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Church of St Mary, High Street, St Mary Cray, London Borough of Bromley

Tree-ring Analysis of Timbers from the Spire and Bell Frame

Alison Arnold and Robert Howard

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CHURCH OF ST MARY, HIGH STREET, ST MARY CRAY, LONDON BOROUGH OF BROMLEY

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SUMMARY

A total of 12 core samples was obtained from the spire and bell frame of the Church of St Mary. Analysis of nine of these samples (three having insufficient rings for reliable analysis), produced three site chronologies. The first site chronology (SMCCSQ01), comprising three spire samples, is 54 rings long and spans the years AD 1324–77. Interpretation of the sapwood indicates these timbers are coeval, being felled in the late-fourteenth century or very early fifteenth century. The second site chronology (SMCCSQ02), comprising two samples from the north frame of the bell frame, is 70 rings long and spans the years AD 1505–74. Interpretation of the sapwood indicates these timbers are also coeval, being felled in the late-sixteenth century. The third, and final, site chronology (SMCCSQ03) again comprises two samples, both from the south frame of the bell frame. This site chronology is 52 rings long but it cannot be reliably dated, although it is likely that the timbers are coeval. Two of the nine measured samples remain both ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Mr Peter Moyle, Chair of the Restoration Committee at the Church of St Mary, as well as both Mr Nigel Pointer and Mr Donald Pointer, for their very great help in gaining access to, and information on, the spire. We must also thank Ian Harper, Historic England Heritage at Risk Architect/Surveyor, for requesting this programme of analysis. Finally we would like to thank Shahina Farid and Cathy Tyers (Historic England Scientific Dating Team) for commissioning this programme of analysis, and for the help and assistance provided during reporting.

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INTRODUCTION

The Church of St Mary, set in the old heart of St Mary Cray (Fig 1a–c) is a Grade II* listed building built of flint rubble, with brick and stone dressings beneath a tiled roof. The west tower is topped by a cedar-shingled spire (Fig 2a/b). The church dates to the mid-thirteenth century and it retains important fabric from that time along with early fourteenth century features. It has undergone considerable adaptation and restoration during the intervening centuries, which include the rebuilding of the aisles in the fourteenth century, work on the chancel in the fifteenth century, the building of an early sixteenth century south chapel and a, potentially, sixteenth-century bellframe (one bell in the tower, now moved to the steel frame inserted in 1913, is inscribed '*Robert Mot made me 1583*'). The south porch was replaced, and the south vestry was added by E Nash between 1861–3. Further significant restoration work was carried out in 1876, and again in 1895.

The Church of St Mary is currently on the Heritage at Risk register suffering from slow, long term, decay. The congregation, however, have secured a grant from the Heritage Lottery Fund for the repair of the tower and the cedar shingles of the spire that have curled badly and are slipping off the roof.

SAMPLING

A dendrochronological survey of the spire and bell-frame timbers was requested by Ian Harper in advance of these repair works with the aim of providing independent dating evidence for these two areas of the church in order to inform the repair and restoration programme being undertaken with a view to the eventual removal of the church from the Heritage at Risk register.

An initial assessment of the timbers showed that although many of them were derived from relatively fast-grown trees with potentially low numbers of growth rings, and that there had been some repair, or alteration, to the spire there were sufficient timbers with sufficient rings to make analysis worthwhile. The assessment also indicated that the fragmentary remains of the bell frame contained a small number of timbers suitable for analysis.

Thus, from the suitable timbers available a total of 12 samples was obtained by coring. Each sample was given the code SMC-C (for St Mary Cray Church) and numbered 01–12 (Table 1). Seven of these samples, SMC-C01–C07, were obtained from the timbers to the spire, with a further five samples, SMC-C08–C12, being obtained from the timbers of the bell frame. The locations of these samples were recorded at the time of sampling on a simple schematic sketch plan (Fig 3), and on annotated photographs, shown here as Figures 4a–h. Due to the urgency with which the results of this analysis were required more detailed plans and sections were not available for incorporation into this report.

ANALYSIS AND RESULTS

Each of the 12 samples obtained from the spire and bell-frame timbers was prepared by sanding and polishing. It was seen at this time that three samples, SMC-C06 and C07 from the spire and sample SMC-C11 from the south frame of the bell frame, had less than 40 rings, the minimum here deemed necessary for reliable analysis. As a result they were rejected from this programme of analysis. The annual growth ring widths of the remaining nine samples were measured, the data of these measurements being given at the end of this report. The data of the nine measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix) this resulting in the production of three separate groups of cross-matching samples.

The first group comprises three samples, SMC-C01, SMC-C03, and SMC-C04, all of them from the spire timbers. These three samples were combined at their indicated relative off-set positions to form site chronology SMCCSQ01, this having an overall length of 54 rings (Fig 5a). Site chronology SMCCSQ01 was then compared with a series of relevant reference chronologies for oak, cross-matching with a number of these with a first-ring date of AD 1324 and a last measured ring date of AD 1377. The evidence for this dating is given in Table 2.

The second group comprises two samples, SMC-C08 and SMC-C09, both of them from the north frame of the bell frame. These two samples were also combined at their indicated relative off-set positions to form site chronology SMCCSQ02, this having an overall length of 70 rings (Fig 5b). Site chronology SMCCSQ02 was also compared with a series of relevant reference chronologies for oak, cross-matching with a number of these with a first-ring date of AD 1505 and a last measured ring date of AD 1574. The evidence for this dating is given in Table 3.

The third and final group also comprises two samples, SMC-C10 and SMC-C12, both of them from the south frame of the bell frame. These two samples were likewise combined at their indicated relative off-set positions to form site chronology SMCCSQ03, this having an overall length of 52 rings (Fig 5c). Site chronology SMCCSQ03 was also compared with a series of relevant reference chronologies for oak but there was no satisfactory cross-matching and the samples must, therefore, remain undated.

The three site chronologies were then compared to the two remaining measured but ungrouped samples, SMC-C02 and SMC-C05, both from spire timbers, but there was no further satisfactory cross-matching. These two ungrouped samples were then compared individually to the full corpus of reference data, but there was no satisfactory cross-matching and both individual samples must remain undated.

This analysis may be summarised thus:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
SMCCSQ01	3	54	1324–77
SMCCSQ02	2	70	1505–74
SMCCSQ03	2	52	undated
Ungrouped	2	---	undated
Unmeasured	3	---	---

INTERPRETATION

None of the dated samples from either the spire or the bell frame retain complete sapwood (the last growth ring produced by the tree before it was felled), and it is thus not possible to provide a precise felling date for any timber. The dated samples do, though, retain some sapwood or at least the heartwood/sapwood boundary.

The heartwood/sapwood boundary on the three samples from the spire, SMC-C01, SMC-C03, and SMC-C04, and dated as site chronology SMCCSQ01, is at virtually identical positions, this indicating that the timbers are likely to be coeval. The average date of the boundary on these three samples is AD 1362. Allowing for the minimum and maximum numbers of sapwood rings the trees are likely to have had (the 95% confidence interval being 15–40 sapwood rings), and given that the latest extant sapwood ring is dated AD 1377, gives these spire timbers an estimated felling date in the range AD 1378–1402. The timbers were thus felled, and probably used in construction very shortly afterwards, in the latter part of the fourteenth century or, just possibly, the first years of the fifteenth century.

Similarly, the heartwood/sapwood boundary on the two samples of the north frame of the bell frame, SMC-C08 and SMC-C09, and dated as site chronology SMCCSQ02, is also almost identical, again indicating that the two timbers are likely to be coeval. The average date of the boundary on these two samples is AD 1559. Allowing for the minimum and maximum numbers of sapwood rings the trees are likely to have had, and given that the latest extant sapwood ring is dated AD 1574, gives these bell frame timbers an estimated felling date in the range AD 1575–99. The timbers were thus, felled and probably used in construction very shortly afterwards, in the last-quarter of the sixteenth century.

In respect of the two samples from the south frame of the bell frame, SMC-C10 and SMC-C12 in site chronology SMCCSQ03, although the timbers are undated it is likely, again, given the similarity of the heartwood/sapwood boundary that the timbers are coeval.

DISCUSSION AND CONCLUSION

Dendrochronological analysis has identified the presence of late fourteenth or possibly very early fifteenth century rafters in the spire and shown that the north frame of the bell frame contains timbers dating to the late-sixteenth century. This latter date is consistent with the inscription of 1583 on one of the bells relocated in the steel frame.

The cross-matching of the three samples of site chronology SMCCSQ01and of the two samples of site chronology SMCCSQ02 suggests that in each case the respective timbers were probably derived from discrete woodland sources. Indeed, in the case of site chronology SMCCSQ02, it is likely that the timbers (both very short posts) have been derived from a single tree. The highest levels of similarity between site chronology SMCCSQ01and the reference chronologies are found with those from surrounding counties. This would suggest that the timbers used for the spire are from a relatively local regional woodland source. The source of the timber used for the north bell frame, in site chronology SMCCSQ02, is less clear, the cross-matching being more geographically widespread.

Site chronology SMCCSQ03 remains undated and whilst it is relatively short it has no obvious growth disturbances which would hamper successful dating. It will also be seen that two samples, SMC-C02 and SMC-C05, remain ungrouped and undated. While sample SMC-C02 is at the lower limit with respect to numbers of rings required, sample SMC-C05 certainly has sufficient rings and neither sample shows particularly compressed or distorted rings. The presence of ungrouped and undated samples, however, is a frequent feature of tree-ring analysis, this often occurring for no apparent reason.

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TABLES

Table 1: Details of tree-ring samples from the Church of St Mary, High Street, St Mary Cray, London Borough of Bromley

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Spire					
SMC-C01	North rafter 3 (from east)	50	13	1328	1364	1377
SMC-C02	North rafter 4	49	9	------	------	------
SMC-C03	North rafter 7	52	14	1324	1361	1375
SMC-C04	West rafter 3 (from north)	45	15	1333	1362	1377
SMC-C05	South west middle upper rafter	79	h/s	------	------	------
SMC-C06	South rafter 5 (from east)	nm	---	------	------	------
SMC-C07	East rafter 4 (from north)	nm	---	------	------	------
	Bell frame					
SMC-C08	North frame, east upright	64	15	1511	1559	1574
SMC-C09	North frame, west upright	54	h/s	1505	1558	1558
SMC-C10	South frame, east upright	48	9	------	------	------
SMC-C11	South frame, middle upright	nm	---	------	------	------
SMC-C12	South frame, west upright	51	9	------	------	------

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

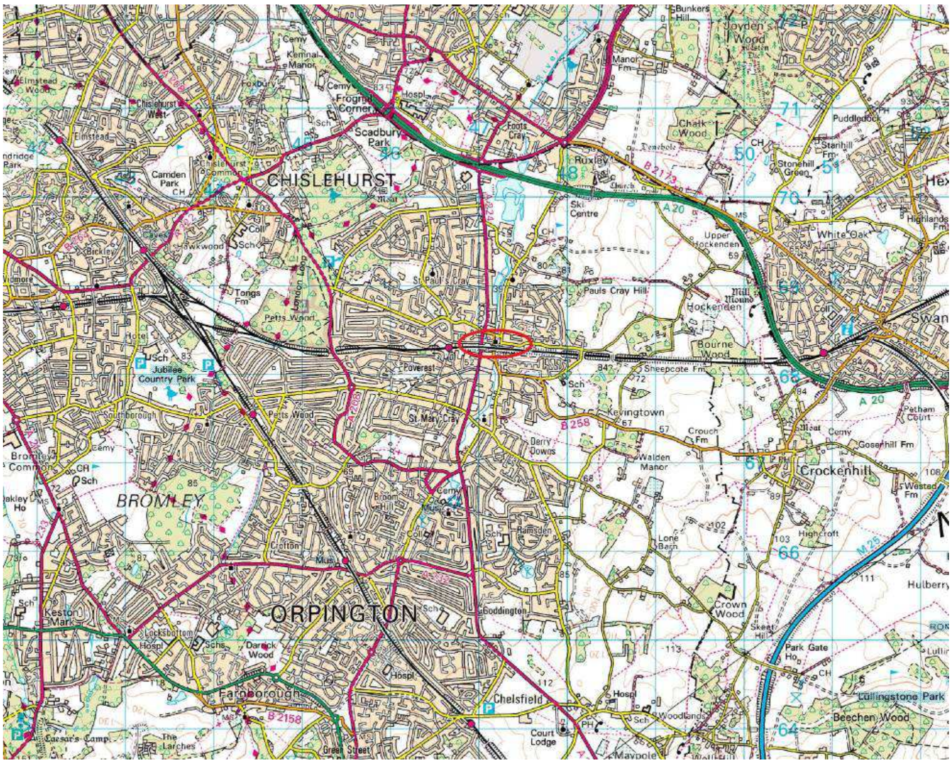
Table 2: Results of the cross-matching of site sequence SMCCSQ01 and relevant reference chronologies when the first-ring date is AD 1324 and the last-ring date is AD 1377

Reference chronology	Span of chronology	*t*-value	Reference
Priory House, Ely Cathedral, Cambridgeshire	AD 1315–1426	7.1	(Howard *et al* 1992)
Falconers Hall, Good Easter, Essex	AD 1324–1457	7.0	(Bridge 1996)
Cressing Temple Church, Essex	AD 1274–1378	7.0	(Tyers 1995)
Hays Wharf, Southwark, London	AD 1248–1647	6.9	(Tyers 1996a; Tyers 1996b)
Home Farm, Newdigate, Surrey	AD 1261–1639	6.9	(Bridge 1998)
Old Manor House, Mapledurham, Oxfordshire	AD 1278–1438	6.8	(Haddon-Reece *et al* 1987)
Netteswellbury Barn, Harlow, Essex	AD 1245–1439	6.6	(Tyers 1997)
Cobham Hall, Cobham, Kent	AD 1317–1662	6.6	(Arnold *et al* 2003)

Table 3: Results of the cross-matching of site sequence SMCCSQ02 and relevant reference chronologies when the first-ring date is AD 1505 and the last-ring date is AD 1574

Reference chronology	Span of chronology	*t*-value	Reference
Combermere Abbey, Whitchurch, Cheshire	AD 1602–1727	6.2	(Howard *et al* 2003)
Breakspear House, Hillingdon, London	AD 1497–1610	6.1	(Arnold and Howard 2010)
Aldeby Hall, Aldeby, Norfolk	AD 1422–1608	6.0	(Arnold and Howard 2013 unpubl)
Tithe Barn, Sandiacre, Derbyshire	AD 1427–1611	6.0	(Howard 2004 unpubl)
Huson Farm, Tenterden, Kent	AD 1436–1571	5.9	(Howard *et al* 1990)
Hales Hall, Loddon, Norfolk	AD 1458–1594	5.8	(Arnold and Howard 2014)
Oakham Castle, Oakham, Rutland	AD 1383–1620	5.8	(Arnold and Howard 2013)
Town Hall, Alcester, Warwickshire	AD 1374–1625	5.8	(Arnold and Howard 2014 unpubl)

FIGURES



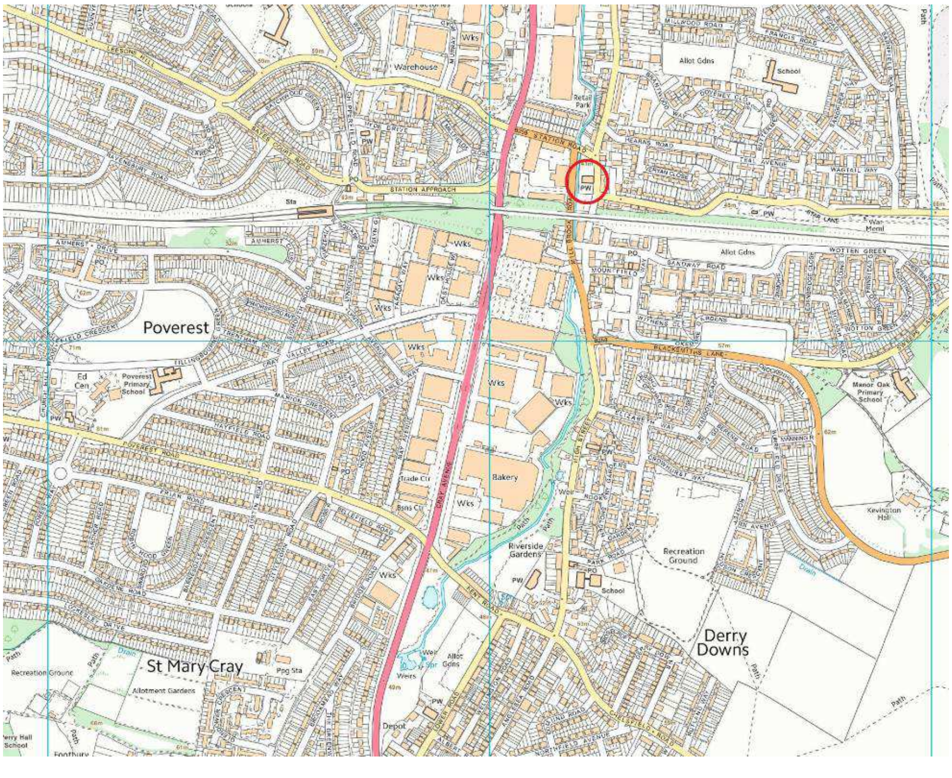


Figure 1a/b: Maps to show the location of the Church of St Mary, St Mary Cray. © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

Figure 1c: Map to show the detailed location of the Church of St Mary, St Mary Cray. © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

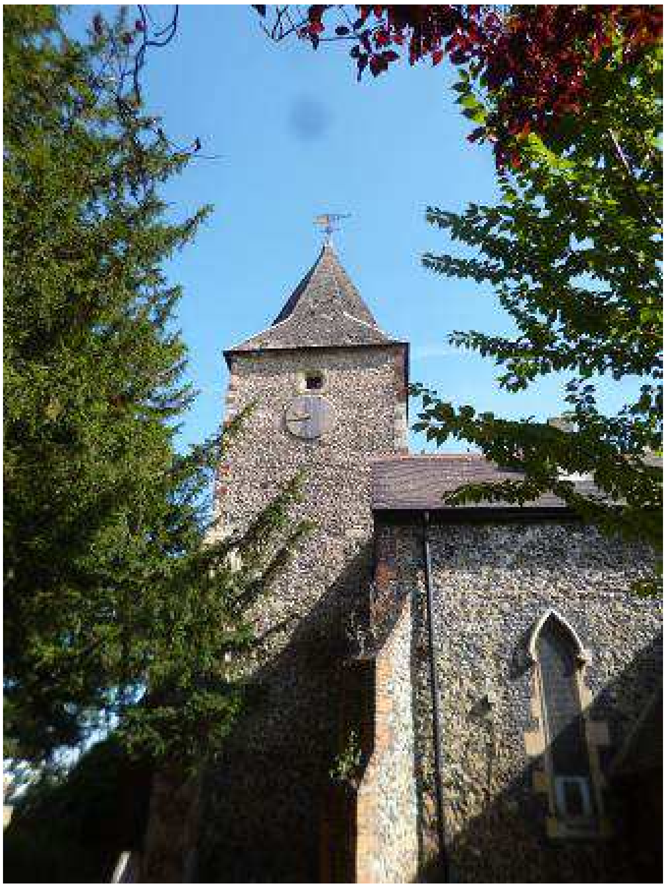


Figure 2a/b: External and internal views of the spire at Church of St Mary, St Mary Cray (photographs Robert Howard)

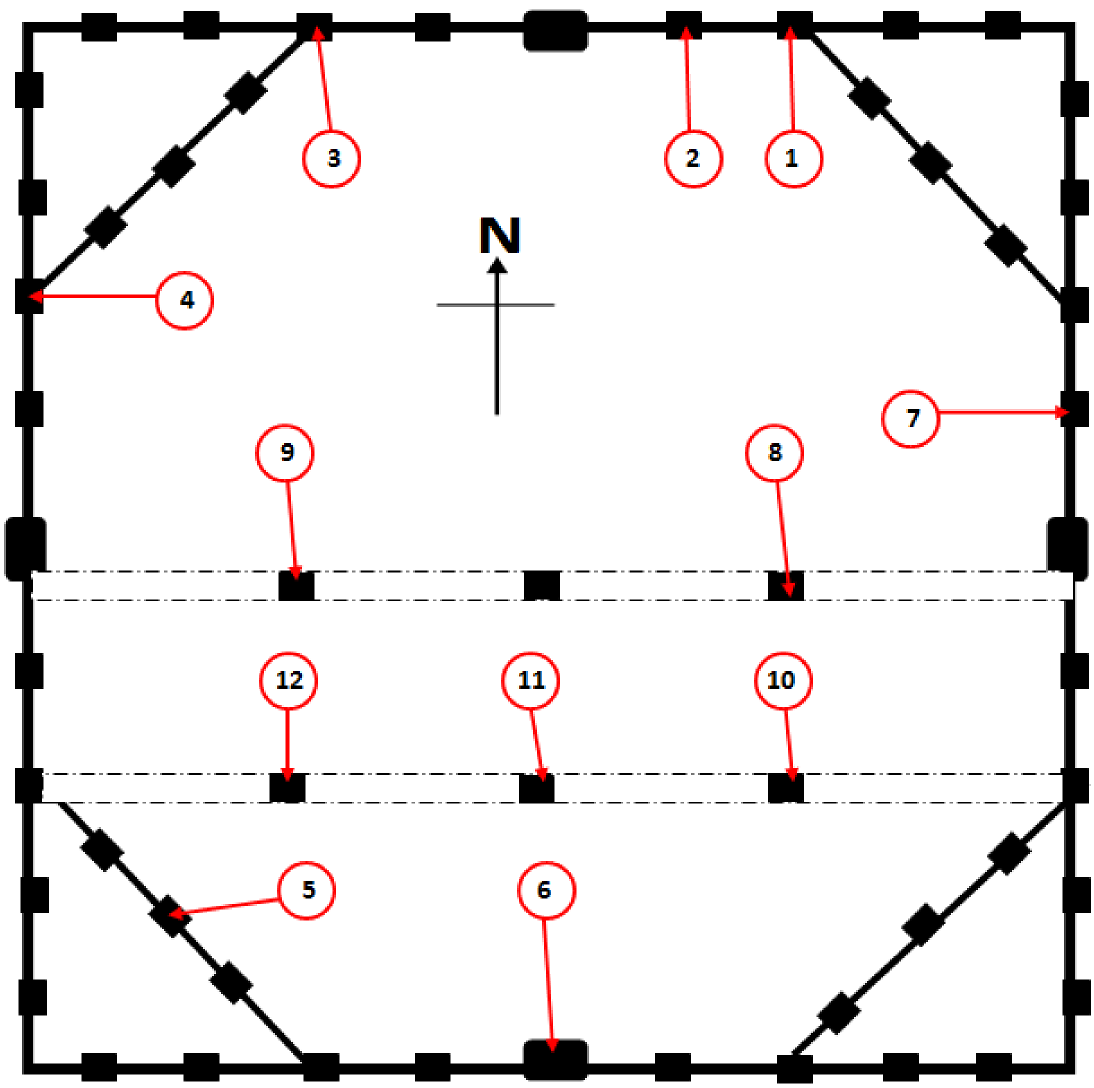
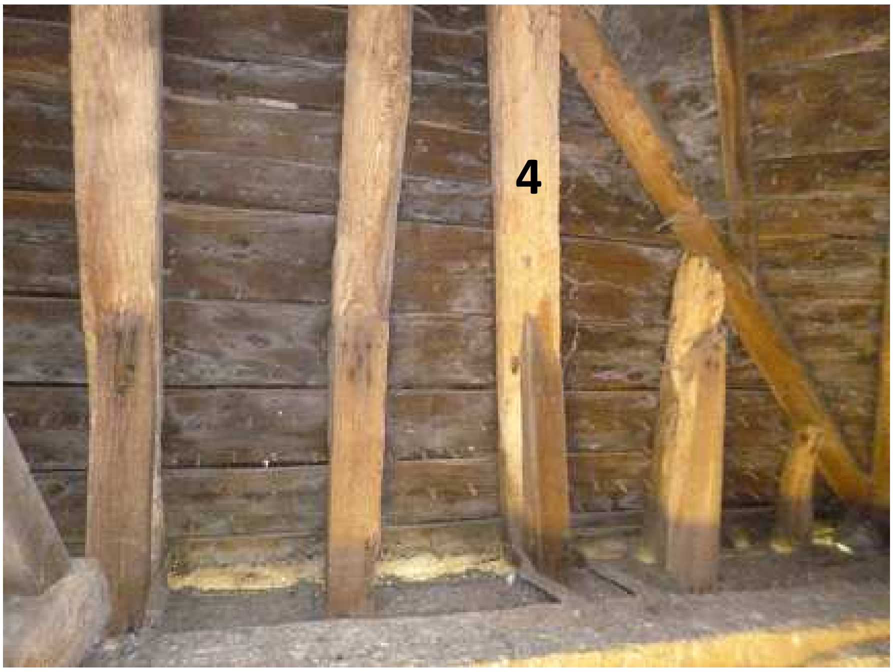


Figure 3: Schematic sketch plan at spire base to aid location of the sampled timbers

Figure 4a/b: Annotated photographs to help locate the sampled timbers (photographs Robert Howard)



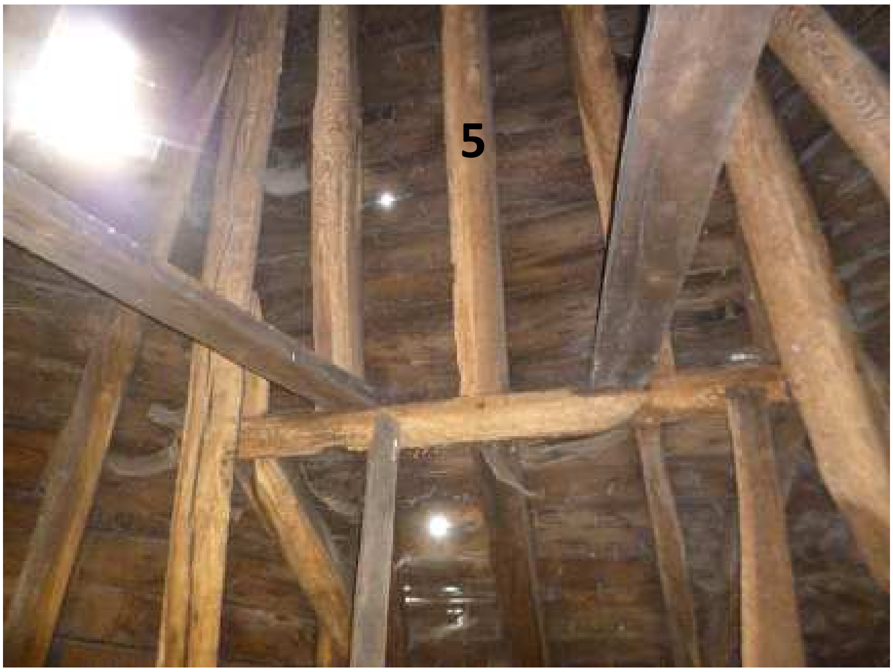


Figure 4c/d: Annotated photographs to help locate the sampled timbers (photographs Robert Howard)

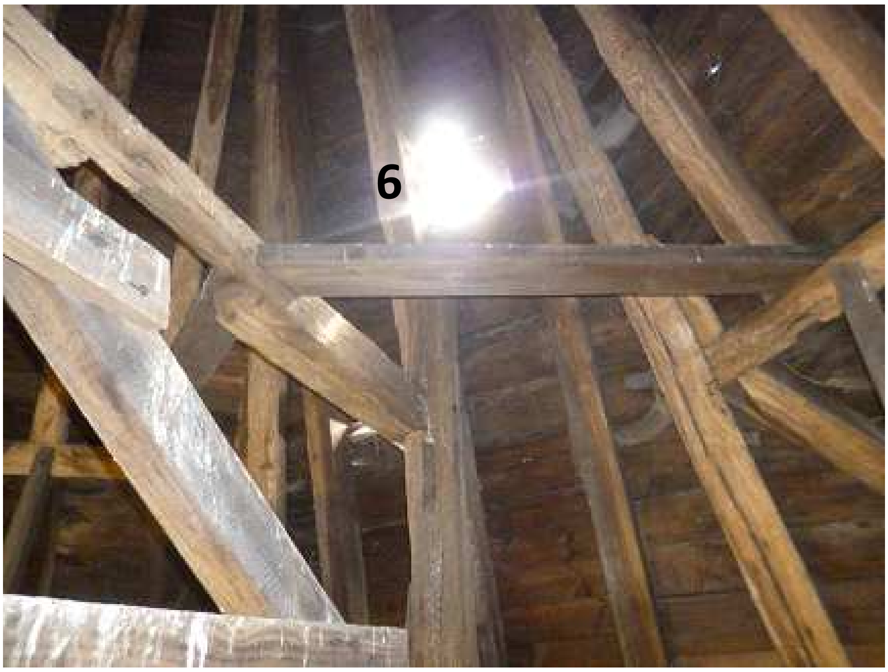
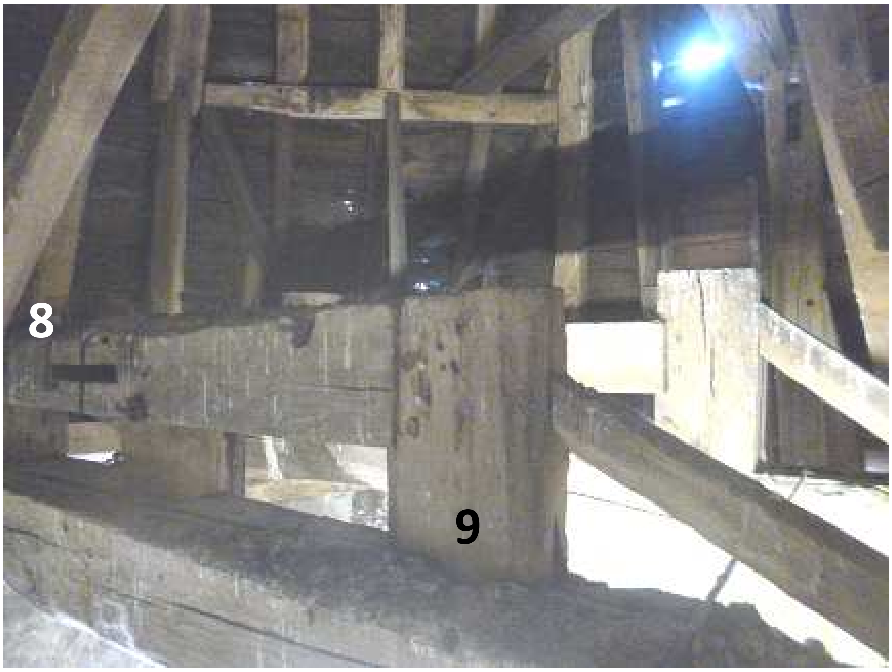


Figure 4e/f: Annotated photographs to help locate the sampled timbers (photographs Robert Howard)



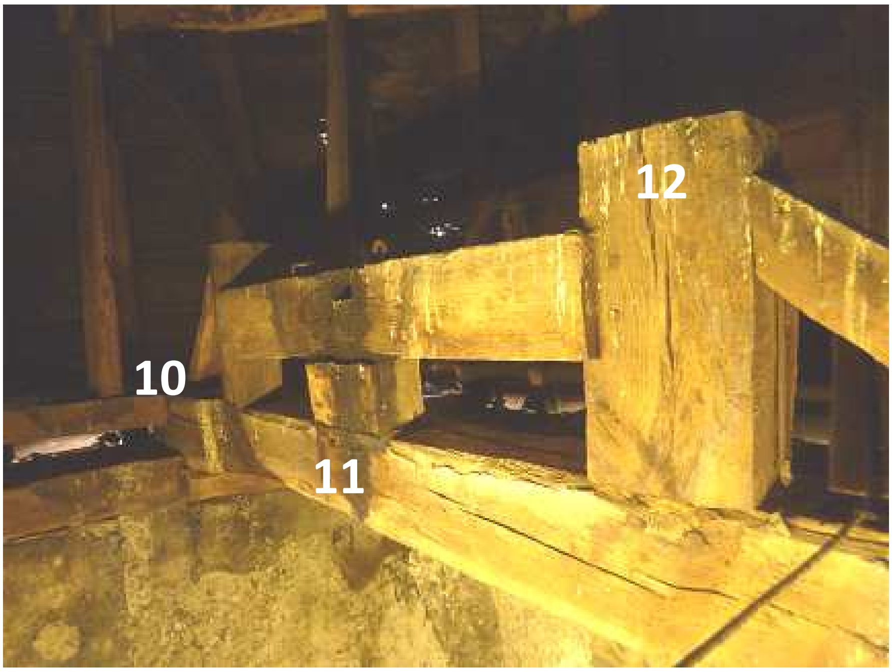
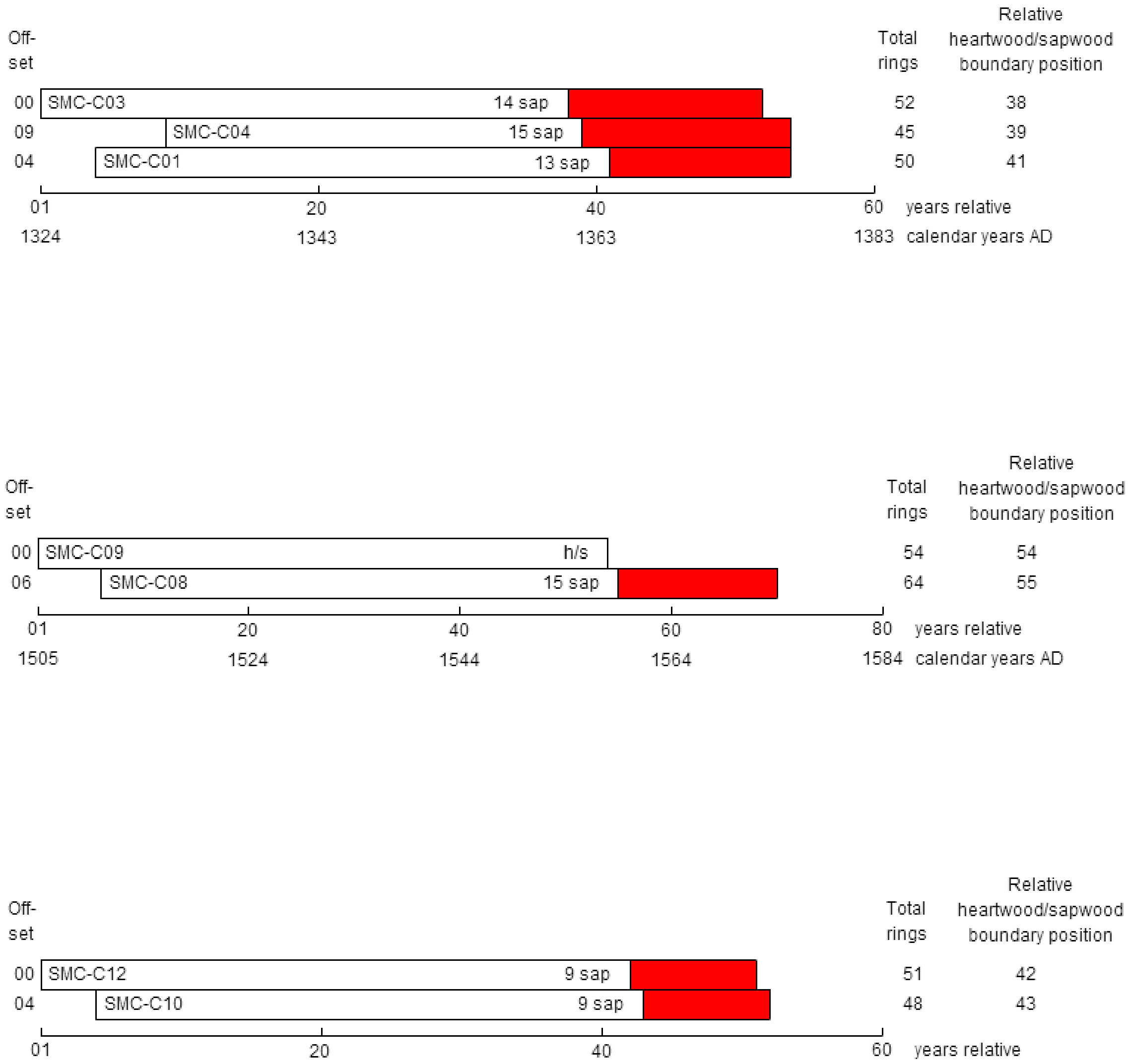


Figure 4g/h: Annotated photographs to help locate the sampled timbers (photographs Robert Howard)



White bars = heartwood rings; shaded bars= sapwood rings; h/s = the heartwood/sapwood ring is the last ring on the sample

Figure 5a–c: Bar diagrams of the dated samples in the site chronologies SMCCSQ01 (top) and SMCCSQ02 (middle) and the undated samples in site chronology SMCCSQ03 (bottom)

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

SMC-C01A 50
227 329 263 100 134 179 267 289 184 101 67 185 203 223 216 112 98 110 147 246
187 118 94 126 139 276 227 186 148 171 156 137 145 63 178 347 310 315 321 281
215 281 323 279 254 181 196 207 189 191
SMC-C01B 50
225 324 265 102 139 176 278 279 187 91 75 181 189 221 212 96 82 128 180 244
215 125 103 138 125 264 239 202 149 153 152 157 142 69 156 356 335 313 324 273
218 284 320 288 264 171 198 204 178 201
SMC-C02A 49
155 134 131 207 178 135 179 167 200 130 162 150 173 229 166 139 155 136 205 237
117 93 221 271 163 240 174 242 350 380 241 221 139 139 90 108 235 156 84 87
126 164 157 137 73 146 237 171 197
SMC-C02B 49
152 138 129 198 182 138 174 168 212 129 159 146 160 216 166 133 153 127 216 229
103 89 217 272 141 253 177 238 343 391 240 217 126 107 111 112 233 184 78 93
150 159 159 135 60 126 241 173 208
SMC-C03A 52
105 115 96 273 237 331 325 142 144 117 144 166 144 95 142 257 236 164 164 171
160 171 242 297 315 304 164 230 167 287 310 287 198 204 200 223 181 118 251 286
284 257 266 239 221 273 256 185 225 189 255 218
SMC-C03B 52
103 111 89 283 235 327 326 129 141 123 150 155 146 90 164 229 243 162 171 182
122 175 260 294 305 284 164 253 164 289 318 293 204 183 208 228 173 132 278 295
288 245 279 236 218 264 236 197 234 182 259 220
SMC-C04A 45
120 141 159 149 100 138 261 236 160 254 226 157 275 231 246 285 259 176 239 195
358 331 378 309 182 204 246 221 146 246 275 305 306 275 222 183 245 212 158 193
204 279 250 261 300
SMC-C04B 45
119 140 158 149 99 154 249 240 162 248 231 149 297 243 250 280 257 167 228 195
343 348 382 287 203 191 287 218 154 253 277 306 299 256 240 176 231 221 169 218
192 260 231 267 291
SMC-C05A 79
131 360 289 331 447 274 143 335 216 380 257 310 185 181 178 148 210 228 280 253
157 157 190 188 246 235 200 154 108 122 118 144 115 87 126 136 100 121 114 121
167 189 167 104 121 86 52 36 42 25 28 34 39 49 73 92 81 54 79 106
87 115 109 75 129 156 114 113 114 75 87 148 178 139 165 151 193 133 165
SMC-C05B 79
132 376 297 383 447 219 125 321 223 403 266 308 187 178 178 150 206 235 270 263
164 142 214 182 259 235 202 150 97 123 125 139 110 93 120 143 105 114 120 120
157 185 175 109 109 96 49 39 36 26 29 33 38 48 75 90 82 55 84 98
90 115 104 75 131 160 117 112 109 85 89 146 174 150 163 147 202 144 166
SMC-C08A 64
273 409 552 459 494 398 404 496 382 297 226 350 229 246 212 210 292 414 212 164
300 220 234 185 229 314 284 257 342 439 432 276 239 226 257 231 259 187 199 134
170 131 172 204 251 141 176 121 150 202 141 227 164 120 132 135 128 163 157 125
142 167 190 196

SMC-C08B 64
274 409 547 462 490 407 400 499 368 296 224 329 239 227 214 220 282 428 220 155
309 206 235 182 242 309 278 268 339 428 464 271 218 234 268 233 251 181 156 159
165 114 178 185 273 133 159 141 176 197 125 224 150 137 143 137 126 168 152 140
144 140 193 199
SMC-C09A 54
298 173 163 181 436 416 426 336 397 355 342 325 250 299 306 244 163 250 144 230
180 183 197 341 160 129 251 150 205 175 260 232 214 253 340 473 443 228 204 231
257 180 192 203 245 163 167 106 129 166 230 137 148 171
SMC-C09B 54
309 179 149 188 446 419 414 342 398 349 356 316 239 342 297 223 167 219 171 217
193 182 217 344 171 136 234 167 198 192 248 260 237 237 360 484 440 222 219 212
260 168 203 207 250 155 165 112 135 175 234 114 161 172
SMC-C10A 48
433 356 212 210 170 192 146 261 326 177 379 256 218 190 251 280 254 245 269 289
566 368 210 219 199 316 394 360 251 336 413 245 289 304 286 401 318 265 316 396
265 251 242 321 485 295 328 301
SMC-C10B 48
425 353 222 210 171 188 149 262 305 185 370 251 228 190 253 271 266 248 279 310
559 369 208 211 200 328 410 368 286 346 419 238 286 319 269 401 329 267 309 406
269 261 240 308 545 265 345 290
SMC-C12A 51
263 121 227 528 425 353 222 210 171 188 241 419 443 478 382 242 186 205 236 342
257 343 315 452 596 359 200 210 203 249 367 271 247 402 446 243 282 254 209 281
258 193 248 414 315 316 314 308 545 265 345
SMC-C12B 51
265 112 227 538 433 356 212 210 170 192 229 414 460 478 357 219 187 196 246 332
253 339 323 428 563 309 201 217 204 239 377 248 240 403 442 226 283 214 226 253
215 217 332 360 309 310 318 321 485 295 328

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 Nottingham Tree-ring Dating 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 1998). 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 A1 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 A1, 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 A2 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 8–10 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 A2; it is about 150mm long and 10mm 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 A1: 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

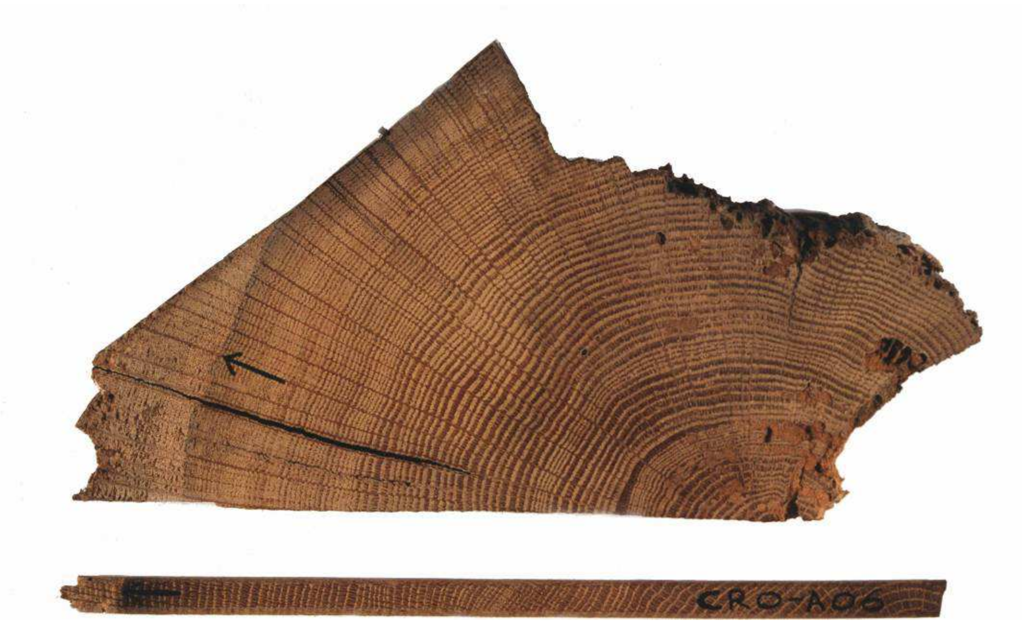


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: 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 A4: 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 A2. 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 A3).

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 A4). 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 A5 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 A5. 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 A5 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 straightforward 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 (or the last full year before felling, if it was felled in the first three months of the following calendar year, 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 A2, 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 region 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 A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, 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; Miles 1997, 50–5). Hence, provided that 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, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage 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 Figure A6 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 Figure A6. 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 Figure A7. 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

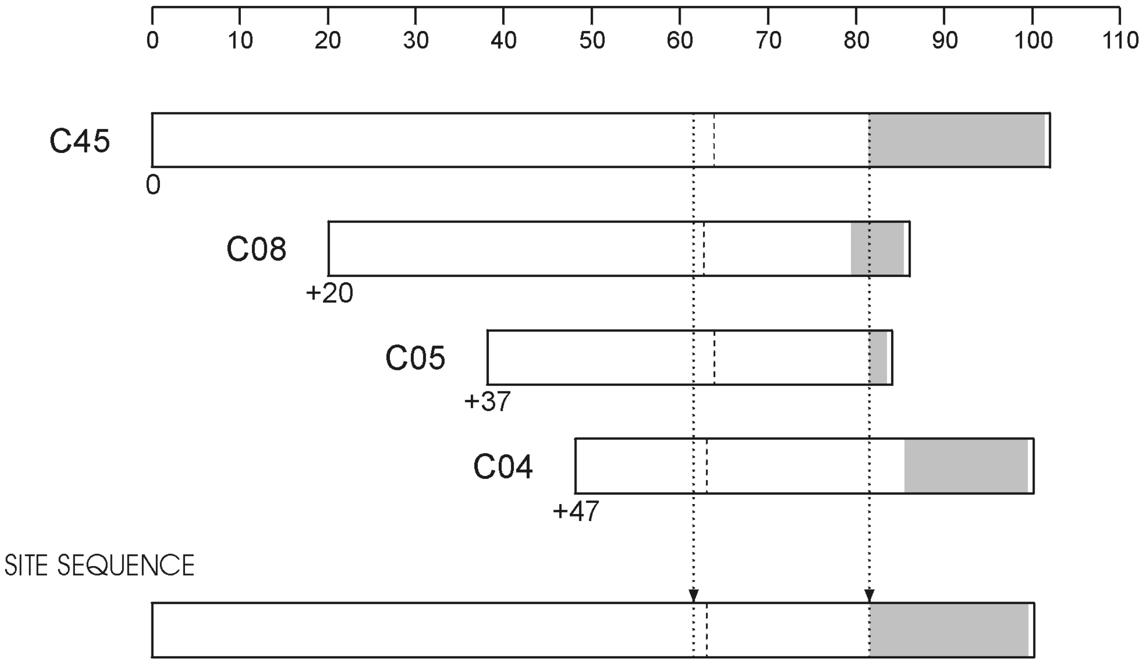


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

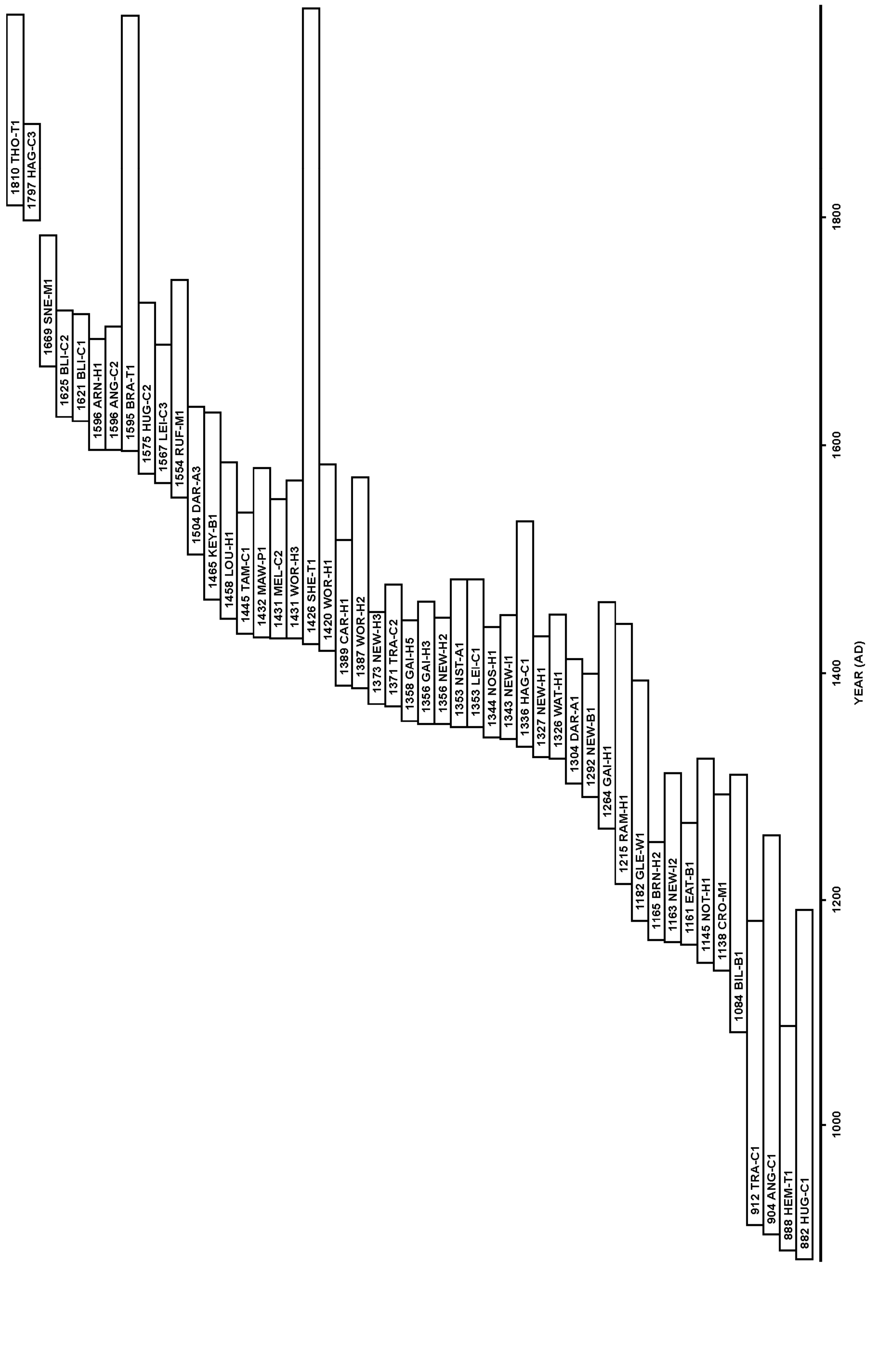
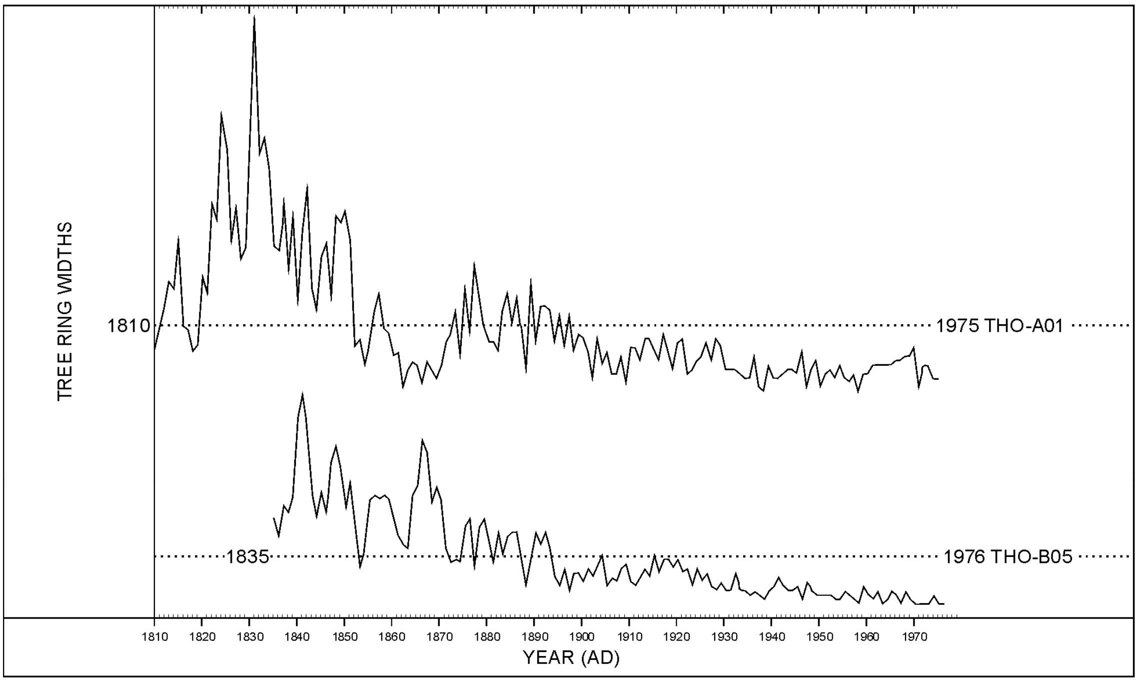


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

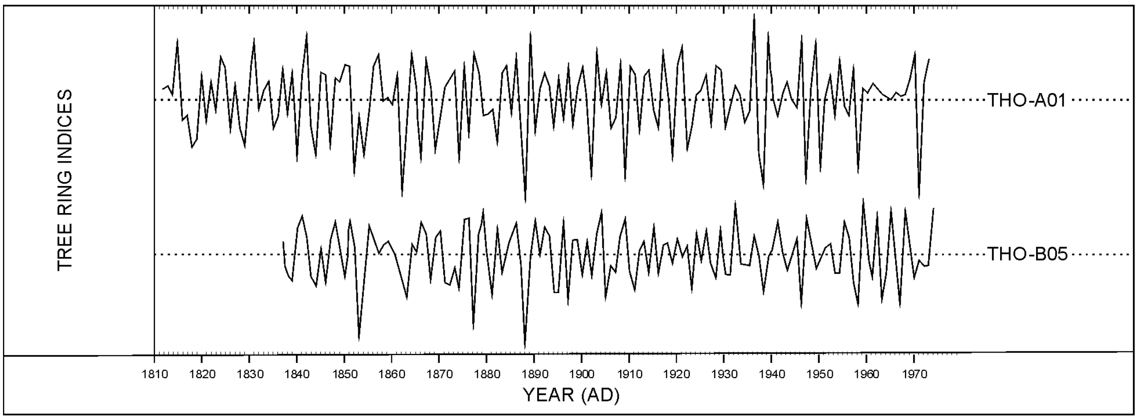


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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 A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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