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TREE-RING ANALYSIS OF TIMBERS FROM THE CUPOLA CAPPING THE SOUTH-EAST TOWER AT COBHAM HALL, GRAVESEND, KENT

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Summary

Dendrochronological analysis of samples from fourteen oak timbers of the cupola on the south-east tower of Cobham Hall was undertaken. This resulted in the production of two site chronologies. The first, consisting of three samples, has seventy rings; the second, consisting of four samples, has eighty-one rings. Neither of these could be dated. None of the remaining ungrouped samples could be dated individually.

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Introduction

Cobham Hall, Gravesend (TQ 679684, see Fig 1) is a particularly impressive building and one of the largest and most important houses in Kent. At present an "H" plan, parts of the structure were built between 1584 and 1587 and another portion begun in 1591. More building work was undertaken between 1662 and 1672. A series of octagonal towers, capped by cupolas, rise above the house.

Structural surveys of the cupolas on the octagonal towers of the hall have revealed considerable deterioration of the timbers within. This has required a substantial amount of repair and renovation and a number of rafters have had to be removed from the cupolas, particularly from that covering the south-east tower.

The rafters of the cupola, which rise up to meet at a central point above a king-post, are footed in wall-plates set at the top of the tower. The east and west wall-plates are tied by one continuous beam. From this east-west tiebeam run interrupted beams to the north and south wall plates. A plan of the south-east cupola, provided by Sell Wade Postins, architects, is shown in Figure 2.

Analysis and dating by dendrochronology was requested by English Heritage. The purpose of this was to establish, if possible, the date of the timbers within a cupola topping the south-east tower.

Sampling

As a result of very extensive decay within the cupola of the south-east tower, all but one timber had to be removed by the building contractors. These were stored on site prior to sampling. About twenty timbers were assessed for tree-ring dating purposes. Some of these timbers were discarded because they had too few rings for satisfactory analysis; others were discarded because they were too rotted to provide usable material.

In all a total of fourteen samples was obtained by slicing the remaining timbers with a chain saw. Each sample was given the code COB-A (for Cobham. site "A"), and numbered 01 - 14. None of the timbers sampled had any identifying marks, labels or context numbers, and no record had been kept of exactly where each timber had come from within the cupola. It is thus not possible to be precise as to their original positions and no drawing showing their positions could be made. Details of the samples are given in Table 1.

Where possible a single sample is obtained from each timber. The sample is measured twice along the same radius giving the same number of rings for each reading. At Cobham Hall one sample, COB-A07, required slices from two different radii to obtain the inner and outermost rings. Thus, as shown in the data of the fourteen measured samples at the end of the report, the A and B readings of sample COB-A07 have different numbers of rings.

Analysis

All fourteen samples were prepared, measured and compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a level of t=4.5 two groups of samples formed. The first, consisting of three samples, cross-matched as shown in the bar diagram Figure 2. At these off-sets the relative positions of the heartwood/sapwood boundaries are consistent with a group of timbers having the same felling date. Because of this the ring-widths of the three samples were combined at these relative positions to form COBASQ01, a site chronology of 70 rings. Site chronology

COBASQ01 was compared with a full range of reference chronologies for oak, especially against those from Kent, but there was no satisfactory cross-matching at any position.

The second group to form at a t-value of 4.5 consisted of four samples. These cross-match as shown in the bar diagram Figure 3. At these off-sets the relative positions of the heartwood/sapwood boundaries are consistent with a group of timbers having the same felling date. Because of this the ring-widths of the four samples were combined at these relative positions to form COBASQ02, a site chronology of 81 rings. Site chronology COBASQ02 was also compared with a full range of reference chronologies for oak, but again there was no satisfactory cross-matching at any position. The two site chronologies, COBASQ01 and COBASQ02 were then compared with each other. There was, however, no satisfactory cross-matching.

All fourteen samples were then compared individually with a full range of relevant reference chronologies for oak, especially against those from Kent, but also those from the Baltic. There was no satisfactory cross-matching by this method.

Conclusion

None of the samples date. Thus it is not possible to make an interpretation based on tree-ring evidence of the date of the cupola.

The lack of dating may be due to some problem with the samples. Some of them do show periods of stressed growth with narrow rings and some show slight complacency, although not severe in any case. This might cause some difficulty in comparing the growth-ring sequences with the reference chronologies.

However, a more likely explanation is that there are rather few reference chronologies for Kent and the South-east covering the probable time span of the samples; for example, the Kent Master chronology ends in AD 1540. If these timbers were felled in the late sixteenth century or later, which is likely given the construction history of the building, they are unlikely to have sufficient overlap with the Kent Master to date reliably.

Table 1: Details of tree-ring samples from the Cupola capping the south-east tower at Cobham Hall, Gravesend, Kent

Sample no.	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
COB-A01	Cupola rafter	74	h/s	------	------	------
COB-A02	Cupola rafter	68	h/s	------	------	------
COB-A03	Cupola rafter	77	h/s	------	------	------
COB-A04	Cupola rafter	54	h/s	------	------	------
COB-A05	Cupola rafter	70	h/s	------	------	------
COB-A06	Cupola rafter	65	h/s	------	------	------
COB-A07	Cupola rafter	56	h/s	------	------	------
COB-A08	Cupola rafter	71	h/s	------	------	------
COB-A09	Cupola rafter	60	h/s	------	------	------
COB-A10	Cupola rafter	59	h/s	------	------	------
COB-A11	Cupola rafter	57	h/s	------	------	------
COB-A12	Cupola rafter	84	h/s	------	------	------
COB-A13	Cupola rafter	63	h/s	------	------	------
COB-A14	Cupola rafter	71	h/s	------	------	------

* h/s = heartwood/sapwood boundary on sample

Figure 1: Map to show general location of Cobham Hall

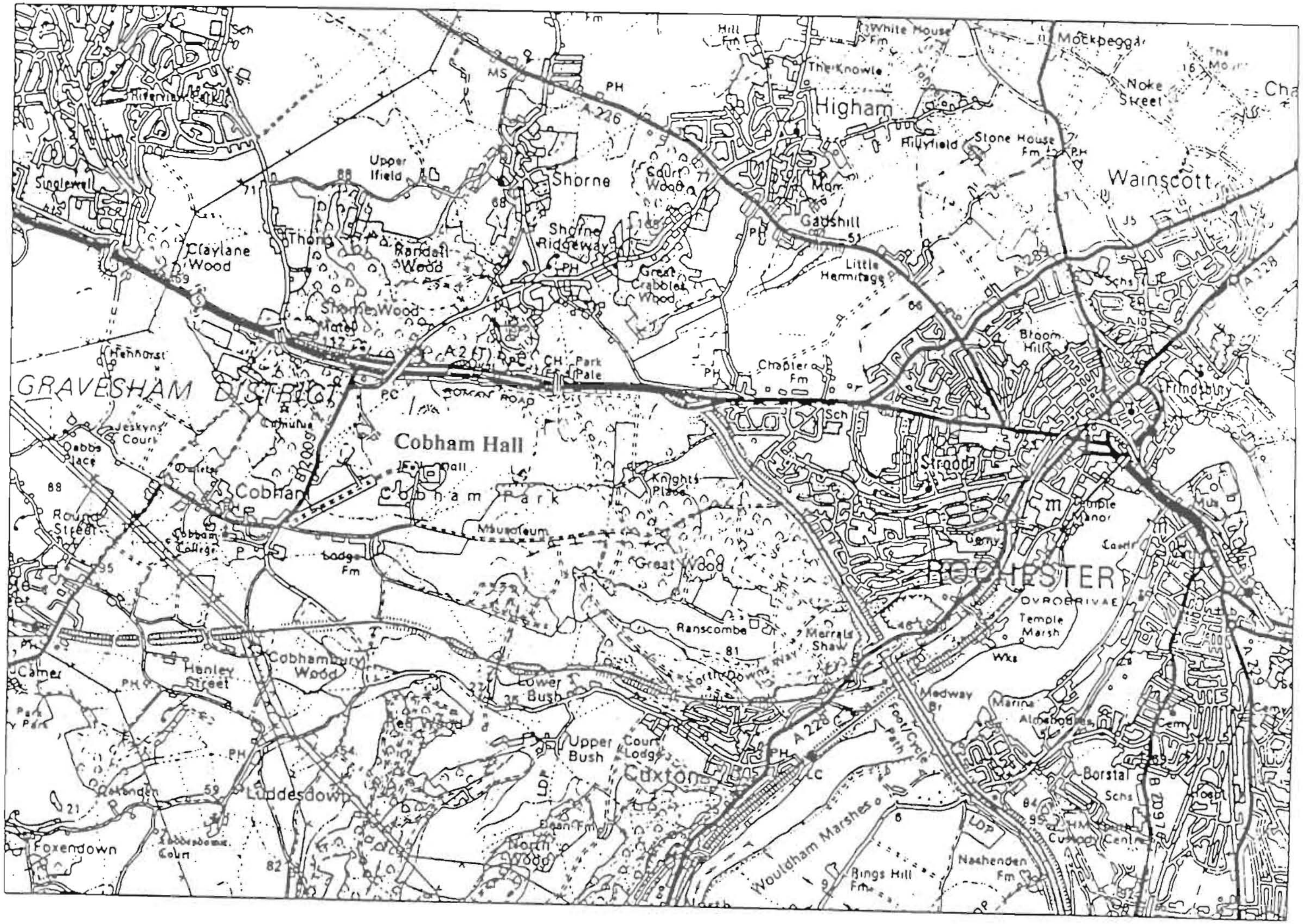

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Figure 2: Bar diagram of samples in site chronology COBASQ01

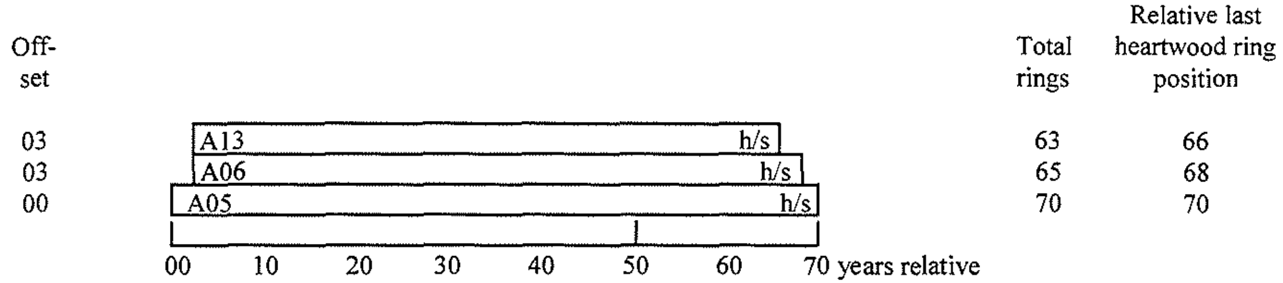
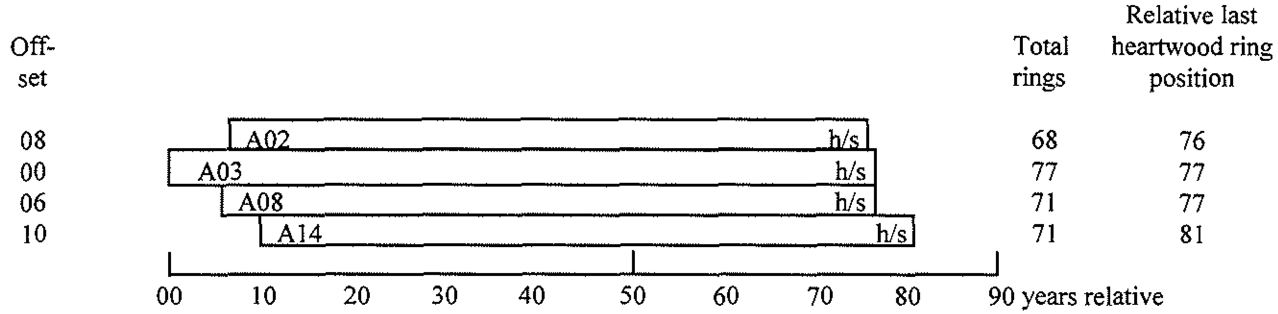


Figure 3: Bar diagram of samples in site chronology COBASQ02



White bar = heartwood rings
h/s = the heartwood/sapwood boundary is the last ring on sample

Data of fourteen measured samples - measurements in 0.01 mm units

COB-A01A 74
321 246 95 95 78 70 54 88 74 110 140 201 211 324 237 255 238 300 399 292
198 252 330 308 205 260 326 266 317 168 289 264 278 311 240 146 193 211 199 235
188 231 284 261 210 226 167 175 171 203 192 382 733 463 266 217 208 132 183 187
190 215 180 139 183 161 224 272 252 263 145 190 172 203
COB-A01B 74
283 258 99 96 83 50 70 86 70 107 141 195 228 319 244 253 249 307 394 273
191 236 318 303 203 246 319 276 320 207 258 274 272 324 241 150 191 190 179 213
193 206 268 246 187 175 162 181 177 199 197 416 707 452 271 203 222 130 185 184
200 188 182 149 182 198 204 274 253 261 123 203 159 199
COB-A02A 68
90 88 148 135 198 239 260 310 319 321 205 114 250 337 330 238 221 205 217 263
214 181 150 163 184 152 325 268 182 252 175 199 207 254 252 241 204 351 331 254
277 199 256 279 337 403 372 265 321 206 207 138 205 567 618 290 170 158 113 119
119 108 208 143 145 146 137 241
COB-A02B 68
113 87 140 120 188 249 257 284 324 323 189 122 252 342 330 230 226 197 210 271
219 162 164 151 170 171 317 266 187 218 192 206 204 261 250 221 228 356 313 186
276 202 253 303 335 413 388 245 299 243 224 132 207 568 606 290 157 154 104 129
112 121 191 155 125 151 143 223
COB-A03A 77
323 271 258 168 247 182 200 361 438 144 219 204 249 285 251 358 297 250 245 147
161 197 195 171 168 121 154 194 142 109 121 129 133 70 121 128 123 124 112 148
159 177 212 184 193 197 171 175 236 179 172 222 205 225 189 174 138 134 137 101
213 331 342 209 121 109 76 99 139 128 239 199 150 131 142 209 201
COB-A03B 77
356 280 263 180 236 185 184 383 414 132 209 199 243 298 263 355 279 248 259 145
167 187 200 182 165 110 166 195 141 122 105 138 142 67 139 142 117 144 99 161
160 179 211 191 193 177 216 161 239 178 146 214 203 229 200 164 142 129 141 91
224 319 336 207 111 109 83 101 141 119 218 191 160 125 146 203 207
COB-A04A 54
205 211 246 238 263 242 330 356 288 390 300 196 176 215 220 183 178 147 221 138
167 144 154 154 109 125 426 361 221 319 184 157 174 128 148 86 60 64 76 106
110 68 80 76 91 93 81 109 91 91 84 83 88 102
COB-A04B 54
190 231 244 240 265 238 266 415 294 376 295 195 156 219 238 182 169 161 213 133
165 142 158 141 111 123 466 350 233 318 185 151 179 127 149 82 64 62 81 103
121 65 79 81 85 97 84 105 105 76 87 78 99 103
COB-A05A 70
117 188 166 116 174 102 105 79 66 129 34 62 87 113 92 75 81 74 78 96
288 230 248 197 153 216 263 252 242 222 257 239 256 202 243 234 235 222 215 238
181 164 170 179 160 132 164 160 232 172 198 118 114 134 228 433 484 371 202 173
225 303 340 194 288 231 143 130 184 167
COB-A05B 70
106 204 178 115 177 103 93 78 68 125 37 55 92 116 97 69 84 72 75 106
285 252 207 177 142 220 253 246 244 227 255 236 240 219 253 231 232 227 215 231
193 149 169 185 153 131 176 148 219 191 202 120 119 127 235 433 493 345 215 174
217 314 283 195 250 275 142 134 182 161
COB-A06A 65
101 145 170 109 80 81 45 48 82 118 168 109 72 77 88 65 123 391 358 273
243 213 217 244 199 214 202 198 196 206 197 202 184 166 170 159 181 146 151 133
176 154 107 141 113 170 147 150 113 108 110 187 493 636 384 156 119 139 242 188
156 197 214 282 243

COB-A06B 65
90 139 172 106 80 85 47 53 76 133 160 123 65 80 73 71 129 489 339 283
218 213 212 257 194 204 189 201 219 196 190 209 181 174 173 173 182 150 141 161
167 137 122 137 115 167 149 150 121 109 105 187 495 647 376 157 114 146 253 197
167 200 201 201 222
COB-A07A 56
282 327 498 343 242 249 277 68 318 348 294 233 486 458 439 494 370 315 253 386
239 298 282 59 60 87 73 80 94 158 169 168 231 330 212 312 354 249 292 349
386 540 559 451 390 514 356 382 415 412 427 388 353 277 297 358
COB-A07B 48
274 334 317 237 332 518 475 462 349 322 252 403 253 276 293 60 58 82 85 74
91 174 153 189 231 268 228 301 356 260 281 341 362 510 586 430 374 585 386 377
398 429 406 419 290 315 294 380
COB-A08A 70
96 139 137 92 98 102 137 120 152 159 225 223 185 82 189 206 191 183 227 239
287 315 391 166 255 208 270 207 408 367 255 303 249 217 206 223 206 219 219 252
195 198 265 204 214 185 207 274 187 196 156 169 151 118 226 234 309 249 167 132
88 89 93 99 179 159 110 120 97 162
COB-A08B 70
102 137 132 77 110 100 142 118 152 162 209 222 172 95 181 200 214 177 225 237
278 312 391 165 257 220 258 221 399 351 290 314 244 197 225 245 198 202 218 249
196 185 261 195 221 184 206 260 204 198 153 159 163 120 234 235 323 237 170 130
89 80 102 82 183 145 131 124 101 144
COB-A09A 60
362 402 397 299 243 380 343 350 327 311 383 188 224 354 280 391 372 401 387 319
297 221 325 670 420 268 259 360 406 297 292 326 323 205 151 128 173 320 180 209
215 306 236 337 298 338 384 285 246 166 335 288 240 206 199 198 208 197 164 199
COB-A09B 60
312 488 424 301 248 391 353 354 324 322 407 204 214 378 263 404 368 365 397 292
289 205 352 678 417 271 259 370 397 300 327 324 321 207 156 147 183 356 184 216
211 263 280 329 283 352 395 285 240 147 355 285 245 201 195 212 199 209 172 212
COB-A10A 59
498 559 413 242 275 380 250 421 267 215 254 206 247 196 299 278 318 225 310 319
291 289 325 258 281 150 201 147 196 222 152 262 374 197 187 150 209 234 222 222
282 220 207 159 226 191 179 177 199 124 167 279 304 258 286 285 263 238 297
COB-A10B 59
433 553 406 251 269 390 248 424 274 225 236 221 236 184 315 297 297 231 309 308
286 260 343 245 240 159 198 138 208 234 134 270 370 202 194 129 223 225 246 227
269 208 199 161 224 203 171 178 195 118 186 267 309 261 268 278 238 246 254
COB-A11A 57
849 986 536 436 402 488 413 517 433 286 404 336 306 340 394 450 361 248 226 341
301 457 231 232 308 276 228 232 315 304 279 228 320 316 260 252 329 278 281 140
147 178 131 165 166 242 269 193 307 168 242 288 242 203 278 248 227
COB-A11B 57
843 980 540 442 392 489 399 540 446 297 403 340 291 344 407 457 371 239 226 376
297 455 243 225 303 263 222 241 313 323 290 223 343 294 253 253 330 287 263 137
148 174 144 162 149 244 262 211 311 170 252 304 244 207 242 237 246
COB-A12A 84
372 301 275 411 613 625 682 529 733 579 740 406 249 264 484 366 590 362 235 263
200 423 349 301 244 293 213 196 253 166 158 157 87 78 76 77 60 40 74 55
69 121 141 177 124 53 88 81 58 61 36 64 74 88 77 127 125 137 155 202
155 119 97 124 91 138 124 103 118 190 138 142 90 144 113 139 177 125 164 157
98 69 80 121
COB-A12B 84
363 308 279 431 616 613 665 527 655 622 704 425 274 250 525 369 484 357 242 254
211 419 349 294 247 292 200 190 251 165 150 169 84 86 86 67 57 46 56 53
73 128 151 154 130 52 91 76 60 49 49 59 78 81 91 142 108 149 167 219
164 135 100 111 97 147 124 100 140 183 111 148 86 145 112 141 172 131 168 146
96 74 87 111

COB-A13A 63
242 267 145 169 117 82 112 60 61 86 145 88 78 82 70 83 114 454 245 196
205 144 225 256 241 258 226 244 243 273 211 240 224 260 246 293 217 210 192 208
178 177 181 175 271 222 193 122 119 128 223 374 418 365 224 183 214 320 281 194
253 284 232
COB-A13B 63
216 298 166 159 91 99 111 51 58 102 147 100 74 91 70 74 123 439 251 196
198 143 215 264 244 258 221 249 232 266 245 250 221 209 288 307 181 238 212 198
198 167 218 189 271 204 201 123 121 109 228 380 435 363 235 194 192 310 289 213
261 316 219
COB-A14A 71
227 178 210 224 204 288 288 268 209 147 225 264 232 166 217 211 293 304 219 130
164 200 240 180 378 293 218 284 181 187 174 211 249 203 251 250 240 233 289 238
174 220 270 224 210 184 182 169 190 184 231 327 367 245 199 227 156 214 174 270
414 238 227 220 201 425 231 137 182 155 198
COB-A14B 71
226 178 210 214 205 294 288 297 210 164 219 242 186 174 231 210 272 311 242 123
161 179 245 190 334 275 219 278 189 198 186 196 225 181 262 236 230 203 286 236
191 221 265 212 184 199 183 169 177 196 233 329 369 249 227 237 149 214 183 264
434 227 201 219 214 451 251 148 172 159 142

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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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. 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 we inspect the timbers in a building 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. Similarly the core has just over 100 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.

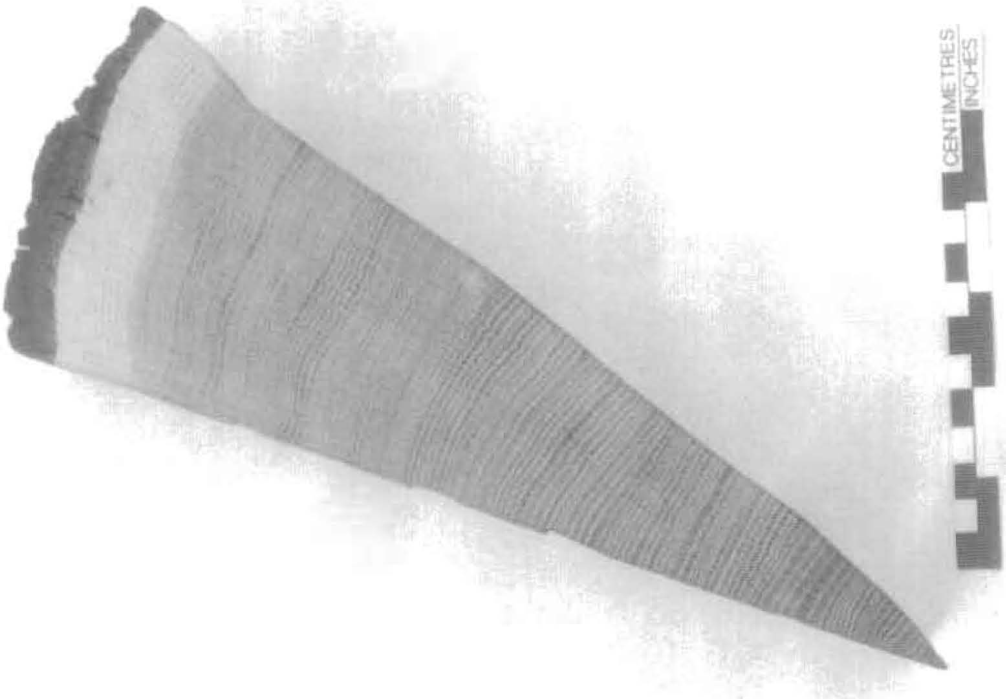


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

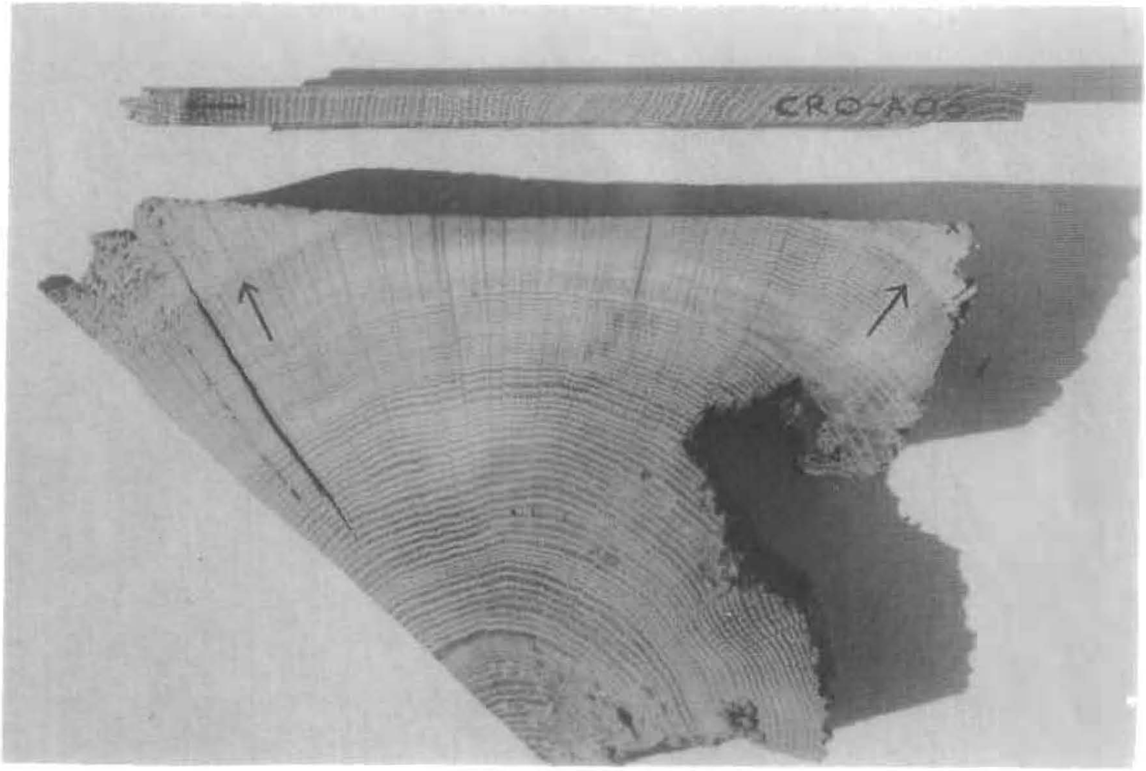


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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 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.

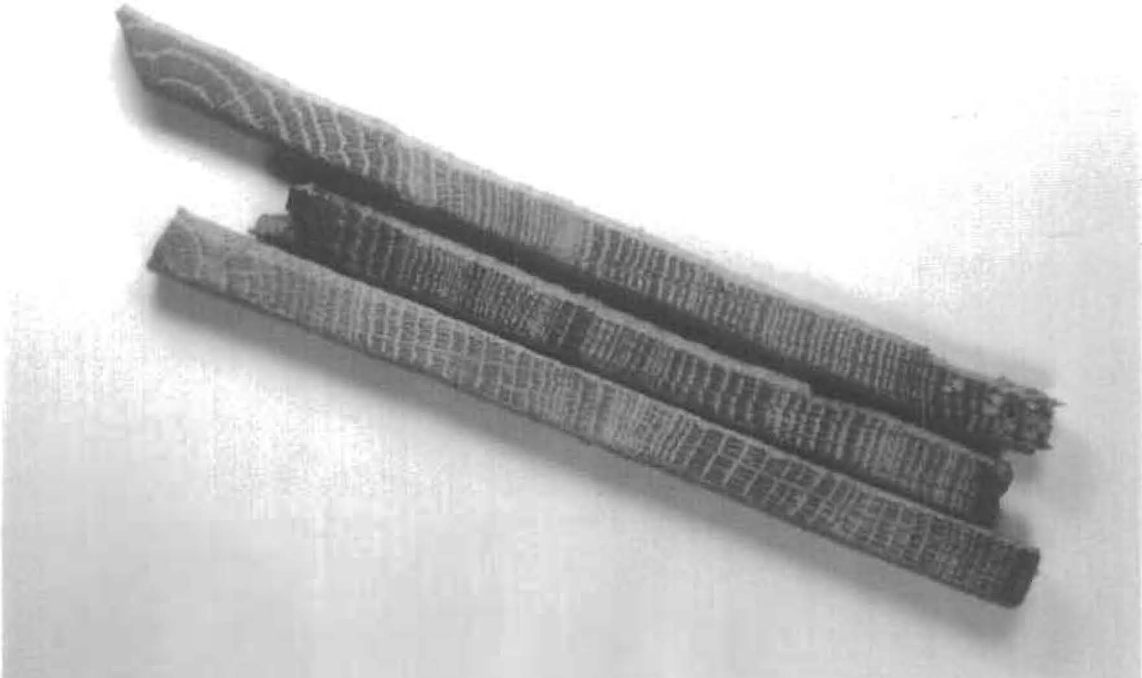


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 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 inspecton 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 is insured with the CBA.

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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45. 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 between these two whatever the position of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the 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 from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

   Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

   Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

   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. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

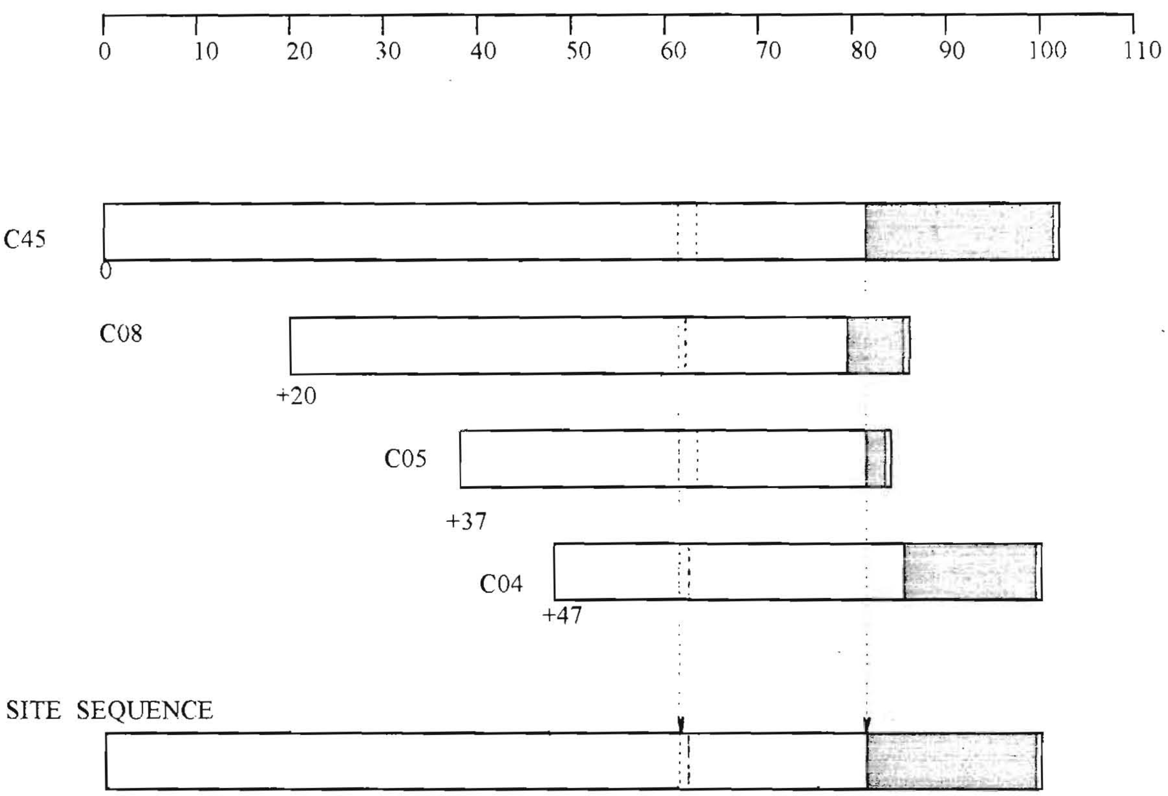


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ*, and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 1988b, 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* 1988a). 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 (1988b) 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 (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

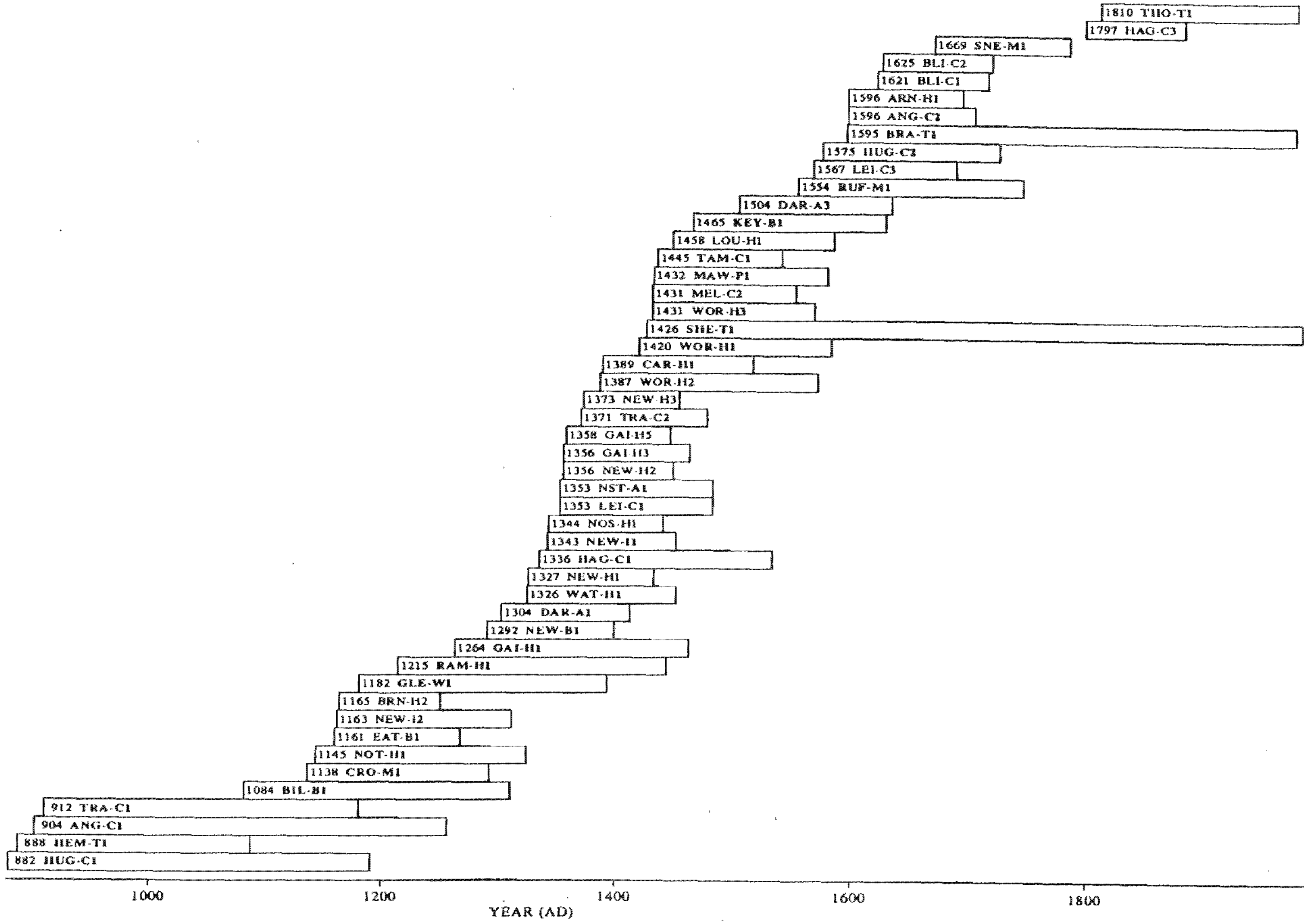


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

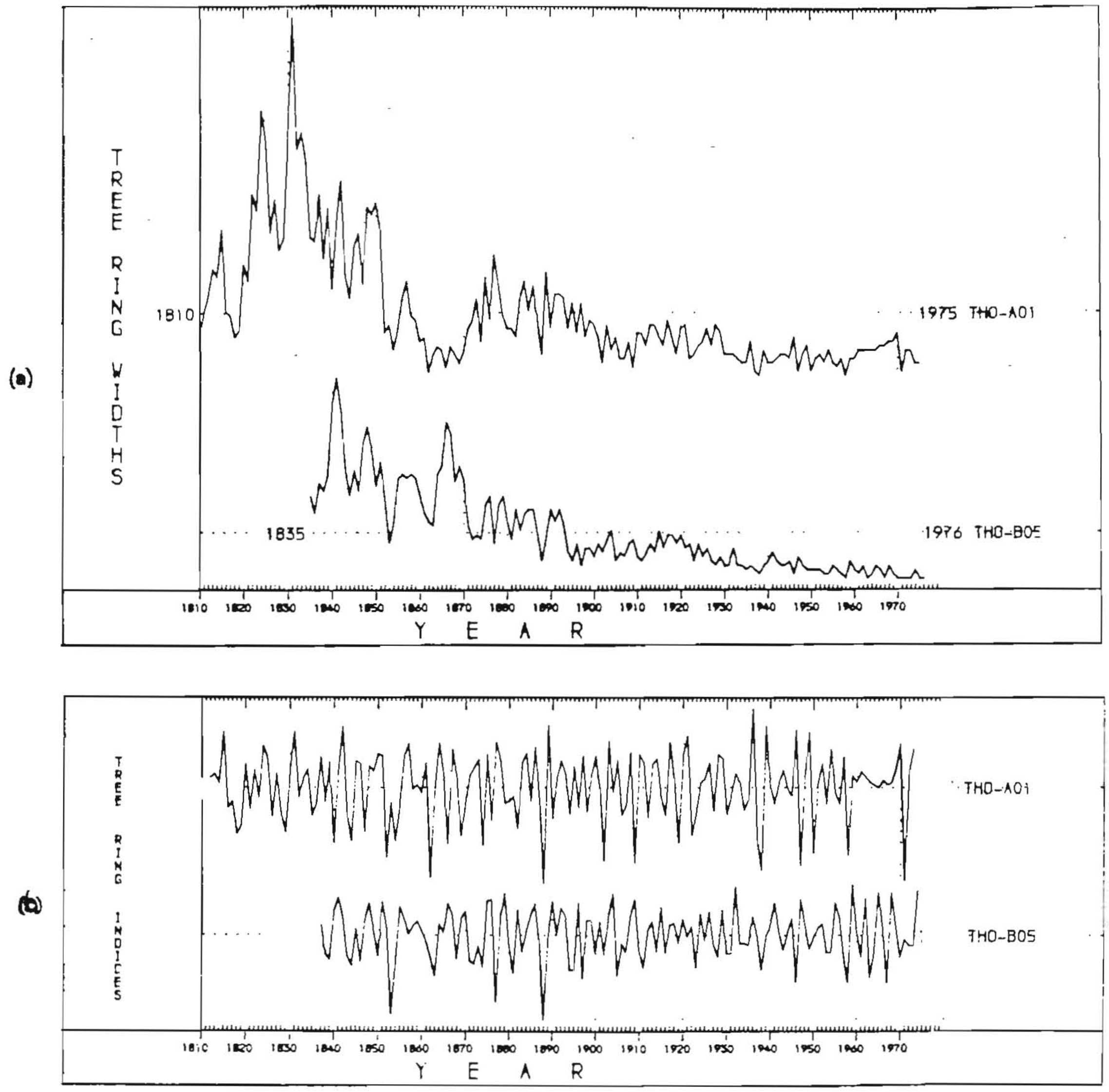


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

REFERENCES

Baillie, M G L, 1982 *Tree-Ring Dating and Archaeology*, London.

Baillie, M G L, 1995 *A Slice Through Time*, London

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

Hillam, J, Morgan, R A, and Tyers, I, 1987, Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, **3**, 165-85

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

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, **8**, 381-90

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

Laxton, R R, and Litton, C D, 1988b *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, A.D. 1158 to 1540, *Medieval Archaeol*, **33**, 90-8

Litton, C D, and Zainodin, H J, 1991 Statistical models of Dendrochronology, *J Archaeol Sci*, **18**, 429-40

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

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