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Tree-Ring Analysis of Timbers from Mount Grace Priory Guesthouse, Saddle Bridge, Northallerton, North Yorkshire

A J Arnold, R E Howard and C D Litton

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Summary

Twenty-seven core samples were taken from timbers of the roof trusses, and inserted first and second floors at this building. Analysis of 26 of these resulted in the construction of five site sequences. Unfortunately, none of these site sequences, or any of the 11 ungrouped samples could be dated by comparison with any available reference chronology, and all samples remain undated.

Keywords

Dendrochronology
Standing Buildings

Author's address

Nottingham Tree-Ring Dating Laboratory, School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD

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Introduction

Set against the hillside beneath the North York Moors, Mount Grace Priory, Staddlebridge (Figs 1 and 2; SE 44889850), is the seventh of eight Carthusian foundations within England, and was established in AD 1398 by Thomas de Holand, Duke of Surrey. The following years saw the construction of the monastery on the site of de Holand's manor of Bordelby. A charter of liberties and franchises was granted to the monks in AD 1399 by Richard II. This and the bestowing of alien priories within England and France provided the priory with temporary financial security.

However, with the death of de Holand in AD 1400 and the loss of several of the alien priories the priory was left in a much weakened state. A situation only improved by the patronage of Thomas de Beaufort, Earl of Dorset in AD 1417. This led to a period of stability and increased popularity for the monastery that continued throughout the fifteenth century and resulted in further expansion in the AD 1470s, and again in the AD 1520s.

The priory survived until the signing of the Act of Surrender in AD 1539, after which its new owner, Sir James Strangways, allowed the buildings to fall into ruin. In AD 1653 the site was purchased by Thomas Lascelles, with whose family the priory remained until AD 1744 when it was acquired by Mauleverers of Arncliffe, and subsequently the Yorkshire Antiquarian William Brown. In AD 1898 the estate was purchased by Sir Lowthian Bell, with the estate passing to the Treasury in AD 1953. The site is now owned by the National Trust and managed by English Heritage.

Mount Grace Priory is today entered through the manor house built by Thomas Lascelles in AD 1654. Lascelles incorporated the southern portion of the fifteenth-century monastic guest range in his house. Entered through a two-storey porch at the centre of its west wall, the ground floor was divided by substantial cross-walls, incorporating fireplaces, into a central hall, northern kitchen, and the southern parlour. Access to the first floor and garrets was via a stair-wing built on the east side of the building, adjacent to the hall. At first-floor level were five bedrooms separated by timber partitions, one of which can still be seen today.

The house was again enlarged and renovated in AD 1900-01 by Sir Lowthian Bell and his architect Ambrose Poynter in the style of the Arts and Crafts movement. The northern, ruinous portion of the monastic guest range was re-roofed, and this, along with the Lascelles manor house, was reorganised into a series of bedrooms, dressing rooms, and bathrooms. Extensions were constructed to the south and north of the stair wing.

The roof under investigation is of seven bays but only five of the trusses are visible (and one of these is almost entirely boxed in). The trusses are of principal rafters and collars. Additionally, some of the principal rafters have a separate piece of wood jointed in at the very bottom of them. The timbers of the trusses are mostly of medieval appearance (in their patina) thus raising the question as to whether they might in fact belong to the original building, thereby making them fifteenth century, or to Lascelles house, placing them in the seventeenth century. There are a number of purlins which are modern replacements.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was hoped that this would provide a clearer understanding of this monument, the best preserved Carthusian monastery in the country. Three areas for investigation were included in the brief. The timbers of the roof trusses, and the first and second-floor inserted floors. Producing dating evidence for the roof would help establish its importance and to inform future work and presentation. Obtaining a date for the inserted first and second floors would help in the understanding of the phasing of these features which are thought to relate to the extension of the building in the sixteenth century and in AD 1901.

The Laboratory would like to thank the site custodians for their advice and assistance with access. The above introduction is based on the English Heritage guide to the site (Coppack 2000).

Sampling

Fifteen core samples were taken from the principal rafters (including three taken from the base sections), and collars of this roof. Only five trusses were accessible, and one of these (truss 3) was almost totally boxed in which meant only the lower principal rafter on the east side could be sampled. Ten samples were taken from the main floor beams of the second floor and two samples from the main floor beams of the first floor. The cores were taken using a 15mm diameter corer attached to an electric drill and the resulting holes filled with dowels, which were stained. Each sample was given the code NMG-P (for Northallerton, Mount Grace Priory) and numbered 01-27. The position of all samples was noted at the time of sampling and has been marked on Figures 3-5. Further details relating to the samples can be found in Table 1. For the purpose of this report roof trusses and ceiling beams have been numbered north to south.

Analysis and Results

At this stage it was noticed that one of the samples (NMG-P19) had too few rings for secure dating, and so was rejected prior to measurement. The remaining 26 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).

Roof timbers

Firstly, five samples matched each other and were combined at the relevant offset positions to form NMGPSQ01, a site sequence of 80 rings (Fig 6).

Three samples matched each other and were combined at the relevant offset positions shown in Figure 7 to form NMGPSQ02, a site sequence of 77 rings (Fig 7).

Three further samples matched each other and were combined at the relevant offset positions to form NMGPSQ03, a site sequence of 74 rings (Fig 8).

Finally, two samples matched each other and were combined at the relevant offset positions to form NMGPSQ04, a site sequence of 123 rings (Fig 9).

Attempts to date these four site sequences and the two ungrouped samples by comparing them against a series of relevant reference chronologies for oak were unsuccessful and all samples remain undated.

Inserted Floors

Comparison of the samples taken from the inserted first and second floors resulted in two samples matching each other. These two samples were combined at the relevant offset positions (Fig 10) to form NMGPSQ05, a site sequence of 128 rings. Attempts to date this site sequence by comparing it against the reference chronologies were unsuccessful and these samples remain undated.

Attempts to date the remaining ungrouped samples by individually comparing them against the reference material were unsuccessful and these samples also remain undated.

Interpretation and Discussion

Analysis of the 15 samples taken from the roof trusses resulted in the construction of four site sequences, one of five samples and 80 rings (NMGPSQ01), a second of three samples and 77 rings (NMGPSQ02), a third again of three samples and 74 rings (NMGPSQ03), and finally the fourth containing two samples and of 123 rings (NMGPSQ04). Despite being compared to an extensive range of reference chronologies from Britain and elsewhere in Europe these, and the remaining two ungrouped roof samples. could not be dated.

The two samples taken from the first-floor inserted floor did not group, and when compared individually against the reference chronologies no consistent match could be found.

Out of the nine samples analysed from the second-floor inserted floor only two grouped, forming a site sequence of 128 rings (NMGPSQ05). Again, attempts to date this site sequence and the ungrouped samples by comparing them with the reference material were unsuccessful and these samples remain undated.

Obviously these results are very disappointing. The most common reason for site chronologies not dating is because of insufficient data, ie, they have a low number of rings or contain only a small number of samples.

The best replicated site sequence here (NMGPSQ01) contains five samples but only has 80 rings, while the longest site sequence of 128 rings (NMGPSQ05) is only constructed from two samples. As such, two of the most common problems are represented at this site.

Additionally, in the case of one of these site sequences, NMGPSQ03, the three samples that it contains match each other at such a high level (sample 8 matches 11 at t=13.0 and 14 at t=10.3 and samples 11 and 14 match each other at t=12.5) as to suggest that all three beams these samples are taken from came from the same tree. This would make the dating of this site sequence as difficult as that of a single sample.

The poor intra-site matching between the samples taken from the beams of the inserted second floor might suggest that again we are not looking at trees from a single source being used in its construction. Indeed, this floor is thought to date to the renovations of AD 1901, by which time it is more likely, that rather than coming from a one local source, the timber yard concerned would be supplied by a number of sources. With these samples not only do we have the acknowledged difficulty of trying to date single samples but also this is compounded by the relative dearth of reference material from this late date.

A final point of interest is that the timbers of the inserted first and second floors tends to be derived from slower grown, older trees than those of the roof.

Bibliography

Coppack, G, 2000 *Mount Grace Priory*, English Heritage. London

Table 1: Details of tree-ring samples from Mount Grace Priory Guesthouse, Staddlebridge, Northallerton, Yorkshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof timbers						
NMG-P01	East principal rafter, truss 1	59	18c(+c5)	----	----	----
NMG-P02	West principal rafter, truss 1	59	h/s	----	----	----
NMG-P03	Collar, truss 1	64	h/s	----	----	----
NMG-P04	East principal rafter, truss 2	58	7c(+c7)	----	----	----
NMG-P05	West principal rafter, truss 2	77	12c(+c5)	----	----	----
NMG-P06	Collar, truss 2	54	--	----	----	----
NMG-P07	East principal rafter (low), truss 3	73	h/s	----	----	----
NMG-P08	East principal rafter (low), truss 4	70	--	----	----	----
NMG-P09	East principal rafter, truss 4	99	h/s	----	----	----
NMG-P10	West principal rafter, truss 4	116	--	----	----	----
NMG-P11	West principal rafter (low) truss 4	70	h/s	----	----	----
NMG-P12	Collar, truss 4	62	h/s	----	----	----
NMG-P13	East principal rafter, truss 6	74	--	----	----	----
NMG-P14	West principal rafter, truss 6	69	h/s	----	----	----
NMG-P15	Collar, truss 6	58	--	----	----	----
Inserted second floor						
NMG-P16	Beam 2	91	--	----	----	----
NMG-P17	Beam 3	56	--	----	----	----
NMG-P18	Beam 4	87	--	----	----	----
NMG-P19	Beam 5	NM	--	----	----	----
NMG-P20	Beam 6	133	--	----	----	----
NMG-P21	Beam 7	70	--	----	----	----
NMG-P22	Beam 8	105	--	----	----	----
NMG-P23	Beam 9	123	--	----	----	----

NMG-P24	Beam 10	104	h/s	----	----	----
NMG-P25	Beam 11	92	--	----	----	----
Inserted first floor						
NMG-P26	Beam 2	68	17	----	----	----
NMG-P27	Beam 3	108	8	----	----	----

*NM = not measured
h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber, all or part lost in sampling

Figure 1: Map to show the location of Mount Grace Priory, Staddle Bridge, North Yorkshire

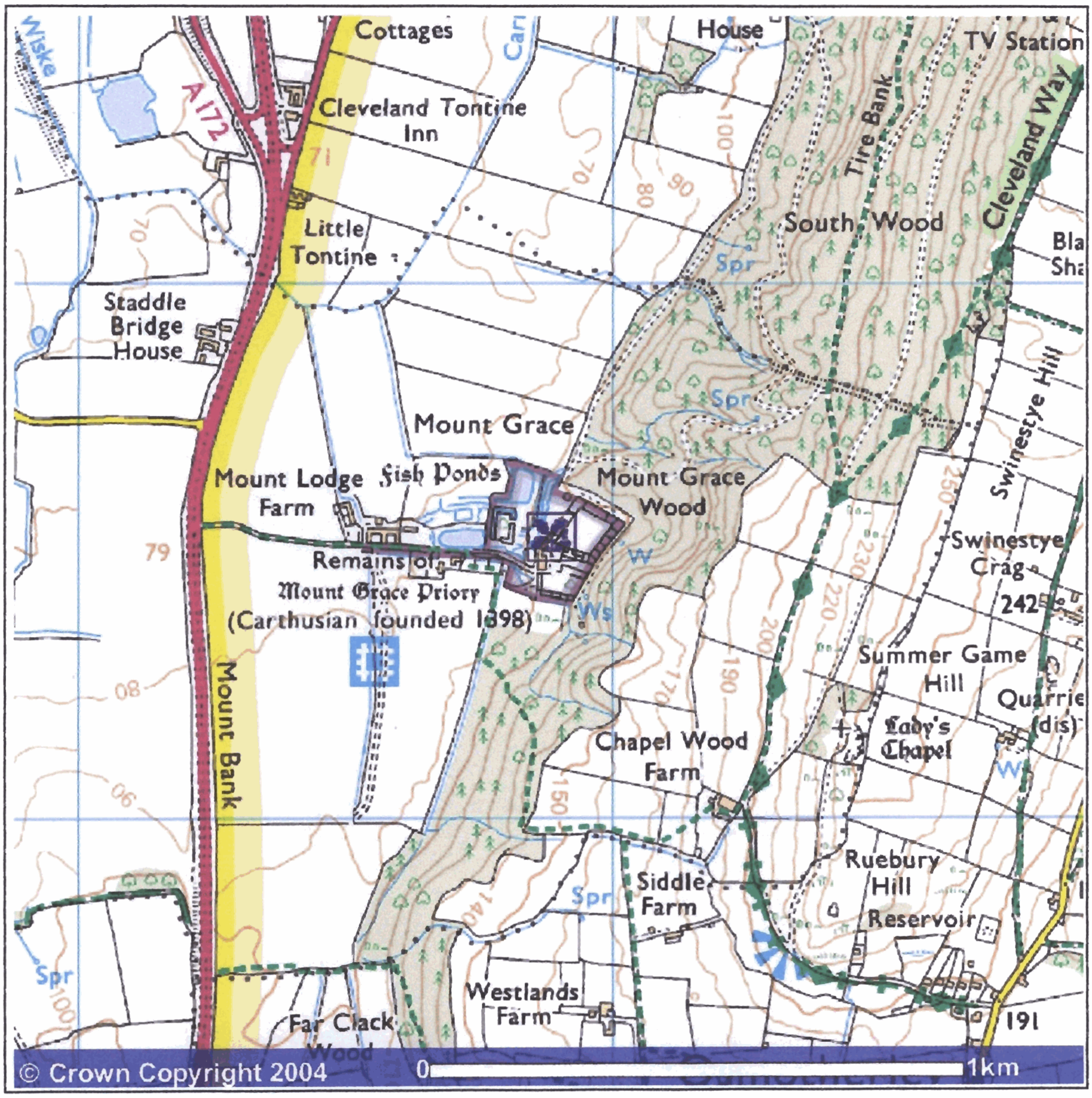

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Figure 2: Site plan, with the guesthouse outlined blue

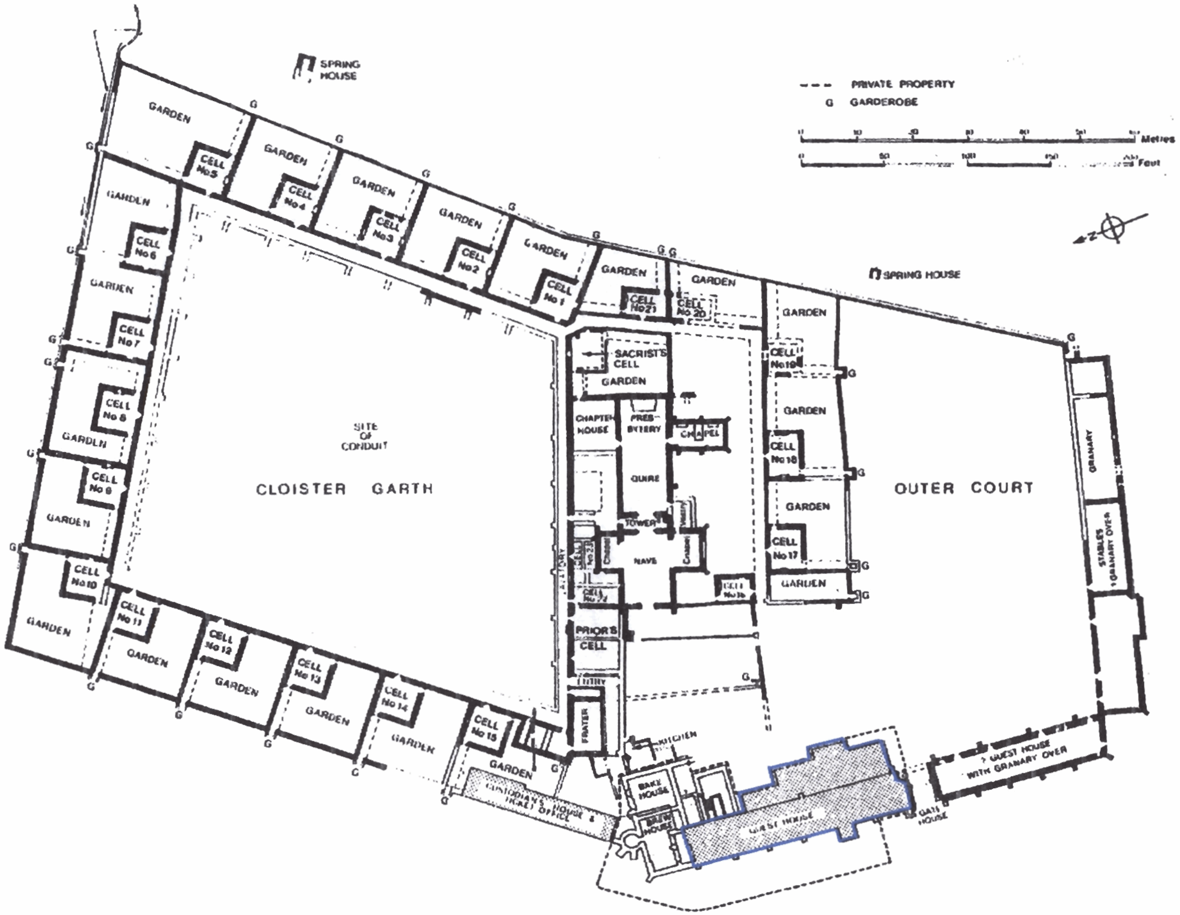


Figure 3: Ground-floor plan, showing the location of samples NMG-P26 and NMG-P27 (Department of the Environment)

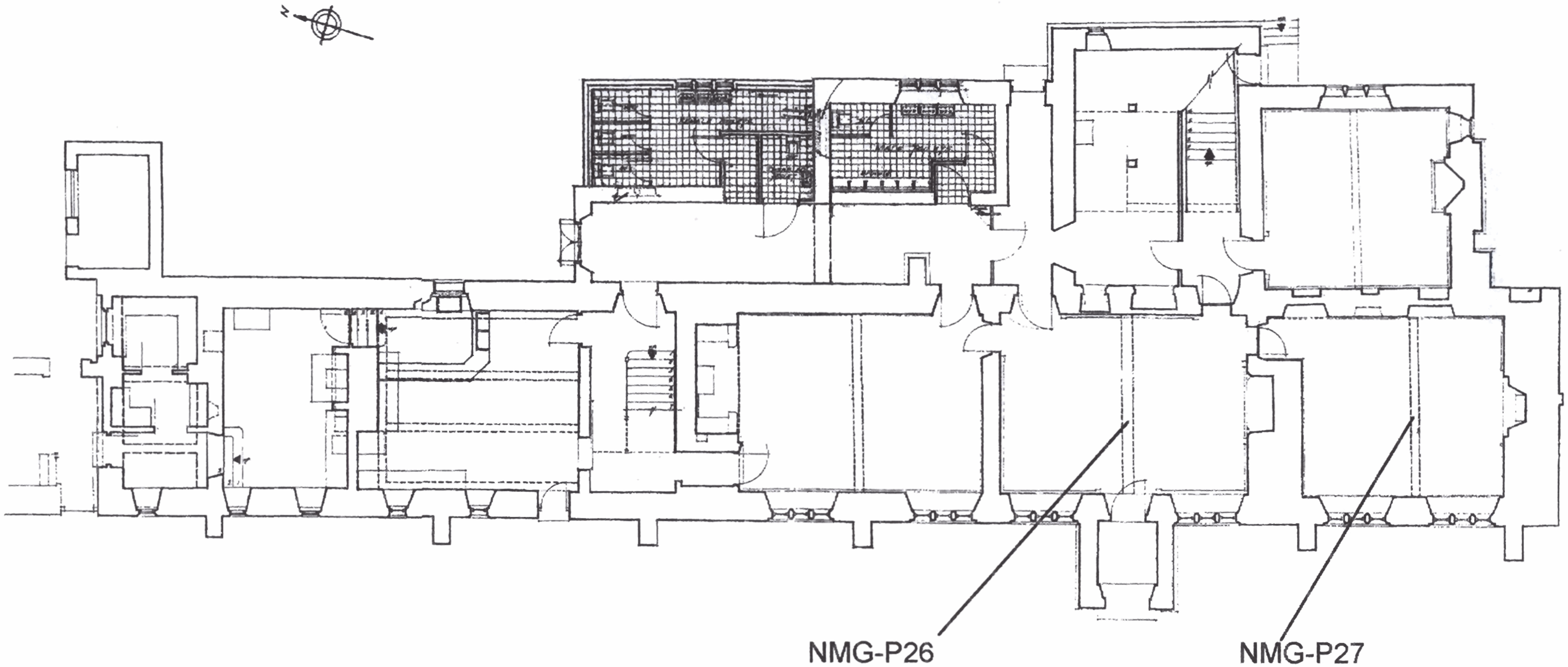


Figure 4: First-floor plan, showing the location of samples NMG-P16-25 (Department of the Environment)

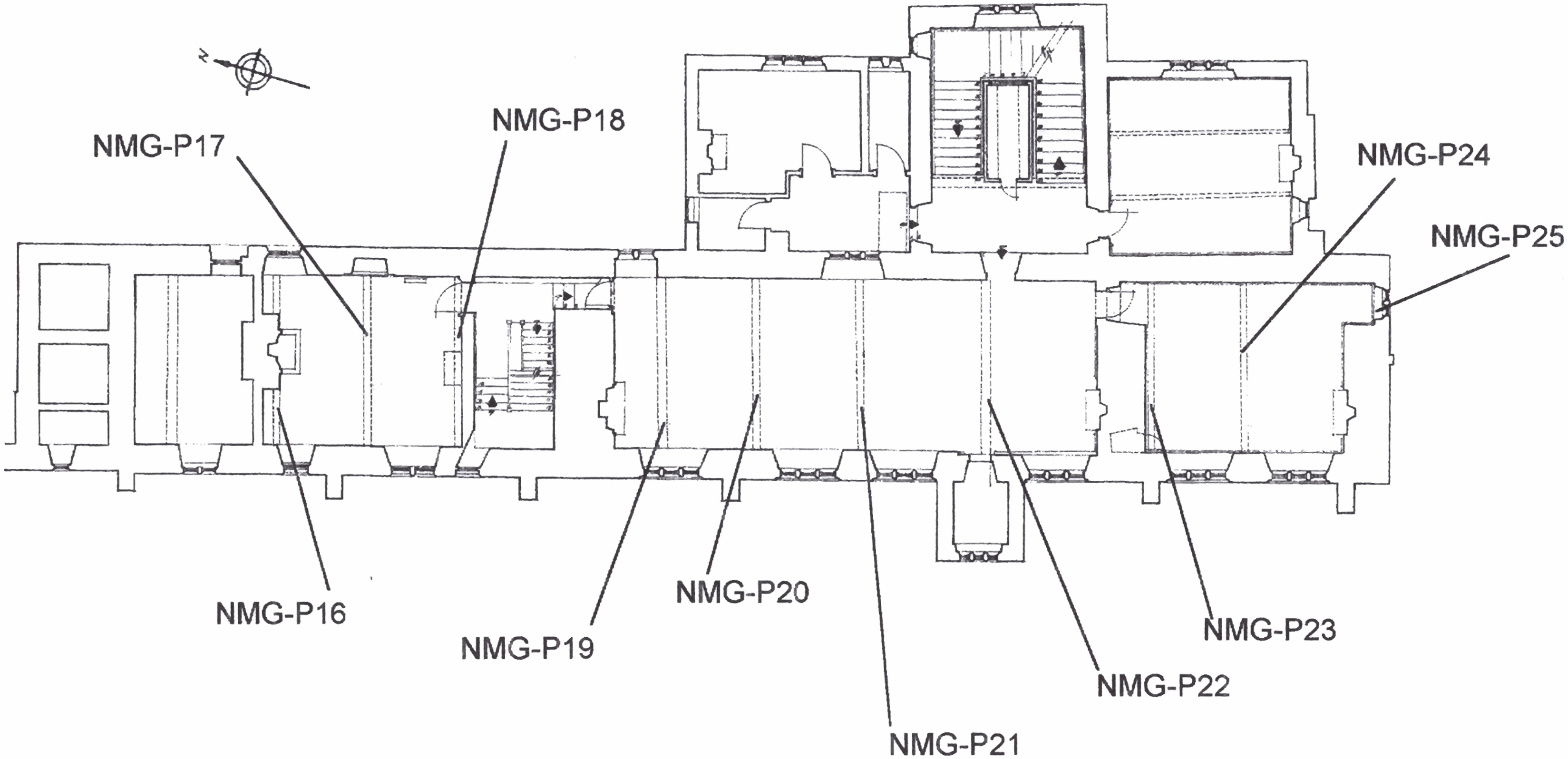


Figure 5: Second-floor plan, showing the location of samples NMG-P01-15 (Department of the Environment)

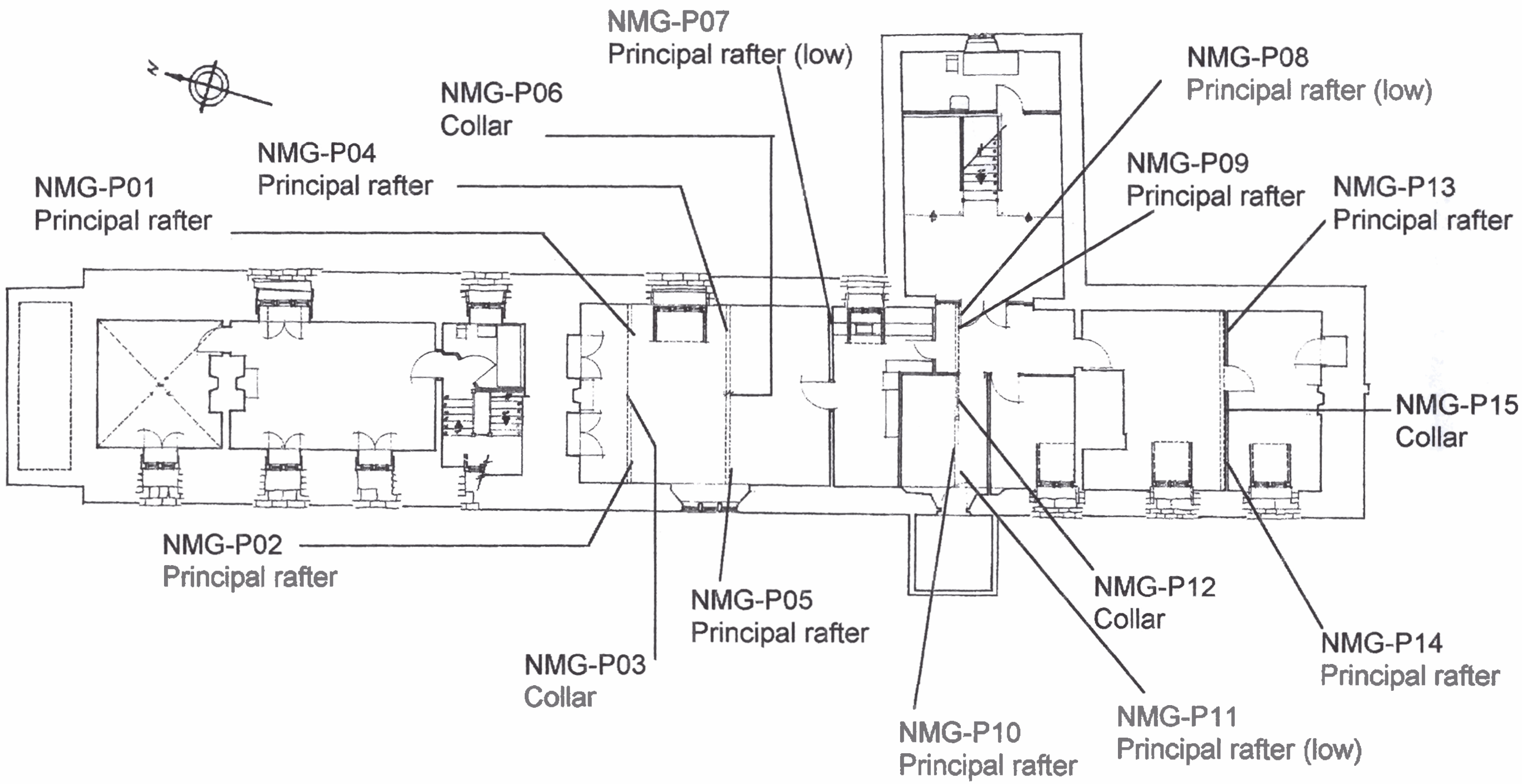
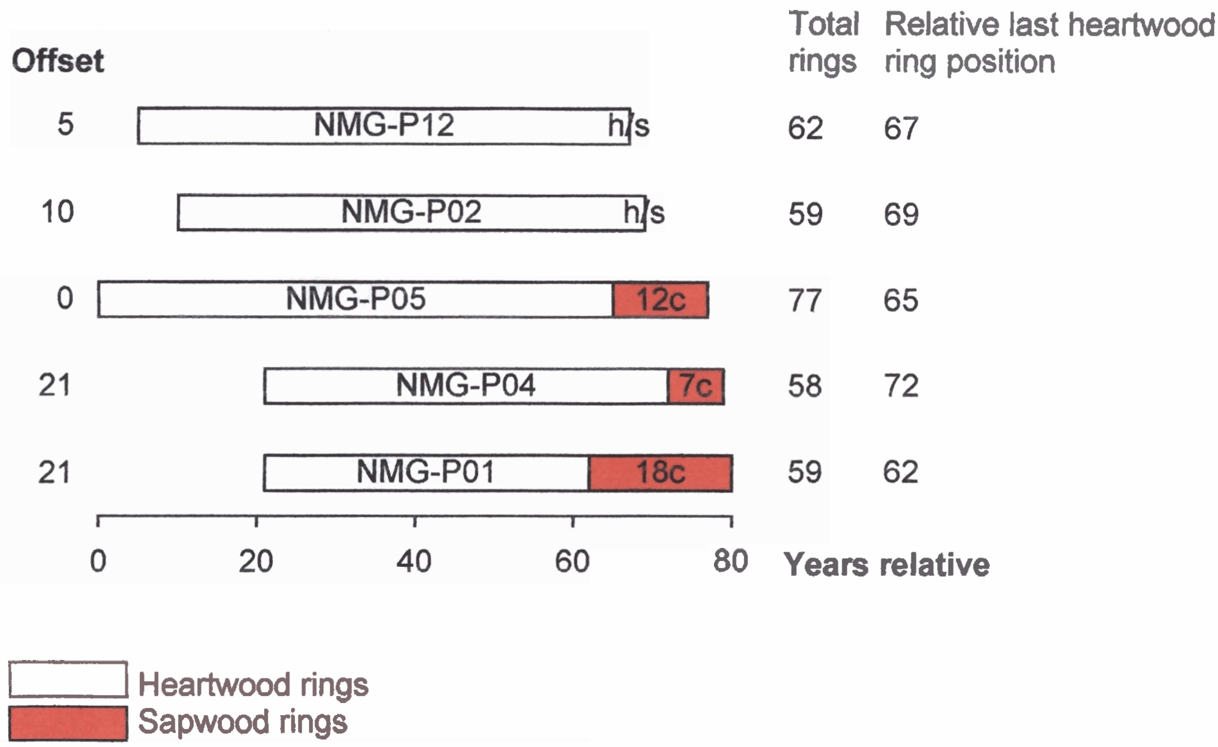
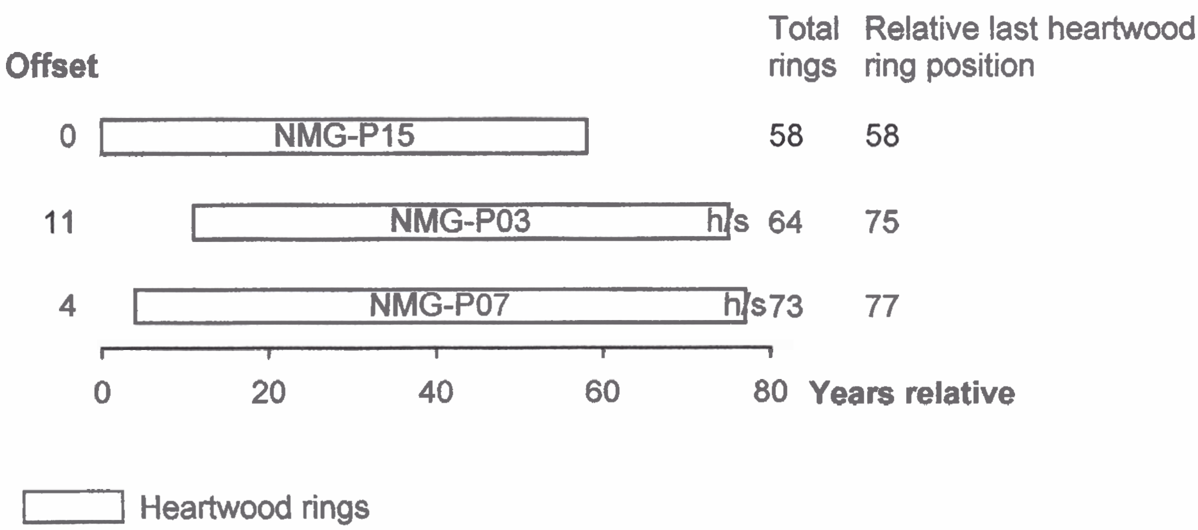


Figure 6 Bar diagram of samples in undated site sequence NMGPSQ01



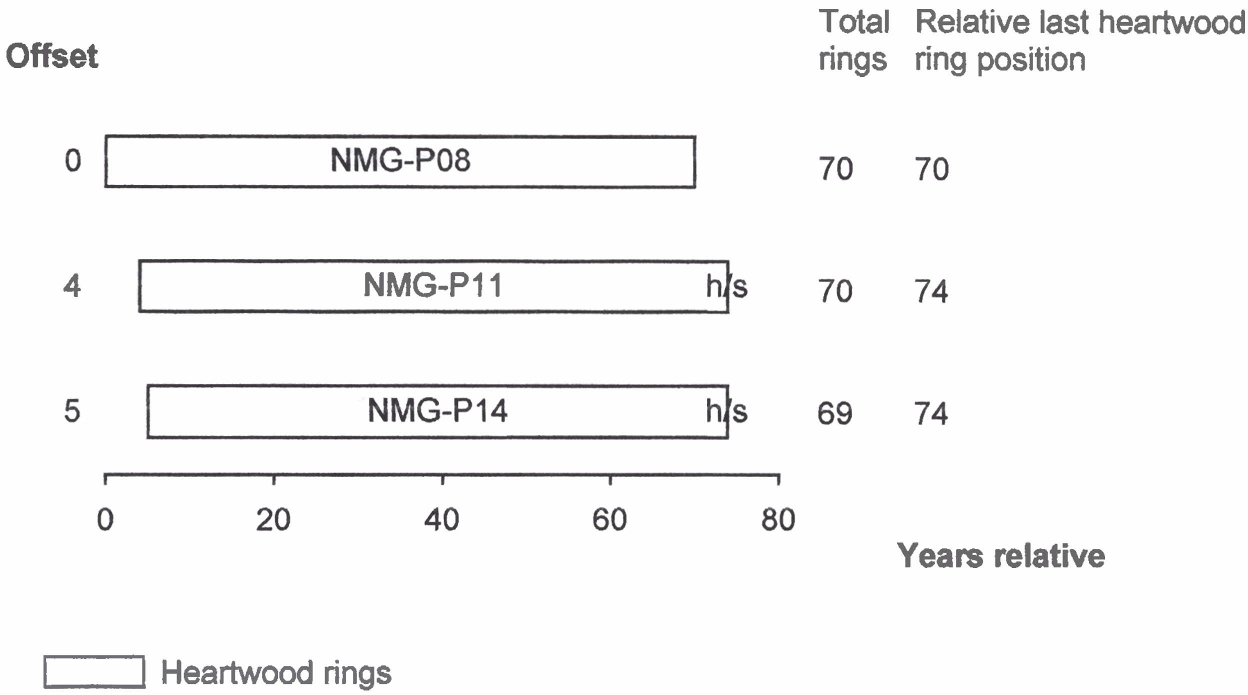
h/s = the heartwood/sapwood boundary ring is the last ring on the sample
c = complete sapwood on timber, part lost in sampling

Figure 7: Bar diagram of samples in undated site sequence NMGPSQ02



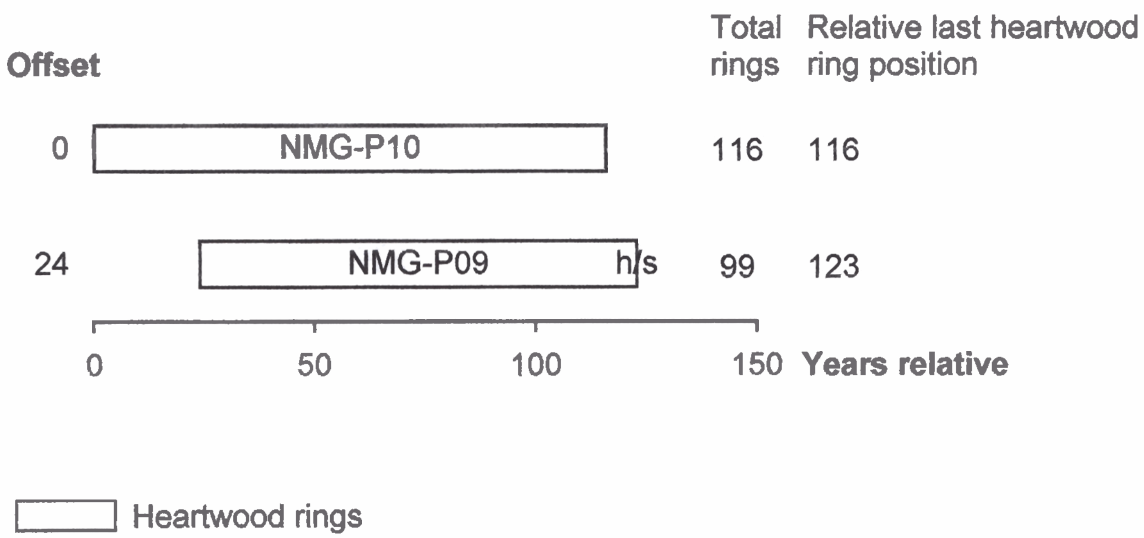
h/s = the heartwood/sapwood boundary ring is the last on the sample

Figure 8: Bar diagram of samples in undated site sequence NMGPSQ03



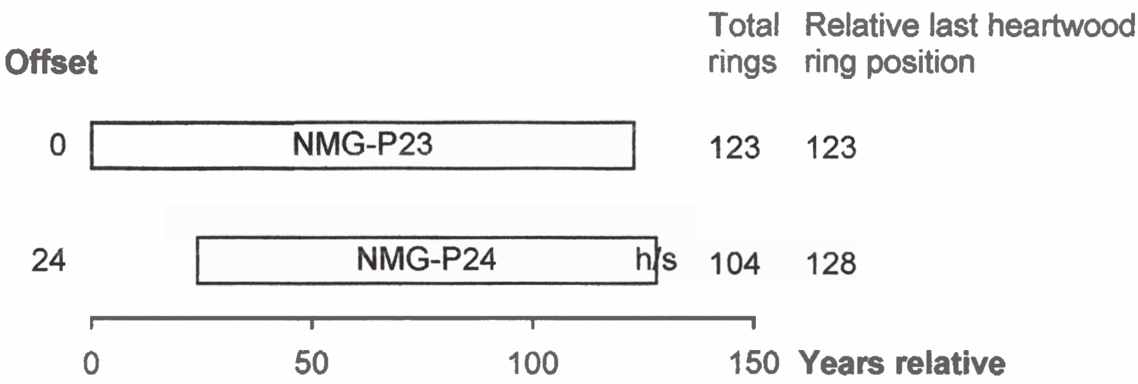
h/s = the heartwood/sapwood boundary ring is the last on the sample

Figure 9: Bar diagram of samples in undated site sequence NMGPSQ04



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

Figure 10: Bar diagram of samples in undated site sequence NMGPSQ05



Heartwood rings

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

Data of measured samples – measurements in 0.01mm units

NMG-P01A 59
222 361 325 294 257 209 61 102 230 131 105 144 237 209 271 194 218 212 190 120
137 143 162 184 181 261 161 258 262 204 176 181 144 212 215 244 212 142 244 226
171 181 198 233 182 133 125 117 169 99 163 140 212 117 69 99 165 160 132
NMG-P01B 59
199 313 320 271 250 204 83 99 233 129 114 135 230 216 284 226 187 209 189 133
126 149 168 182 200 257 156 261 230 219 172 181 150 210 211 244 204 142 243 234
154 189 179 231 186 155 122 106 157 118 150 136 213 131 67 82 173 152 165
NMG-P02A 59
188 285 197 180 183 261 296 309 232 158 264 414 339 334 401 327 366 144 170 236
216 134 269 314 344 268 289 297 260 243 226 241 224 208 228 221 291 214 184 208
222 186 196 196 195 211 227 199 168 236 204 170 229 287 314 215 245 177 177
NMG-P02B 59
190 293 207 170 188 241 294 297 241 169 304 398 346 371 394 339 365 142 172 239
225 150 257 315 350 300 299 291 258 225 251 235 244 207 231 219 310 223 189 227
220 194 190 188 202 195 239 176 166 201 197 159 216 278 314 217 251 156 194
NMG-P03A 64
110 175 172 195 146 119 86 161 206 147 127 160 134 172 128 105 116 145 130 156
167 210 92 67 71 106 160 195 130 178 199 193 153 151 177 158 219 142 165 166
165 156 164 191 132 148 156 161 163 160 182 181 172 216 219 182 237 245 194 155
150 162 182 218
NMG-P03B 64
125 175 171 206 156 118 99 168 182 133 138 152 130 165 113 106 109 139 143 179
167 187 100 74 64 111 182 187 114 167 178 195 140 145 164 155 228 126 169 177
152 150 160 183 156 154 161 156 170 155 189 185 171 212 214 173 243 255 189 170
148 158 180 214
NMG-P04A 58
560 618 520 497 361 288 160 188 384 389 321 344 447 356 358 317 354 311 257 191
129 210 265 364 288 263 186 347 295 294 281 209 259 301 278 234 170 165 199 429
292 375 325 249 292 188 163 185 261 255 370 347 342 179 118 187 318 235
NMG-P04B 58
556 624 525 501 365 282 168 184 383 392 318 335 450 349 367 309 349 318 247 200
126 225 267 355 289 253 201 335 325 273 283 217 235 288 286 235 172 157 199 432
315 366 331 266 280 192 155 179 284 263 377 345 328 181 109 197 316 266
NMG-P05A 77
222 203 168 169 139 165 251 245 238 295 284 248 256 269 309 290 305 287 287 198
263 350 273 294 311 233 213 96 144 263 215 198 288 402 302 332 251 274 265 231
137 84 142 205 276 261 224 161 206 267 211 195 184 162 197 179 158 119 94 123
233 175 205 234 228 161 159 85 120 132 173 216 197 169 175 107 102
NMG-P05B 77
233 203 172 153 150 172 254 245 240 294 284 254 260 268 295 299 307 294 288 201
264 341 286 292 317 240 209 95 155 258 217 198 290 403 295 332 249 280 268 224
138 78 129 219 275 250 224 144 232 267 197 216 168 166 183 192 166 114 101 113
226 177 212 226 225 175 132 92 118 145 162 204 185 152 182 91 131
NMG-P06A 54
151 187 157 188 100 44 31 34 33 23 37 60 72 47 47 55 43 54 47 39
80 110 97 131 163 140 145 163 148 135 198 213 119 135 140 179 153 190 169 139
216 173 196 241 154 142 171 118 137 281 126 185 210 154

NMG-P06B 54
143 200 145 168 97 43 28 32 31 23 37 60 67 50 45 50 44 57 48 39
93 105 86 137 146 129 151 160 161 140 194 213 130 132 136 179 168 192 169 149
212 180 194 246 154 139 161 112 152 271 130 185 216 128
NMG-P07A 73
152 193 211 204 202 217 199 194 189 236 261 210 202 155 230 246 281 250 282 265
238 248 239 278 267 221 227 192 263 138 130 71 137 217 289 205 318 280 382 268
201 220 246 228 219 224 334 198 169 288 230 135 185 198 219 246 308 323 247 176
263 286 257 380 257 299 203 146 201 195 200 292 215
NMG-P07B 73
164 210 207 210 197 215 207 189 174 228 246 234 188 154 225 231 292 246 287 263
250 243 255 261 275 209 233 186 269 145 119 93 152 204 266 232 322 273 383 274
187 228 251 220 240 242 315 197 171 278 243 112 188 211 212 246 274 324 243 170
264 278 259 373 278 259 191 138 190 213 194 295 205
NMG-P08A 70
187 258 204 318 242 302 210 154 192 113 166 253 224 234 198 223 133 115 148 113
133 230 119 75 130 157 172 240 151 135 175 100 122 154 179 247 216 178 193 205
172 175 136 162 150 188 165 175 171 192 212 117 100 134 194 178 161 84 126 233
193 174 131 176 187 177 156 126 129 158
NMG-P08B 70
189 256 214 308 283 287 199 146 191 123 173 268 220 240 201 233 126 97 148 113
127 245 115 88 109 159 178 263 152 124 169 107 119 147 184 245 219 171 201 205
174 179 135 178 153 192 179 169 175 189 169 120 106 137 193 157 170 94 120 203
178 165 121 170 194 168 147 151 121 142
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152 158 181 167 180 222 329 125 84 115 167 183 150 185 200 185 146 140 141 155
216 170 232 227 198 212 245 240 216 170 127 105 213 155 207 213 218 153 135 111
80 94 151 154 130 171 206 195 162 145 146 152 125 138 118 117 99 107 136 124
92 117 87 124 126 163 96 192 200 215 169 119 87 103 135 128 127 90 87 91
103 142 113 140 162 124 132 123 134 81 90 91 126 112 125 121 101 77 93
NMG-P09B 99
158 157 178 169 176 230 315 129 89 115 171 185 164 171 190 173 146 139 114 168
231 177 230 269 186 202 232 248 226 192 103 110 216 155 207 237 225 158 132 123
80 102 135 162 124 178 209 188 163 158 136 152 144 134 130 102 105 111 129 124
81 117 89 124 128 173 90 206 192 214 159 125 90 100 141 130 113 86 89 79
115 142 113 136 171 124 119 122 127 78 89 95 118 116 130 124 95 77 82
NMG-P10A 116
147 145 112 79 89 106 144 220 178 164 104 116 142 243 255 186 192 185 135 149
186 171 159 151 147 108 105 107 125 147 156 169 97 130 159 179 139 179 158 135
120 122 85 93 103 103 118 144 115 96 108 125 104 93 76 76 80 86 112 137
157 136 106 100 68 47 80 101 77 131 120 96 100 122 87 121 99 90 109 68
57 66 72 97 68 100 63 82 86 116 62 90 123 129 92 97 67 75 68 101
80 79 73 88 96 127 84 103 118 94 103 85 98 65 71 76
NMG-P10B 116
156 137 116 81 95 94 120 239 135 143 107 127 149 237 234 178 192 168 146 157
196 173 160 142 131 111 98 118 127 144 155 174 101 126 169 174 160 192 161 142
131 118 89 89 109 103 121 143 121 96 123 129 87 94 90 61 88 83 105 145
155 137 106 100 66 55 71 90 82 126 123 103 101 111 93 118 102 98 97 63
57 59 76 91 75 93 78 73 90 107 74 96 114 126 104 90 67 74 66 91
90 82 77 82 96 123 78 103 113 96 96 91 86 81 49 86

NMG-P11A 70
258 270 205 141 119 86 99 186 165 171 136 124 86 76 108 90 107 146 84 63
91 128 178 197 96 84 141 86 121 111 174 185 204 127 162 169 133 144 118 144
113 123 125 142 148 153 199 124 86 120 144 141 151 65 112 167 112 137 129 130
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NMG-P11B 70
280 271 208 143 115 93 92 190 159 171 131 131 80 81 103 103 100 155 81 55
98 138 161 195 95 89 142 83 127 106 182 190 209 139 161 174 141 158 121 149
101 152 132 152 150 164 196 144 78 121 132 142 142 82 96 177 108 144 122 125
133 113 119 108 111 97 138 80 114 102
NMG-P12A 62
190 219 243 217 256 227 185 95 101 86 154 215 257 133 76 168 281 232 232 288
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230 276 155 197 210 220 201 174 163 183 195 179 139 130 154 215 193 180 171 166
131 154
NMG-P12B 62
196 230 245 236 270 229 184 102 102 98 143 223 244 137 82 169 280 238 223 290
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127 155
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225 228 190 197 270 216 181 136 76 82 100 106 117 143 119 79 105 73 72 58
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NMG-P13B 74
235 236 187 195 266 222 171 130 72 81 108 103 115 153 115 88 104 75 72 59
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NMG-P14A 69
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151 153 120 106 111 180 109 119 108
NMG-P15A 58
328 289 332 354 304 356 166 193 266 206 123 133 149 130 118 115 69 83 109 101
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126 119 133 105 79 101 122 161 113 115 95 73 85 79 82 57 84 125

NMG-P16A 91
184 191 128 104 117 99 102 92 84 81 70 87 72 78 75 70 86 96 80 106
110 140 78 84 67 84 89 115 114 130 134 132 129 129 143 137 100 106 137 130
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NMG-P17A 56
358 307 155 370 292 313 303 262 137 285 314 417 339 292 276 230 296 212 299 299
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NMG-P17B 56
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394 313 205 222 226 198 183 173 196 211 285 225 216 203 346 266 286 261 248 253
211 190 224 262 244 247 232 280 192 202 148 145 165 218 142 168
NMG-P18A 87
61 33 47 81 134 144 207 231 157 274 158 265 328 181 239 299 217 269 214 110
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287 251 239 258 249 239 209
NMG-P18B 87
75 32 47 78 134 150 205 222 150 283 160 275 321 171 246 287 233 261 184 118
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NMG-P20A 133
77 104 87 107 79 96 70 111 49 47 74 113 35 37 66 77 87 47 40 28
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72 35 42 52 89 62 100 153 303 186 225 161 135 133 166 129 93 85 103 80
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NMG-P20B 133
87 101 86 110 90 69 74 108 62 43 89 84 35 37 67 82 85 52 42 31
38 45 37 76 49 32 25 46 63 49 62 95 41 45 78 59 54 65 29 49
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NMG-P21A 70
159 219 183 182 146 137 161 170 148 225 135 116 98 152 99 218 303 141 93 118
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NMG-P21B 70
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NMG-P22A 105
113 81 47 32 37 54 40 43 59 70 61 78 93 74 76 97 107 150 156 116
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94 79 63 61 45 79 82 129 84 141 146 155 91 131 142 183 131 190 130 167
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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.

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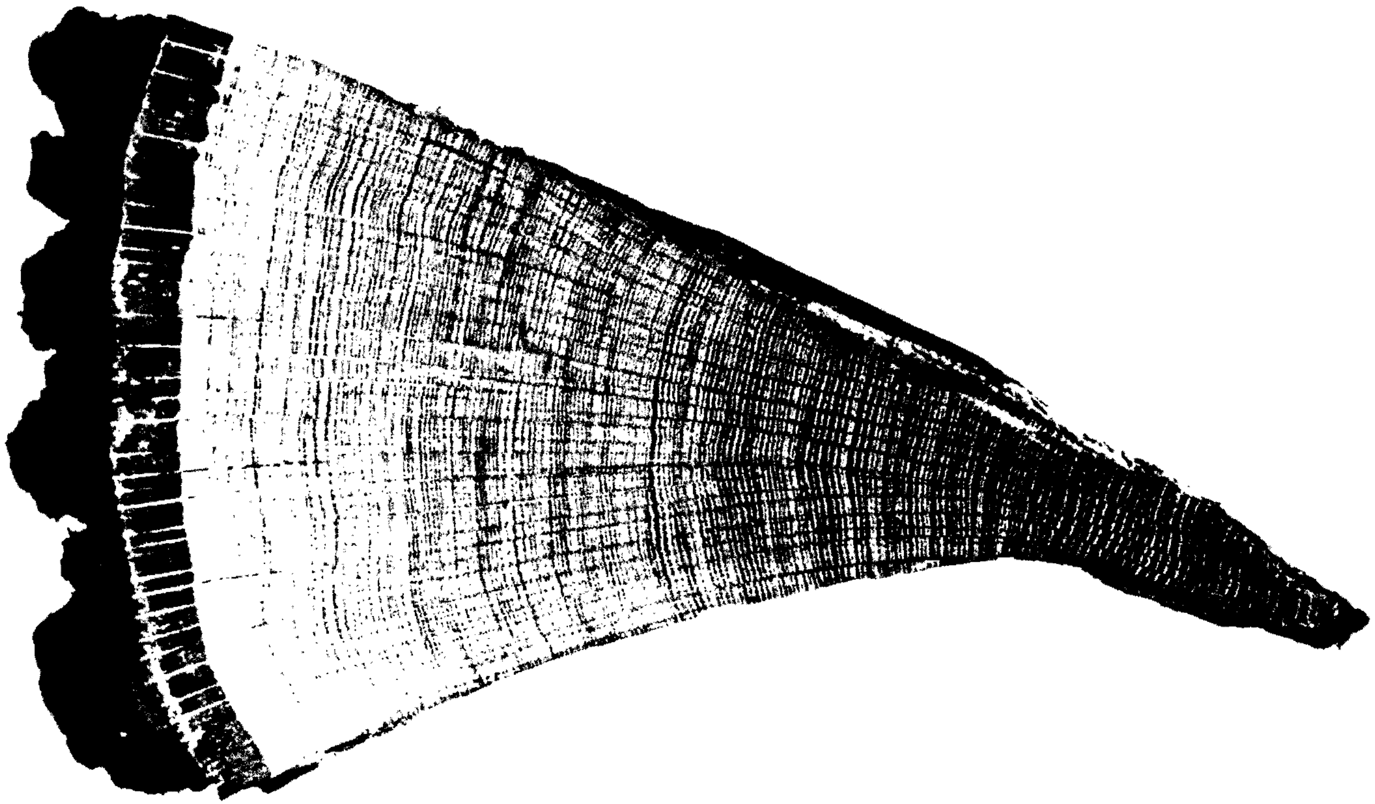

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

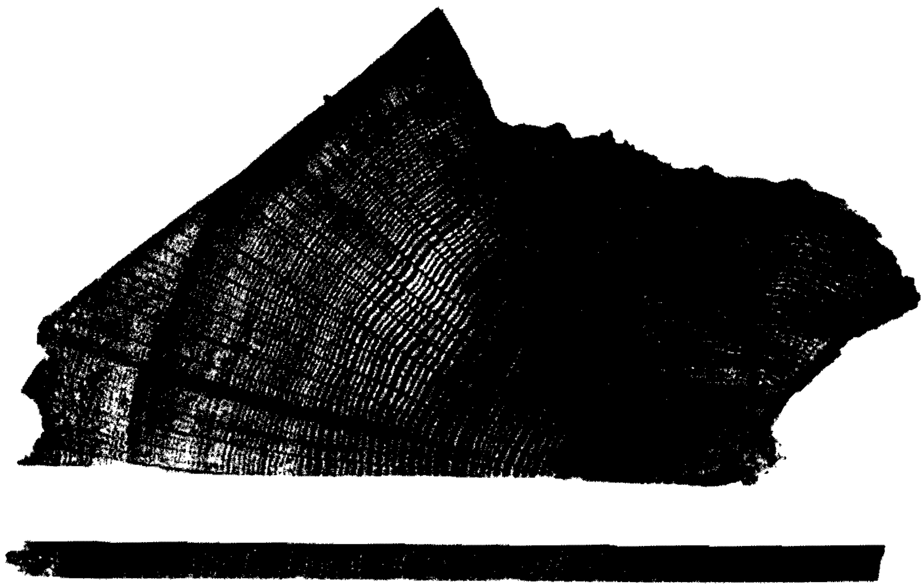

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

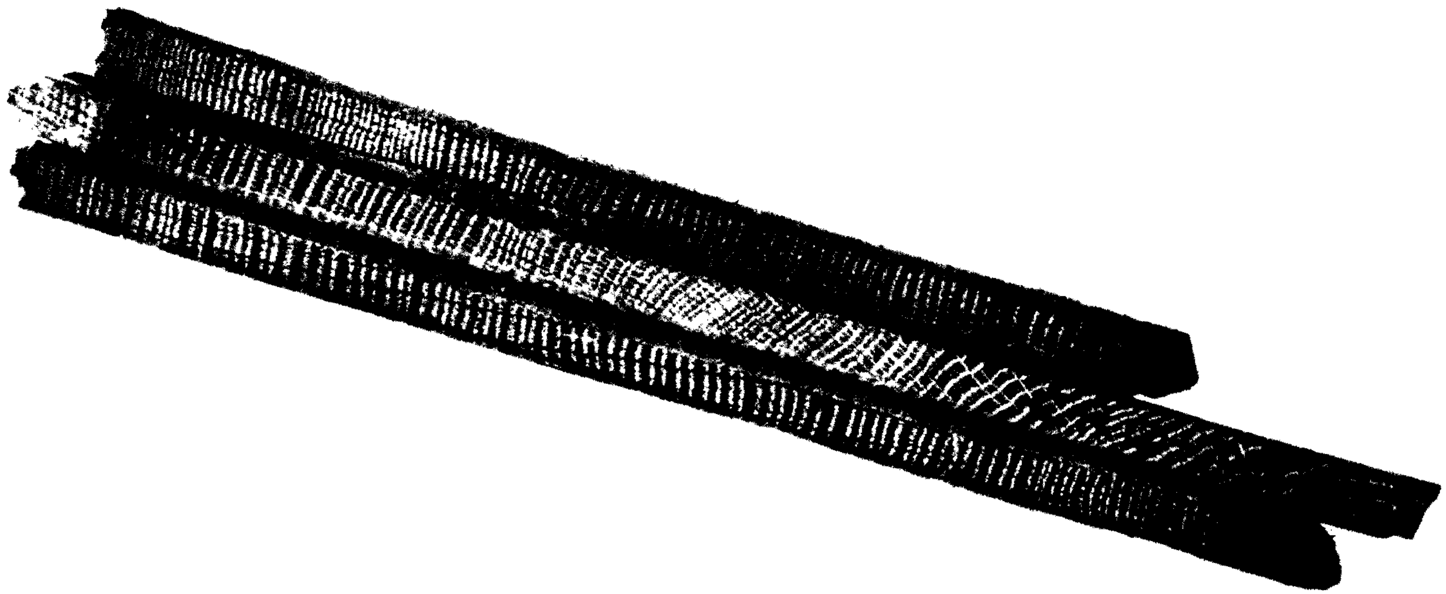

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

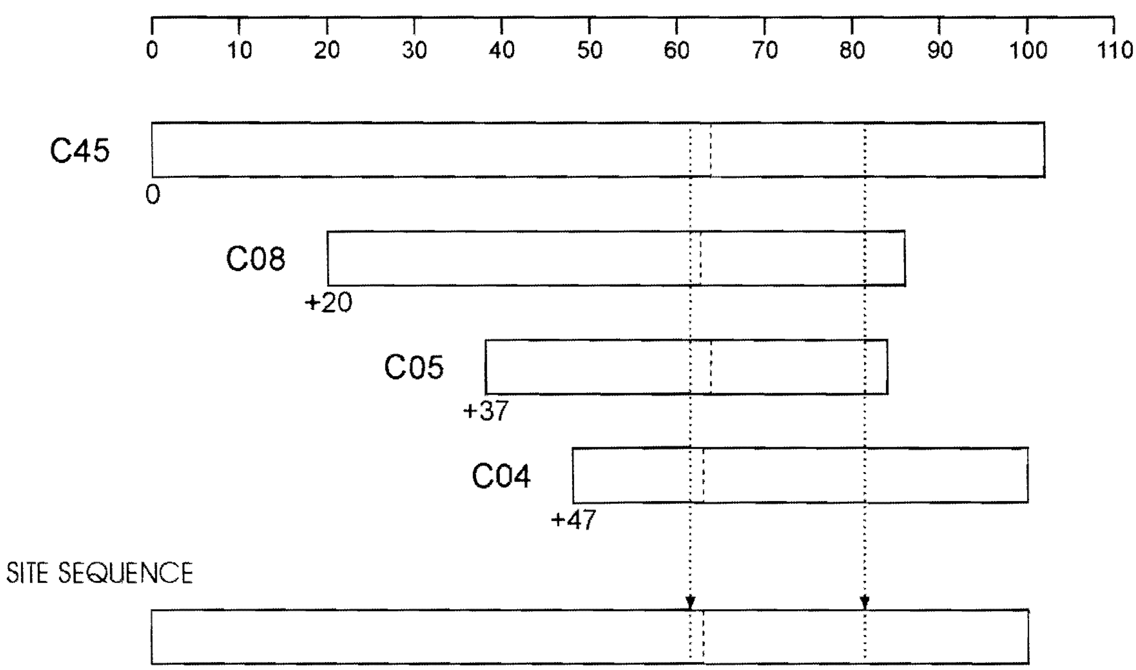

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

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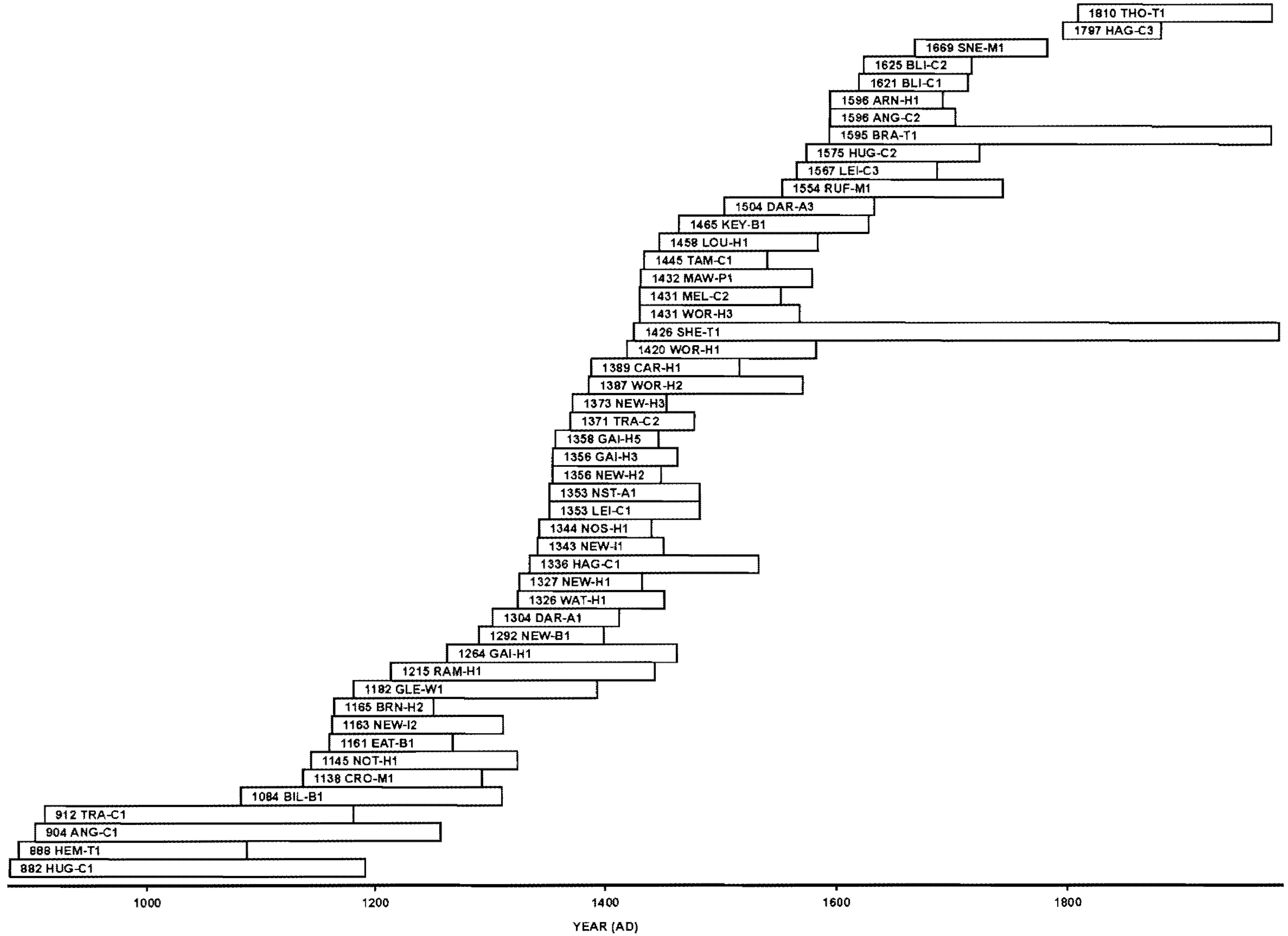
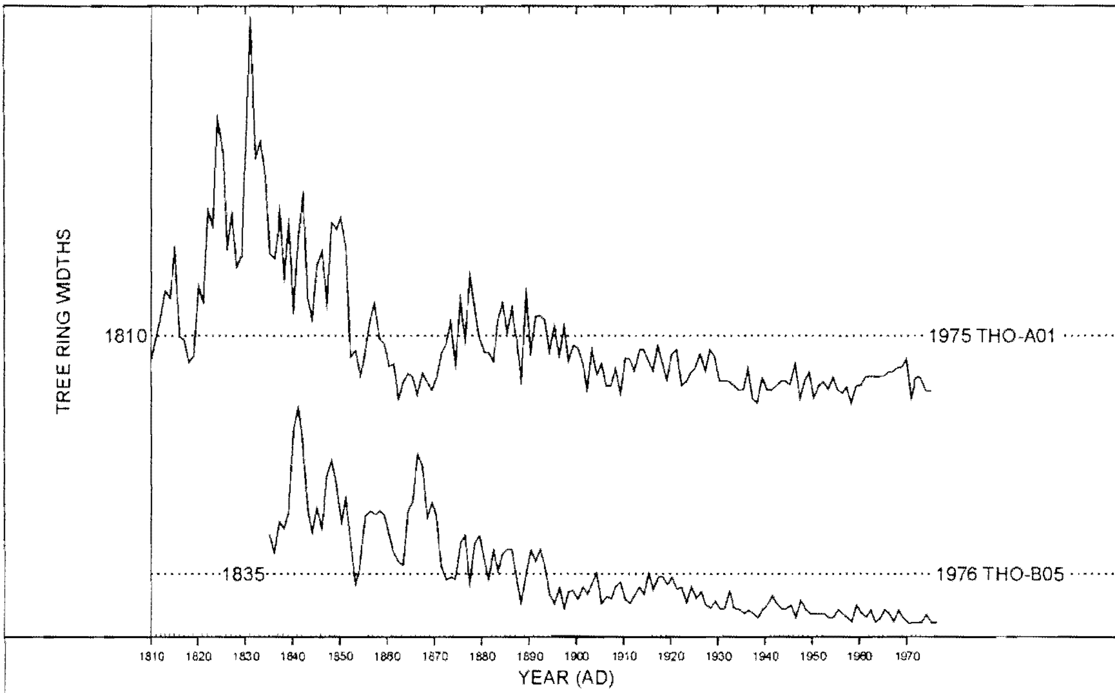


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

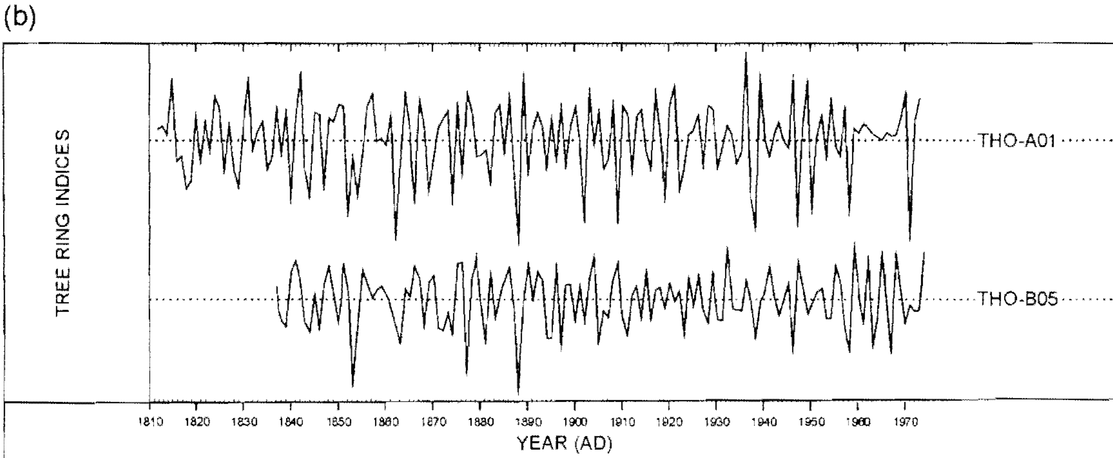


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

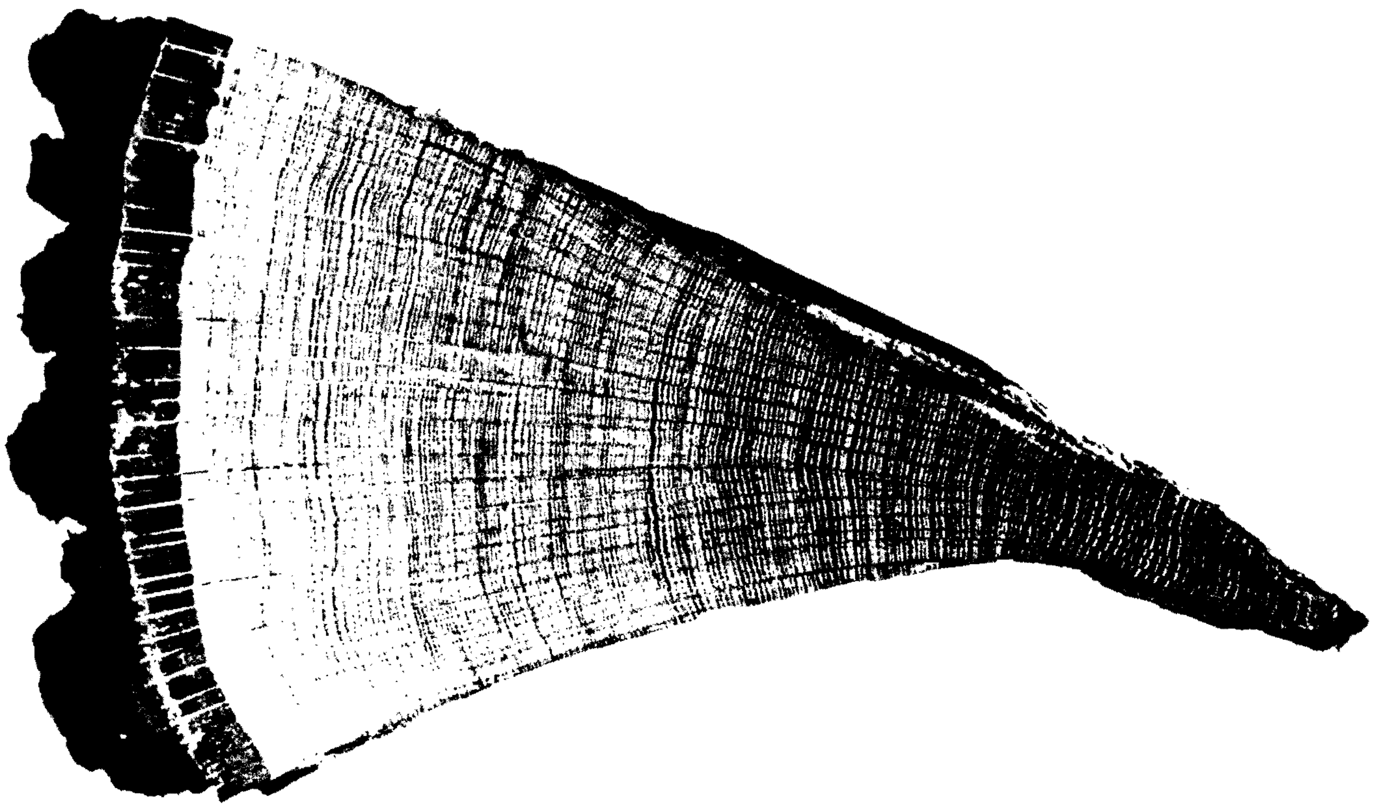


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

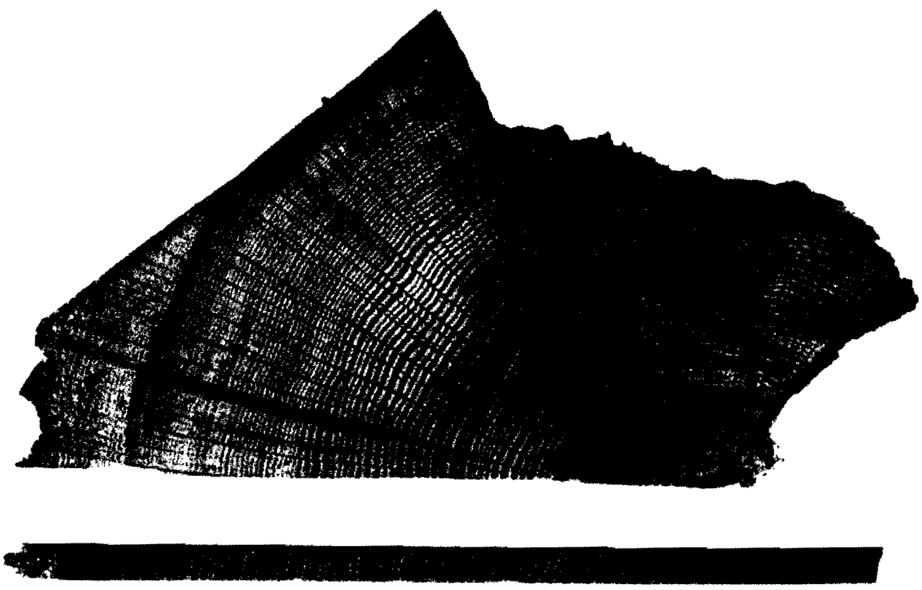


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

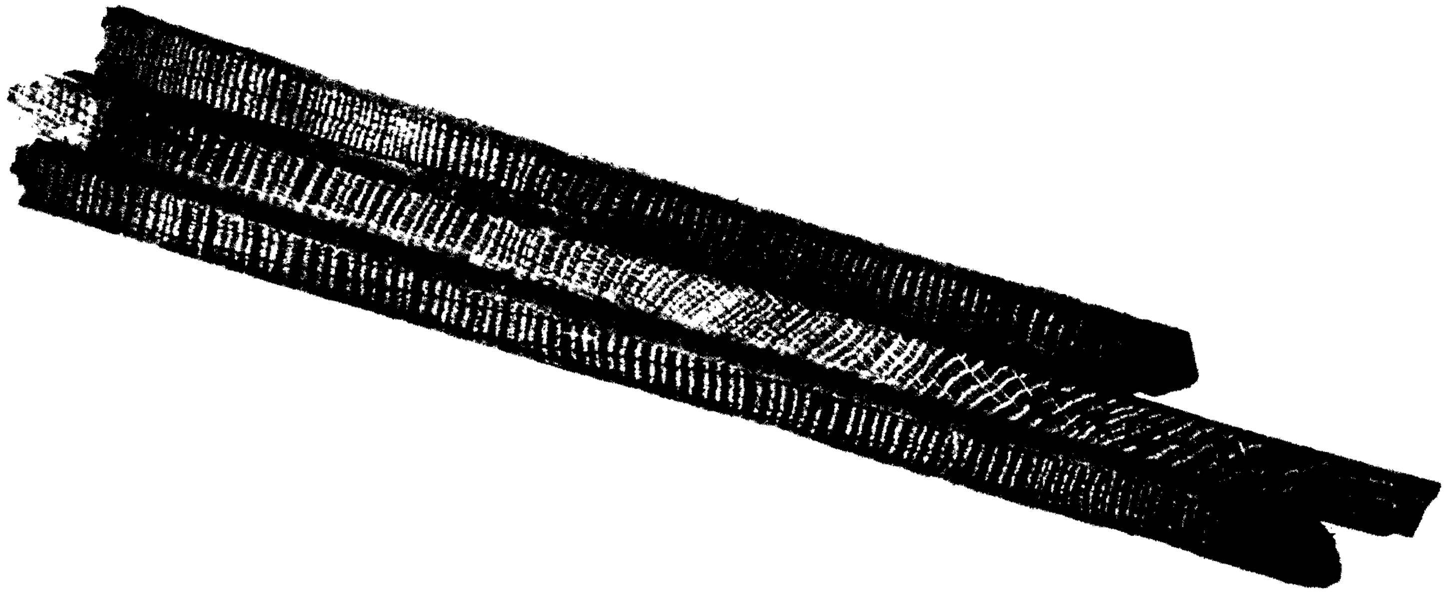


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

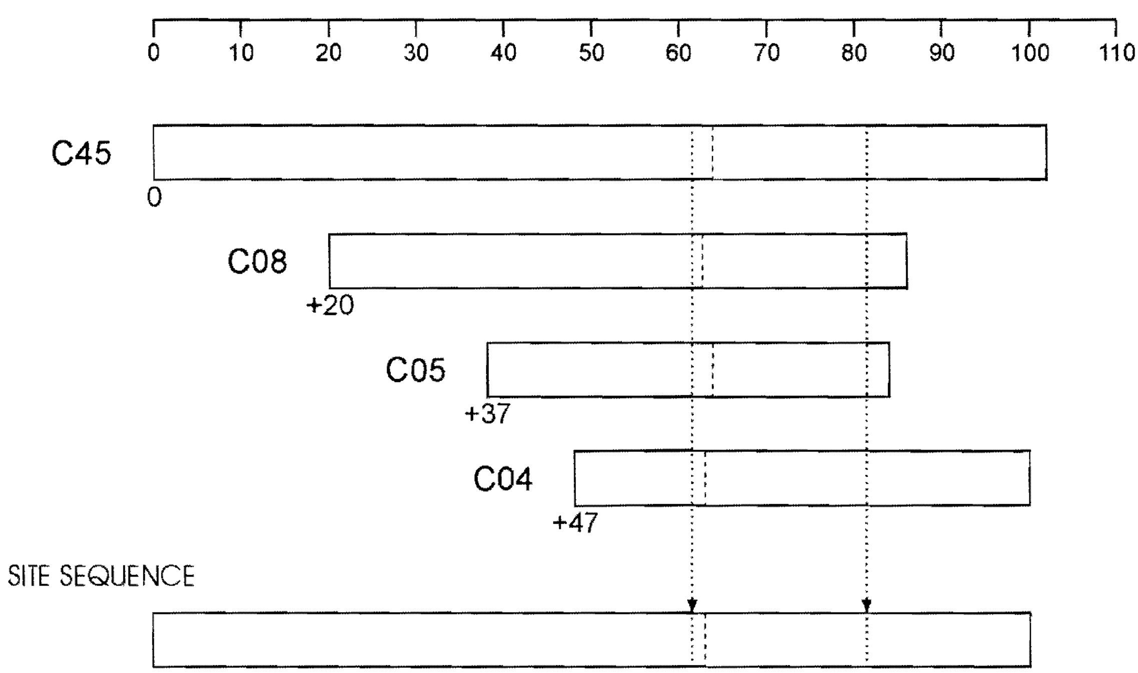


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

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

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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.

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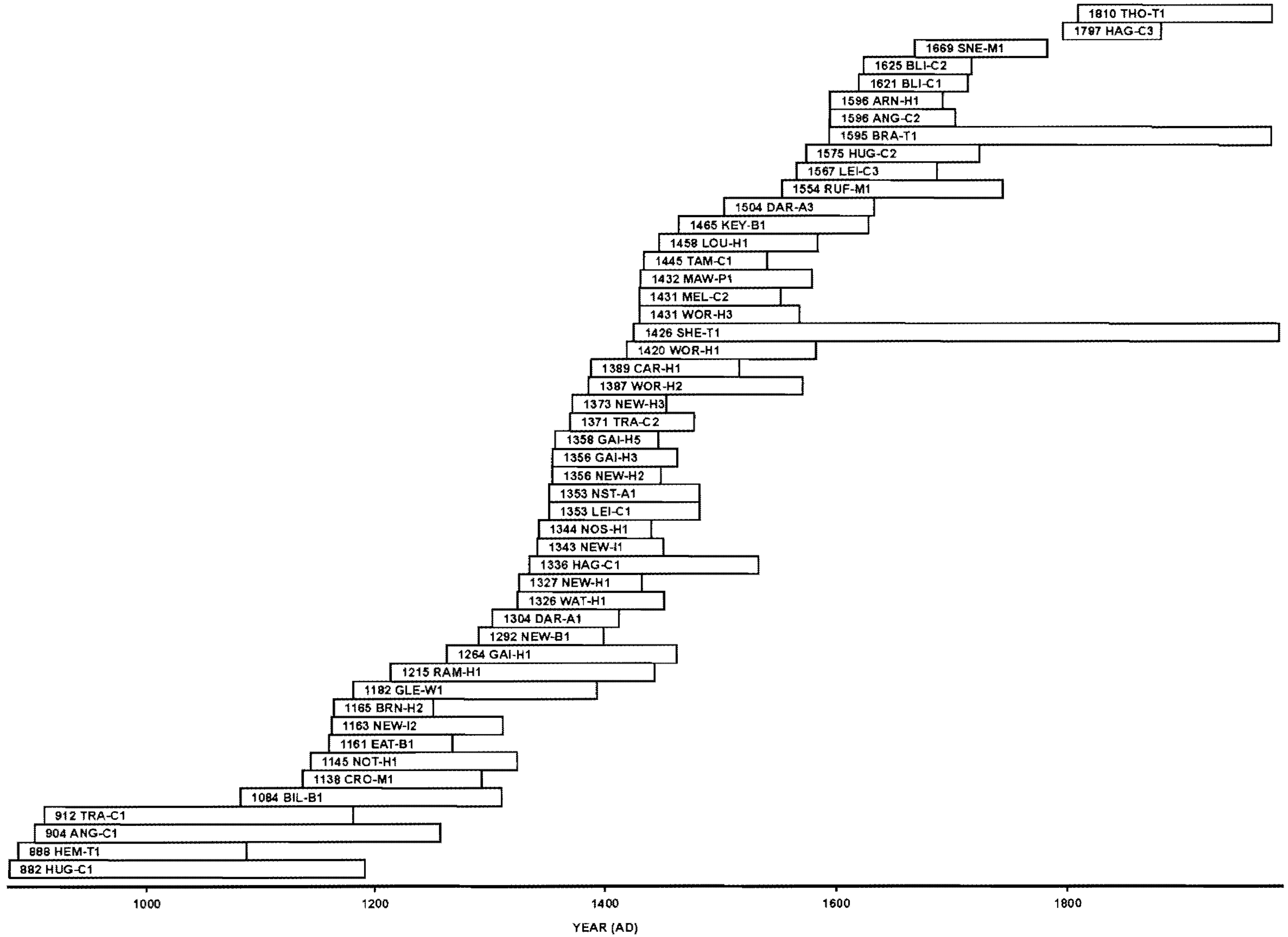

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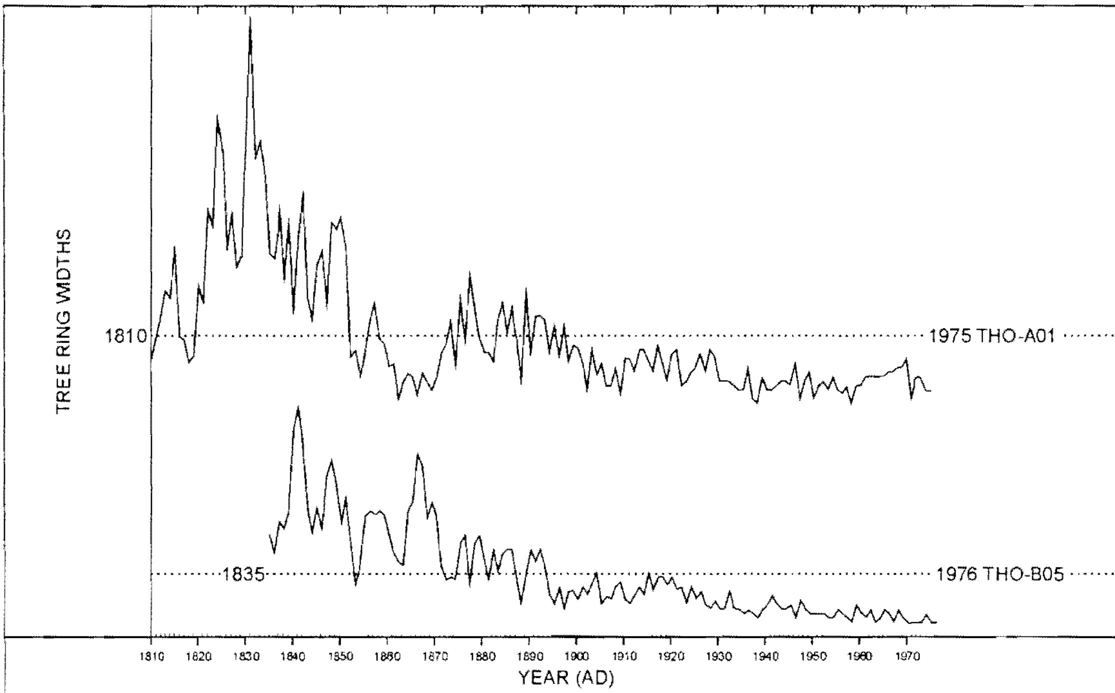

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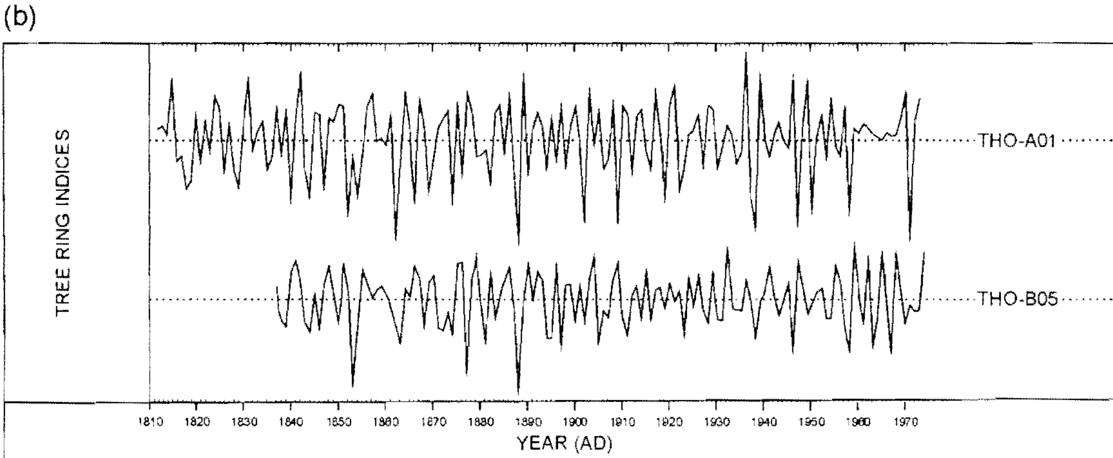

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