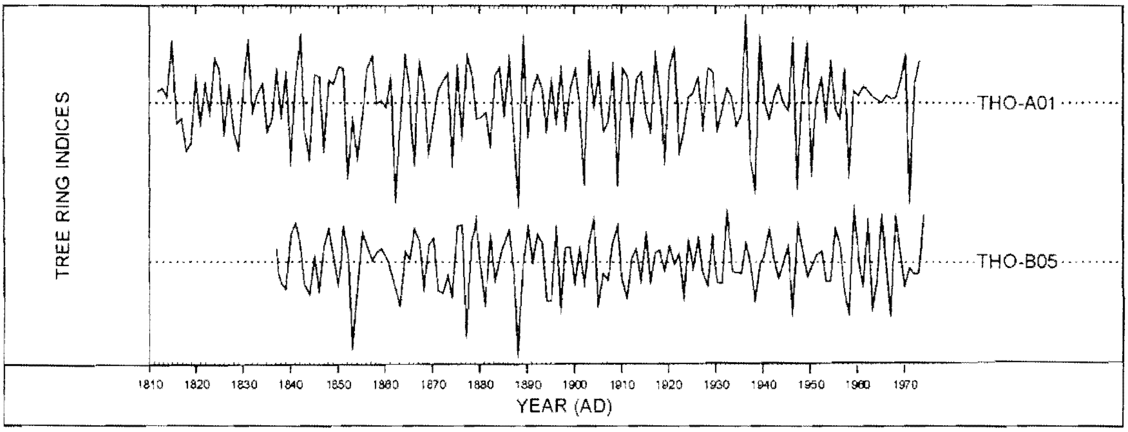


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Fig 7. (b) The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

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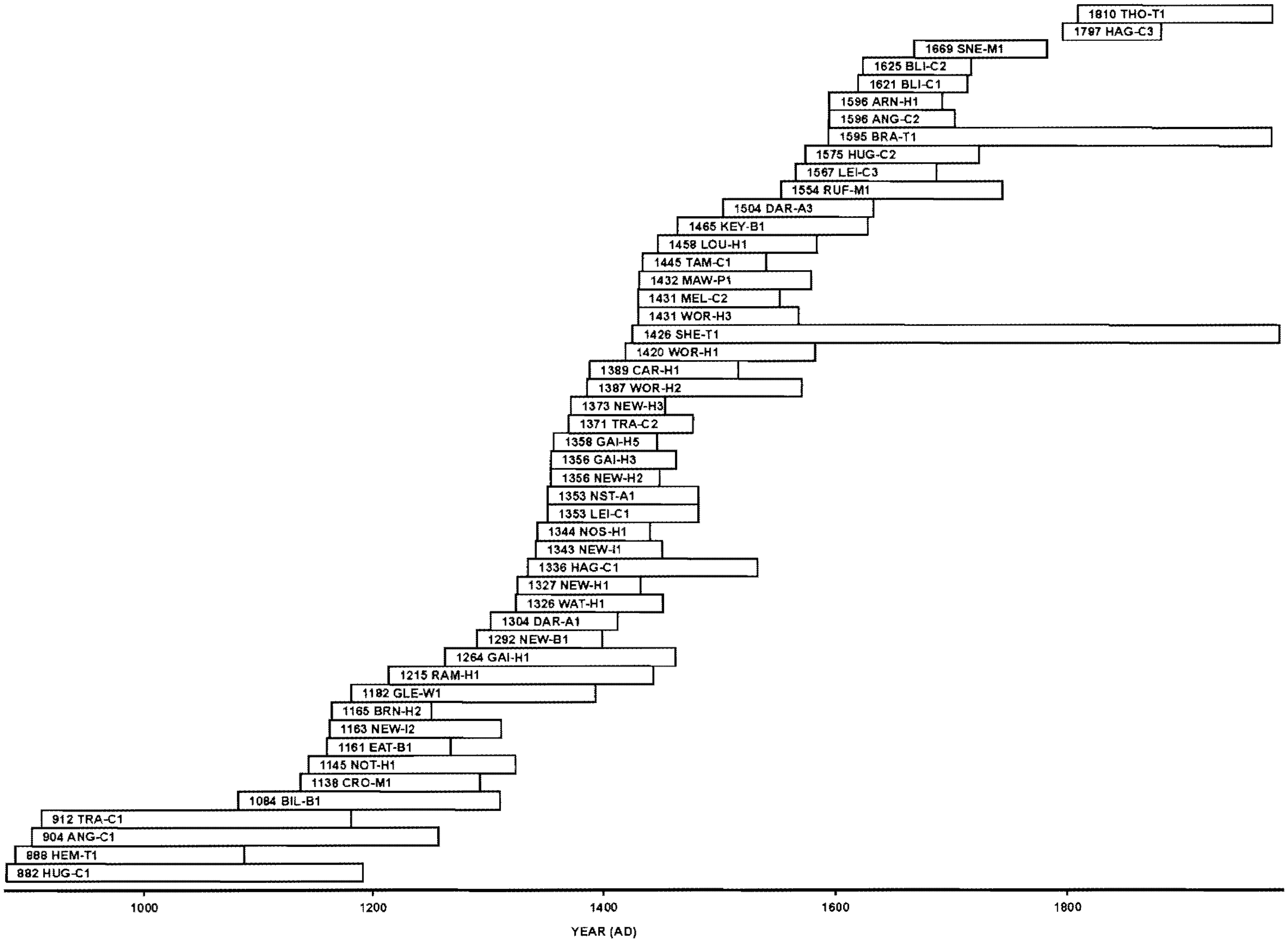
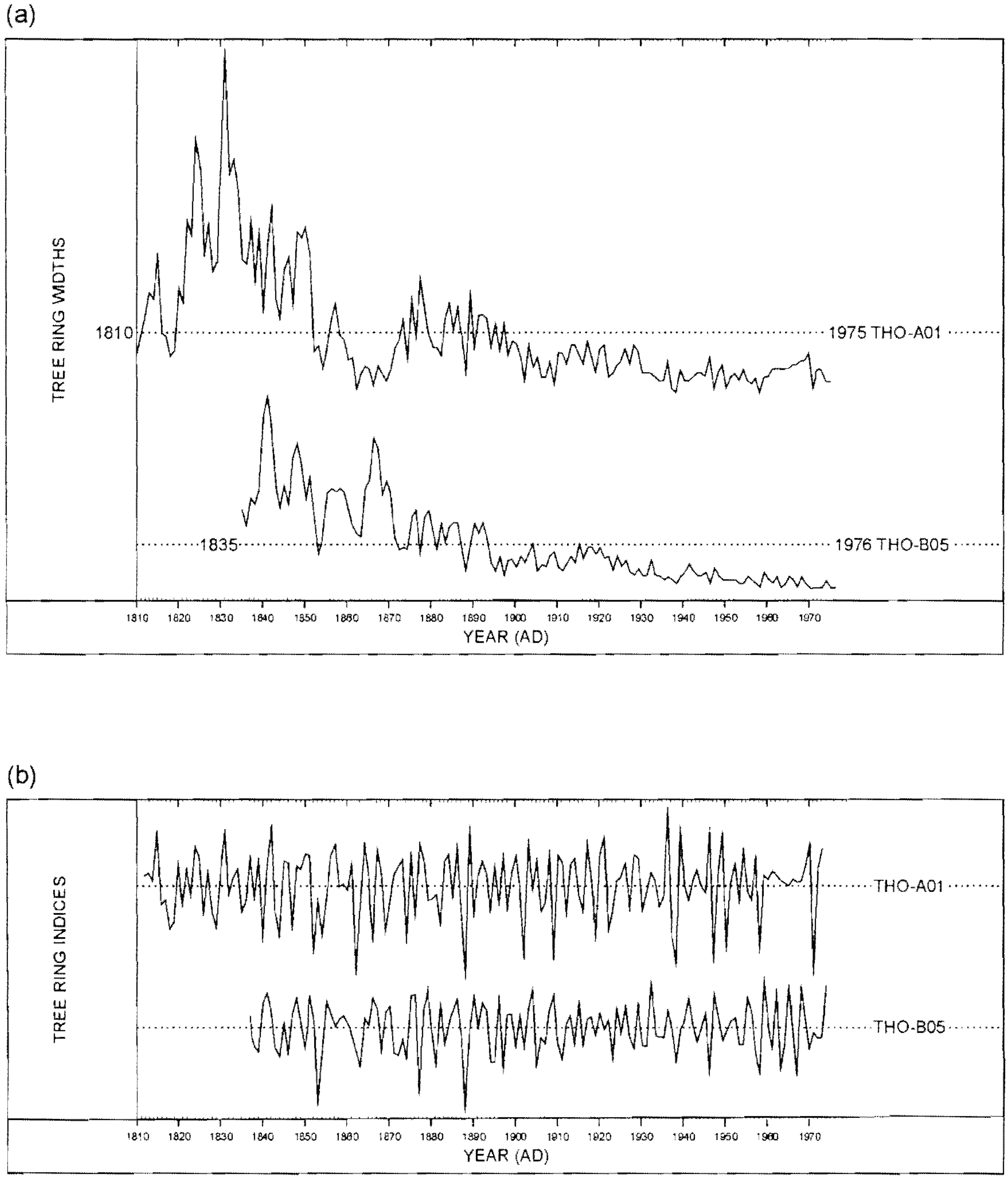


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



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