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Summary

A total of 26 core samples was obtained from the roof and first-floor frame timbers of the Accounts Office on the roof of the Dean's Cloister at Windsor Castle. Of this total, 15 were measured and analysed, the analysis of these producing three site chronologies. The first site chronology comprises four samples with a combined overall length of 85 rings. Unfortunately this site chronology cannot be dated, though it is likely that the timbers represented were all felled at the same time.

The second site chronology comprises two samples having a combined overall length of 57 rings. This site chronology cannot be dated though again it is likely that the two timbers represented were felled at the same time as each other.

The third site chronology comprises three samples having an overall length of 65 rings. This site chronology can be dated as spanning the years AD 1437 – AD 1501. Interpretation of the sapwood would suggest the timbers represented, from both the roof and the first floor, have a felling date in the range AD 1511 – 36.

None of the remaining six measured but ungrouped samples can be dated.

Keywords

Dendrochronology
Standing Building

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Introduction

On the basis of documentary evidence it is known that the Dean's Cloister, adjacent to St George's Chapel at Windsor Castle (SU 973 765, Fig 1), was originally built between AD 1350 - 53, against an earlier wall of the mid-thirteenth century Royal Lodgings to the north. It consists of a rectangular covered walk, lit by fine tracery windows, enclosing a small garden with a fountain. The Accounts Office, a first-floor timber-framed extension to number 2, Canon's Cloister, situated over the west end of the north range of the Cloister, was thought from documentary evidence to be dated to *c* AD 1490 as there is a reference in AD 1491 to 'work done above the Cloister, next to the library', (Compotus of the Canon 1490 - 91). The position of the Cloister in the north corner of the Lower Ward of the Castle, with the location of the Accounts Office, is shown in Figure 2.

The roof of the Cloister as a whole has undergone remedial treatment in stages over recent years, the existing AD 1960s copper covering being removed to expose the largely mid-nineteenth century timbers beneath. In almost every case the timbers beneath have been of softwood.

The most recent programme of roof repairs, beginning in AD 2004, has involved the removal of further nineteenth-century lead from the western ranges of the Cloister, and the removal of AD 1960s copper covering and roof boards from part of the northern range, specifically that over the Accounts Office. Like those sections worked on previously, the roof beams of the exposed western portion are also of softwood.

The roof timbers of the northern range, above the Accounts Office, are, however, largely of oak, with only a small number of more recent softwood timbers being present. Furthermore, the roof of this section looks more complicated, not being of simple common rafters as in the western range, but having a ridge beam, purlins, wall plates, and common rafters as well as ceiling joists. On structural grounds it would appear that the beams of this roof have been re-arranged at some time perhaps to allow a new chimney flue to be built. This was probably in the mid-nineteenth century. On the basis of stylistic evidence in the form of stone and brickwork, construction of the original roof is likely to have taken place in the early-sixteenth century. There are other structural timbers, in the form of main joists, in the floor-frame of the room below. The date of these timbers is uncertain. A more complete analysis of the timbers is given in Jones (2004).

The Laboratory must take this opportunity to thank a number of people who were involved, or in some way assisted, with this programme of tree-ring analysis. Firstly we would like to thank Tim Tatton-Brown, consultant archaeologist, for his help in disentangling this complicated set of timbers, for his help and advice on their possible phasing, and for his contribution to the introduction above. We would also like to thank Martin Ashley and Andrew Harris, of Martin Ashley, Architects, for their help in accessing the site, and for their thoughts and comments on the timbers. The Laboratory would also like to thank the staff of Paul Webb Roofing for their very great help, expertise, and generosity during sampling. Finally we would also like to thank Mr Ian Poole, Clerk of Works at Windsor Castle, and the staff of the Pass Office, for their help in accessing the site too. The Laboratory must also pay particular thanks to Howard Jones the recording archaeologist, who has produced a most excellent series of drawings of this roof, and provided a full set of notes.

Sampling

Sampling and analysis by tree-ring dating of the timbers in the roof and floor timbers of the Accounts Office were commissioned by English Heritage. This was requested to inform a programme of grant-aided repairs by providing precise dates, if possible, for the earliest material represented, potentially fourteenth century, any subsequent repairs or alterations, and the quantity or extent of any such remaining material.

The roof of the Accounts Office comprises a less than straightforward set of timbers, an illustration, in which the various timbers are described, is given in Figure 3. The main element consists of a ridge beam which breaks the roof into a larger, shallow pitched, western part, and a smaller, slightly more steeply pitched, eastern part. The western slope has a single purlin, the east slope has double purlins, with all three purlins almost certainly being nineteenth-century inserts. There are also wall plates to each slope.

In the north part of each slope there are short east-west ceiling joists which run between the wall plates and the purlins. These ceiling joists, however, are missing between the purlins and the ridge. In the southern part of each slope, again only in the area between wall plates and purlins, there are further ceiling joists which run north - south.

Above these ceiling joists are the rafters of the roof. On the east slope these run from wall plate to ridge beam. On the west slope they stop short of the wall plate, tapering to rest on the backs of the ceiling joists.

Some of the timbers, the ridge beam for example, some rafters, and some ceiling joists, are of softwood, as are the boards immediately beneath the copper. These softwood timbers were not included in the sampling brief.

Some of the roof timbers show redundant features such as lap mortices and peg holes. Whilst this would normally suggest that the timbers were reused from another building, it was considered that this might not necessarily be so here. It was believed that while some timbers might be reused from elsewhere, and that some indeed were later insertions, it was considered likely that many original timbers had simply been moved and re-set within the present roof.

From these roof timbers a total of 23 core samples was obtained, from timbers with evidence of reuse as well as those without. Each sample was given the code WIN-B (for Windsor Castle, site 'B') and numbered 01 - 23. Further cores, WIN-B24 - 26, were obtained from three floor joists of the room below, access made possible by the lifting of a small number of floor boards in the Accounts Office.

The number of samples taken allows for both the potential complexity of the structure and the fact that the majority of timbers are derived from fast grown trees, many of the beams having ring numbers close to the minimum of 54 required for reliable analysis. These 26 samples thus represent a core from almost every available oak timber. The exceptions to sampling were those timbers which could be clearly seen to have too few rings for satisfactory analysis, ie, had fewer than 54 rings.

The positions of the 26 samples obtained are shown on drawings made by Howard Jones. These drawings are reproduced here as Figure 4a/b. Details of the samples are given in Table 1. In this report the timbers have been described and numbered from north to south, or from east to west, as appropriate.

Analysis

Each of the 26 samples obtained was prepared by sanding and polishing. It was seen at this point that, as expected, 11 samples from timbers considered to be borderline prior to sampling did indeed have less than the minimum of 54 rings necessary, and these were rejected. The annual growth-ring widths of the remaining 15 samples were measured, the data of these being given at the end of the report. The data of these 15 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix) and at a minimum *t*-value of 4.5 three satisfactory site chronologies could be formed.

The first site chronology, WINBSQ01, consists of four samples cross-matching with each other at relative positions as shown in the bar diagram, Figure 5. These four samples have a combined overall length of 85 rings. Site chronology WINBSQ01 was compared with an extensive range of British and European site chronologies, not only those held by the Nottingham Laboratory but also by other laboratories such as the Sheffield Dendrochronology Laboratory. Despite this extensive comparison there was no satisfactory cross-matching against any of the available reference chronologies.

The second site chronology, WINBSQ02, consists of two samples cross-matching with each other at relative positions as shown in the bar diagram, Figure 6. These two samples have a combined overall length of 57 rings. Site chronology WINBSQ02 was also compared with an extensive range of reference chronologies, but again there was no satisfactory cross-matching against any available reference chronology.

The third site chronology, WINBSQ03, consists of three samples cross-matching with each other at relative positions as shown in the bar diagram, Figure 7. These three samples have a combined overall length of 65 rings. Site chronology WINBSQ03 was also compared with an extensive range of reference chronologies, indicating satisfactory *t*-values when the date of its first ring is AD 1437, and the date of its last ring is AD 1501. Evidence for this dating is given in the *t*-values of Table 2.

Each of the remaining ungrouped samples was compared individually with the reference chronologies, but there was no satisfactory cross-matching, and these samples must also remain undated.

Interpretation and conclusion

Of the 26 samples obtained 15 were measured. Of these, nine have been formed into one of three site chronologies. Unfortunately only one of these site chronologies can be dated, the other two site chronologies, and the ungrouped individual samples, remain undated.

Interpretation of the sapwood on the dated samples would indicate that the timbers represented, two from the Accounts Office roof, both trimmer beams, and a joist from the first-floor frame, have an estimated felling date in the range AD 1511 - 36. The dating of this material indicates that it probably relates to the original, early-sixteenth century, construction phase, a date which would fit the stylistic evidence of the brick-noggin filled timber-framing.

Although undated, the cross-matching of the samples in the two other site chronologies would suggest that the respective timbers within each site chronology, rafters and ceiling joists, are likely to be of the same date.

The lack of cross-matching between many of the samples, and the subsequent lack of dating, is likely to be as a consequence of several related factors. Firstly, it is possible, though perhaps unlikely, that, as had previously been considered on structural grounds, many of the timbers had, after all, been taken from other buildings and reused here. This has the effect of making many of the timbers singletons which are often more difficult to date than groups of coeval timbers, which can be cross-matched with each other to produce a replicated site chronology.

Secondly, many of the samples, whilst having at least the minimum number of rings for satisfactory analysis, ie 54, are relatively short. Of the 15 measured samples 12 have 65 rings or less. This makes cross-matching between samples from a site, or the cross-matching between individual samples and reference chronologies, more difficult. Successful cross-matching is also hampered by the sudden growth retardation and hence the erratic nature of the growth pattern of some samples. It is also possible that the growth pattern found in these particular samples from the roof of the Accounts Office is not represented in any available reference chronology. This means that there is nothing against which the site chronologies, or the individual samples, can be reliable cross-matched and dated, although both fourteenth and sixteenth-century material from Windsor Castle has been successfully dated in the past (Hillam and Groves, 1994, Miles and Haddon-Reece, 2003).

Unfortunately there are no other oak timbers in the roof of the Accounts Office that could be sampled. There are, however, further timbers in the first- and second-floor rooms of the accounts and related offices of the same general building that may be suitable for analysis and may be of the same date. These are likely to include other floor joists. It would be highly advisable that, should work ever be undertaken in these rooms, or these timbers become part of the present programme of work, further samples be taken from these. This material is perhaps less likely to have been disturbed and therefore less likely to represent material of mixed date and mixed source (that is, reused from different buildings). It is possible that the sampling of such timbers would provide sufficient singe-phase data to produce a well-replicated site chronology which is therefore more likely to date.

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Table 1: Details of samples from the Accounts Office roof, Dean's Cloister, Windsor Castle

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	West slope					
WIN-B01	Principal ceiling joist 5 (from north)	nm	---	------	------	------
WIN-B02	Ceiling joist 3 (from east)	55	h/s	------	------	------
WIN-B03	Ceiling joist 4 (from north)	nm	---	------	------	------
WIN-B04	Ceiling joist 3 (from north)	nm	---	------	------	------
WIN-B05	Ceiling joist 2 (from north)	54	h/s	AD 1443	AD 1496	AD 1496
WIN-B06	Ceiling joist 1 (from north)	55	h/s	AD 1437	AD 1491	AD 1491
WIN-B07	Ceiling joist 1 (from east)	nm	---	------	------	------
WIN-B08	Ceiling joist 2 (from east)	nm	---	------	------	------
	East slope					
WIN-B09	Rafter 9 (from north)	nm	---	------	------	------
WIN-B10	Principal ceiling joist 5 (from north)	73	9	------	------	------
WIN-B11	Ceiling joist 4 (from east)	60	3	------	------	------
WIN-B12	Ceiling joist 3 (from east)	57	21C	------	------	------
WIN-B13	Ceiling joist 2 (from east)	57	14C	------	------	------
WIN-B14	Ceiling joist 2 (from north)	74	6	------	------	------
WIN-B15	Ceiling joist 1 (from east)	nm	---	------	------	------
WIN-B16	East wall plate	113	no h/s	------	------	------
WIN-B17	Ceiling joist 3 (from north)	56	6	------	------	------
WIN-B18	Rafter 6 (from north)	64	no h/s	------	------	------
WIN-B19	Rafter 7 (from north)	58	no h/s	------	------	------
WIN-B20	Rafter 5 (from north)	nm	---	------	------	------
WIN-B21	East wall plate of south bay window	54	10	------	------	------
WIN-B22	Chock to west side, bay window	nm	---	------	------	------
WIN-B23	West wall plate to south bay window	54	no h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	First-floor frame					
WIN-B24	Main joist 3 (east)	nm	---	------	------	------
WIN-B25	Main joist 2 (middle)	nm	---	------	------	------
WIN-B26	Main joist 3 (west)	65	h/s	AD 1437	AD 1501	AD 1501

h/s = heartwood/sapwood boundary is last ring on
C = complete sapwood retained on sample

Table 2: Results of the cross-matching of site chronology WINBSQ03 and relevant reference chronologies when first ring date is AD 1437 and last ring date is AD 1501

Reference chronology	Span of chronology	*t*-value	
England London	AD 413 – 1728	7.8	(Tyers and Groves 1999 unpubl)
HAYS-W85	AD 1248 – 1647	7.5	(Tyers 1996a)
LPH1-T25	AD 1334 – 1599	6.3	(Tyers 1996b)
26 Westgate Street, Gloucester	AD 1399 – 1622	5.7	(Howard *et al* 1998)
MC10---H	AD 1386 – 1585	5.5	(Fletcher 1978 unpubl)
Restoration House, Rochester, Kent	AD 1378 – 1505	5.3	(Howard *et al* 1997)
Wales and West Midlands	AD 1341 – 1636	5.0	(Siebenlist-Kerner 1978)
Kent-88	AD 1158 – 1540	5.0	(Laxton and Litton 1989)

Figure 1: Map to show general location of Windsor

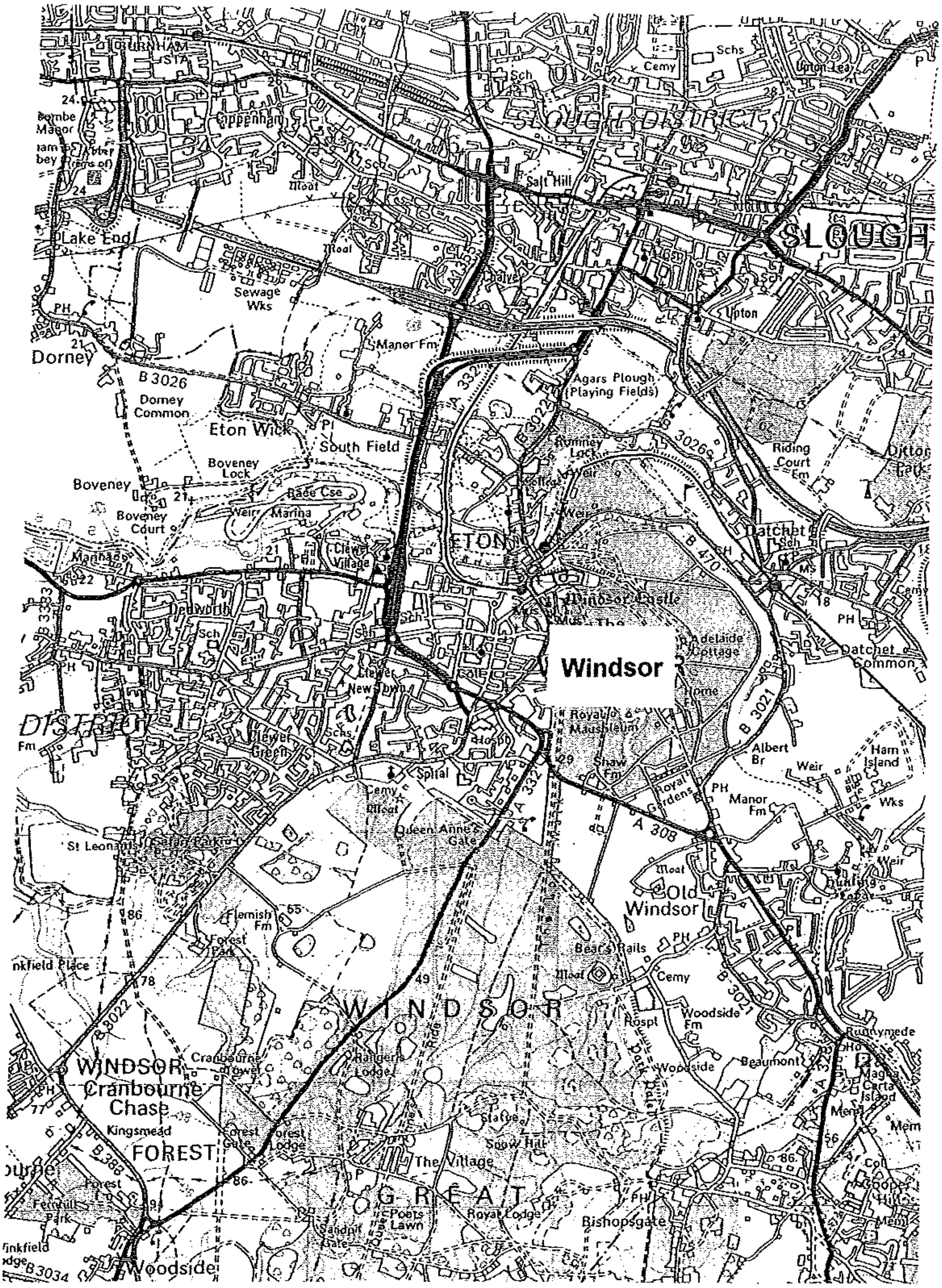


Figure 2: Plan to show the position of the Cloisters and the Accounts Office within the Castle
(after Hope 1913)

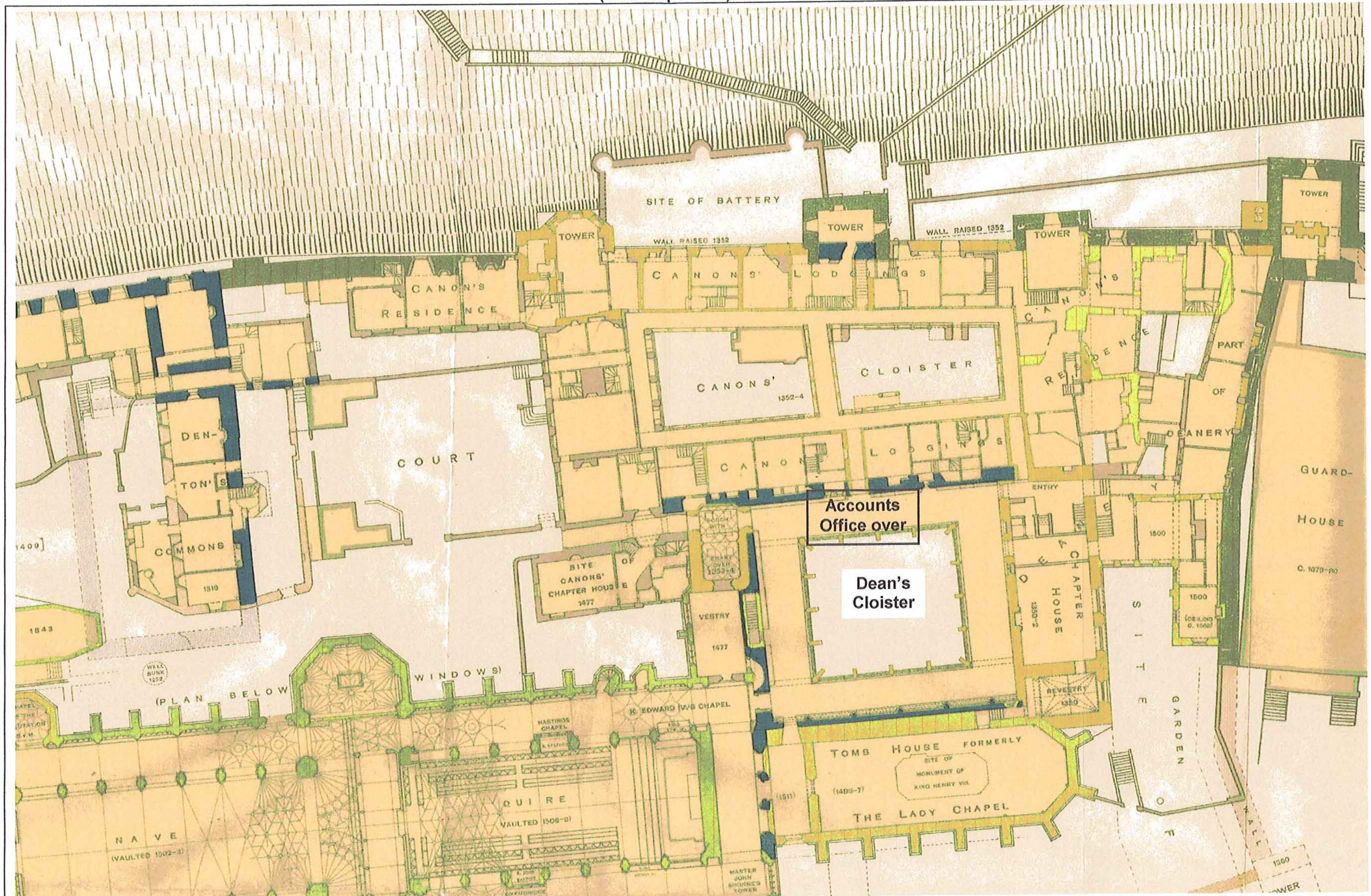


Figure 3: Plan to show layout of timbers in the Accounts Office roof
(after Howard Jones)

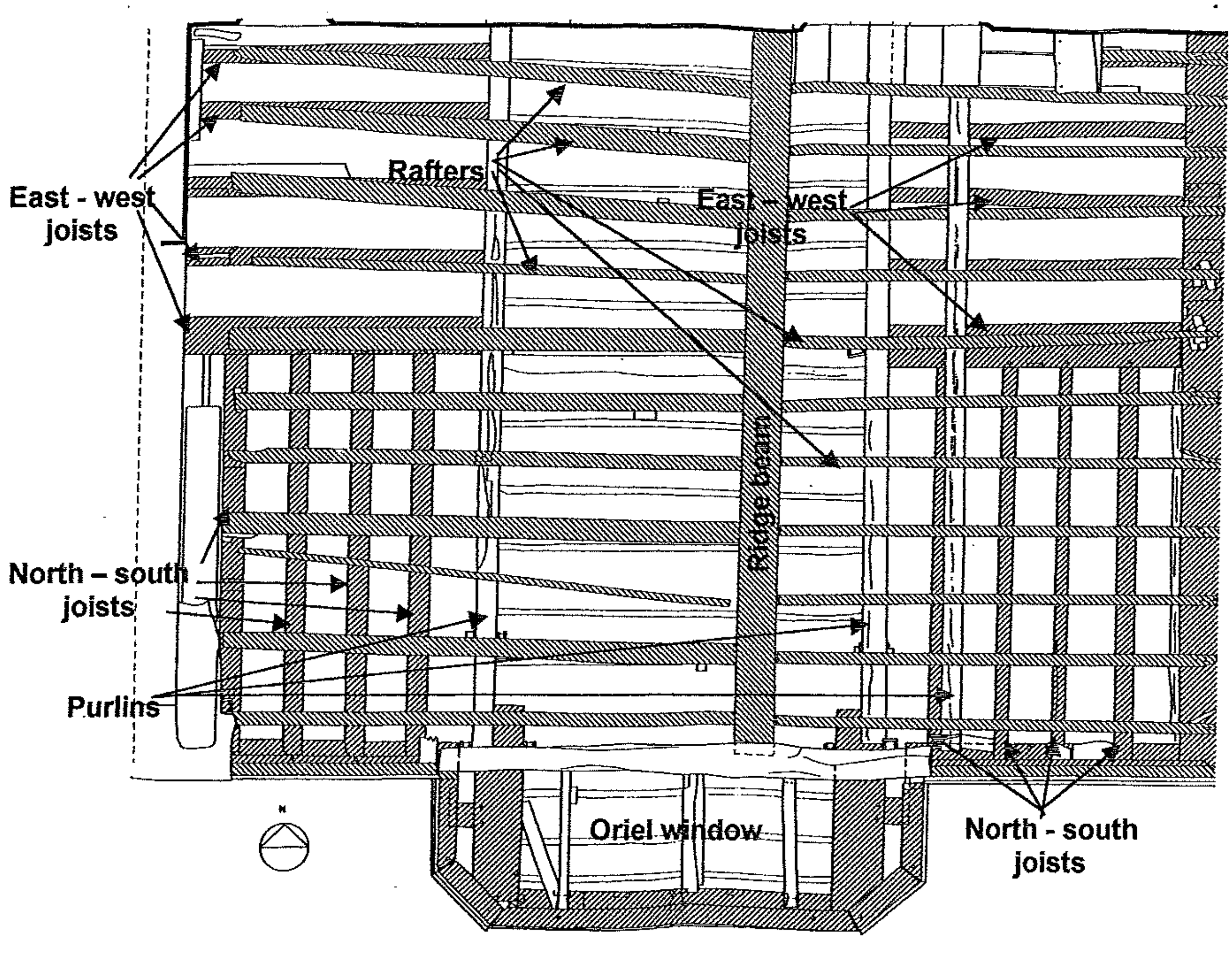


Figure 4a: Plan to show position of sampled timbers in the Accounts Office roof (after Howard Jones)

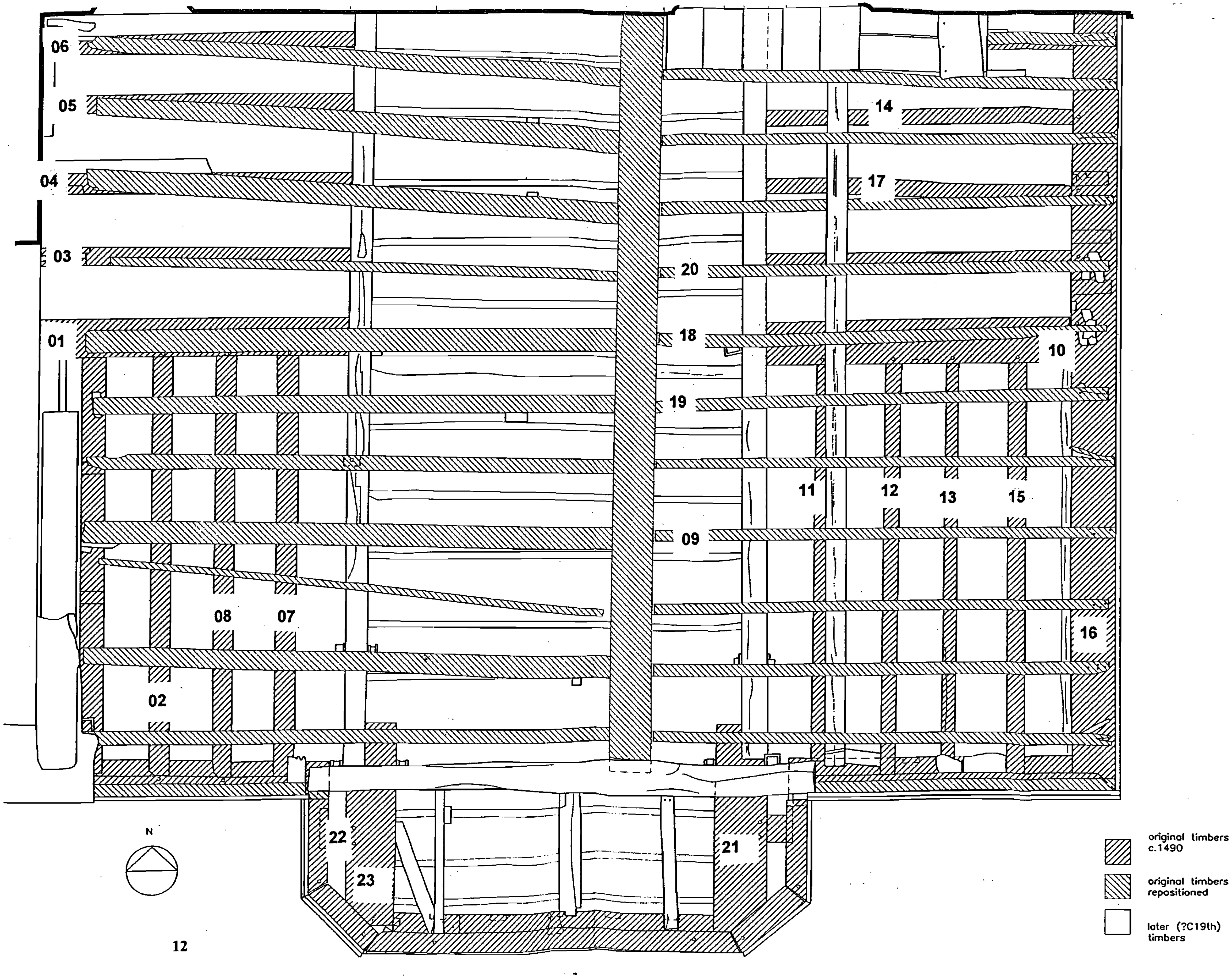


Figure 4b: Section to show position of sampled timbers in the floor-frame of the Accounts Office (viewed from the south looking north) (after Howard Jones)

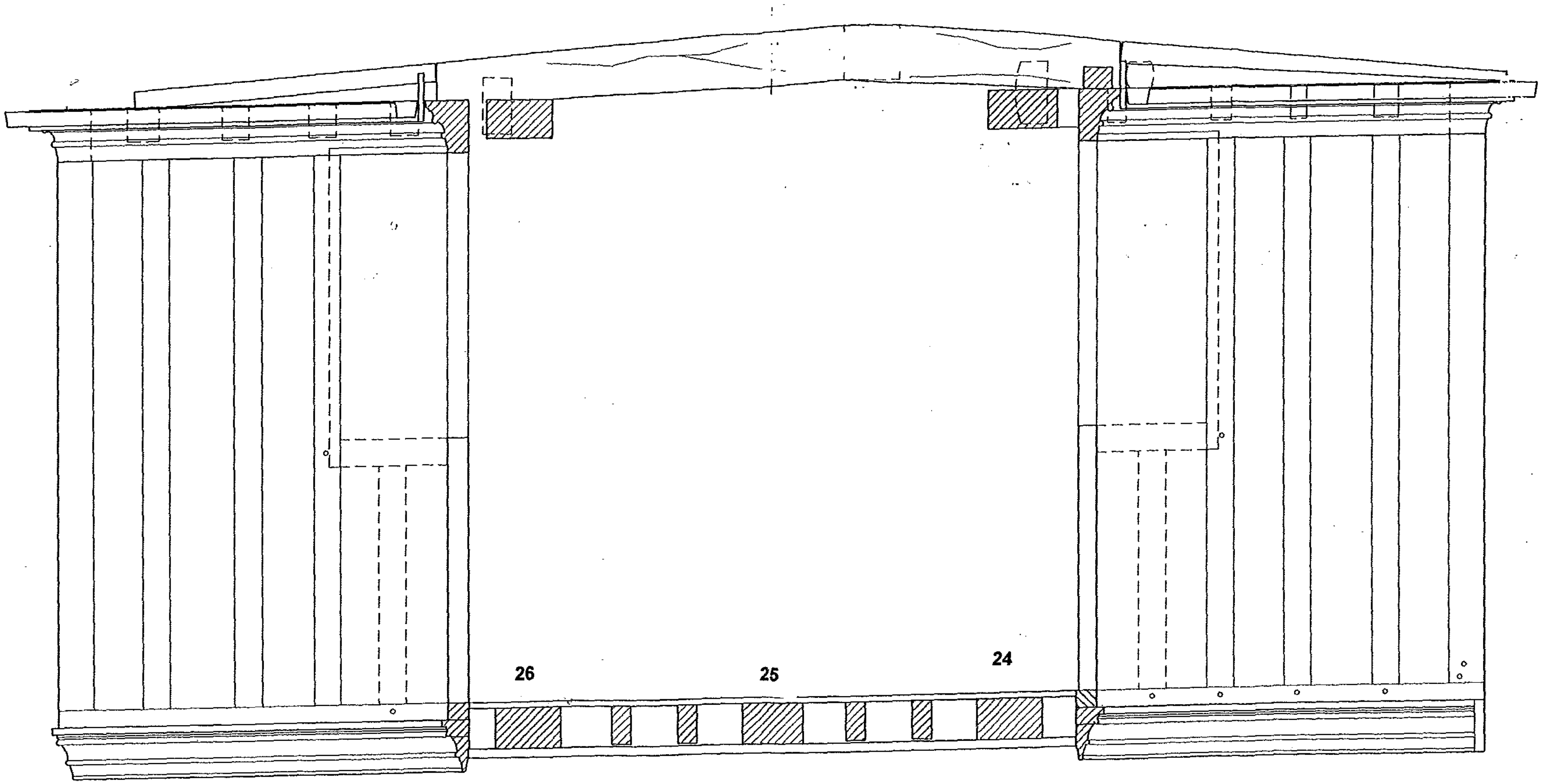


Figure 5: Bar diagram of the samples in site chronology WINBSQ01

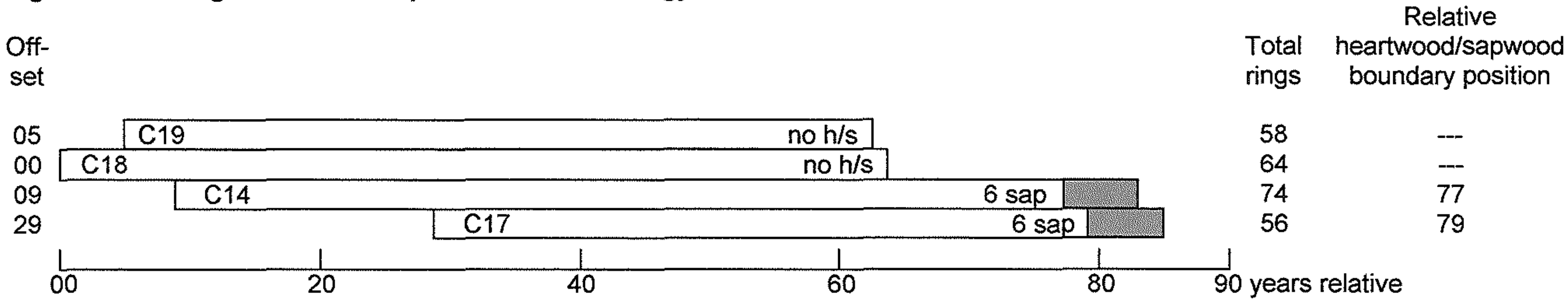
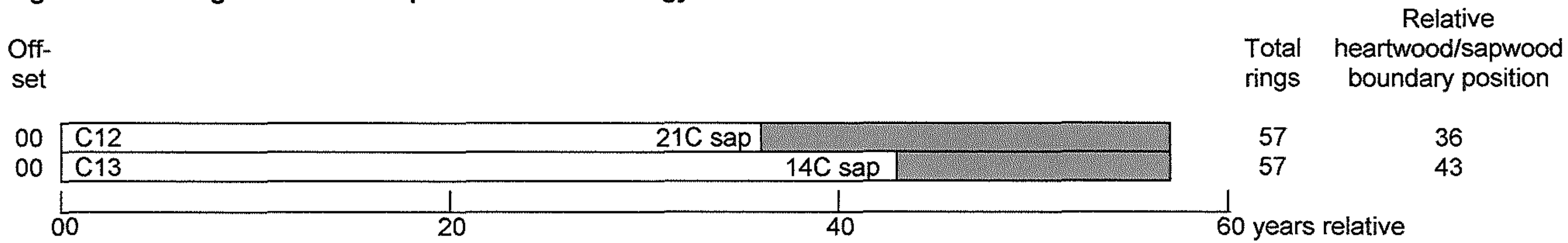
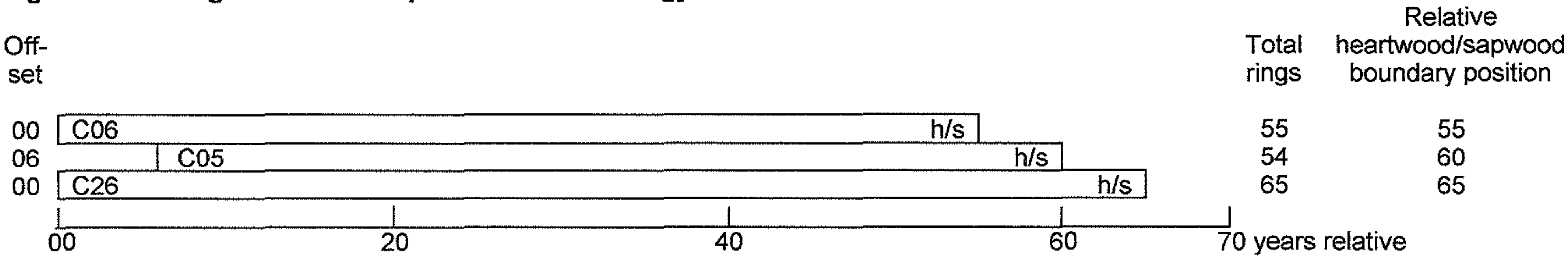


Figure 6: Bar diagram of the samples in site chronology WINBSQ02



white bars = heartwood rings, shaded area = sapwood rings
h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample, the last measured ring date is the felling date of the timber

Figure 7: Bar diagram of the samples in site chronology WINBSQ03



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

Data of measured samples – measurements in o.01 mm units

WIN-C02A 55
185 154 154 273 246 305 326 206 154 181 174 232 240 246 203 264 328 342 291 313
278 217 249 191 145 259 258 326 239 256 199 152 162 234 295 291 219 142 190 224
238 162 95 124 123 131 100 60 111 125 155 74 182 223 220
WIN-C02B 55
129 134 161 298 250 319 289 205 159 189 174 251 238 254 239 231 299 299 255 339
283 223 230 200 140 265 264 308 252 265 197 144 194 242 279 309 223 144 167 204
142 166 100 123 117 131 95 63 118 116 141 92 180 222 215
WIN-C05A 54
344 379 383 267 329 331 392 360 412 317 326 439 320 306 342 291 273 301 331 348
342 204 225 342 266 292 347 384 344 339 259 318 506 303 218 288 319 252 353 368
162 151 96 215 145 133 211 184 195 87 148 107 70 189
WIN-C05B 54
377 368 374 304 326 326 383 360 395 318 326 444 324 312 325 304 282 291 349 327
344 208 222 359 303 238 289 398 351 352 275 336 475 305 244 294 295 255 369 386
183 145 108 209 141 138 213 181 210 68 153 104 74 198
WIN-C06A 55
123 288 199 144 95 110 118 127 114 129 84 125 163 156 133 74 102 265 374 330
294 300 282 408 387 346 444 244 327 454 359 342 359 529 409 392 296 402 467 318
209 276 298 243 333 283 266 261 257 342 303 268 245 279 321
WIN-C06B 55
177 254 211 139 105 104 124 131 121 133 82 130 146 140 130 99 94 178 338 342
304 272 269 426 379 344 399 265 343 454 338 391 338 485 426 433 275 366 471 342
169 281 285 258 369 271 233 276 253 349 347 254 275 256 339
WIN-C10A 73
234 168 263 250 202 184 238 197 224 218 255 266 210 272 232 225 242 211 156 230
212 180 235 241 244 290 261 262 296 335 298 214 303 269 138 190 200 266 251 312
263 308 171 175 246 214 184 187 187 202 193 306 296 308 335 218 333 202 254 250
283 275 334 281 207 185 195 204 152 162 147 106 135
WIN-C10B 73
190 134 256 254 189 154 254 199 247 232 246 277 220 260 245 214 233 226 158 222
200 181 245 244 241 303 246 274 300 330 299 226 301 271 139 206 188 263 265 294
273 299 168 187 252 225 171 216 184 177 204 306 285 295 310 225 332 205 259 236
288 272 315 271 224 183 189 179 152 157 142 98 155
WIN-C11A 60
516 830 444 318 336 340 291 200 169 271 244 188 190 201 156 130 152 101 91 71
105 148 142 180 145 85 71 90 125 108 222 166 169 274 274 269 188 198 164 290
294 190 215 275 329 210 196 328 164 170 198 198 139 148 132 119 107 121 119 158
WIN-C11B 60
435 574 430 311 323 344 345 200 167 253 229 185 204 203 151 128 157 113 82 79
113 152 134 181 134 76 88 88 123 114 233 197 168 295 266 264 192 190 156 297
296 193 224 264 328 214 226 337 145 176 208 188 144 138 141 127 94 122 121 160
WIN-C12A 57
145 129 167 273 221 166 169 249 191 206 166 234 262 113 157 125 157 169 225 263
156 149 137 164 227 227 213 172 169 145 98 150 151 171 225 167 160 145 216 199
145 156 203 162 160 139 161 130 171 188 158 207 133 121 89 122 182
WIN-C12B 57
140 133 169 265 193 158 172 233 202 212 169 182 242 131 156 121 153 155 243 257
157 160 133 161 224 236 213 152 170 139 132 149 134 174 216 165 162 146 226 203
180 150 214 171 148 136 167 130 174 179 180 189 151 118 88 118 138

WIN-C13A 57
135 127 166 264 220 156 159 239 189 210 156 229 259 117 159 125 276 399 409 456
531 486 500 528 392 458 507 163 343 182 243 349 287 344 196 206 162 145 200 179
204 149 225 218 188 242 314 237 228 231 288 344 241 184 208 229 229
WIN-C13B 57
139 123 166 263 221 156 162 238 207 212 159 216 249 121 159 125 287 392 477 479
448 507 526 527 375 515 505 181 317 198 240 334 306 342 209 219 154 141 199 184
201 147 219 213 180 241 319 266 260 246 284 336 259 170 208 243 255
WIN-C14A 74
188 170 168 176 118 131 135 119 190 171 200 204 211 189 179 190 242 210 190 180
338 372 231 264 330 298 305 352 178 206 399 216 261 119 293 254 234 331 270 362
246 125 177 345 248 300 279 195 219 233 227 286 211 188 113 122 85 111 206 125
173 106 97 111 79 83 121 128 151 141 89 135 108 143
WIN-C14B 74
188 195 161 175 121 130 132 121 213 193 190 197 213 196 179 195 242 212 191 179
401 389 246 280 337 288 312 350 197 200 376 222 251 116 263 263 233 292 266 364
250 132 167 322 286 298 279 212 214 233 215 293 220 191 115 121 83 114 201 122
174 109 103 101 78 80 114 118 152 161 76 135 102 175
WIN-C16A 113
162 304 406 431 279 174 128 96 165 156 361 359 288 208 170 170 225 151 151 187
165 158 192 246 156 206 199 151 120 151 124 190 195 204 154 150 75 95 127 102
92 123 137 147 153 150 145 112 82 87 75 84 97 134 114 138 118 109 73 59
77 138 123 91 75 106 112 51 105 152 194 210 145 74 40 71 50 69 85 31
42 42 39 39 49 61 93 122 119 185 129 158 158 164 157 138 181 277 296 260
288 229 197 158 187 227 285 253 232 222 110 240 237
WIN-C16B 113
178 306 416 411 292 179 141 81 171 167 345 356 293 198 177 163 214 156 147 186
173 149 195 248 159 189 197 167 116 150 120 197 190 198 151 153 90 98 120 103
100 113 144 142 153 155 138 108 68 93 96 78 99 136 104 140 120 116 77 58
69 138 130 84 83 108 106 48 113 159 185 219 153 87 43 50 60 79 64 40
49 36 40 46 52 57 101 109 122 174 152 156 147 165 153 149 158 296 277 266
302 223 208 163 168 220 287 240 246 215 113 258 260
WIN-C17A 56
348 369 229 261 329 288 304 459 306 425 586 407 507 406 384 374 398 400 432 463
313 171 252 321 261 331 324 334 258 308 298 297 277 258 218 179 202 175 210 136
180 191 141 147 171 140 184 166 154 232 143 179 166 206 293 278
WIN-C17B 56
389 369 236 278 331 288 309 384 295 500 542 416 477 347 423 372 409 445 401 463
311 180 234 305 250 351 334 296 305 283 233 294 286 255 230 179 126 160 193 141
169 207 151 144 165 155 193 165 145 231 147 185 159 213 283 287
WIN-C18A 64
221 231 209 200 270 166 243 177 158 198 198 159 179 131 120 122 135 232 197 189
187 213 197 177 185 240 212 181 177 250 167 147 126 157 142 150 163 155 149 249
158 126 125 164 140 151 144 153 167 142 96 150 160 168 161 164 130 124 156 155
192 151 193 171
WIN-C18B 64
230 224 219 198 254 208 224 160 155 198 180 171 175 127 128 132 123 189 174 205
202 209 194 181 194 243 217 187 183 251 115 128 164 138 140 147 165 161 150 244
163 146 149 136 158 128 131 159 173 137 103 158 152 151 175 157 140 128 159 158
222 145 200 183
WIN-C19A 58
138 157 162 174 196 204 149 196 116 134 115 107 136 206 184 196 181 156 173 175
223 216 204 187 247 150 154 156 155 141 164 150 149 150 205 150 148 138 156 148
183 146 160 190 138 115 164 148 174 187 158 128 126 160 148 207 158 173
WIN-C19B 58

102 168 152 170 207 209 156 171 134 110 123 111 147 194 188 197 192 152 192 171
232 218 196 176 264 147 159 155 154 143 144 169 179 150 198 140 127 141 157 161
178 141 170 202 132 100 159 154 168 192 140 137 133 156 149 208 153 161
WIN-C21A 54
82 108 67 107 125 271 239 216 179 273 241 242 266 261 257 282 310 203 207 317
365 422 473 476 339 309 316 337 404 381 345 350 329 371 416 377 457 365 293 378
442 406 548 389 320 478 432 334 337 328 332 370 368 386
WIN-C21B 54
105 107 68 110 126 267 256 207 170 276 238 230 269 262 258 278 311 203 228 317
363 422 481 473 329 314 326 363 380 376 338 364 324 381 429 401 433 366 305 372
430 404 535 395 322 518 466 327 337 333 331 369 353 362
WIN-C23A 54
281 362 290 241 366 333 404 489 530 397 331 295 240 351 376 339 386 228 342 396
353 392 322 320 330 404 394 399 284 326 356 403 421 376 322 325 325 390 324 518
446 313 502 506 398 398 475 501 478 413 270 345 297 290
WIN-C23B 54
295 373 285 245 365 399 378 497 518 385 345 300 261 328 376 336 383 232 332 390
354 405 336 331 338 396 412 364 318 322 368 379 417 408 318 331 329 389 331 501
458 327 494 508 440 392 463 484 494 420 274 403 297 295
WIN-C26A 65
572 464 548 340 443 450 480 496 484 275 362 416 530 565 572 330 349 484 379 304
264 280 222 254 284 234 326 216 233 325 248 254 257 348 290 220 242 216 353 170
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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.

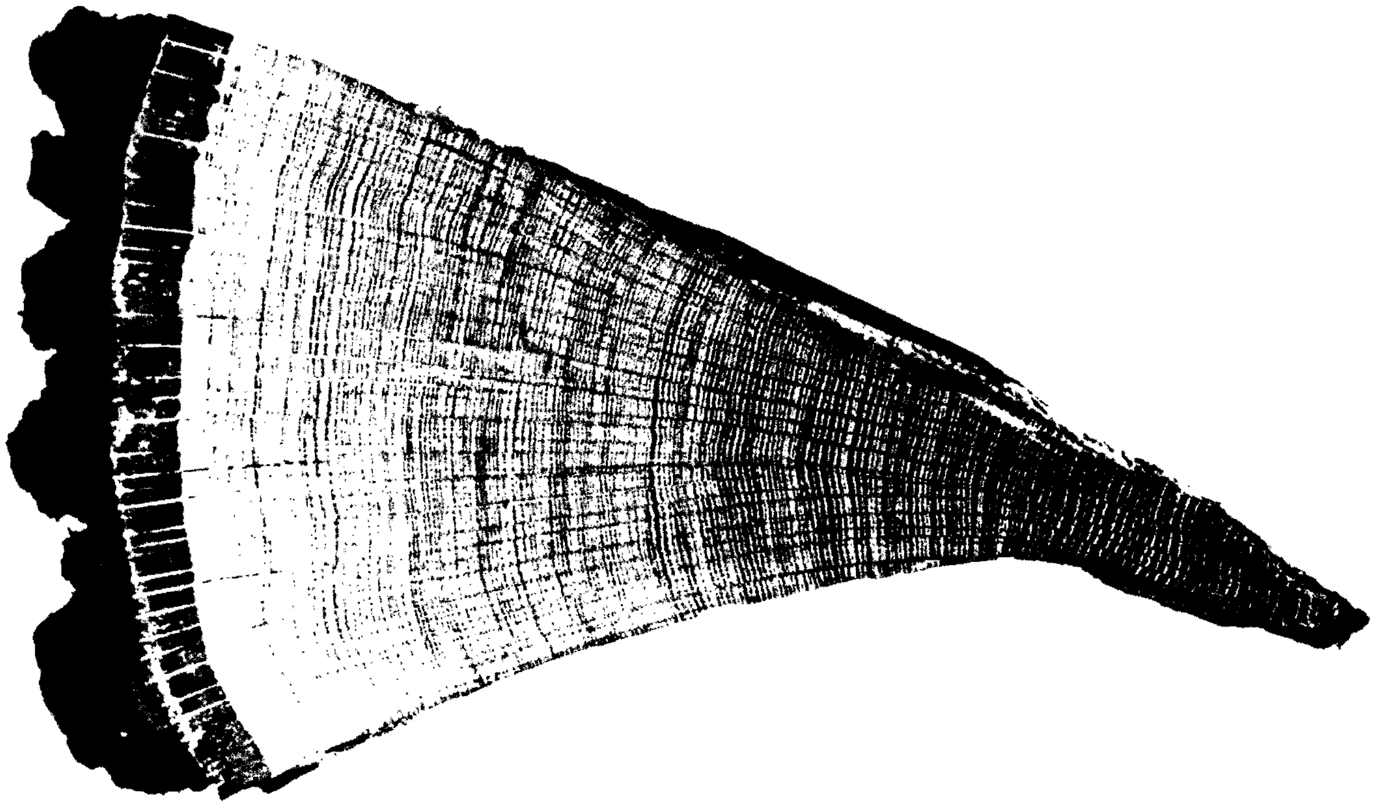


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

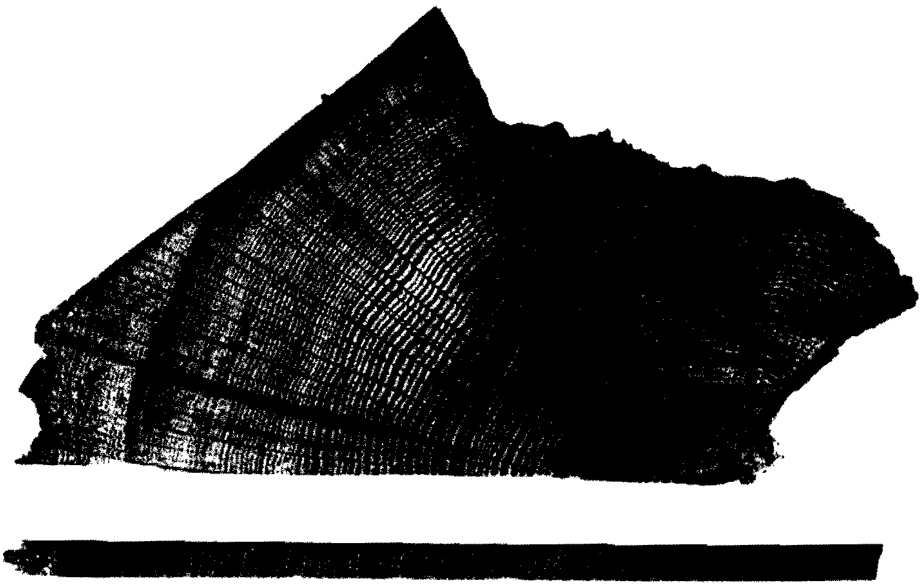


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig. 3 Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

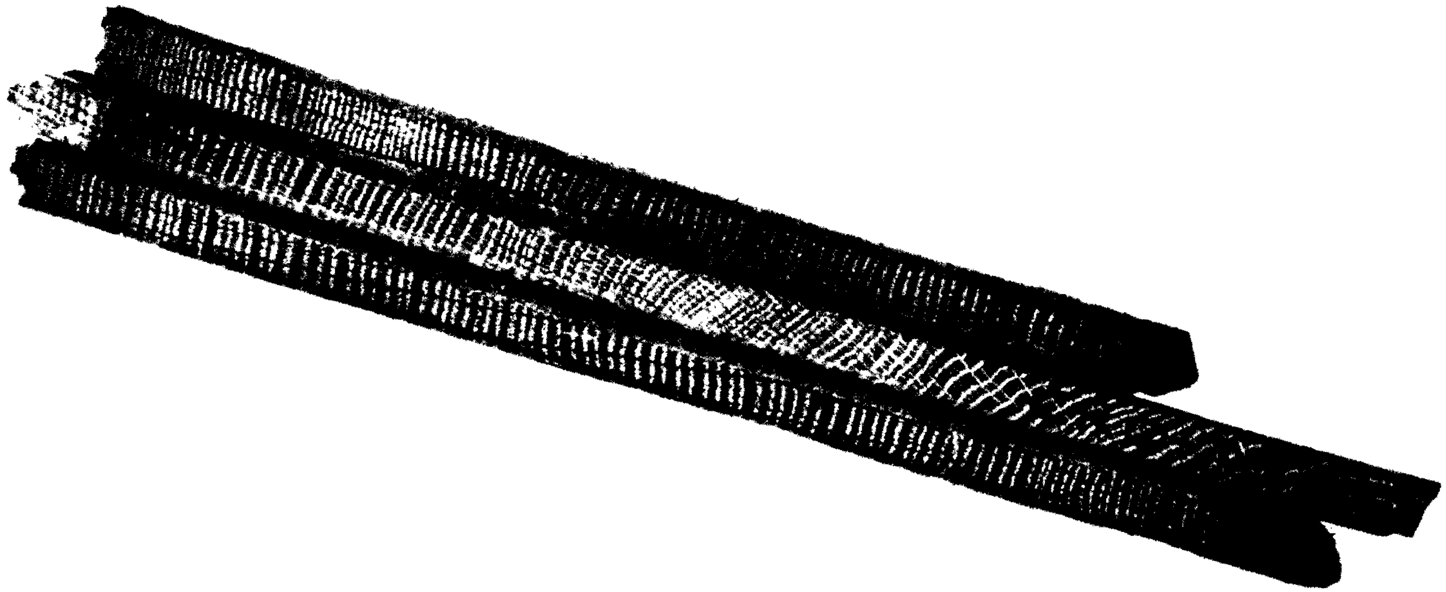


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

2. ***Measuring Ring Widths***. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples***. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984-1995).

This is illustrated in Fig 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a *site sequence* of the building being dated and is illustrated in Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. ***Estimating the Felling Date***. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree. Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases. The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called *sapwood* rings, are usually lighter than the inner rings, the *heartwood*, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. (Oak boards quite often come from the Baltic and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56)).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to *t*-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

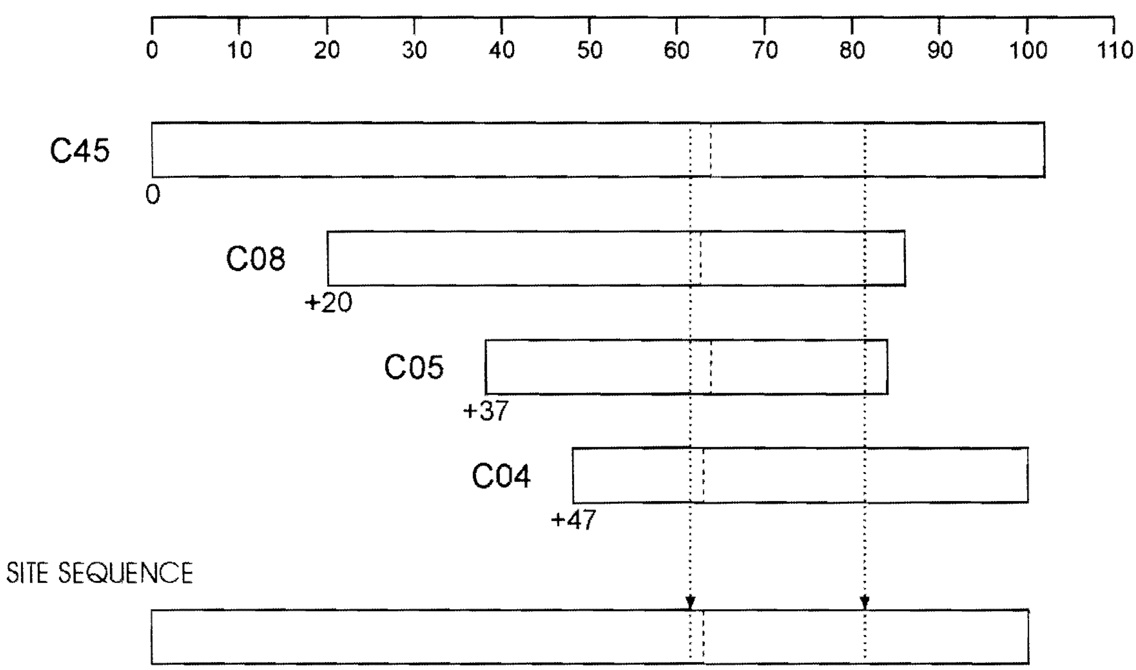


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t*-values.

The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

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

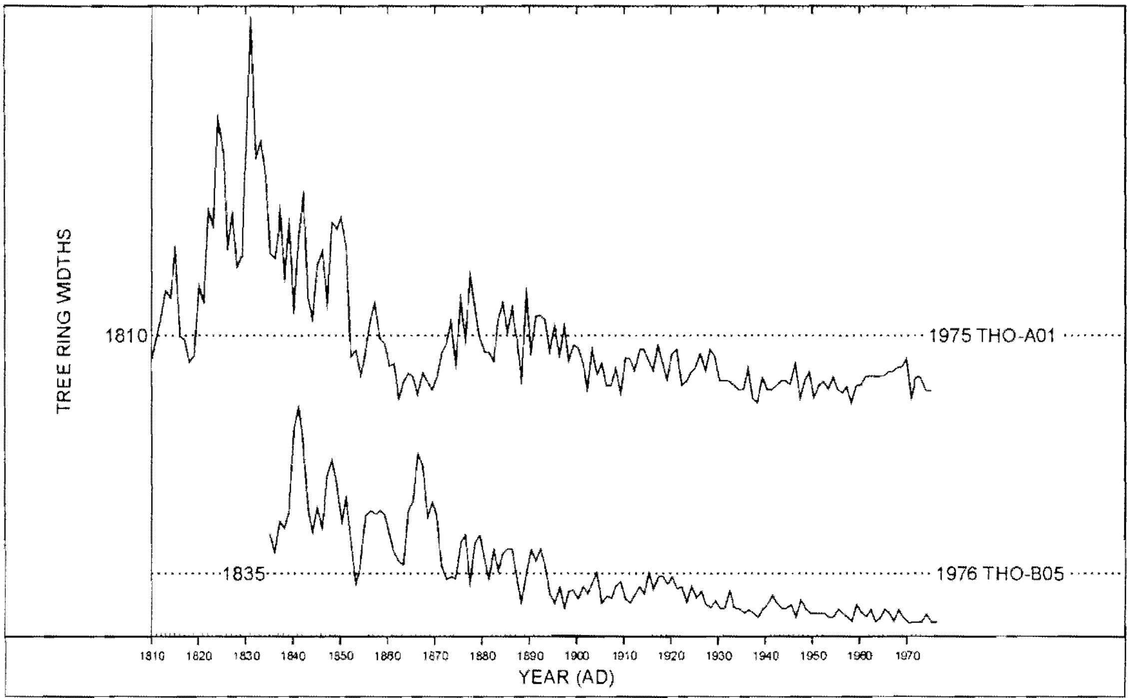
Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction***. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. ***Master Chronological Sequences***. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. ***Ring-width Indices***. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomena can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

(a)



(b)

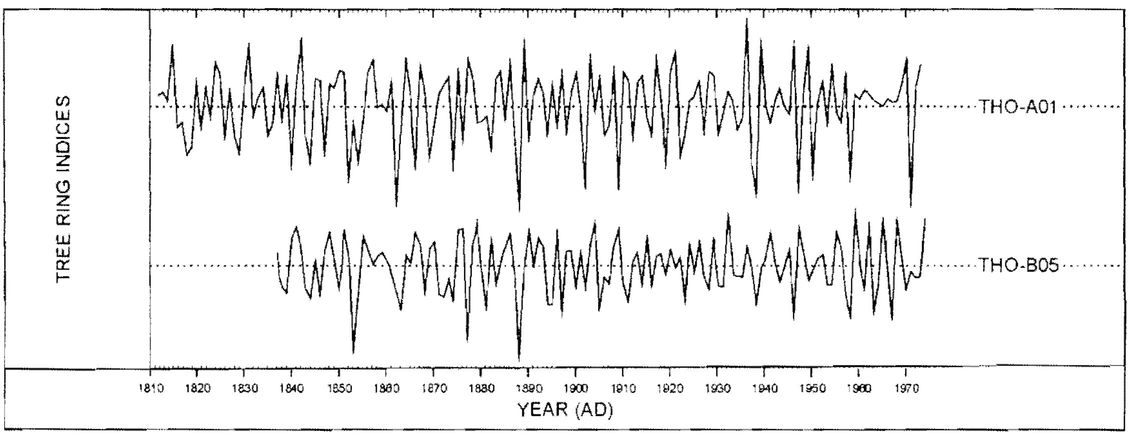


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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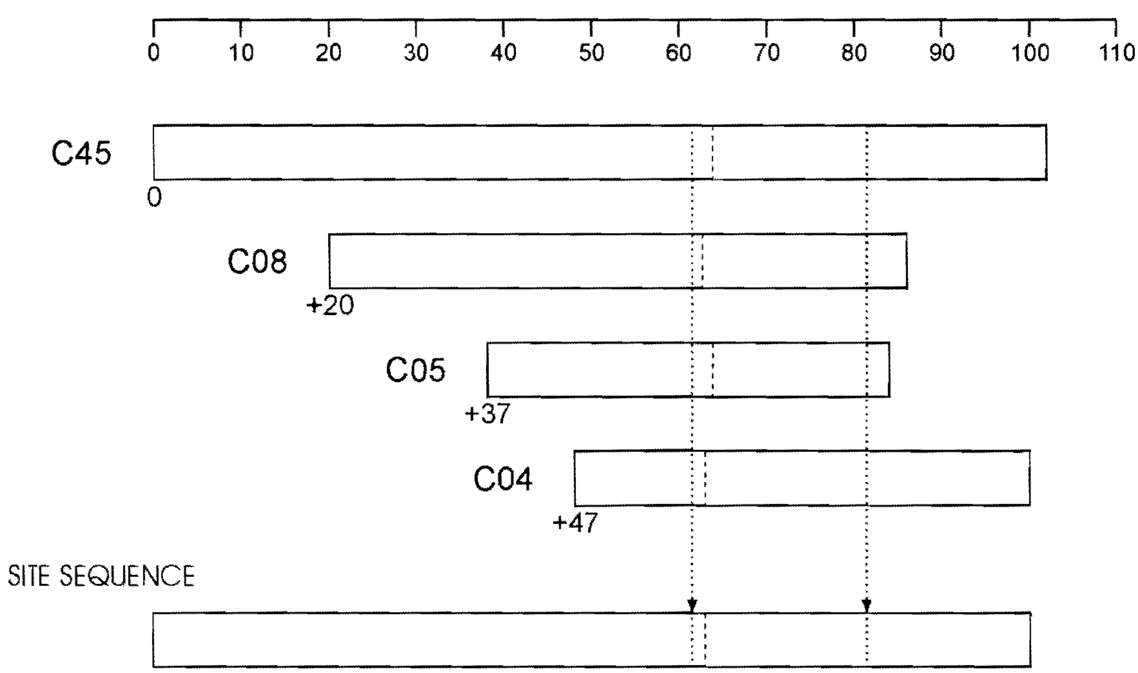

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5. ***Estimating the Date of Construction***. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. ***Master Chronological Sequences***. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. ***Ring-width Indices***. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomena can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

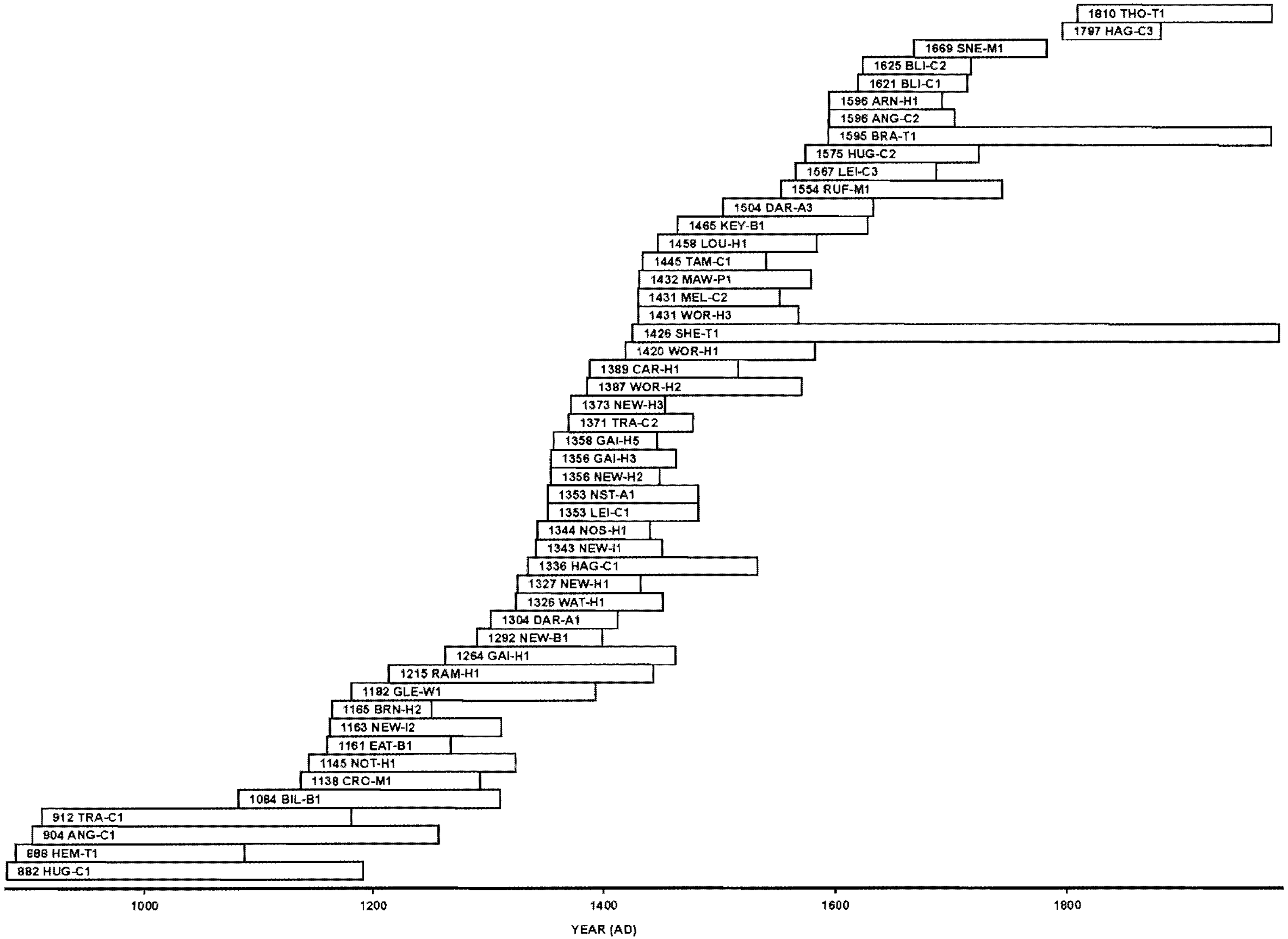
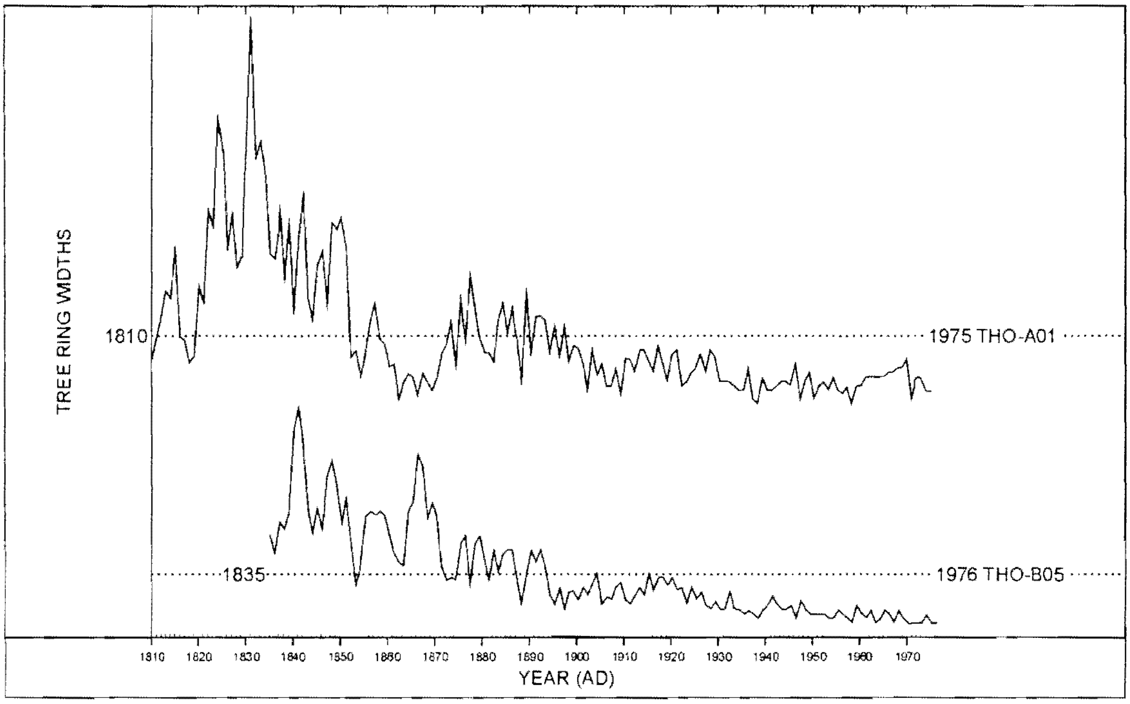


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

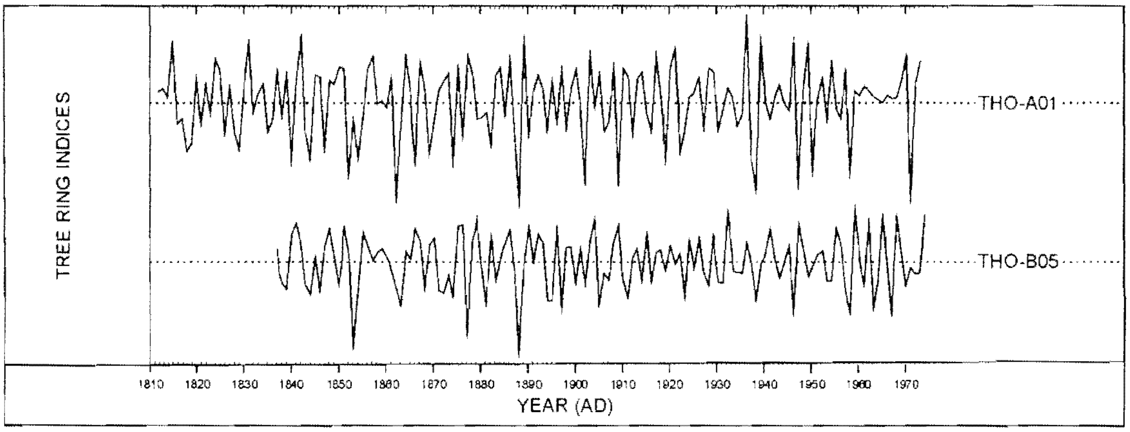


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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