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TUCKERS HALL, 140 FORE STREET, EXETER, DEVON
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard and Cliff Litton

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Tree-Ring Analysis of Timbers

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Summary

Analysis by dendrochronology of 17 out of 20 samples obtained from this site (three samples having been rejected) has produced a single site chronology, comprising seven samples, having an overall length of 87 rings. These rings are dated as spanning the years AD 1356–1442.

Interpretation of the heartwood/sapwood boundary on the samples would indicate the timbers have an estimated felling date in the range AD 1451–76. Such a felling date is consistent with the date of construction obtained from the documentary evidence.

Keywords

Dendrochronology
Standing Building

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Introduction

Traditionally, the earliest known reference to Weavers, Tuckers, and Shearmen in Exeter is in AD 1459, as a consequence of a dispute with the Cordwainers as to their antiquity and precedence in the Mayor's procession on Midsummer Night. Eleven years later, in AD 1470, the Guild of Weavers, Tuckers, and Shearers, whose job it was to regulate the woollen cloth trade in Exeter, was given a piece of land in Fore Street by William and Cecilia Bowden. It was on this plot that the Guild built a chapel, now Tuckers Hall, a grade-11* listed building (Figs 1 and 2; SX 917 923). The woollen trade made Exeter (and Devon) wealthy and a centre for international trade from the AD 1430s until the end of the eighteenth century. Exeter was at one time the third-most important city in the woollen cloth trade in the country, following Bristol and Norwich.

The first rules of the Guild were approved by the Mayor in AD 1483 and provided for a Court of Assistants, comprising a maximum of 27 members. Three of these Assistants hold the office of Master, Head Warden, and Underwarden annually. The Guild obtained a Royal Charter in AD 1620, and became the Incorporation of Weavers, Fullers and Shearmen. Meetings of the Court of Assistants, which are known as "Halls", take place twice a year, in May and November. The Clerk co-ordinates the meetings, keeps the minutes, and carries out correspondence. The Guild appoints a Beadle, who is responsible for the day-to-day running of Tuckers Hall.

It has been estimated that at the end of the sixteenth century, there were about 100 skilled fullers, tuckers, and weavers in Exeter, comprising about 10% of the adult male population. However, although the men were of some standing within the city, they did not have the same wealth as the merchants who financed the woollen industry. Although the craftsmen leased or owned their own workshops and mills, they were often at the beck and call of the merchants.

By AD 1700, the City was exporting about 300,000 cloths a year, or about one quarter of the nation's wool output, while the membership of the Guild numbered four hundred craftsmen. By the end of the eighteenth century, trade was reduced by the Napoleonic Wars and the success of, first, Norwich, and second, the northern wool towns. However, even with the decline of the woollen trade from Exeter, the Guild continued to function, mainly to administer various ancient charities, and provide relief for their members' families who were going through hard times.

The original chapel was a simple open hall with a fine wagon roof with ornately carved bosses and six vertical windows. At the time of the Reformation the chapel was converted into a hall for the Guild to avoid its being confiscated. After the Reformation the building was divided into two storeys, and the upper room was finely panelled and used for meetings of the Guild. There was a school for the children of the cloth-workers on the ground floor from the late-seventeenth century until AD 1841. Many of the major figures in Exeter's history held office in the Guild. The records of the organisation survive, making a significant contribution to the documentary history of the City of Exeter.

It is difficult to reconstruct the external appearance of the chapel from what survives of its fabric in AD 2007. It seems that it originally extended further west than the existing hall, although possibly by only one bay. Its east end was probably the existing east wall. It was of rubble construction, built mostly of Heavitree breccia, a rough, red conglomerate stone, which can still be seen on the north wall. Judging from what is known of other buildings of this status and date, the masonry was probably lime-plastered and the chapel originally roofed with small slates from either the South Hams or Cornwall, laid in diminishing courses. Like its doorway, where one order of original decoration has survived, the masonry of its Perpendicular traceried windows is likely to have been Beer stone, quarried in east Devon. Archaeological evidence for three early windows on the south side survived into the nineteenth century and in AD 2007 the relieving arch of a medieval window still exists in on the north side.

The difference in the beams that support the first floor of the building suggests that the chapel had a gallery at its west end, supported on a single chamfered crossbeam, with a timber front to the gallery.

The most important and legible survival from the chapel period is its splendid oak roof (Fig 3). This is of the wagon type, typical of church roofs in the Perpendicular style in the counties of Devon and Cornwall. It is divided into panels by moulded ribs with carved bosses at the intersections. Since *c* AD 1901 it has been exposed as a fully 'open' roof; the plain curved braces to the rafters exposed to view, with plaster behind the common rafters. The roof is more elaborately decorated than most of the surviving examples of medieval wagon roofs in parish churches. The wall plates are carved with trails. Original slots on the main timbers were clearly designed to take some sort of decorative finish, presumably cusping. No original cusping survives. Presumably it was removed when the roof was plastered over. The existing cusping was installed in AD 1990.

The wagon roof is one strand of the county's rich inheritance of surviving medieval roof forms. There were two distinct medieval roofing traditions in Devon, one for churches and chapels, which almost invariably had wagon roofs, and a separate tradition for domestic and secular public buildings of the same period. These were usually arch-braced or had some form of cruck construction. The roof of Exeter's Guildhall in the High Street, believed to have been erected just one year before the cloth-workers' chapel roof, is an arch-braced design, and not a wagon roof. Some of the Exeter parish churches preserve wagon roofs, eg St Martin's in Cathedral Close, but these are much plainer than Tuckers Hall.

Sampling

Sampling and analysis by tree-ring dating of the Tuckers Hall were commissioned by English Heritage. The purpose of this programme of work was to inform statutory advice in the context of the repairs to the roof, which is thought to be original. It was hoped that tree-ring dating would confirm the documentary evidence and establish the date at which the two main timbers supporting the first-floor frame, the other timbers of the frame being hidden, were inserted. It was further hoped that the data obtained during this analysis would contribute to the further development of local reference material for this part of the south-west

Thus, from the timbers available (all of oak, *Quercus* spp.) a total of 20 samples was obtained by coring. Each sample was given the code EXT-F (for Exeter, site 'F') and numbered 01–20. Eighteen samples, EXT-F01–18, were obtained from the roof of the hall, with a further two samples, EXT-F19 and F20, being taken from the only two available timbers of the inserted ground-floor ceiling. Although only two timbers of this phase were available, normally an insufficient number to provide reliable dating, they were considered of such importance to the history of the building that it was felt important that an attempt be made to date them. Given the size of the beams and the number of rings they potentially contained, it was hoped that they might overlap chronologically and cross-match well with the data provided by the other earlier samples from this site, and with the available reference chronologies in general.

The positions of these samples are marked on plans and drawings made by Acanthus Ferguson Mann, Architects, and provided by Exeter Archaeology. These are reproduced here as Figures 4a–g. Details of the samples are given in Table 1. In this Table the timbers have been located and numbered from east to west, and further identified on a north-south basis as appropriate.

The Laboratory would like to take this opportunity to thank the Court of Assistants, the governing body of Tuckers Hall, for their help and cooperation during sampling, and for their enthusiasm for this programme of tree-ring analysis. We would also like to thank John Allan of Exeter Archaeology for his helpful advice and discussions on the likely phasing of the building, and the comprehensive use of Exeter Archaeology notes in the introduction above. We would also like to acknowledge the use of drawings made by Acanthus Ferguson Mann, Architects.

Analysis

Each of the 20 samples obtained was prepared by sanding and polishing. It was seen at this point that three samples had very low ring numbers, probably being derived from very fast-grown trees, and these were rejected from this programme of analysis. The annual growth rings of the remaining 17 samples were, however, measured (the data of these measurements are given at the end of the report). The data of these 17 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). This allowed for a group of seven samples to be formed, cross-matching with each other as shown in the bar diagram, Figure 5.

The seven cross-matching samples were combined at their respective offsets to form site chronology EXTFSQ01, this having an overall length of 87 rings. This site chronology was compared to a series of relevant reference chronologies for oak, this indicating a consistent cross-match with a number of these when the date of the first ring is AD 1356 and the date of the last ring is AD 1442. The evidence for this dating is given in Table 2.

Site chronology EXTFSQ01 was compared with the 10 remaining measured but ungrouped samples, but there was no further satisfactory cross-matching. The 10 remaining ungrouped sample were then compared individually with a full range of reference chronologies for oak, but there was no further cross-matching and they must therefore remain undated.

Interpretation and conclusion

Analysis by dendrochronology of 17 out of 20 samples obtained from this site has produced a single dated site chronology, EXTFSQ01, comprising seven samples distributed throughout the length of this roof, its 87 rings dated as spanning the years AD 1356–1442. Given the highly moulded and carved nature of the timbers, none of the samples in this site chronology retains complete sapwood. This means that the precise felling date for the timbers cannot be determined. Some of the samples do, however, retain the heartwood/sapwood boundary, ie, only the sapwood rings are missing. The average date of this boundary, on the five dated samples where it exists, is AD 1436. Allowing for a 95% confidence limit of 15–40 sapwood rings that the trees used here are likely to have had when they were felled would give the timbers represented an estimated felling date in the range AD 1451–76. Such a felling date range encompasses the documentary date for this building and would suggest that the dated timbers are part of the original structure. Two other dated samples do not retain the heartwood/sapwood boundary and in theory it is not possible to be certain when the trees they represent were felled, except that it is unlikely to be less than 15 years after the last measured ring dates, AD 1410 and AD1421, respectively. There is no reason, therefore, to suspect that they were not felled at the same time as the other dated timbers.

Judging by the degree of cross-matching between two of the dated samples, EXT-F17 and F18, it is possible that the two timbers represented, the north rafters from frames 21 and 22 respectively, are derived from the same tree, or at least from two trees growing adjacent to each other; between these two samples we find a cross-match with a value of t=13.1. The cross-matching between the other dated samples would suggest that the trees represented were growing further apart from each other, possibly in slightly different areas of woodland.

Where this original woodland was cannot be determined precisely through tree-ring analysis. It would, however, appear that the dated timbers were all of a south-west of England source. As can be seen from Table 2, which shows the reference chronologies against which site chronology EXTFSQ01 has been dated, the highest t-values, ie the greatest degree of similarity, are with reference data made up of material with a distinct west, and generally south-west of England bias. Indeed, it may be of interest to note that some of the timber used at Tuckers Hall is likely to have come from the same source as that used in Exeter Guildhall, only a short distance from Tuckers Hall. As can be seen from Table 2 there is a cross-match with this material with a value of t=12.8.

Ten of the measured samples remain ungrouped and undated. It will be seen from Table 1 that while some of these do have low ring numbers, they are all theoretically sufficient, and some in fact have more rings than those samples which were dated. It is possible that these undated samples represent trees growing in slightly different locations and are thus, in effect, 'singletons'. Such samples are usually more difficult to date reliably than those combined in a well-replicated set of data.

Amongst the undated samples are those from the two beams of the ground-floor ceiling. Despite their size, they do not have particularly high numbers of rings. These neither cross-match each other nor can be independently dated, and as they are highly likely to be of a later date than the roof timbers this means that they could easily be derived from a different woodland source.

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Table 1: Details of samples from the roof of Tuckers Hall, 140 Fore Street, Exeter

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
EXT-F01	North archbrace, frame 3	72	h/s	AD 1356	AD 1427	AD 1427
EXT-F02	South archbrace, frame 3	56	no h/s	------	------	------
EXT-F03	North archbrace, frame 4	nm	---	------	------	------
EXT-F04	South archbrace, frame 4	73	h/s	AD 1364	AD 1436	AD 1436
EXT-F05	North archbrace, frame 8	57	h/s	------	------	------
EXT-F06	North rafter, frame 9	nm	---	------	------	------
EXT-F07	North rafter, frame 10	nm	---	------	------	------
EXT-F08	North rafter, frame 11	53	no h/s	AD 1358	------	AD 1410
EXT-F09	South archbrace, frame 11	46	h/s	------	------	------
EXT-F10	South archbrace, frame 12	55	no h/s	------	------	------
EXT-F11	North rafter, frame 13	65	h/s	------	------	------
EXT-F12	South archbrace, frame 14	57	no h/s	------	------	------
EXT-F13	North rafter, frame 18	51	h/s	AD 1392	AD 1442	AD 1442
EXT-F14	South archbrace, frame 18	64	h/s	------	------	------
EXT-F15	North rafter, frame 19	65	5	AD 1377	AD 1436	AD 1441
EXT-F16	North rafter, frame 20	60	h/s	------	------	------
EXT-F17	North rafter, frame 21	80	h/s	AD 1358	AD 1437	AD 1437
EXT-F18	North rafter, frame 22	51	no h/s	AD 1371	------	AD 1421
EXT-F19	East ground-floor ceiling beam	61	no h/s	------	------	------
EXT-F20	West ground-floor ceiling beam	80	h/s	------	------	------

* h/s = the last ring on the sample is the heartwood/sapwood boundary
nm = sample not measured

Table 2: Results of the cross-matching of site chronology EXTFSQ01 and relevant reference chronologies when first ring date is AD 1356 and last ring date is AD 1442

Reference chronology	Span of chronology	*t*-value	
Exeter Guildhall, High Street, Exeter	AD 1314–1456	12.8	(Howard *et al* 1999)
The Commandery, Worcester	AD 1284–1473	6.6	(Arnold and Howard 2006)
Kingswood Abbey, Gatehouse, Glos	AD 1307–1428	6.4	(Arnold *et al* 2003)
Muchelney Abbey, Somerset	AD 1148–1498	6.3	(Bridge 2002)
Brockworth Court (barn), Brockworth, Glos	AD 1352–1456	5.5	(Howard *et al* 1998)
Leigh Barton, Churchstow, Devon	AD 1345–1484	5.4	(Groves 2006)
Lodge Park, Aldsworth, Glos	AD 1324–1587	5.3	(Howard *et al* 1995)
Lacock Abbey, Lacock, Wilts	AD 1314–1448	5.2	(Esling *et al* 1990)

Figure 1: Map showing the general location of Tucker's Hall, Exeter.

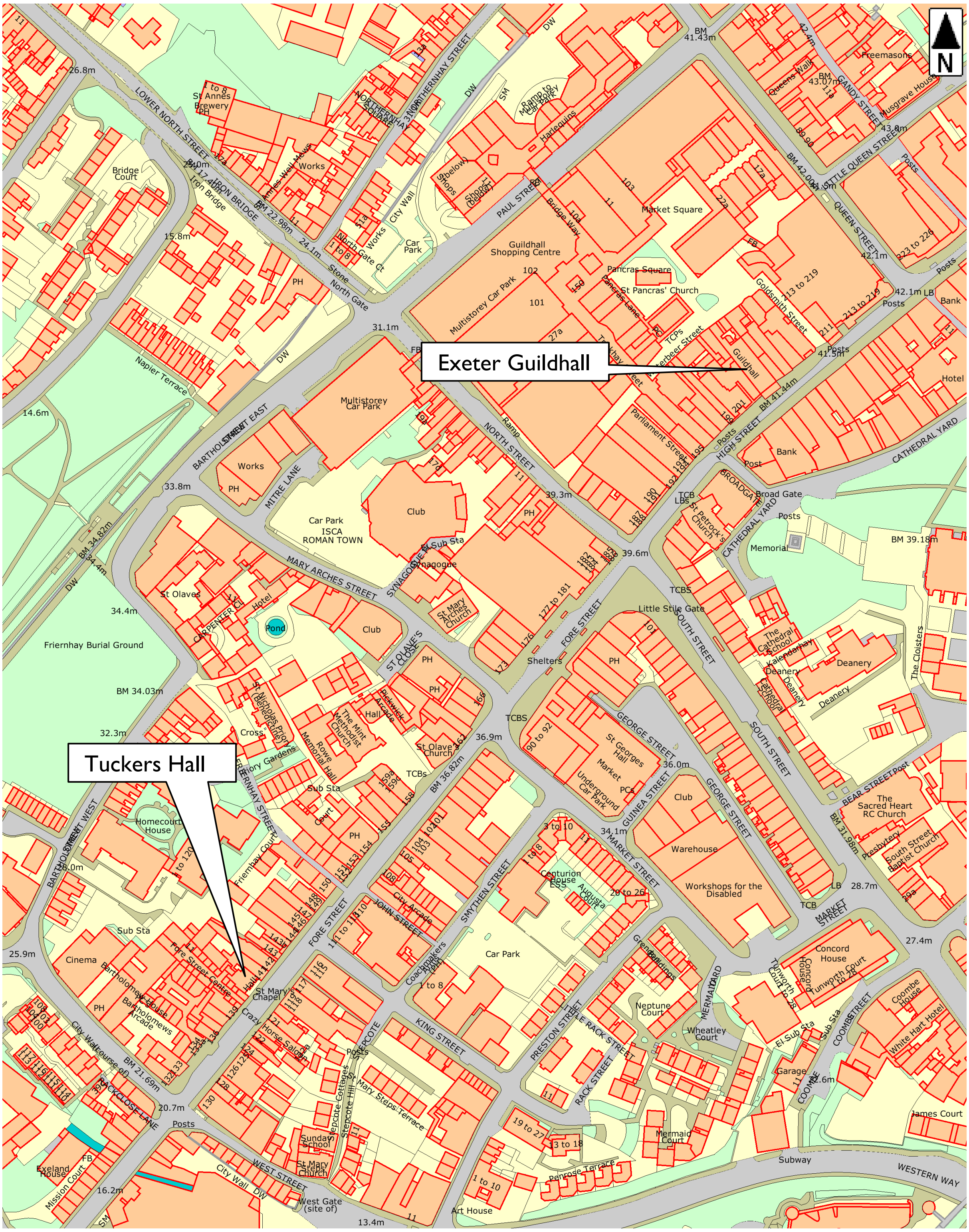


Figure 2: Central Exeter, showing the locations of Tuckers Hall and the Exeter Guildhall.

Figure 3: View of the wagon roof to Tuckers Hall

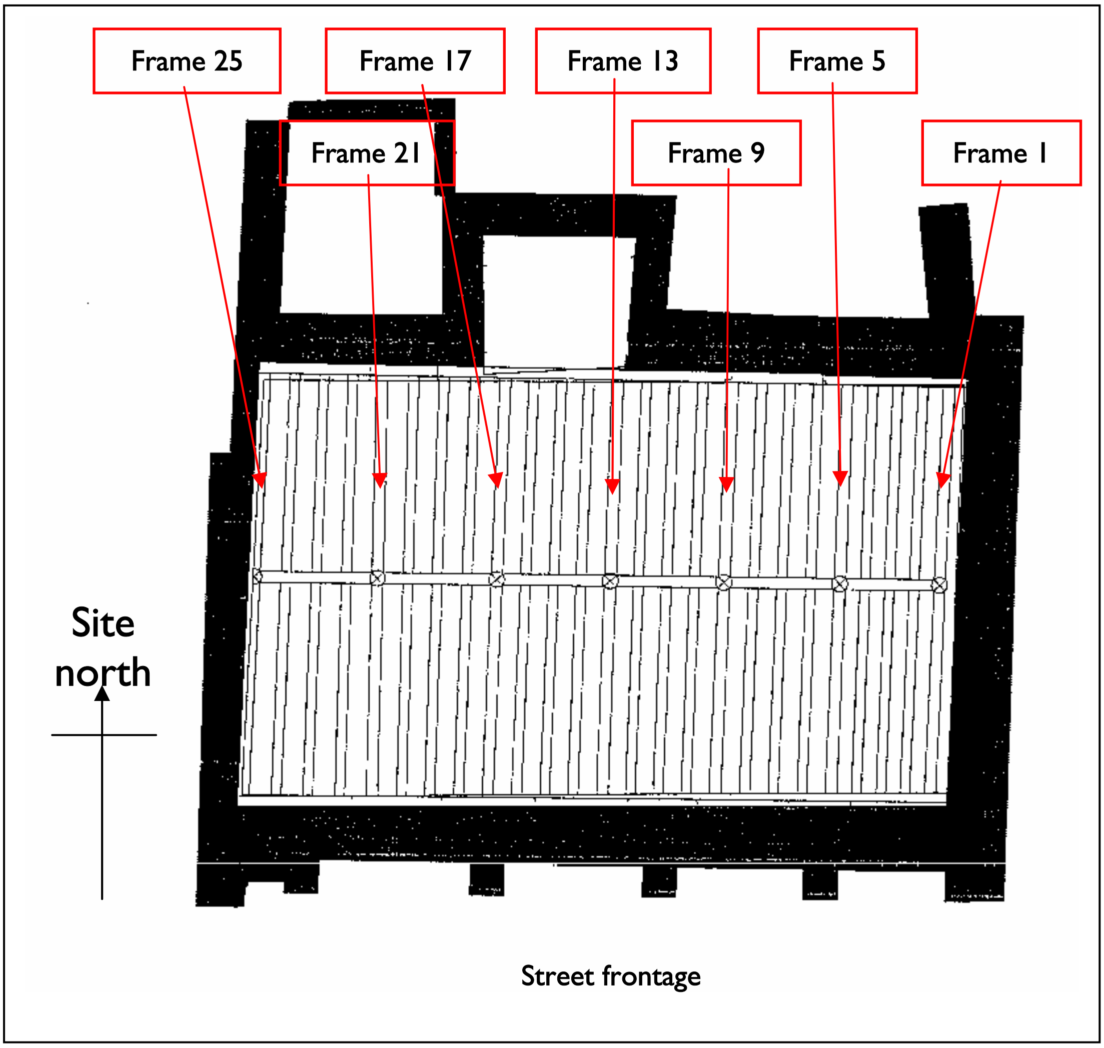


Figure 4a: Plan showing frame numbers to help locate sampled timbers (after Acanthus Ferguson Mann Architects)

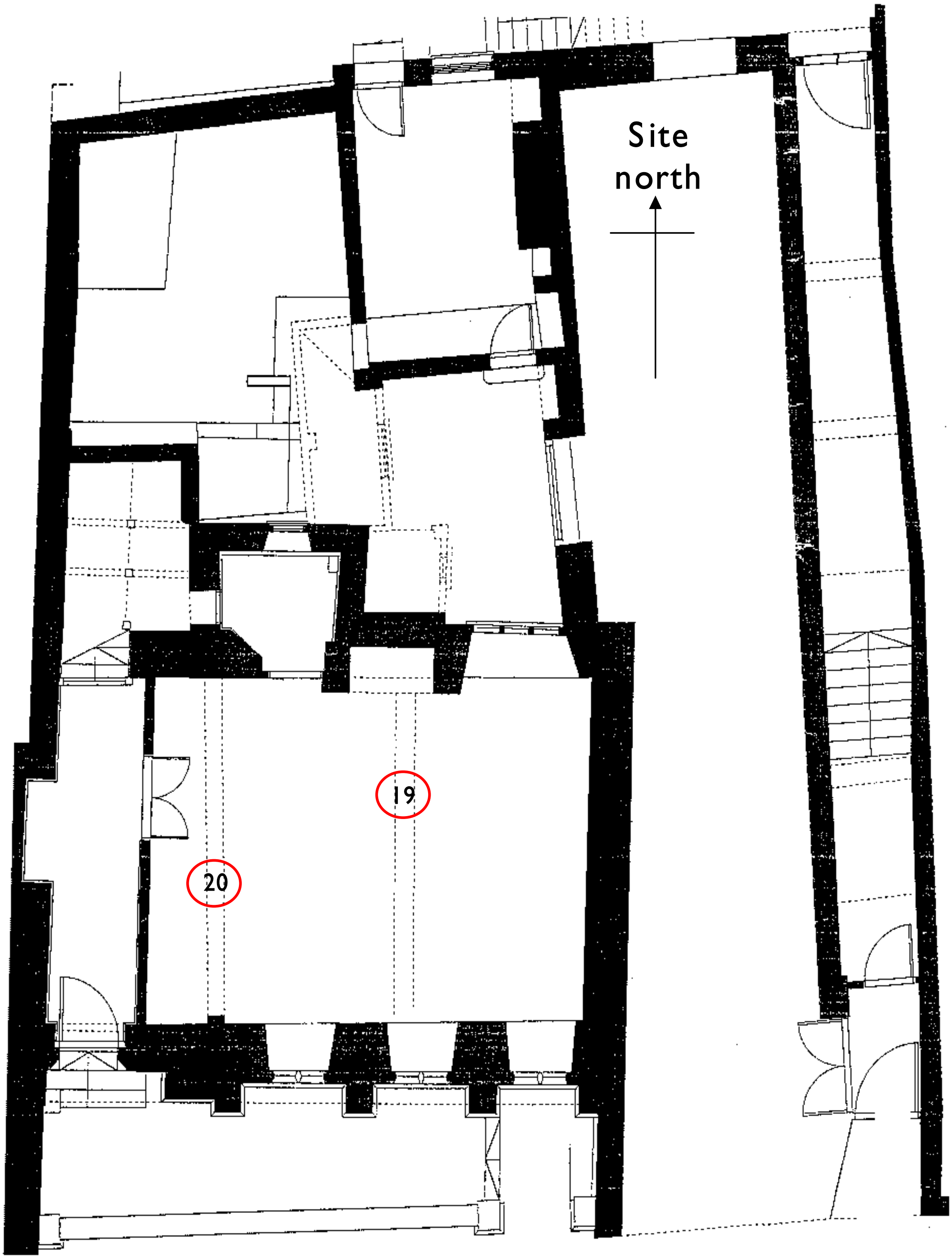


Figure 4b: Plan to show location of samples from the ground-floor ceiling beams (after Acanthus Ferguson Mann architects)

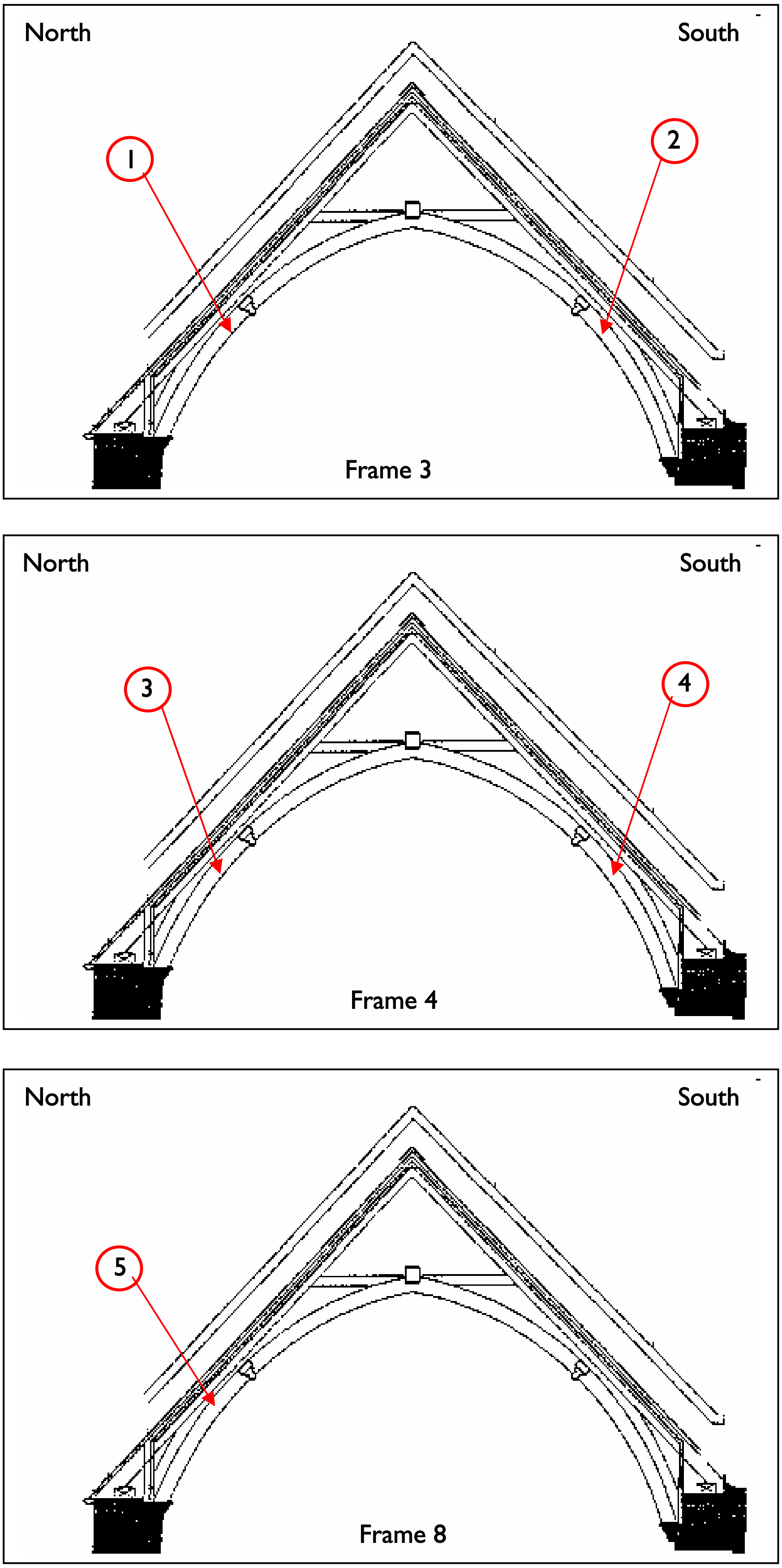
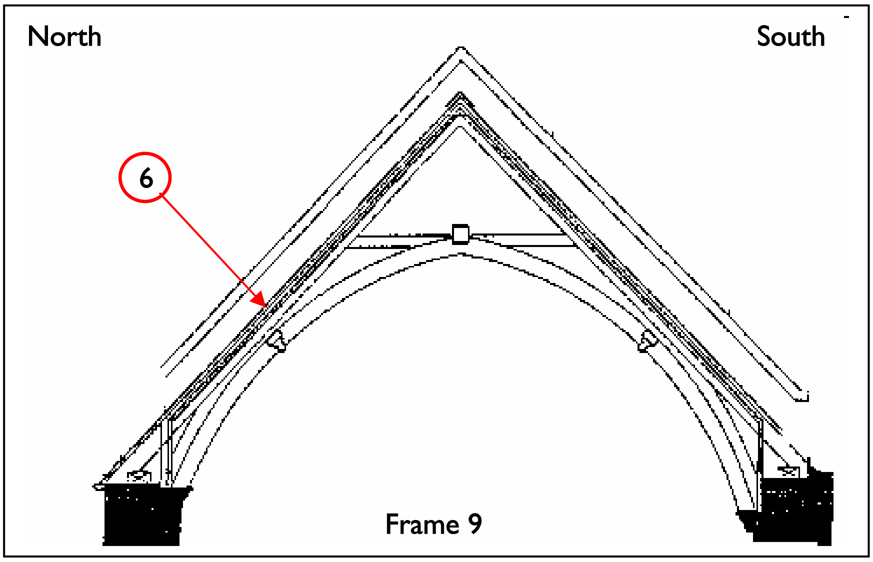
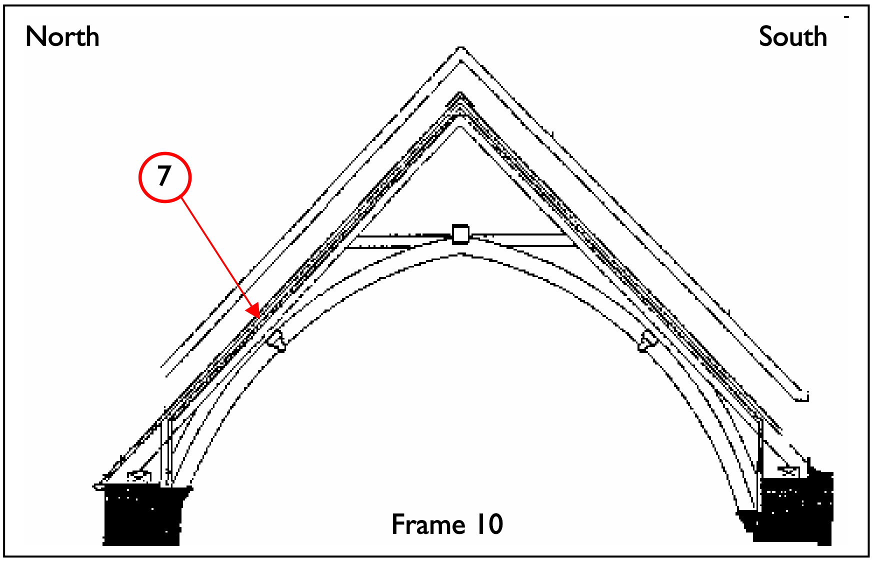


Figure 4c: Section to show sampled timbers in frames 3, 4, and 8 (after Acanthus Ferguson Mann Architects)





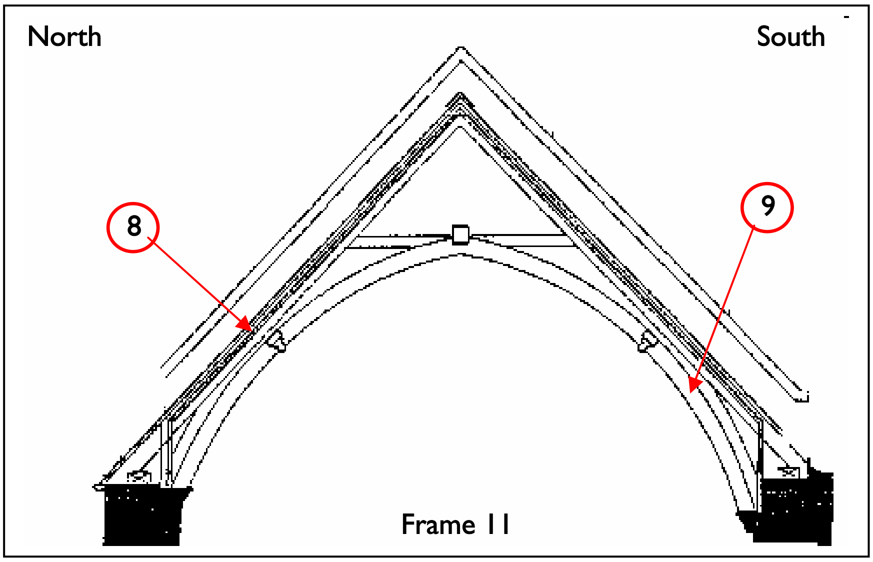
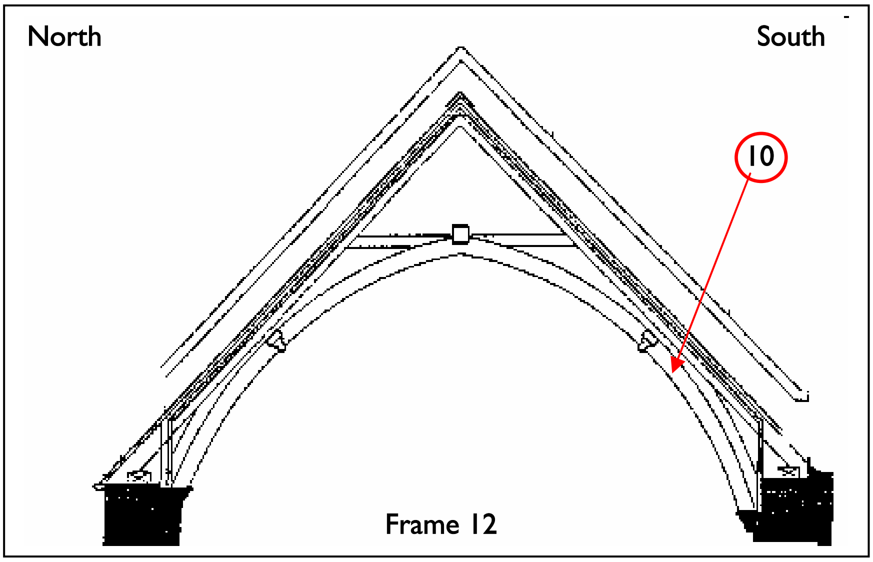
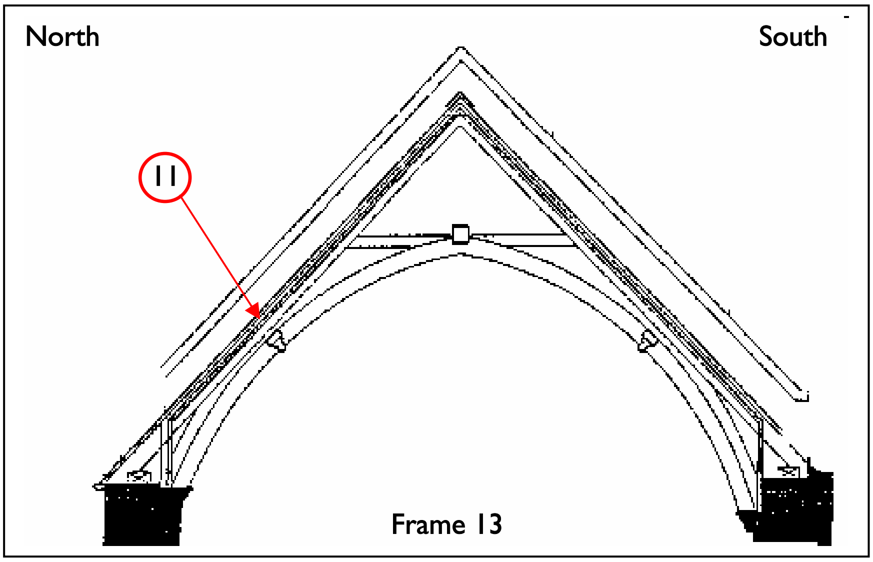


Figure 4d: Section to show sampled timbers in frames 9, 10, and 11 (after Acanthus Ferguson Mann Architects)





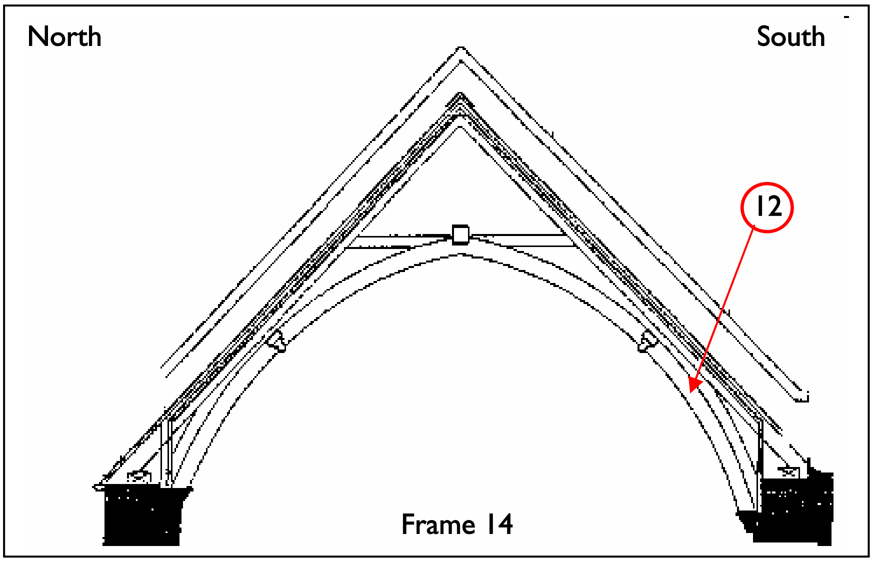
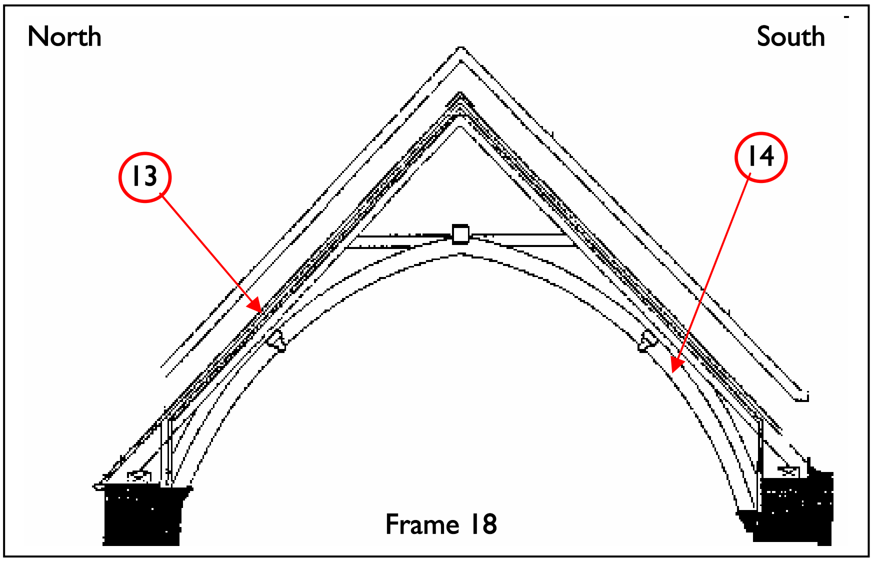
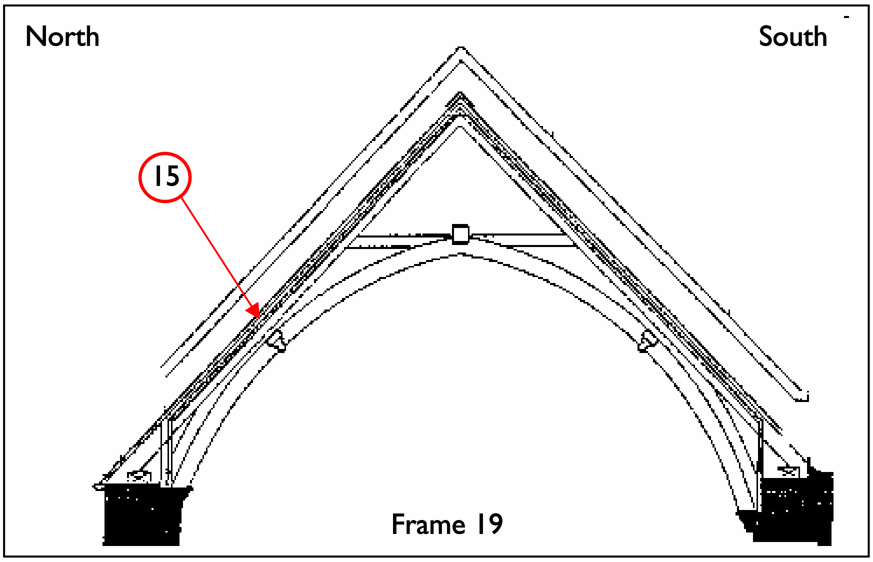


Figure 4e: Section to show sampled timbers in frames 12, 13, and 14 (after Acanthus Ferguson Mann Architects)





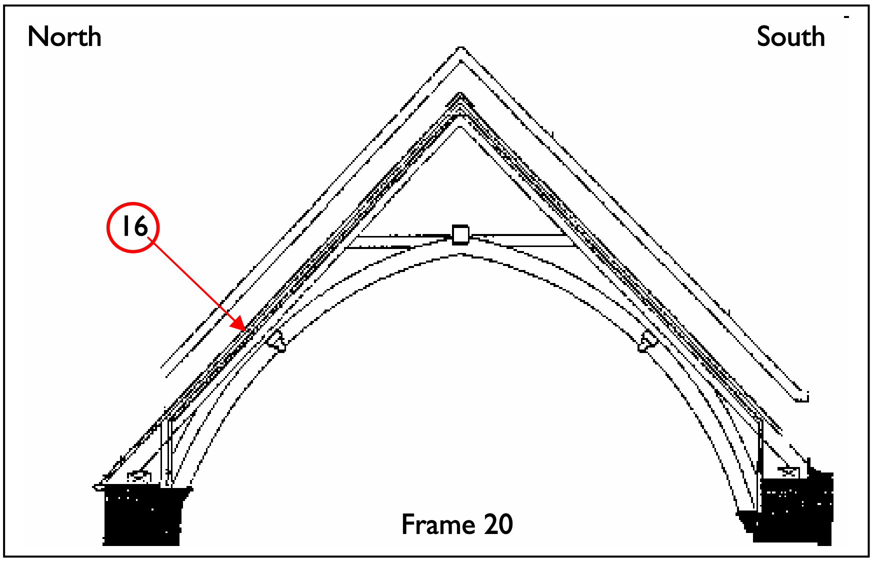
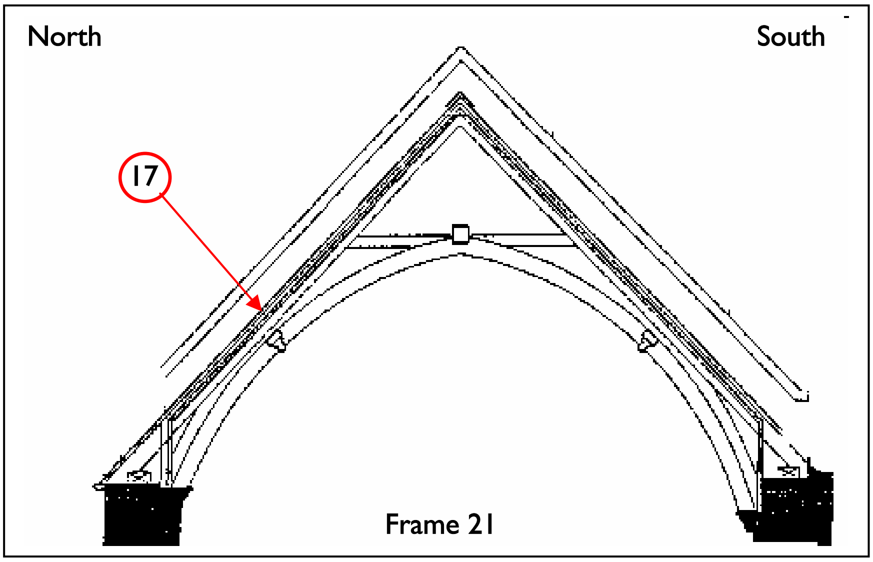


Figure 4f: Section to show sampled timbers in frames 18, 19, and 20 (after Acanthus Ferguson Mann Architects)



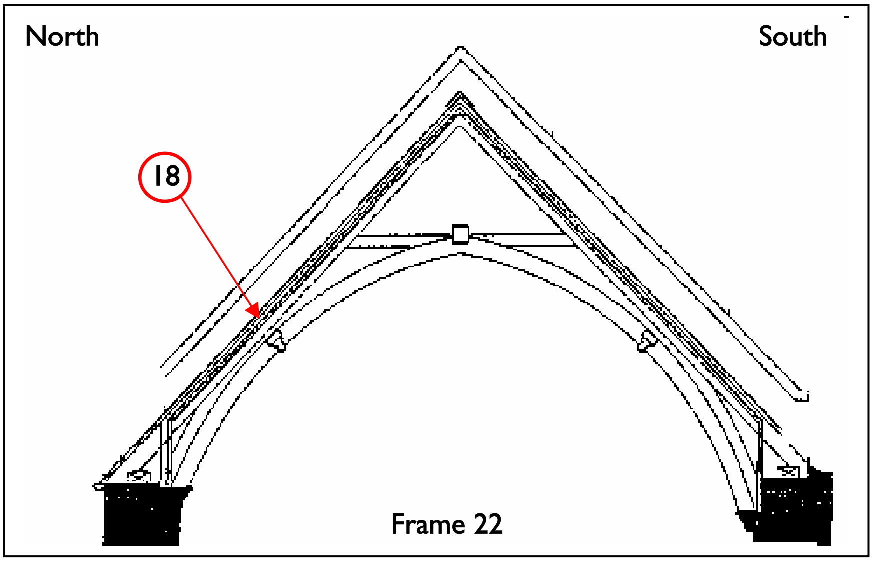
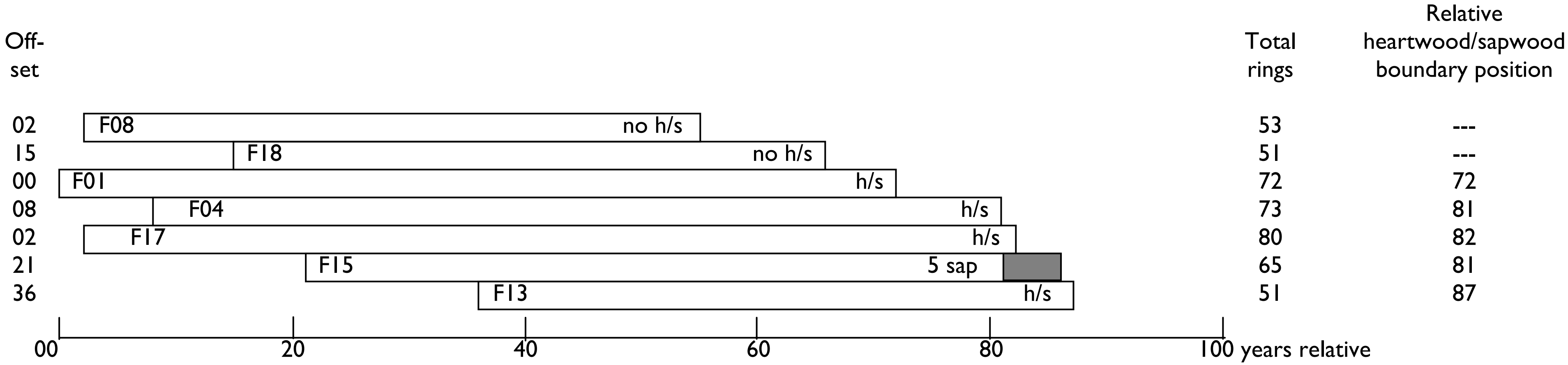


Figure 4g: Section to show sampled timbers in frames 21 and 22 (after Acanthus Ferguson Mann Architects)



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary, only the sapwood rings are missing

Figure 5: Bar diagram of the samples in site chronology EXTFSQ01

Data of measured samples – measurements in 0.01 mm units

EXT-F01A 72
193 168 211 215 127 132 141 239 232 163 192 160 141 144 109 79 126 129 136 118
105 135 155 200 160 133 110 110 111 156 151 140 155 119 123 82 87 158 110 133
80 73 91 114 125 80 107 166 135 170 209 179 178 134 175 190 185 202 213 212
149 191 351 158 222 214 186 275 369 280 161 151
EXT-F01B 72
196 167 224 209 119 121 153 241 258 164 191 159 143 133 98 96 102 139 139 118
110 134 151 185 162 126 106 109 110 149 141 141 147 116 109 108 93 167 122 136
80 81 107 112 107 86 108 160 117 143 186 186 197 138 174 182 197 187 222 201
142 196 328 185 203 227 168 297 371 266 173 167
EXT-F02A 56
72 44 49 50 113 63 142 111 250 281 215 228 152 190 119 126 125 195 511 672
829 498 273 631 609 596 574 384 204 144 251 131 249 201 184 175 231 205 259 166
191 203 201 415 249 224 206 171 189 289 342 417 348 157 119 134
EXT-F02B 56
92 39 46 46 122 63 139 123 207 267 198 285 146 179 98 130 127 217 446 684
803 446 255 589 523 539 561 373 203 137 249 135 250 240 189 182 248 210 232 145
195 212 201 438 260 227 197 159 182 297 307 423 394 174 114 143
EXT-F04A 73
434 351 584 474 387 436 291 209 199 259 623 403 276 154 149 212 191 148 185 151
141 126 151 191 198 236 205 176 100 191 168 154 162 92 104 143 178 247 165 203
123 136 476 201 232 247 292 216 237 186 215 275 157 112 164 88 234 171 164 197
184 152 116 72 87 67 96 85 200 145 117 143 103
EXT-F04B 73
440 357 569 481 385 427 310 215 207 261 587 369 275 152 137 185 184 156 192 161
138 125 145 192 203 221 216 179 100 183 178 154 155 95 110 137 197 254 159 207
114 134 523 208 226 234 267 243 219 192 210 290 156 121 167 93 232 167 157 188
173 143 112 83 91 77 80 89 226 111 122 167 108
EXT-F05A 57
219 218 304 344 219 295 377 342 265 304 304 172 174 183 157 215 290 253 289 179
204 192 184 210 167 204 179 161 194 143 147 151 147 179 256 252 170 127 158 162
144 153 209 167 215 242 189 193 175 172 168 206 163 150 145 96 109
EXT-F05B 57
310 225 305 386 239 343 400 345 273 290 283 171 161 158 121 222 295 251 284 193
197 202 190 199 170 202 175 161 185 139 156 143 166 182 247 250 171 133 165 157
164 140 216 176 205 249 186 202 170 174 166 188 173 143 136 98 145
EXT-F08A 53
243 223 163 144 176 396 338 250 203 263 279 253 173 159 131 123 180 148 111 127
112 132 138 203 315 259 273 247 299 383 392 238 197 145 99 237 153 212 229 220
159 258 291 260 223 314 220 210 508 297 355 296 347
EXT-F08B 53
239 224 171 147 175 417 393 244 195 262 277 284 174 154 131 109 175 176 116 97
104 137 142 196 304 258 272 252 298 371 399 240 185 138 128 203 155 194 184 206
173 269 305 250 248 323 217 209 502 296 362 295 346
EXT-F09A 46
267 388 472 340 442 365 417 256 203 311 172 233 225 291 290 309 308 248 171 190
177 221 261 257 320 214 458 330 421 394 270 171 274 247 159 186 181 280 252 137
202 219 236 174 152 156
EXT-F09B 46
266 397 455 342 445 346 381 276 180 322 197 244 229 288 272 308 328 264 178 201
174 212 276 254 299 226 461 312 430 394 260 171 273 252 144 202 200 294 205 175
201 219 238 173 142 143

EXT-F10A 55
162 341 236 269 451 289 278 386 300 270 284 242 170 150 171 137 165 154 117 125
126 132 132 90 92 114 121 100 111 80 75 80 83 76 66 60 57 69 80 71
71 96 63 68 41 68 64 70 63 81 47 46 53 60 57
EXT-F10B 55
168 292 222 277 472 280 297 372 320 262 258 263 180 143 161 138 176 178 131 122
105 128 123 96 87 125 113 90 109 91 62 85 82 72 69 61 67 72 71 77
70 91 64 63 37 68 74 68 72 72 41 55 54 58 57
EXT-F11A 65
452 477 483 434 540 453 361 381 486 419 536 519 462 357 401 346 426 440 443 371
391 284 231 127 161 177 138 149 176 208 172 119 128 167 161 163 166 83 75 97
115 128 117 182 235 183 164 110 91 113 130 127 118 103 111 66 155 149 144 84
98 124 125 104 130
EXT-F11B 65
459 470 475 431 551 446 370 382 494 409 531 509 469 350 407 351 418 393 437 357
391 279 227 121 158 170 143 139 177 222 165 112 127 166 147 171 153 88 77 98
94 130 118 180 233 179 164 111 92 102 127 125 119 108 107 63 157 162 132 95
99 128 96 109 130
EXT-F12A 57
217 336 468 429 321 334 266 394 360 310 258 310 221 197 169 248 135 158 167 158
106 121 228 141 78 100 81 98 111 126 219 203 188 102 186 338 256 244 272 251
268 254 292 159 262 239 200 231 173 206 113 200 264 228 195 138 130
EXT-F12B 57
269 333 411 454 307 339 264 394 361 309 279 289 221 198 171 228 141 160 165 150
118 105 251 133 78 107 77 99 121 122 214 197 181 110 194 343 262 234 259 275
266 268 293 165 261 258 223 263 178 220 118 204 268 221 192 147 116
EXT-F13A 51
134 252 185 192 204 134 153 208 192 170 129 218 134 160 255 324 344 303 362 348
380 353 298 285 171 169 169 173 265 229 215 294 400 423 169 131 159 134 138 123
172 145 182 164 142 139 102 121 123 150 134
EXT-F13B 51
132 246 197 172 200 138 154 209 198 156 140 204 133 153 265 336 330 311 378 353
339 350 294 282 176 153 177 183 266 236 228 269 359 434 194 116 166 148 140 114
163 140 166 183 134 151 106 115 116 120 107
EXT-F14A 64
331 419 503 338 237 183 199 160 133 149 117 142 113 104 161 109 217 156 171 160
193 168 189 243 300 300 234 192 291 442 401 407 273 385 410 610 600 469 495 401
334 442 401 605 306 333 368 393 234 134 110 97 106 79 91 84 98 119 124 121
156 120 134 113
EXT-F14B 64
338 418 506 336 216 194 178 163 130 172 105 134 120 102 156 114 227 143 173 158
188 172 187 231 309 298 221 178 284 433 394 417 279 379 420 598 594 482 480 405
333 450 394 613 308 356 377 369 245 129 64 112 105 87 89 78 101 102 128 140
151 103 145 111
EXT-F15A 65
126 119 164 150 164 165 135 126 128 158 156 172 148 146 120 110 221 151 243 211
208 255 436 528 430 293 315 205 194 348 296 383 298 295 238 225 206 223 231 140
112 153 118 175 153 140 147 189 136 107 109 124 96 112 104 131 94 114 88 103
99 84 124 129 123
EXT-F15B 65
140 125 165 165 170 152 216 127 128 164 163 152 177 148 118 106 218 158 224 221
219 230 412 494 461 275 318 207 222 394 288 374 297 312 221 228 210 212 231 133
125 161 136 162 156 144 140 188 148 121 105 115 99 121 110 124 93 98 104 94
106 104 100 124 115

EXT-F16A 60
271 111 145 226 185 153 123 145 119 140 138 292 265 171 124 148 228 773 597 507
504 749 584 325 365 494 420 279 159 53 67 64 116 84 121 138 109 173 142 152
123 236 158 129 188 206 225 263 165 200 126 107 108 115 173 246 373 537 402 441
EXT-F16B 60
259 124 155 227 192 157 129 125 123 146 145 252 254 162 121 152 286 754 617 495
457 749 582 331 359 535 440 291 148 61 52 75 117 79 108 132 113 182 145 143
112 232 158 127 197 207 262 240 171 189 121 120 97 118 154 271 355 525 376 462
EXT-F17A 80
429 373 273 307 241 320 302 242 221 261 247 237 181 159 188 166 239 250 254 162
169 179 211 225 204 157 174 177 173 187 136 138 125 95 86 120 98 119 171 119
98 113 159 139 120 99 79 96 189 194 222 196 114 72 100 93 114 153 127 125
139 141 204 183 181 269 293 247 225 175 133 121 179 140 229 143 105 158 180 153
EXT-F17B 80
431 316 266 303 254 324 298 249 232 260 259 225 182 168 182 165 239 265 248 160
172 189 218 214 206 164 166 167 176 197 145 152 122 96 84 122 108 124 168 125
101 115 156 140 118 104 73 94 195 189 221 220 119 58 76 98 129 134 149 113
145 134 218 184 165 268 297 233 264 177 140 117 171 148 216 123 123 160 167 151
EXT-F18A 51
167 158 167 176 233 253 175 199 234 287 281 229 214 206 214 172 194 165 151 149
108 108 143 140 152 170 135 94 137 179 156 136 123 91 93 210 231 310 273 127
100 139 129 158 203 149 131 177 156 268 227
EXT-F18B 51
165 161 160 192 209 252 199 205 246 280 278 226 232 193 203 176 204 159 152 155
108 108 144 144 131 193 128 112 113 169 165 133 125 79 94 217 236 316 267 119
97 141 124 167 185 155 137 179 153 277 233
EXT-F19A 61
393 702 628 394 392 472 349 380 518 476 418 222 214 454 454 268 231 379 320 235
272 264 340 201 433 213 170 295 230 341 280 285 232 228 262 226 220 171 150 267
272 77 66 85 116 151 152 179 341 419 233 182 231 237 322 332 231 212 281 251
299
EXT-F19B 61
394 682 618 426 422 473 375 379 506 478 382 239 213 426 449 260 239 361 324 226
259 284 361 200 401 222 152 287 238 346 280 286 218 224 261 214 240 175 149 264
294 61 63 102 125 154 150 180 356 330 253 211 226 238 331 316 246 196 294 250
297
EXT-F20A 80
281 259 198 161 139 211 164 146 166 155 189 216 160 141 121 105 81 71 80 132
209 254 311 177 186 204 183 176 188 183 153 209 306 155 115 178 143 117 97 169
135 79 132 110 114 124 132 189 205 177 211 183 158 114 119 89 105 118 140 153
190 80 67 82 75 56 73 110 109 53 66 48 67 76 55 74 103 93 111 136
EXT-F20B 80
289 264 181 180 121 214 182 130 178 177 195 217 165 141 122 114 94 82 77 130
197 252 338 171 191 211 165 192 186 168 156 218 311 151 126 144 153 121 89 190
113 89 120 114 125 124 131 174 256 210 225 188 153 118 108 105 96 123 157 137
179 89 72 89 70 58 74 111 92 47 51 51 69 71 52 81 91 87 108 133

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 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.

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.

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

Figure 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.

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

Figure 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.

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 Figure 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 Figure 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 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 phenomenon 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.

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

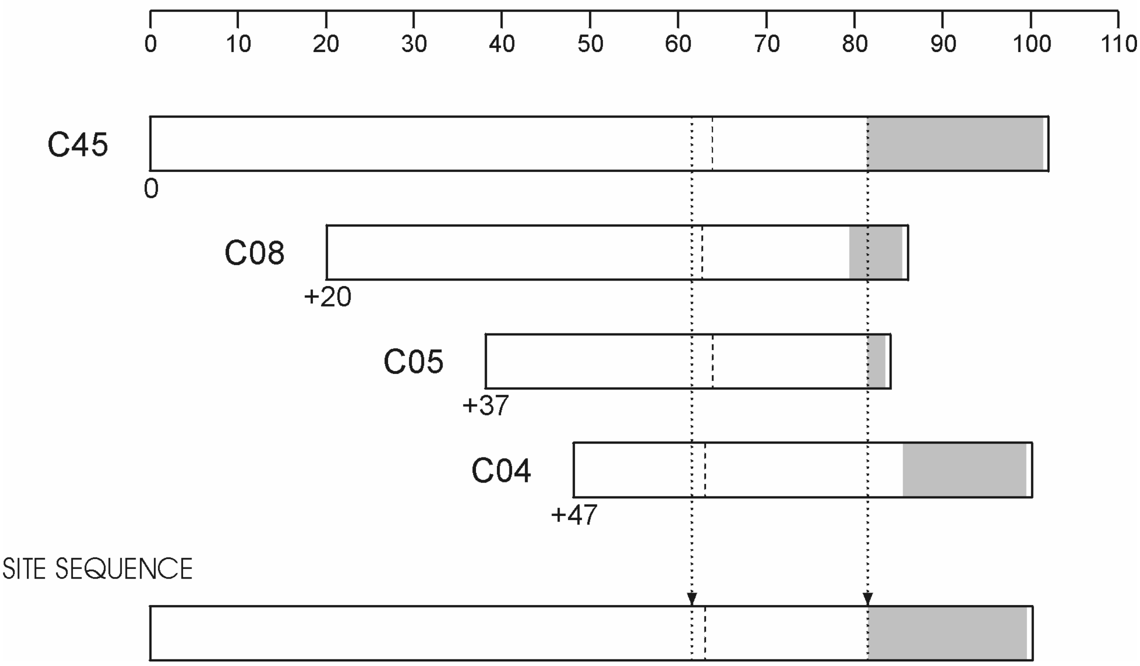


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

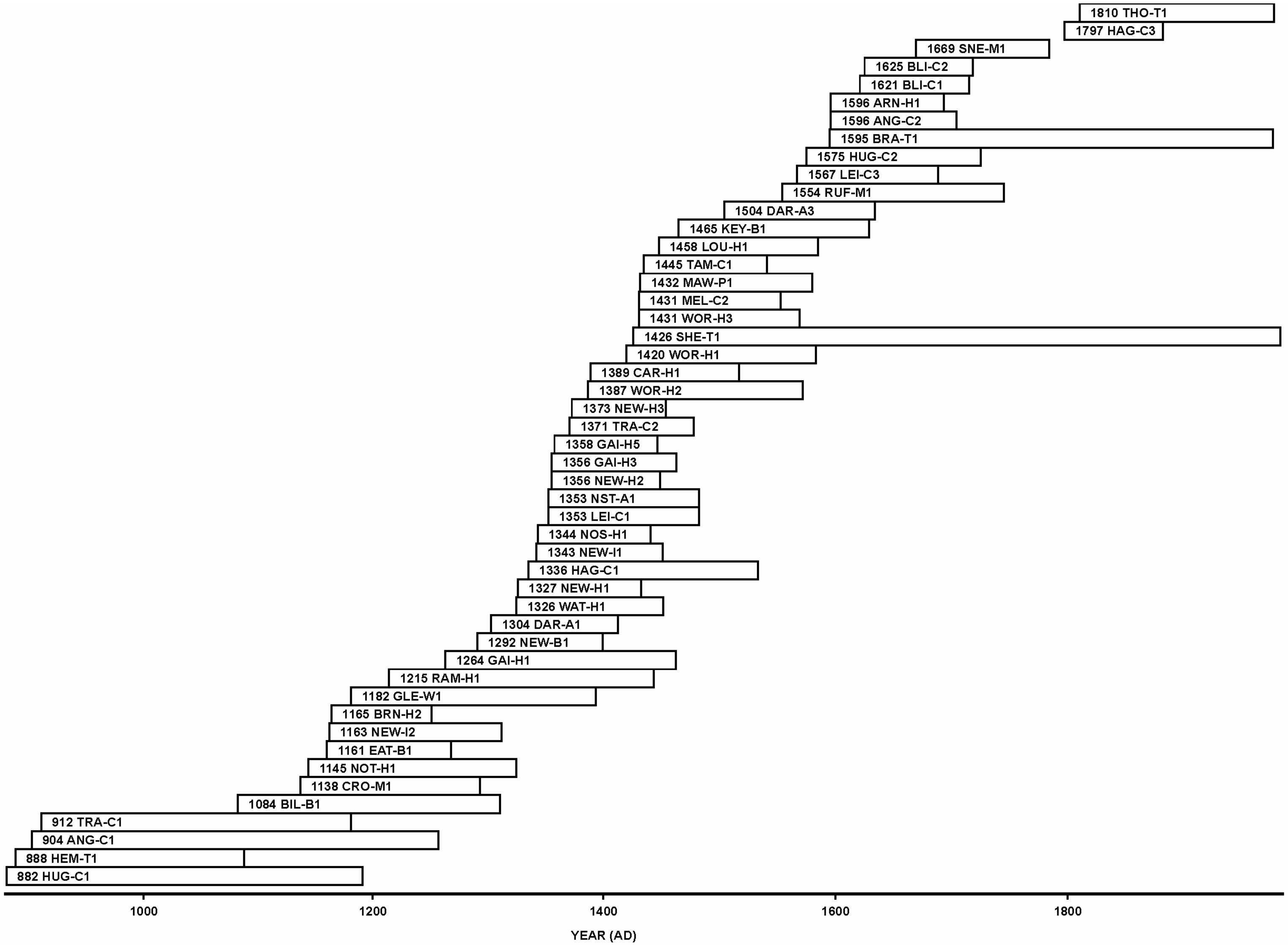
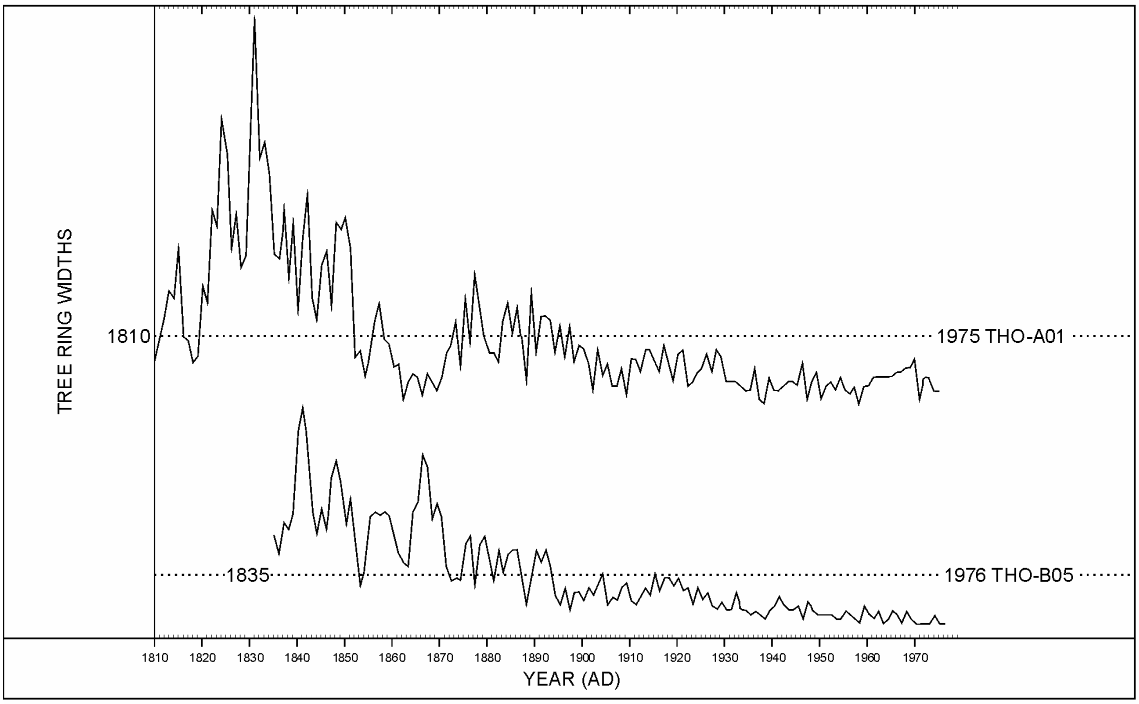


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

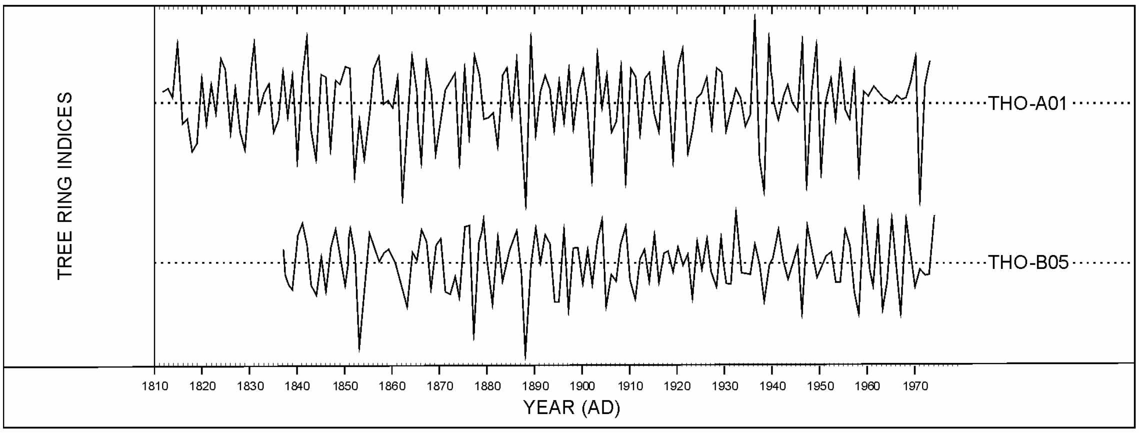


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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