Centre for Archaeology Report 85/2002

Tree-Ring Analysis of Timbers from the North Transept Roof, St Nicholas' Cathedral, Newcastle upon Tyne, Tyne and Wear

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ISSN 1473-9224

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Summary

Eleven samples from the roof timbers of the north transept of St Nicholas' Cathedral, Newcastle upon Tyne, were analysed by tree-ring dating. This analysis produced a single site chronology of ten samples, 181 rings long, and spanning the period AD 1187 - AD 1367. Interpretation of the scant heartwood/sapwood remains on the samples suggests that the timbers represented have an estimated felling date in the range AD 1378 to AD 1413.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM THE NORTH TRANSEPT ROOF, ST NICHOLAS' CATHEDRAL, NEWCASTLE UPON TYNE, TYNE AND WEAR

Introduction

St Nicholas' in Newcastle upon Tyne (NZ 249641; Fig 1) was formerly a parish church, having been elevated in AD 1882. Although it does have some pre-Conquest and Norman remains in the crossing and north arcade the bulk of the cathedral is of fourteenth- and fifteenth-century date. Further alterations were made in the eighteenth century and again in the nineteenth.

A programme of grant aided repairs to the roof of the north transept and the adjacent St George's Chapel are programmed for the summer of AD 2002. This will involve the stripping of the existing lead covering and its replacement with new material. It was believed possible that remedial work to the roof timbers might also be undertaken.

The roof of the north transept consists of a number of arch-braced trusses, the braces rising from wall-posts, set on corbels, to principal rafters. Between the main trusses large common rafters rise from wall plates to a ridge beam. Each pitch of the roof carries double purlins. The roof of St Georges Chapel consists of a series of cross-beams forming square panels. Apart from the common rafters of the north transept roof all the timbers appeared to be heavily moulded and carved.

Sampling

Sampling and analysis by tree-ring dating of the roof of the north transept and St Georges Chapel, was commissioned by English Heritage. The purpose of this was to assist as part of a research programme to better understand these two roof structures of the cathedral, there being no archival evidence which confirms their supposed late fourteenth- or early fifteenth-century date. It was also hoped that research into the roof structures would help identify the date of the raising of the nave walls.

A certain amount of difficulty was experienced at the time of sampling which lead to a smaller number of cores being taken than might otherwise have been the case. Although at the time of sampling scaffolding had been erected to the outside of the north transept, the covering had not been removed. Also, there appears to be some uncertainty as to whether or not the boards beneath the lead will be removed as these appeared to be in good condition, having probably been last replaced in the AD 1930s. Without wholesale lifting of this layer there can be no clear access from above to the roof timbers hidden beneath.

Internally, although a scaffold tower was in place this gave direct access to only the braces of one truss; the wall posts and the upper timbers of the roof here were quite beyond reach. It was only with the use of a hired plank platform, safety harness, and climbing ropes that some of the other timbers of the north transept could by cored at all. Of the six trusses in the north transept only three could be reached.

Unfortunately the timbers of St Georges Chapel were impossible to get to, the roof material not yet being removed and there being no scaffold in place here at all.

Thus, taking safety matters into account and in conjunction with the English Heritage brief, a total of only eleven core samples was obtained from the accessible timbers. Each of these samples was given the code NWC-C (for Newcastle, site "C"), and numbered 01 – 11. Although this might be considered a modest number of samples it is probably not an unfair representation of the remaining original timbers. It was noted at the time of sampling that probably all the principal rafters, possibly most of the purlins, and almost all the common rafters were modern, probably nineteenth, or even twentieth century, oak replacements. This interpretation is largely based on the very clean, square cut, nature of the beams, and the fact that the surfaces of most of them showed the very regular cut marks of a mechanical circular saw.

Timbers were selected for sampling on the basis of their appearing to be original and having sufficient rings for satisfactory analysis by tree-ring dating. One of the major problems encountered at this site was the lack of sapwood, or indeed even the heartwood/sapwood boundary. All the available timbers were either heavily moulded and carved, or heavily trimmed, the sapwood probably having been taken off during original carpentry work.

The positions of these samples are marked on architectural plans provided by English Heritage. These are reproduced here as Figure 2 and Figures 3a - c. Details of the samples are given in Table 1. In this report the trusses, bays, and timbers have been numbered and described from north to south, or from east to west as appropriate.

The Laboratory would like to take this opportunity to thank Derek Govier, Chapter Clark, his assistant and staff of the Cathedral who were most helpful and very obliging at all times and greatly assisted with the access to the roof.

Analysis

Each of the eleven samples from the roof of the north transept was prepared by sanding and polishing and its annual 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 minimum *t*-value of 4.5 two site chronologies formed.

The first site chronology, NWCCSQ01, consisting of six samples and having 155 rings, was satisfactorily dated against a number of relevant reference chronologies for oak as spanning the period AD 1187 to AD 1341. The second site chronology consisting of three samples, NWCCSQ02, was also dated, its 179 rings spanning the period AD 1189 to AD 1367.

These two site chronologies cross-match with each other with a maximum *t*-value of 4.3. This value is found when the first ring of NWCCSQ02 is at plus two years relative to the first ring of site chronology NWCCSQ01; such a relative position is consistent with the independent dating of the two site chronologies. For the purposes of analysis the nine samples in the two dated site chronologies were combined at their indicated relative off-set positions to form a third site chronology, NWCSSQ03. This third site chronology has 181 rings and is dated by comparison with the reference chronologies as spanning the years AD 1187 to AD 1367.

Site chronology NWCCSQ03 was compared with the two remaining ungrouped samples, NWC-C03 and NWC-C05. This indicated a satisfactory cross-match with sample NWC-C03 only with a *t*-value of 4.9, and this sample was combined with those of NWCCSQ03 to form a further site chronology, NWCCSQ04. Site chronology NWCCSQ04 was compared with the remaining single ungrouped sample, NWC-C05, but there was no further satisfactory cross-matching.

Site chronology NWCCSQ04 was then compared to a full range of reference chronologies and again dated as spanning the period AD 1187 to AD 1367. Evidence for the dating of site chronology NWCCSQ04 is given in the *t*-values of Table 2. The relative positions of the ten samples in site chronology NWCCSQ04 are shown in the bar diagram, Figure 4.

Interpretation and conclusion

Analysis by dendrochronology has produced a single site chronology, NWCCSQ04, consisting of ten samples and having 181 rings. This site chronology is dated as spanning the period AD 1187 to AD 1367. Three of the samples come from timbers which, it is believed, retain the heartwood/sapwood boundary. Unfortunately, because of the moulding on the timbers represented this is not certain, it is possible that what is taken for the base of sapwood may in fact be slight rot or surface decay. The samples do not show definite sapwood rings when examined under the microscope. Samples with probable heartwood/sapwood boundaries are coincidentally the three with the latest heartwood rings

However, if it were accepted that the three samples do have the heartwood/sapwood boundary, the average date of this would be AD 1363. Using a 95% confidence limit for the amount of sapwood on mature oaks from this part of England of 15 – 50 rings would give the timbers represented by these samples an estimated felling date in the range AD 1378 to AD 1413. It is most probable that this represents the felling date for all the other dated timbers.

It would thus appear that, as previously believed, the roof of the north transept is indeed of late fourteenth- or early fifteenth-century date.

A single sample, NWC-C05 remains undated. This sample has 67 rings, sufficient for satisfactory analysis, and it shows no signs of complacency or distress that might make cross-matching and dating difficult. It is possible that the timber represented, a common rafter, is of a different date to the other timbers sampled though it did not show signs of being a modern replacement.

If at any time the boards covering the roof are removed, or if any internal scaffolding is put in place, it would certainly be worthwhile examining, and probably coring, the other timbers. Sapwood might be available on the upper faces of the moulded timbers, or at points nearer the ridge which were beyond reach at the time of this programme of sampling.

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Table 1: Details of samples from the north transept roof, St Nicholas' Cathedral, Newcastle upon Tyne

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
NWC-C01	East brace, truss 2	171	h/s	AD 1189	AD 1359	AD 1359
NWC-C02	West brace, truss 2	112	no h/s	AD 1196	------	AD 1307
NWC-C03	West wall post, truss 2	86	no h/s	AD 1240	------	AD 1325
NWC-C04	East common rafter 3, bay 2	56	no h/s	AD 1228	------	AD 1283
NWC-C05	East common rafter 4, bay 2	67	no h/s	------	------	------
NWC-C06	West common rafter 5, bay 2	101	no h/s	AD 1208	------	AD 1308
NWC-C07	East brace, truss 3	114	no h/s	AD 1228	------	AD 1341
NWC-C08	West brace, truss 3	101	h/s	AD 1267	AD 1367	AD 1367
NWC-C09	East common rafter 2, bay 3	57	no h/s	AD 1191	------	AD 1247
NWC-C10	East brace, truss 4	102	h/s	AD 1261	AD 1362	AD 1362
NWC-C11	West brace, truss 4	118	no h/s	AD 1187	------	AD 1304

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

Table 2: Results of the cross-matching of site chronology NWCCSQ04 and relevant reference chronologies when first ring date is AD 1187 and last ring date is AD 1367

Reference chronology	Span of chronology	*t*-value	
Finchale Priory, Co Durham	AD 1174 - 1369	10.7	(Howard *et al* forthcoming)
England	AD 401 - 1981	6.5	(Baillie and Pilcher 1982 unpubl)
Carlisle Guildhall, Cumbria	AD 1054 - 1397	5.9	(Howard *et al* 1994)
Angle Choir, Lincoln Cathedral	AD 912 - 1238	5.9	(Laxton and Litton 1988)
Hansacre Hall, Staffs	AD 965 - 1279	5.9	(Esling *et al* 1990)
Horninglow St, Burton on Trent, Staffs	AD 1101 - 1345	5.8	(Howard *et al* 1995)
Manor House, Burton on Trent, Staffs	AD 1162 - 1339	5.7	(Howard *et al* 1999)
High Street, Burton on Trent, Staffs	AD 1156 - 1387	5.3	(Howard *et al* 1997)
East Midlands	AD 882 - 1981	4.1	(Laxton and Litton 1988)

Figure 1: Map to show general location of St Nicholas' Cathedral

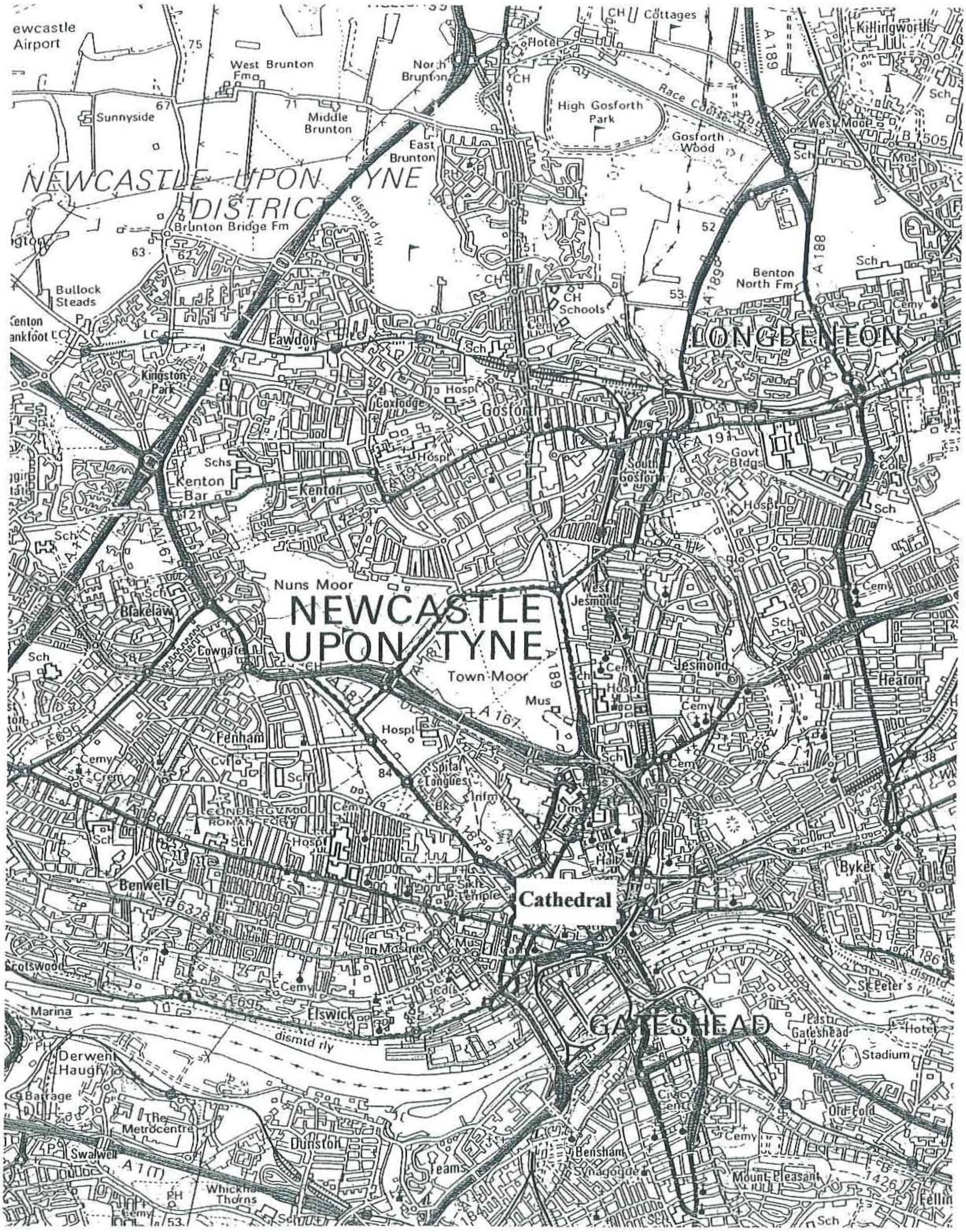


Figure 2: Plan to show approximate position of timbers sampled

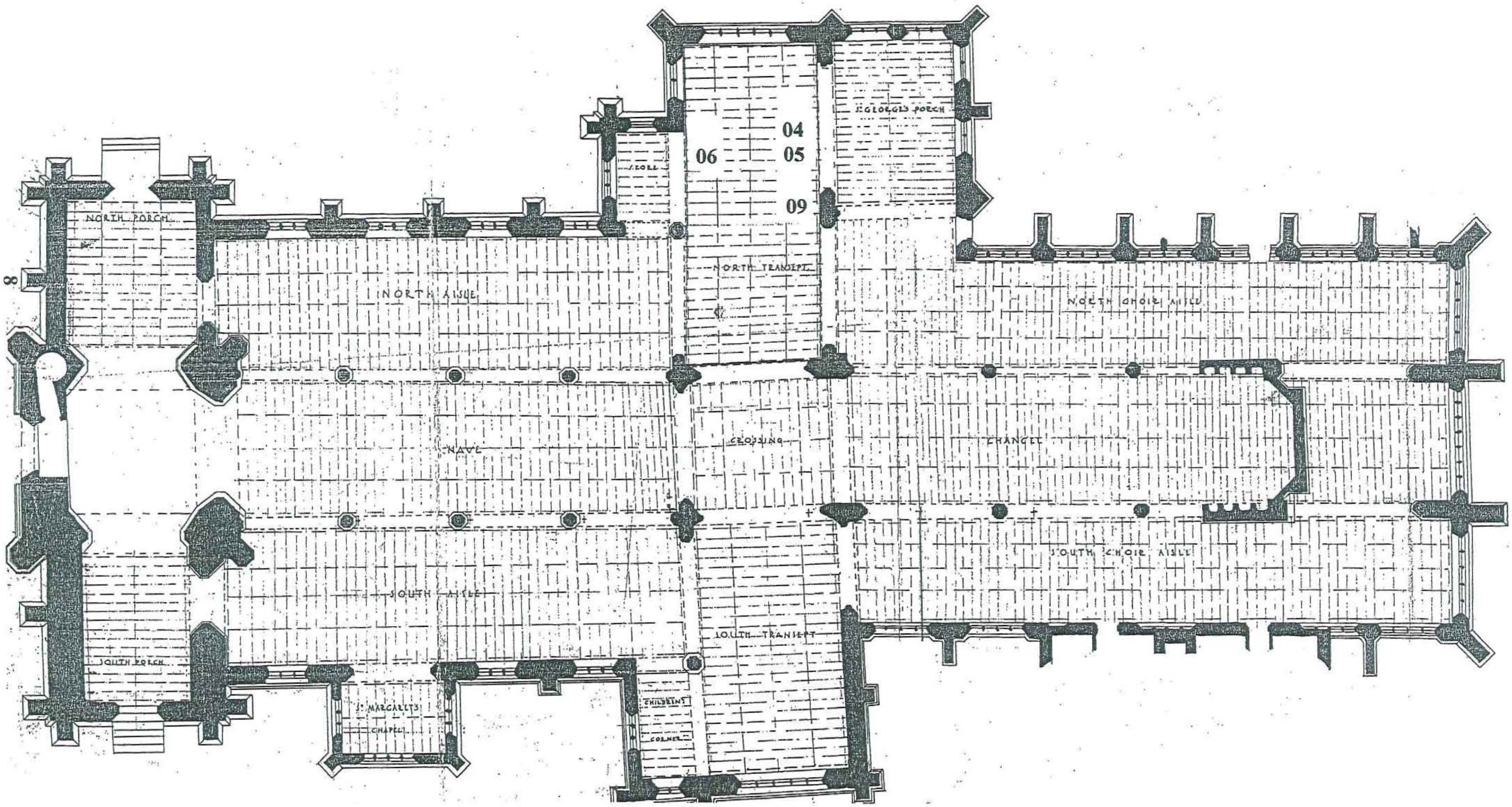


Figure 3a: Drawing to show timbers sampled (truss 2 viewed from the south looking north)

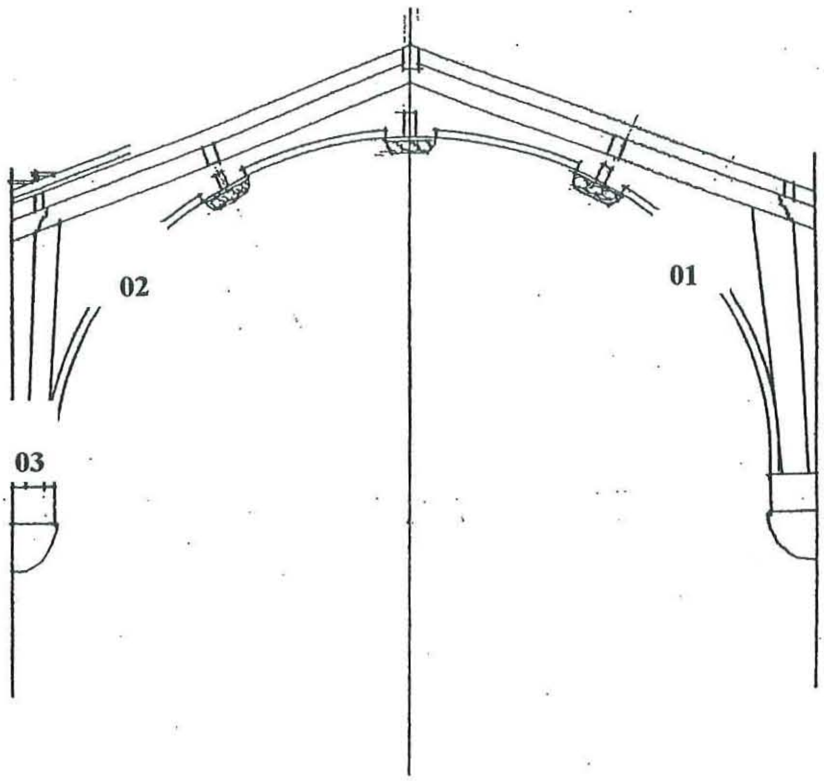


Figure 3b: Drawing to show timbers sampled (truss 3 viewed from the south looking north)

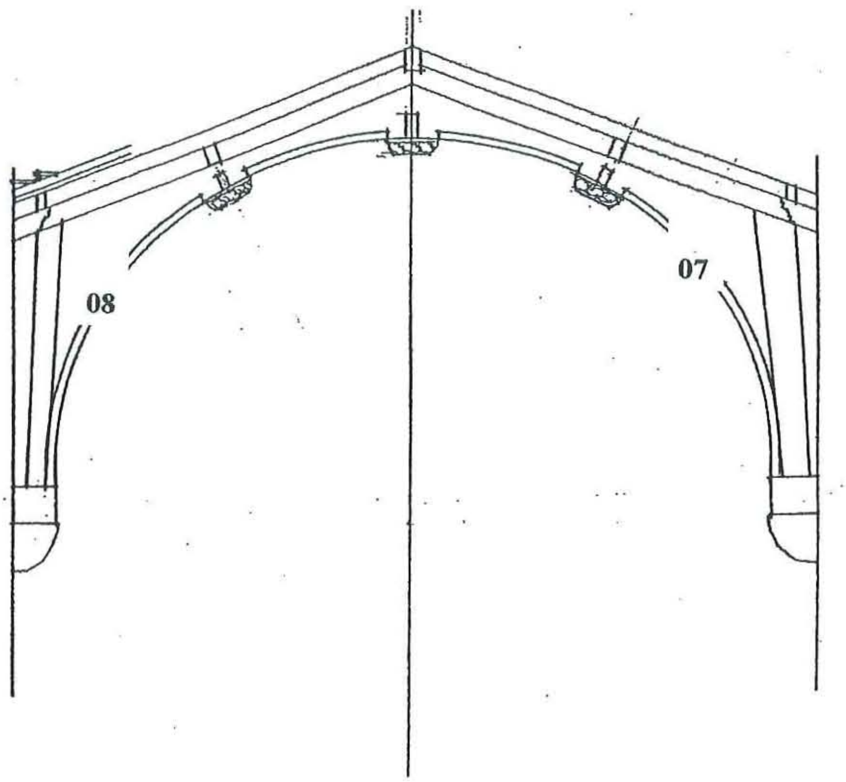


Figure 3c: Drawing to show timbers sampled (truss 4 viewed from the south looking north)

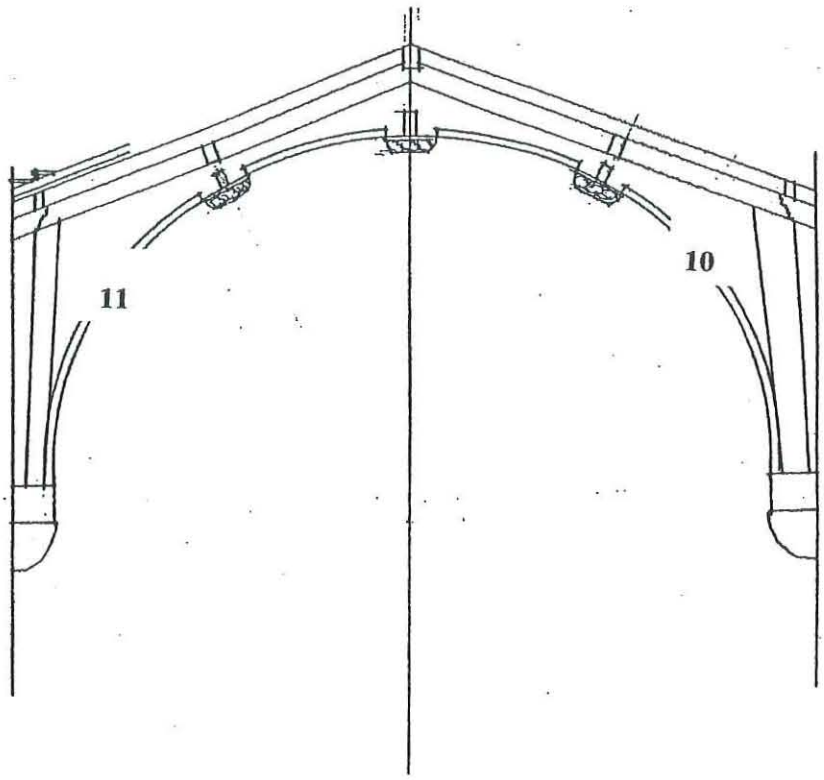
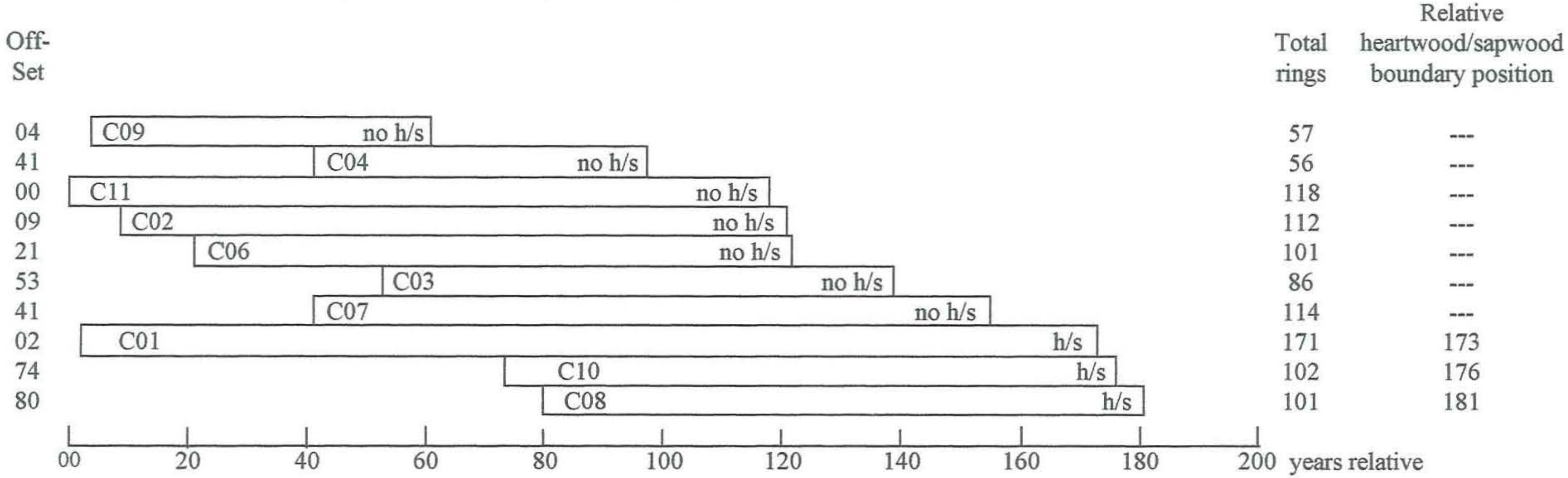


Figure 4: Bar diagrams of the samples in site chronology NWCCSQ04



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

Data of measured samples – measurements in 0.01 mm units

NWC-C01A 171
201 202 145 155 104 230 207 299 297 443 397 286 358 293 438 258 337 249 226 335
338 276 314 293 236 309 325 248 329 316 390 367 322 193 217 241 173 155 141 166
166 183 154 144 152 154 121 78 129 94 139 72 68 53 71 60 60 102 162 173
111 134 109 70 116 79 81 70 86 86 94 85 103 152 140 99 113 156 141 192
134 169 194 136 142 127 97 138 201 125 160 207 196 146 213 300 242 284 272 315
268 174 140 287 196 109 103 159 158 136 89 130 178 158 188 146 207 215 209 119
237 158 120 143 203 160 132 160 186 169 174 137 169 174 175 183 185 155 144 104
156 147 123 123 175 109 190 99 108 172 195 133 69 175 112 80 160 143 228 268
264 188 161 132 193 160 127 168 192 124 210
NWC-C01B 171
199 210 149 171 132 191 105 337 225 460 374 297 354 318 437 305 336 271 211 322
327 278 328 298 238 319 315 263 330 304 387 345 342 203 217 227 189 174 136 152
164 186 170 138 156 145 115 89 121 119 126 70 64 57 74 65 53 106 164 170
115 140 103 74 116 84 74 77 83 78 100 87 117 138 150 110 107 159 147 222
135 150 184 140 138 118 92 137 207 102 166 197 207 159 203 307 236 288 252 346
257 164 136 262 188 128 100 155 167 141 90 160 173 184 144 180 202 213 215 141
222 179 100 175 168 160 126 182 185 152 182 145 155 178 182 181 190 150 147 102
135 156 120 124 173 105 182 116 109 166 203 124 82 173 116 81 152 156 219 275
262 191 164 128 198 154 134 172 173 136 187
NWC-C02A 112
273 253 389 263 279 207 207 227 230 323 385 261 291 256 290 444 413 362 293 298
268 302 280 319 410 513 415 471 422 423 298 268 359 415 279 296 277 227 317 387
227 485 346 429 383 394 389 425 418 492 443 556 537 391 296 336 226 257 340 418
322 385 242 361 201 279 228 321 286 249 243 269 355 258 115 279 293 306 192 219
295 351 255 239 214 333 342 369 410 450 283 253 183 172 207 178 253 221 285 270
306 310 212 158 224 312 249 270 222 242 183 234
NWC-C02B 112
305 261 382 250 244 268 210 215 230 353 407 279 290 240 292 400 383 385 298 291
250 303 292 337 433 500 393 491 425 428 286 247 356 399 289 308 294 230 300 395
216 484 349 440 377 385 384 434 414 494 451 549 533 399 283 350 228 255 337 407
310 379 245 371 198 278 238 338 303 225 265 275 363 248 127 263 297 294 197 224
289 350 251 248 215 334 345 369 403 463 294 251 166 169 210 185 253 225 272 276
293 315 218 145 224 307 237 303 187 260 176 242
NWC-C03A 86
177 154 181 180 223 222 190 251 254 148 134 151 140 175 253 239 198 203 163 119
83 90 123 140 130 83 121 88 115 113 91 146 102 91 80 90 110 112 69 83
87 128 155 143 118 102 111 79 101 83 88 83 92 104 91 78 83 85 94 90
66 75 69 63 62 84 89 76 48 65 76 79 84 57 48 58 62 88 88 77
82 95 109 120 90 60
NWC-C03B 86
191 142 159 180 246 209 183 272 267 135 144 165 137 173 250 256 193 197 149 116
83 94 111 150 130 88 114 90 110 122 103 131 108 87 85 87 107 106 79 77
92 119 154 145 109 95 107 80 94 97 75 71 83 106 82 72 81 98 89 84
65 79 68 57 59 78 93 75 50 65 69 88 72 60 56 60 50 95 86 69
83 92 110 124 95 61

NWC-C04A 56
163 159 158 119 133 117 191 255 192 290 166 234 182 179 251 160 164 159 148 157
150 163 161 130 110 124 118 139 171 150 120 102 81 108 160 146 134 121 124 130
120 154 83 114 110 88 83 79 83 118 89 92 94 87 87 93
NWC-C04B 56
154 161 166 117 136 122 195 274 186 291 175 239 200 168 200 173 126 138 144 174
148 150 188 115 107 121 121 142 147 151 131 95 79 111 165 160 127 112 126 136
112 152 97 100 98 96 83 78 85 121 102 95 102 80 95 99
NWC-C05A 67
94 94 78 76 106 74 125 174 140 130 133 187 123 139 178 209 135 199 230 168
215 193 200 176 170 132 144 138 139 160 118 163 111 81 95 81 95 106 102 157
144 189 132 143 109 180 161 203 252 200 163 244 355 221 150 165 184 181 229 184
194 180 219 169 113 182 193
NWC-C05B 67
90 100 72 81 103 68 130 171 149 133 137 174 119 146 188 196 148 199 229 160
206 207 198 174 178 130 144 138 135 156 128 157 106 82 108 70 101 105 106 151
147 177 135 150 103 181 159 214 252 194 166 241 351 215 149 150 182 192 216 196
179 184 215 169 103 198 197
NWC-C06A 101
178 160 146 176 122 162 136 160 167 224 183 201 199 152 154 144 174 149 137 162
188 202 178 138 117 170 177 177 97 135 82 93 74 83 83 104 107 133 124 193
170 137 144 151 141 173 253 238 198 203 163 120 119 114 138 164 145 114 190 173
193 184 152 197 244 277 221 185 153 182 171 207 179 151 148 169 198 200 210 184
179 211 177 210 276 222 191 188 209 274 206 175 195 236 190 182 171 251 285 260
261
NWC-C06B 101
177 162 151 165 118 164 136 155 168 229 206 213 191 147 156 150 193 131 146 154
190 204 165 144 127 172 181 179 94 143 87 89 72 70 98 107 115 128 132 193
170 135 134 165 137 175 250 256 192 197 145 115 129 121 131 175 133 117 206 158
194 162 150 194 249 265 225 190 157 183 174 196 178 143 163 158 208 205 199 190
190 197 192 193 277 215 207 158 232 273 206 163 210 225 199 183 174 239 283 252
230
NWC-C07A 114
164 159 158 128 136 117 191 251 193 294 192 279 193 142 180 150 223 223 190 250
254 148 162 157 108 149 192 226 180 217 186 171 103 201 361 239 262 219 212 222
246 153 130 186 179 178 112 119 148 196 145 144 124 159 187 218 277 259 226 208
94 113 141 148 217 206 204 148 195 257 226 141 162 189 192 175 128 157 142 211
135 238 188 68 54 36 50 52 74 92 87 75 82 92 109 124 89 69 47 50
93 89 75 89 59 61 82 55 70 97 108 85 90 202
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134 161 166 118 133 122 195 277 187 290 185 294 178 164 158 181 246 207 183 273
267 135 159 159 83 146 211 231 172 194 220 141 107 210 299 281 262 209 227 208
260 153 126 186 181 172 119 121 150 194 144 134 125 169 187 217 274 261 238 175
116 118 167 139 220 176 194 163 216 228 222 153 169 189 175 182 141 170 128 213
139 234 227 71 59 43 44 64 69 80 92 71 83 96 110 120 95 61 54 54
93 93 73 84 72 48 84 52 62 91 110 97 102 184

NWC-C08A 101
85 138 118 106 131 118 124 120 88 101 128 108 89 119 116 102 86 102 92 135
134 176 147 134 173 163 138 127 150 157 120 131 91 93 127 133 161 128 181 159
166 169 194 221 161 198 170 214 156 163 214 137 159 161 204 246 222 183 187 179
226 141 133 155 154 199 225 162 182 140 122 183 185 163 123 169 111 55 193 131
197 261 290 246 198 155 226 224 143 191 171 157 150 117 141 142 159 119 179 239
208
NWC-C08B 101
138 120 118 108 137 128 108 114 83 103 129 108 95 107 117 91 108 94 120 118
133 176 130 138 164 198 124 154 154 172 120 125 99 92 128 133 142 140 182 147
148 158 172 220 175 167 173 193 132 144 224 129 153 155 199 276 235 185 186 183
233 144 135 154 143 192 243 158 224 165 129 190 186 158 138 173 120 70 204 118
198 270 301 232 189 143 230 215 153 198 154 145 148 126 137 138 155 122 185 218
222
NWC-C09A 57
237 151 131 179 228 167 145 188 183 115 130 154 231 153 97 161 113 170 165 190
150 152 176 136 160 150 215 171 160 203 130 111 146 164 105 100 124 154 195 166
128 116 159 196 162 126 187 162 156 161 122 136 131 136 160 175 197
NWC-C09B 57
202 160 131 175 207 175 122 182 177 134 149 151 220 146 101 172 111 175 169 191
169 144 162 140 175 148 217 172 161 178 133 118 130 166 107 104 113 147 191 157
132 103 170 197 180 134 188 145 174 165 126 125 143 136 158 174 189
NWC-C10A 102
267 251 286 368 484 525 326 298 179 159 140 119 193 198 165 188 308 262 192 149
128 203 401 437 569 468 326 312 140 167 147 283 215 233 240 283 525 401 344 427
399 392 323 222 286 462 409 260 398 291 264 236 270 244 170 196 369 318 384 412
298 574 423 431 403 248 223 118 76 104 104 217 311 188 205 157 124 157 181 160
180 276 172 132 296 220 240 314 449 315 262 232 186 215 199 266 282 266 154 151
175 195
NWC-C10B 102
213 254 275 361 496 507 312 301 157 146 130 127 204 200 139 212 335 280 212 155
135 219 378 423 591 485 330 318 147 144 167 226 224 221 236 299 520 408 349 413
397 399 323 228 303 440 430 278 399 292 265 230 284 232 170 200 305 330 382 413
312 565 427 427 396 270 225 101 62 111 100 223 316 187 197 171 137 166 191 155
183 282 156 146 276 235 227 297 442 304 263 220 201 201 212 266 291 252 170 145
156 196
NWC-C11A 118
188 111 130 210 191 154 176 206 260 239 252 367 541 383 315 317 363 306 230 430
249 350 371 398 328 274 387 243 255 220 373 310 272 422 241 100 108 129 130 95
86 110 155 195 231 184 151 160 198 87 104 80 110 95 97 81 128 145 147 142
188 144 178 176 125 127 251 226 343 163 263 234 239 111 188 236 229 212 184 235
194 332 294 177 292 227 226 239 147 218 254 215 168 171 157 145 172 246 204 186
148 158 144 154 159 258 273 236 166 201 261 220 154 210 231 212 250 263
NWC-C11B 118
158 121 128 207 196 159 185 193 242 242 246 377 541 382 417 297 407 340 223 356
246 353 370 401 325 260 397 271 279 215 369 319 271 421 251 127 97 119 130 88
76 95 152 204 247 173 149 182 181 87 109 77 118 83 97 84 135 139 146 136
190 162 165 183 117 110 268 258 348 179 258 239 225 109 206 222 231 201 187 244
191 359 288 175 305 235 226 231 171 214 254 206 173 178 152 149 168 259 191 176
154 156 142 142 170 268 273 244 161 205 250 223 154 213 229 224 234 280

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.

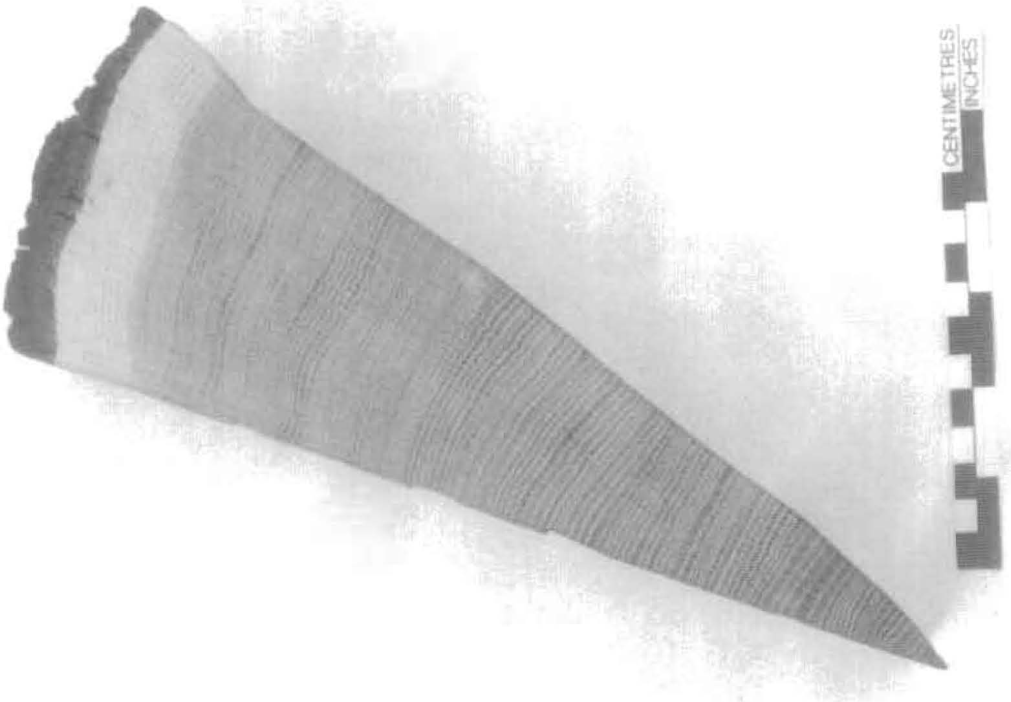

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

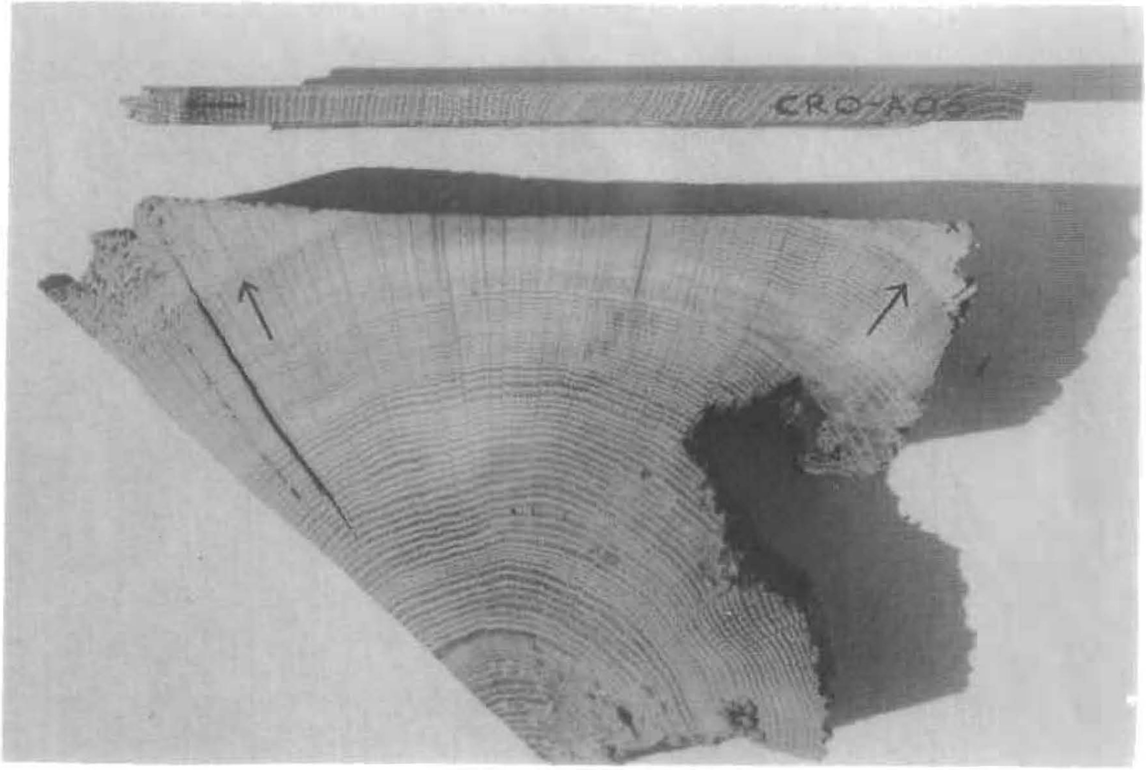

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

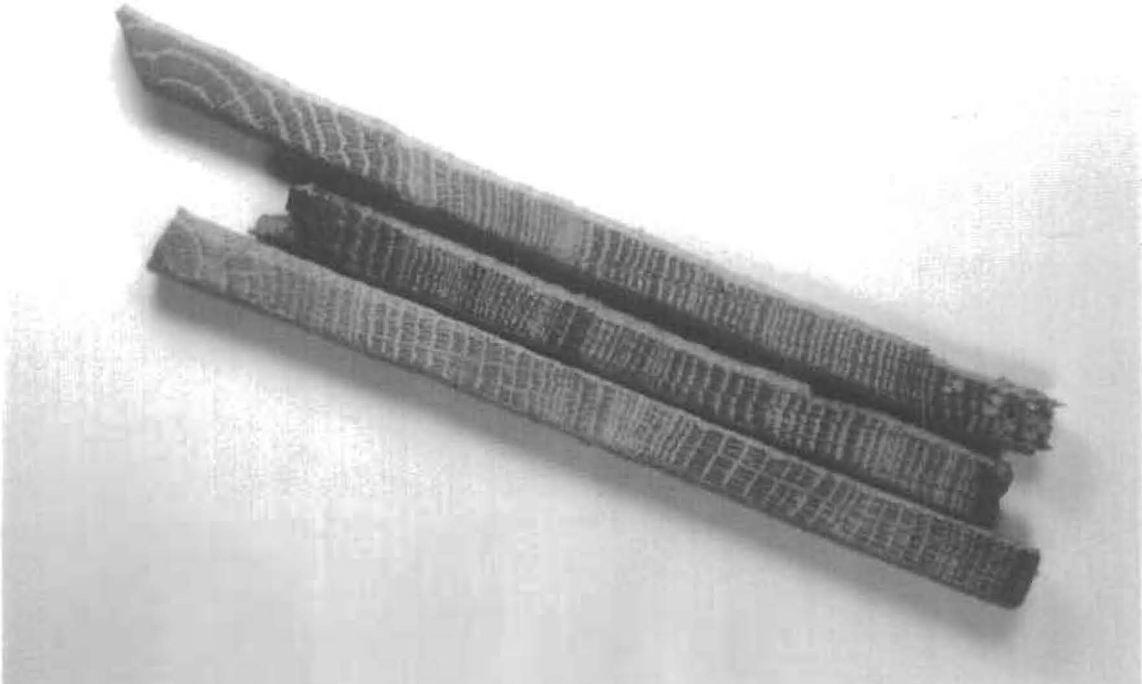

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

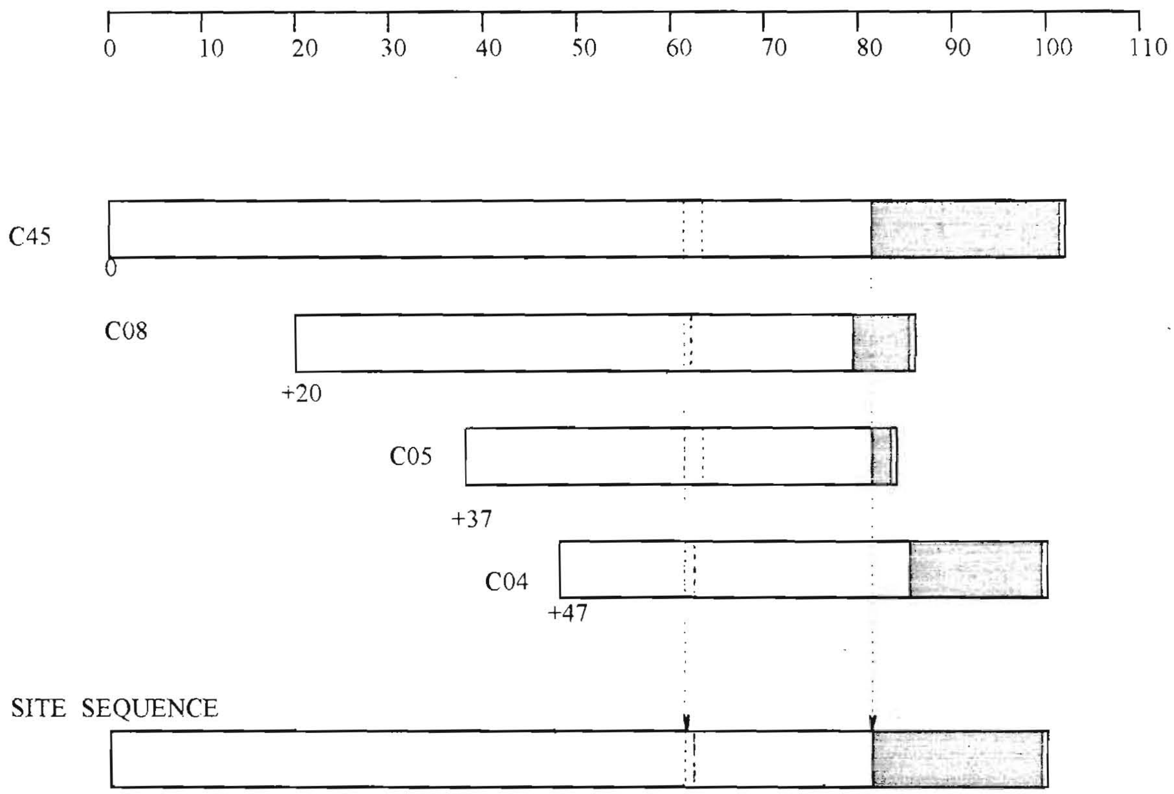

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

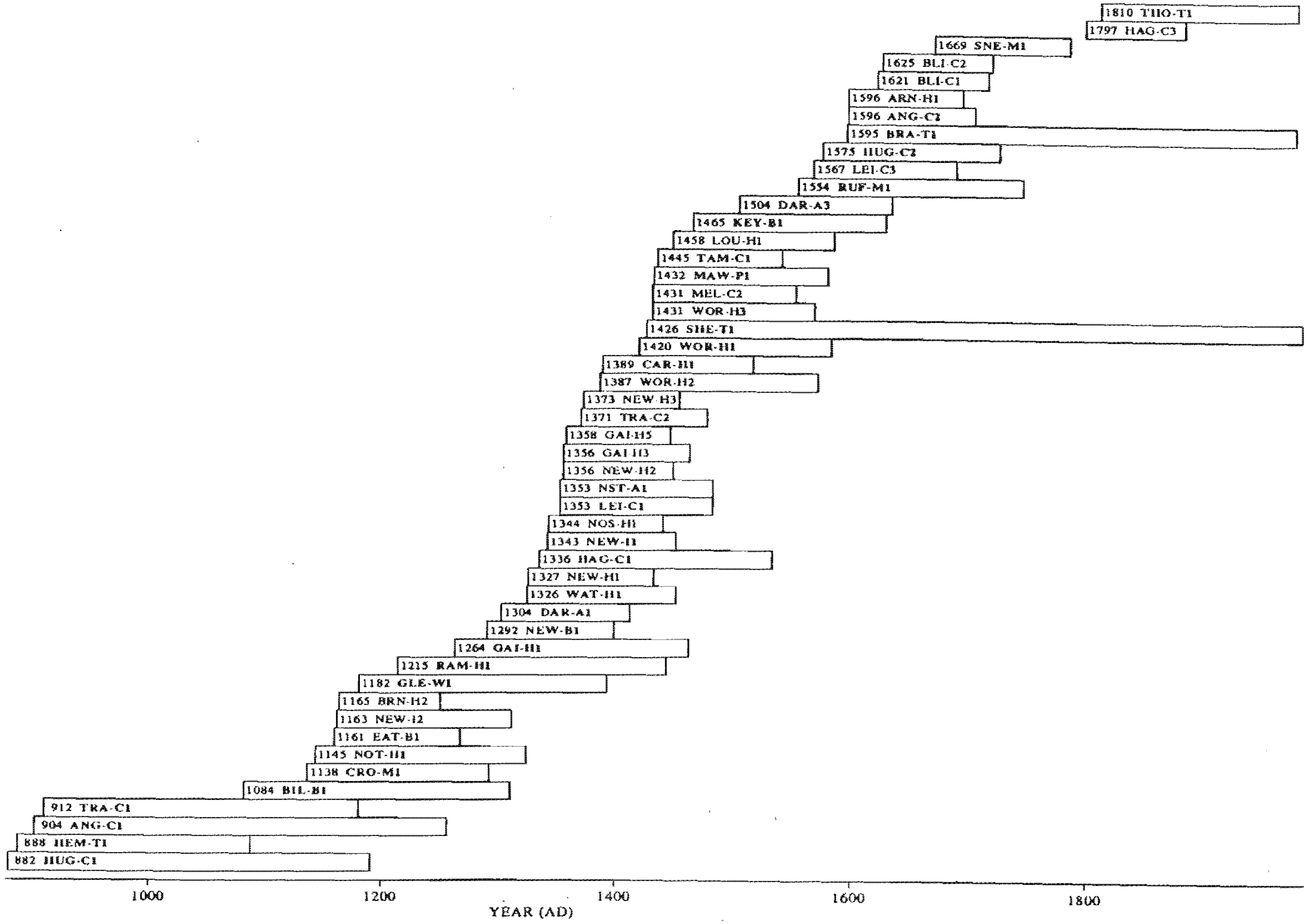

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)

(b)

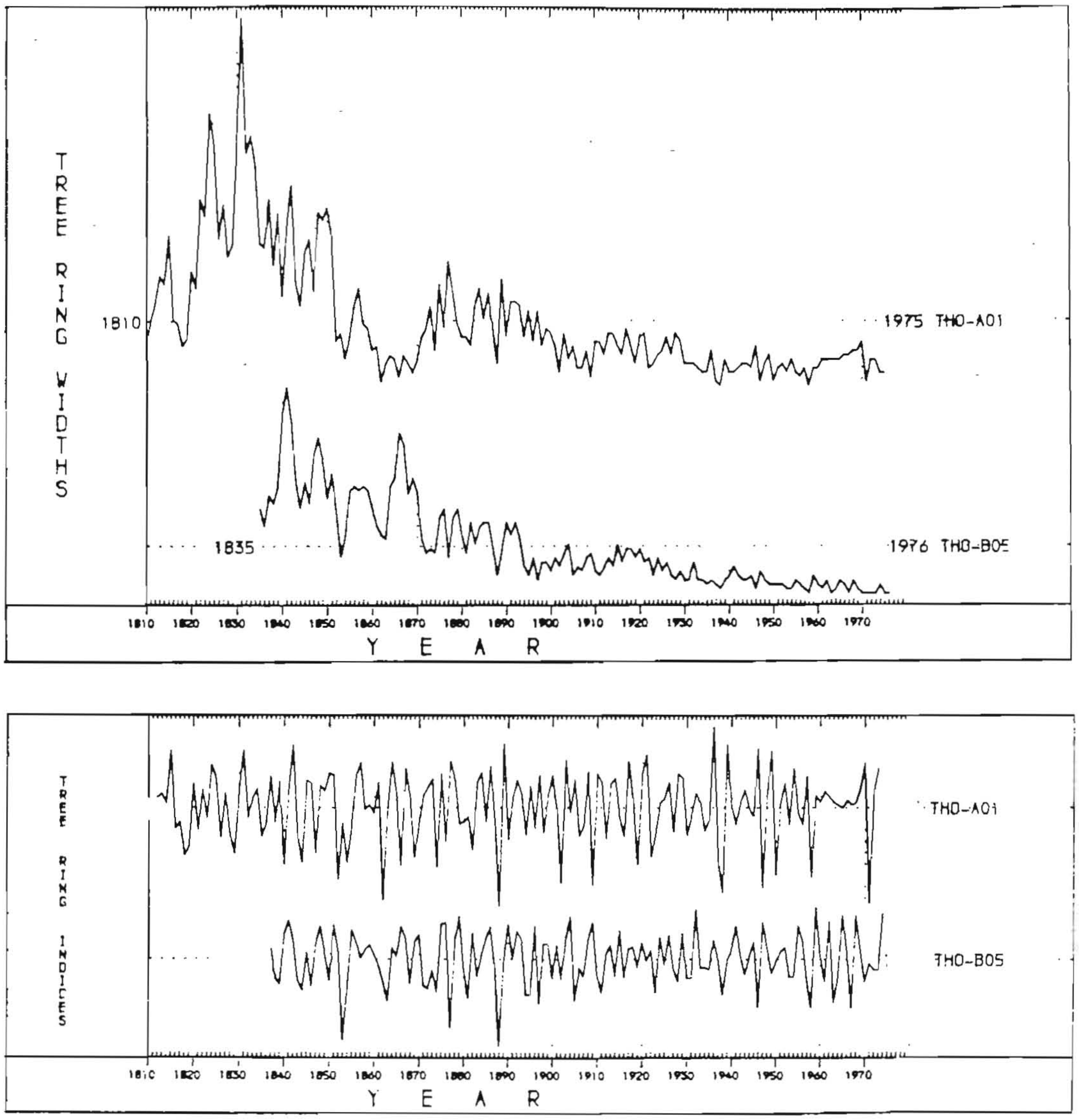

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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