Historic England

Research Report Series 6/2023

Becket's Chapel, 2 Church Street, Wymondham, Norfolk

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

Scientific Dating

Becket's Chapel, 2 Church Street, Wymondham, Norfolk

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

National Grid Reference: TG 10876 01562

Print: ISSN 2398-3841
Online: ISSN 2059-4453

Summary

Dendrochronological analysis was undertaken on samples obtained from 12 timbers from the trusses of the roof of the main body of Becket's Chapel in Wymondham, Norfolk. This analysis produced a single site chronology comprising seven samples, which was 85 rings long overall. These 85 rings were dated as spanning the years AD 1520–1604. Interpretation of the sapwood on the dated samples would indicate that the timbers are derived from trees felled at some point during the period AD 1613–38, suggesting that substantial works were undertaken on the roof at this time.

Contributors

Alison Arnold, Robert Howard and Cathy Tyers

Acknowledgements

We would firstly like to thank Judith Harwood Lawrence and Richard Halsey, Chair and Trustee respectively for Historic Norfolk, who are owners of the chapel. Judith and Richard shared their passion and support for this programme of analysis and were particularly helpful in arranging sampling. Richard Halsey is also thanked for sharing documentary evidence relating to the historical development of the building. We would like to thank Patricia Forero of The Architect Studio for her help with this programme of analysis. Finally, we would like to thank Historic England's Trudi Hughes (Heritage at Risk Surveyor), David Eve (Inspector of Historic Buildings & Areas) and Shahina Farid (Scientific Dating Team) for respectively proposing and commissioning this programme of tree-ring dating.

Front cover image

Becket's Chapel [© Mr Gary Hacon] Source: Historic England Archive IOE01/12725/15

Archive location

The Historic England Archive, The Engine House, Fire Fly Avenue, Swindon SN2 2EH

Historic Environment Record

Norfolk Historic Environment Record, The Archive Centre, Martineau Lane, Norwich, NR1 2DQ

Date of investigation

2018 & 2022

Contact details

Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA
customers@historicengland.org.uk

Alison Arnold and Robert Howard, Nottingham Tree-ring Dating Laboratory, 20 Hillcrest Grove, Sherwood, Nottingham NG5 1FT
roberthoward@tree-ringdating.co.uk,
alisonarnold@tree-ringdating.co.uk

Cathy Tyers, Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA cathy.tyers@historicengland.org.uk

Contents

Illustrations

Tables

Introduction

The Chapel, dedicated to St Thomas à Becket, is located on Church Street in Wymondham, Norfolk (Fig 1). It is Grade 1 listed (Becket's Chapel , Wymondham - 1297495 | Historic England) and is a rare survival of an independent medieval chapel. It is thought to have been founded in the late twelfth century by the son of William d'Aubigny, founder of Wymondham Abbey. In the late AD 1550s/early 1560s, the chapel was converted to a school, and for some time in the seventeenth century a lock-up for un-convicted prisoners was attached to the building and remained in place until at least AD 1848. In AD 1873, the building was restored and used as a public hall, before becoming a school once more. More recently it was used as the Wymondham branch library and then the town's arts centre. Becket's Chapel was added to Historic England's Heritage at Risk Register (Heritage at Risk | Historic England) in 2018, at which time urgent repairs were needed to the roof, gutters, drainage and masonry.

The extant building is believed to originate in the fourteenth century with the List Entry, at the time of writing, suggesting that it was reroofed in the late-fifteenth century. The hammerbeam (false) roof is of seven bays (Figs 2 and 3). The trusses are described in the list entry as principals with chamfered hammer posts from which arched braces go to wall posts, on timber corbels and collars. There are chamfered pendants and two tiers of moulded butt purlins. The recent documentary research undertaken (Halsey pers. comm. 2023), however, indicates that the extant roof is most likely to be later than that indicated in the list entry. It has stylistic features suggesting a mid-sixteenth century date at the earliest, which ties in with several possible dates identified from the documentary research that could be associated with a reroofing period, this ranging from shortly after the dissolution of the monasteries to the fire in Wymondham in AD 1615, which is thought to have destroyed much of the town.

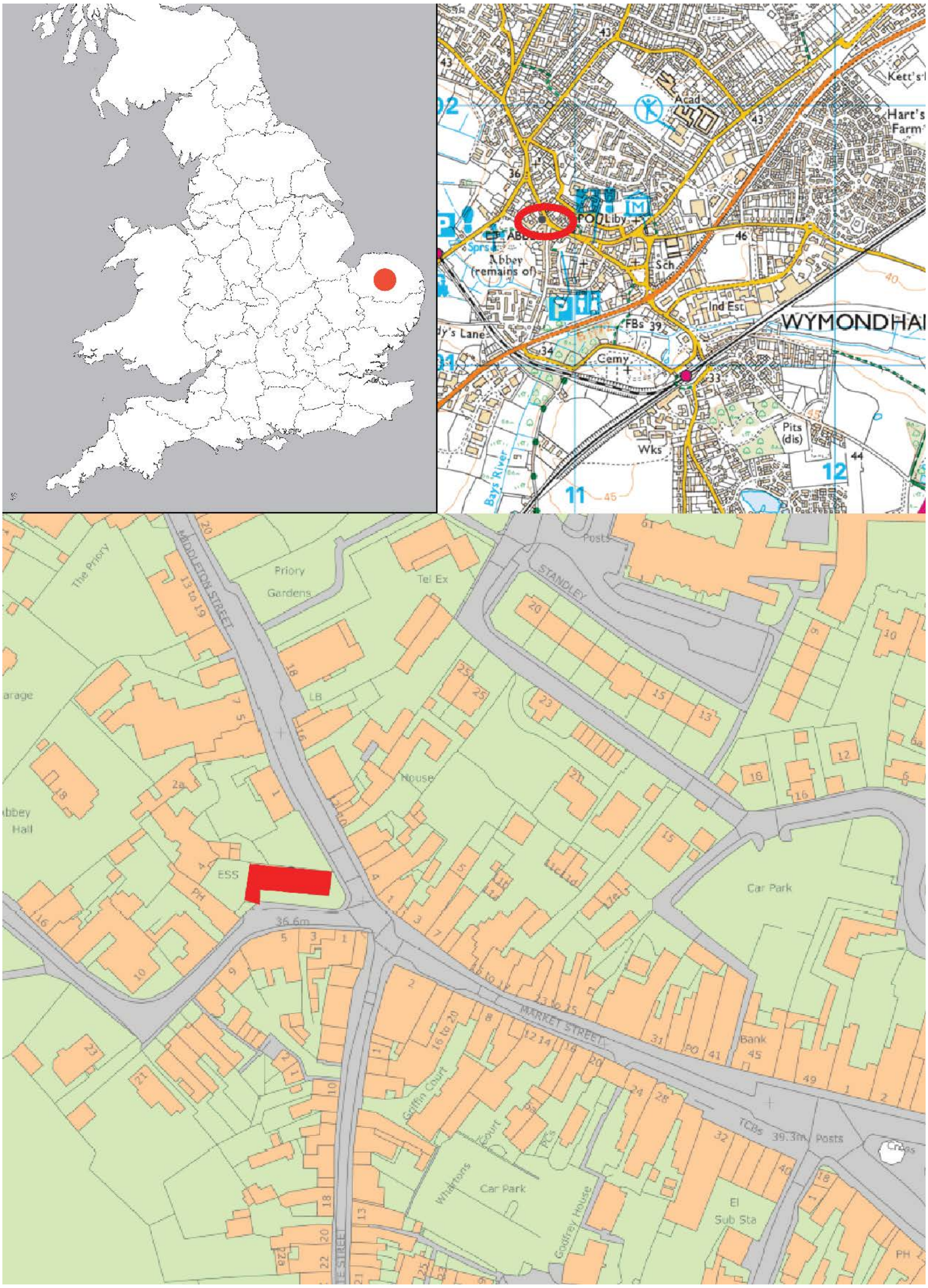


Figure 1: Maps to show the location of Becket's Chapel in Wymondham, Norfolk, marked in red. Scale: top right 1:15,000; bottom: 1:1,600. [© Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900].

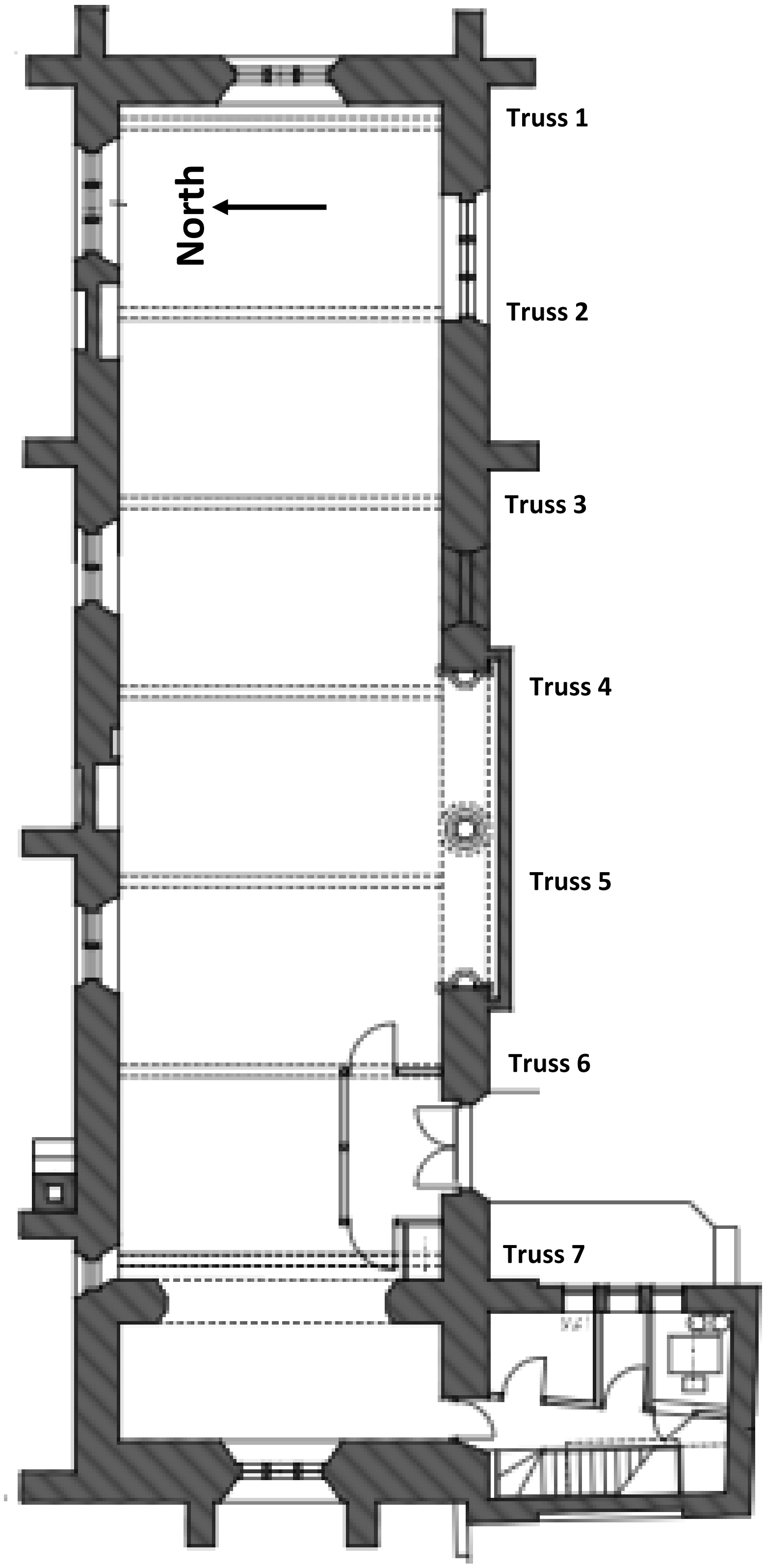


Figure 2: Outline ground floor plan of Becket's Chapel to show arrangement and layout of the trusses [after Lucas Hickman Smith]

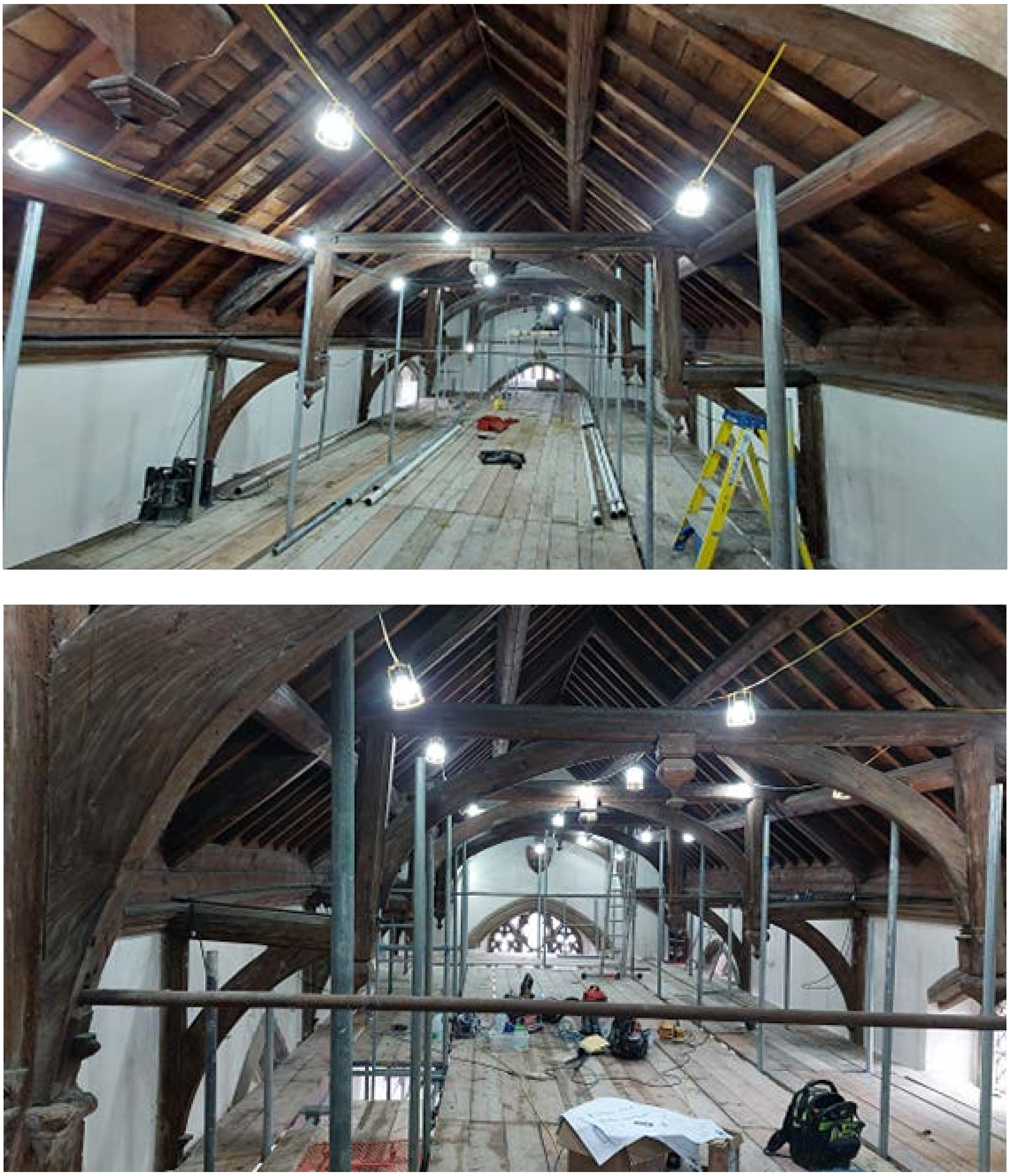


Figure 3a/b: General views of the Chapel roof viewed looking east to west (top) and west to east (bottom) [photographs Robert Howard]

Sampling

The restoration of the structure and fabric of the building is essential to ensure its continued survival and to this end Historic England awarded a grant towards the necessary repairs. As part of this programme of works, tree-ring analysis of the timbers in the building was requested in order to inform the repair and conservation process.

An initial inspection of the timbers throughout the Chapel, in the nave roof, the bay to the west arch and the beams seen in the former south nave aisle, showed that many were derived from particularly fast-grown trees, a common phenomenon of East Anglia. As such, these timbers had too few rings for reliable tree-ring analysis, this limiting the number of potential timbers worth sampling. Thus, from the various seemingly suitable timbers available, samples from a total of 12 oak (*Quercus* spp) timbers were obtained by coring, all from the nave roof. Each sample was given the code WYM-H (for Wymondham) and numbered 01–12. Details of the samples are given in Table 1, with the sampled timbers also being identified in a series of truss illustrations (Figs 4a–e).

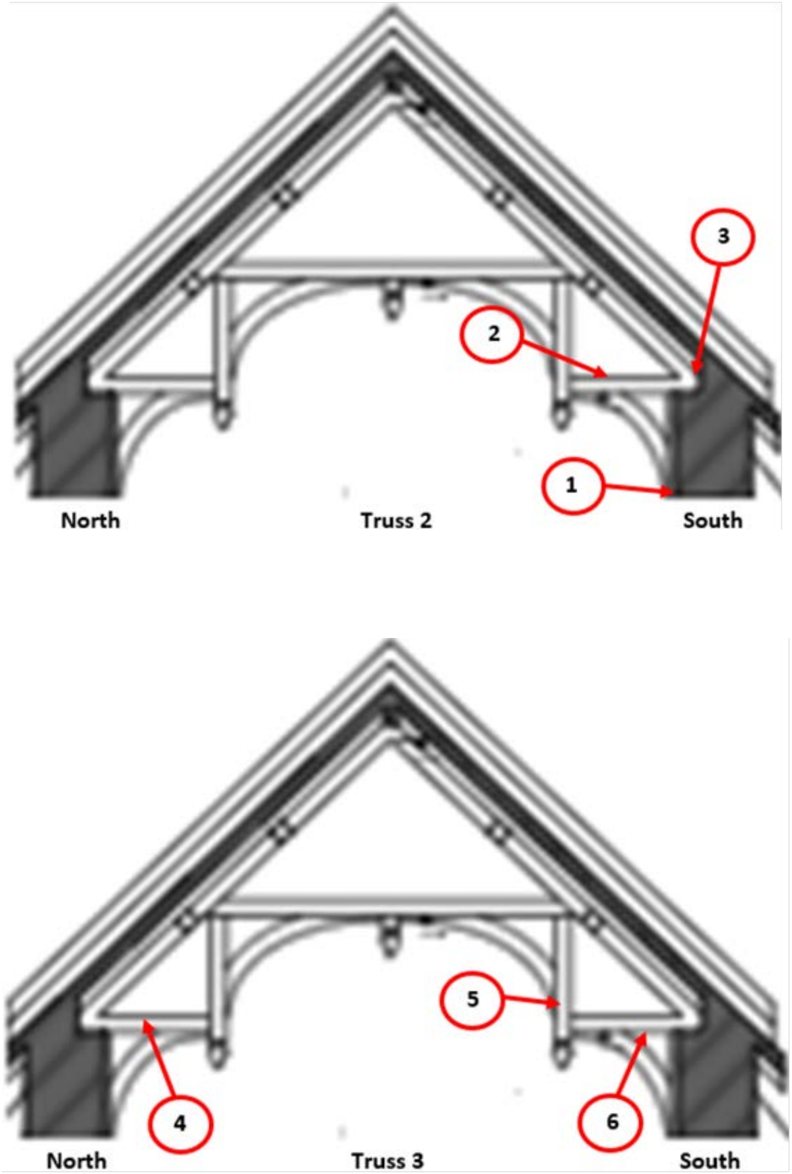


Figure 4a/b: Drawings of the trusses to help identify sampled timbers (see Table 1) [after Lucas Hickman Smith]

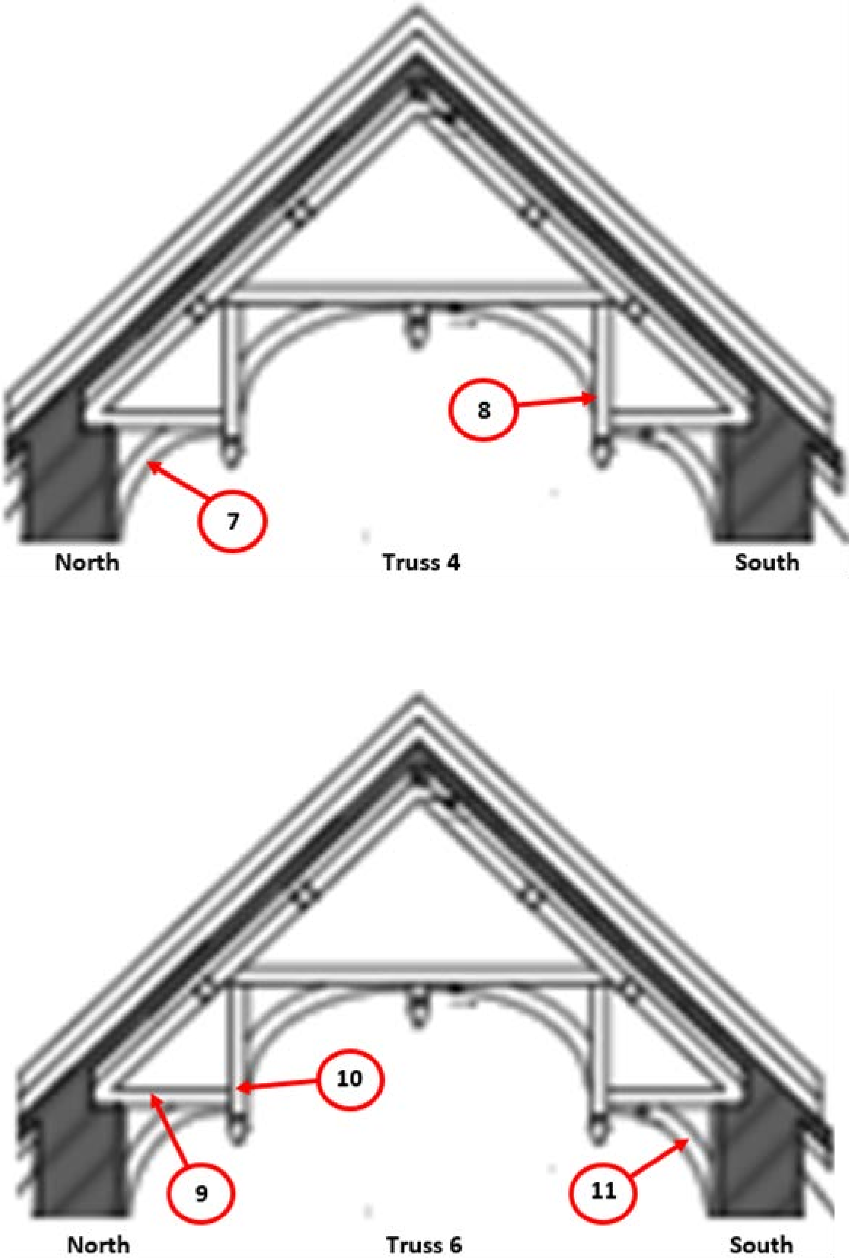


Figure 4c/d: Drawings of the trusses to help identify sampled timbers (see Table 1) [after Lucas Hickman Smith]

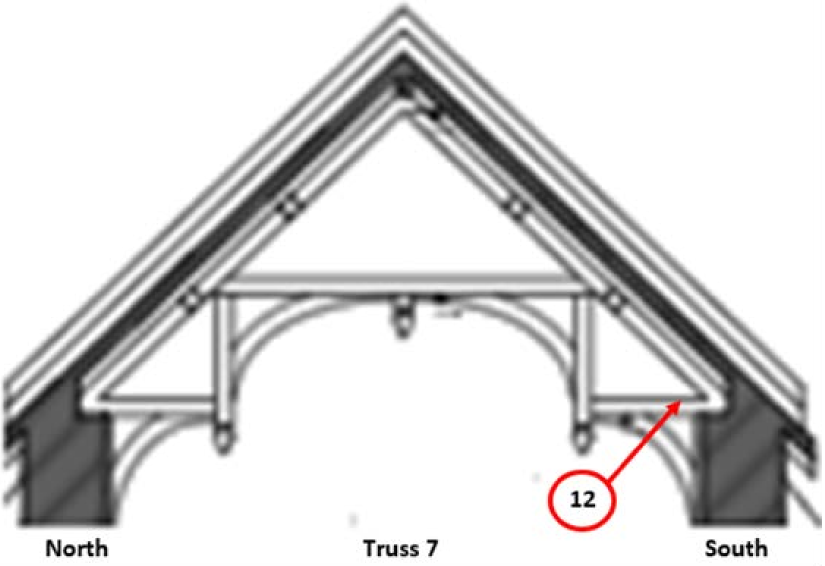


Figure 4e: Drawing of the truss to help identify sampled timber (see Table 1) [after Lucas Hickman Smith]

Table 1: Details of tree-ring samples from Becket's Chapel, 2 Church Street, Wymondham, Norfolk

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
WYM-H01	South wall post, truss 2	64	no h/s	------	------	------
WYM-H02	South hammer beam, truss 2	33	no h/s	------	------	------
WYM-H03	South wallplate, truss 2 – 3	40	no h/s	------	------	------
WYM-H04	North hammer beam, truss 3	52	h/s	1549	1600	1600
WYM-H05	South hammer post, truss 3	40	2	1565	1602	1604
WYM-H06	South hammer beam, truss 3	69	h/s	------	------	------
WYM-H07	North lower brace, truss 4	75	1	1524	1597	1598
WYM-H08	South hammer post, truss 4	45	h/s	1551	1595	1595
WYM-H09	North hammer beam, truss 6	54	4	1549	1598	1602
WYM-H10	North hammer post, truss 6	43	no h/s	------	------	------
WYM-H11	South lower brace, truss 6	63	no h/s	1520	------	1582
WYM-H12	South hammer beam, truss 7	62	h/s	1537	1598	1598

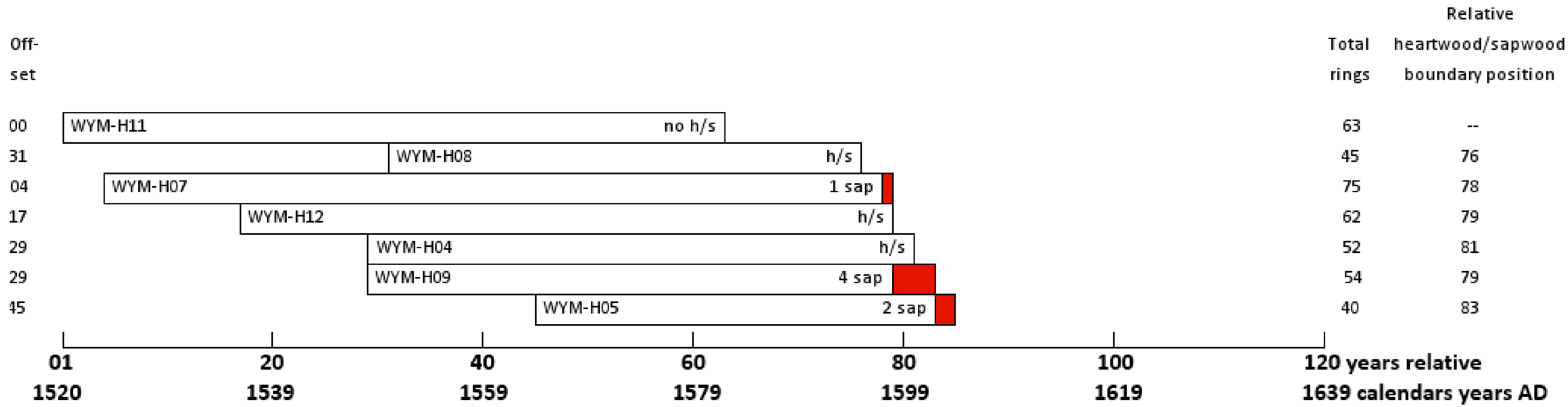
h/s = the heartwood/sapwood ring is the last ring on the sample

Analysis and Results

Each of the samples obtained from the roof trusses to the Chapel was prepared by sanding and polishing. The widths of the annual growth rings of all samples were then measured, these measured data being given at the end of this report. The measured series from all 12 timbers were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of a single cross-matched group comprising seven samples, these seven samples combining with each other at a minimum value of t=3.5, and cross-matching with each other at the positions illustrated in Figure 5.

These seven samples were combined at their indicated offset positions to form WYMHSQ01, a site chronology with an overall length of 85 rings. Site chronology WYMHSQ01 was then compared with an extensive range of oak reference chronologies, this indicating a repeated series of cross-matches when its first ring dates to AD 1520 and its latest ring dates to AD 1604 (Table 2).

Site chronology WYMHSQ01 was then compared with the remaining five ungrouped samples, but there was no satisfactory cross-matching. These five remaining samples were, therefore, compared individually with the full corpus of reference material for oaks, but there was no secure cross-matching identified and all five samples must remain undated for the moment.



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

Figure 5: Bar diagram of the seven dated samples of site chronology WYMHSQ01

Table 2: Results of the cross-matching of site sequence WYMHSQ01 and relevant reference chronologies when the first-ring date is AD 1520 and the last-ring date is AD 1604

Reference chronology	Span of chronology	*t*-value	Reference
Church of St Andrew, Sutton-in-the-Isle, Cambridgeshire	AD 1508–1615	7.8	Tyers 1995
Godwick Great Barn, Godwick, Tittleshall, Norfolk	AD 1406–1597	7.6	Arnold and Howard 2013a
Manor House, Preston, Rutland	AD 1471–1631	7.5	Arnold and Howard 2013b unpublished
Langley Abbey, Langley with Hardley, Norfolk	AD 1436–1611	7.2	Arnold and Howard 2014
Church of St Andrew, Welham, Leicestershire	AD 1443–1633	6.9	Arnold et al. 2005
Church of St Nicholas, Fundenhall, Norfolk	AD 1503–1614	6.5	Bridge 2009
Stoneleigh Abbey, Stoneleigh, Warwickshire	AD 1398–1658	6.4	Howard et al. 2000
Manor House, Alford, Lincolnshire	AD 1500–1668	6.3	Arnold et al. 2003
Holy Cross Church, Epperstone, Nottinghamshire	AD 1477–1647	6.2	Arnold and Howard 2020 unpublished
Lounge open coal pit, Coleorton, Leicestershire	AD 1502–1598	6.2	Howard et al. 1992
Tacolneston Hall, Norfolk	AD 1528–1617	6.1	Tyers 2009
St Peter's Church, Saltby, Leicestershire	AD 1446–1625	6.0	Howard et al. 1995

Interpretation

Dendrochronological analysis has thus successfully dated seven of the 12 timbers from which samples were obtained, these timbers being distributed variously along the length of the Chapel roof.

None of the samples from the seven dated timbers retain sapwood complete to the bark, and it is thus not possible to say, with any precision, when any individual timber was felled. Six of the dated samples do, though, retain some sapwood or at least the heartwood/sapwood boundary ring (h/s in Table 1 and bar diagram). This means that although a sample may have lost some or all of its sapwood rings (the most recent growth of the tree) it is *only* the sapwood rings that have been lost. The relative position and date of the heartwood/sapwood boundary on these six samples is very similar to each other, varying by only seven years from relative position 76 (AD 1595) on sample WYH-M08, to relative position 83 (AD 1602) on sample WYM-H05. Such similarity is indicative of timbers having a similar, if not identical, felling date.

The average heartwood/sapwood boundary ring of the six samples which retain it, is dated to AD 1598. Allowing for a minimum of 15 sapwood rings, and a maximum of 40 sapwood rings (the 95% confidence interval for the number of sapwood rings on oak trees), gives these timbers an estimated felling date at some point between AD 1613 at the earliest and AD 1638 at the latest.

The seventh dated sample, WYM-H11 does not retain its heartwood/sapwood boundary, and, in having lost, not only all its sapwood rings, but an unknown number of heartwood rings as well, it is not possible to say with reliability when the timber was felled. However, with a last heartwood ring date of AD 1582, and allowing for a possible minimum of 15 sapwood rings, the timber is unlikely to have been felled before AD 1597, at the earliest. Thus, with no evidence that the source timber, a brace, is anything other than a primary timber, there is little reason to suspect that it too is not coeval with the other dated timbers and therefore also of an early seventeenth-century date.

Discussion and Conclusion

Tree-ring analysis of timbers from this site has thus successfully dated seven of the 12 nave roof timbers from which samples were obtained. Interpretation of the sapwood and the heartwood/sapwood boundary on the dated samples would indicate that the timbers to the Chapel roof are of early seventeenth-century date. In the absence of any signs of reuse or resetting of timbers, the dendrochronology therefore suggests that substantial works to the roof were undertaken at this time. Thus, from a dendrochronological perspective, the roof of the Chapel would appear to be more recent than the late fifteenth-century date given in the listing entry.

Woodland sources

In some programmes of tree-ring analysis it is possible to suggest the region or general locality from which the timbers used in a particular building might have been sourced. This is usually intimated by any site chronology created during analysis, although having been compared with reference material from all over England, tending to match more closely with reference chronologies from some particular region or area rather than anywhere else. However, as may be seen in Table 2 for site chronology WYMHSQ01, although the reference chronologies listed do include several sites from Norfolk, other reference sites are distributed across Cambridgeshire and into the Midlands. Thus, whilst it is possible that the timber is of relatively local origin, it remains possible that it was derived from slightly further afield.

Undated samples

As may be seen in Table 1, five individual samples remain undated. Although, with only 33 rings, one of these samples is particularly short and hence problematic for secure dating, the other four have, in theory, sufficient numbers of rings for reliable dating, and none of them show features such as distortion or compression which might cause problems with cross-matching. However, for whatever reason, it is a very common, if inexplicable, feature of tree-ring analysis to find that some samples will not date. This undated material will be reviewed periodically as further reference chronologies for the locality become available and these timbers may, in due course, also be dated.

References

Arnold, A. J. and Howard, R. E. 2013a ‘Godwick Great Barn, Godwick, Tittleshall, Norfolk: Tree-ring Analysis of Timbers’, English Heritage Research Report Series, 14/2013 https://historicengland.org.uk/research/results/reports/14-2013 (acc. 01 August 2024)

Arnold, A. J., and Howard, R. E. 2013b ‘Tree-ring Analysis of Timbers from Preston Manor House, Cross Lane, Preston, Rutland’ (Unpublished computer file *PSTASQ01* Nottingham Tree-ring Dating Laboratory)

Arnold, A. J., and Howard, R. E. 2014 ‘Langley Abbey, Langley with Hardley, Norfolk; Tree-ring Analysis of Timbers’, English Heritage Research Department Report Series, 25/2014 https://historicengland.org.uk/research/results/reports/25-2014 (acc. 01 August 2024)

Arnold, A. J., and Howard, R. E. 2020 ‘The Tree-ring Dating of a Number of Bellframes in Nottinghamshire’ (Unpublished computer file NBFGSQ01, Nottingham Tree-ring Dating Laboratory).

Arnold, A. J., Howard, R. E., and Litton, C. D. 2003 ‘Tree-ring Analysis of Timbers from the Manor House, West Street, Alford, Lincolnshire’, Centre for Archaeol Rep, 55/2003: https://historicengland.org.uk/research/results/reports/55-2003 (acc. 01 August 2024)

Arnold, A. J., Howard, R. E., Litton, C. D. and Dawson, G. 2005 ‘The Tree-ring Dating of a Number of Bellframes in Leicestershire’, Centre for Archaeol Rep, 5/2005: https://historicengland.org.uk/research/results/reports/5-2005 (acc. 01 August 2024)

Bridge, M. 2009 ‘St Nicholas’ Church, Fundenhall, Norfolk: Tree-ring Analysis of Timbers from the Belfry Stage, Door, and Doorframe’, English Heritage Research Department Report Series, 86/2009 https://historicengland.org.uk/research/results/reports/86-2009 (acc. 01 August 2024)

Howard, R. E., Laxton, R. R., Litton, C. D., and Simpson, W. G. 1992 List 44: Nottingham University Tree-ring Dating Laboratory Results, Vernacular Architecture, 23, 51–6 https://doi.org/10.1179/vea.1992.23.1.44

Howard, R. E., Laxton, R. R., Litton, C. D., and Simpson, W. G. 1995 List 60: Nottingham University Tree-ring Dating Laboratory Results, Vernacular Architecture, 26, 47–53 https://doi.org/10.1179/vea.1995.26.1.47

Howard, R. E., Laxton, R. R., and Litton, C. D. 2000 ‘Tree-ring Analysis of Timbers from the Buildings and Living Trees at Stoneleigh Abbey, Stoneleigh, Warwickshire’, Ancient Monuments Laboratory Report, 80/2000 https://historicengland.org.uk/research/results/reports/80-2000 (acc. 01 August 2024)

Tyers, I. 1995 ‘Tree-ring Analysis of the Bellframe at St Andrews, Sutton-In-The-Isle, Cambridgeshire’, Ancient Monuments Laboratory Report, 15/95 https://historicengland.org.uk/research/results/reports/15-1995 (acc. 01 August 2024)

Tyers, I. 2009 ‘Tree-ring Dating of 7 Timber Framed Buildings in Tacolneston, Norfolk’, Dendro Co Rep, 20

Data of Measured Samples

Measurements in 0.01mm units

WYM-H01A 64
83 69 255 176 184 105 83 133 126 83 150 164 251 173 223 213 282 141 171 272
309 385 453 235 227 332 324 478 358 305 394 419 237 326 303 327 334 343 426 254
345 564 474 329 417 520 320 392 162 335 210 543 349 407 405 563 426 248 221 390
478 531 625 577
WYM-H01B 64
84 71 257 179 185 120 80 117 128 83 150 156 255 187 214 216 276 159 189 285
318 367 454 226 216 327 308 474 355 297 389 399 259 318 321 306 352 343 395 275
329 553 484 323 431 506 312 398 161 329 212 530 375 410 418 572 406 220 253 390
462 540 621 578
WYM-H02A 33
312 368 502 515 533 484 538 523 496 650 593 625 632 654 512 759 385 340 303 435
415 376 525 387 406 190 319 359 575 571 477 422 309
WYM-H02B 33
300 365 511 506 493 489 548 514 517 620 616 634 613 639 514 742 387 334 304 431
406 376 539 443 415 188 315 369 571 575 455 429 311
WYM-H03A 40
351 487 408 351 491 496 401 373 318 339 266 364 346 325 334 333 332 297 234 317
371 235 243 257 235 257 254 150 271 229 339 222 334 325 276 266 175 190 199 365
WYM-H03B 40
349 509 416 308 491 532 400 341 312 360 245 346 375 328 327 321 328 310 240 301
374 232 271 262 256 249 252 151 262 212 379 268 318 329 260 272 168 201 201 375
WYM-H04A 52
306 360 494 458 523 400 457 482 228 403 442 585 659 557 438 354 278 365 396 433
303 471 240 198 167 271 264 215 110 222 162 254 171 257 281 431 582 356 259 289
259 212 128 236 286 294 338 228 270 284 268 319
WYM-H04B 52
308 363 502 475 537 415 460 483 251 360 470 607 652 599 454 367 279 376 400 457
309 504 242 175 173 245 235 203 117 196 164 265 192 285 275 425 570 364 252 268
262 225 110 255 283 290 332 231 259 284 275 318
WYM-H05A 40
322 344 408 308 384 305 350 165 184 212 241 221 200 253 238 414 267 218 229 350
383 350 309 267 314 201 216 297 385 372 383 251 331 287 200 278 212 298 314 296
WYM-H05B 40
325 334 387 338 359 293 351 155 191 203 234 198 191 246 250 407 264 196 213 336
384 345 309 267 307 207 206 282 390 359 365 263 334 285 217 264 207 322 279 285
WYM-H06A 69
401 533 397 438 375 342 405 437 431 361 477 346 499 579 447 404 348 220 218 314
182 142 207 128 142 79 73 79 94 80 48 42 58 45 51 44 37 37 28 28
57 39 35 30 30 32 31 38 45 50 31 37 42 19 53 89 85 82 75 124
84 96 95 168 204 267 228 203 248
WYM-H06B 69
398 527 389 431 354 336 394 443 401 369 443 347 507 586 464 418 350 218 237 334
176 137 203 141 131 73 80 81 96 79 52 43 56 52 60 36 35 39 28 25
56 37 31 24 26 28 32 43 43 56 26 32 30 33 50 81 87 101 72 123
84 95 92 179 204 278 226 199 251

WYM-H07A 75
381 278 243 203 234 182 110 270 289 258 286 205 221 268 356 235 304 198 54 156
162 206 147 167 203 171 245 222 210 277 202 151 192 101 80 166 192 308 263 178
109 87 86 162 200 210 251 250 107 175 244 267 127 189 192 118 254 159 96 190
307 253 286 265 189 295 285 217 126 298 305 394 398 350 314
WYM-H07B 75
364 278 249 202 225 178 117 262 292 264 294 200 217 290 270 225 326 198 69 156
185 214 150 160 198 177 250 223 211 278 204 162 185 101 85 153 189 310 270 185
106 87 75 173 201 218 245 238 108 173 254 251 139 195 200 117 226 181 91 185
312 254 317 294 206 311 278 212 154 363 322 403 400 347 313
WYM-H08A 45
767 682 708 603 539 421 200 462 458 506 564 433 327 289 245 235 251 268 235 187
154 103 118 111 110 143 117 179 139 304 157 96 114 184 271 309 224 203 196 187
123 142 201 239 260
WYM-H08B 45
807 676 715 580 544 415 197 481 462 490 539 422 333 298 251 243 268 282 250 187
157 104 128 109 118 139 134 189 132 285 163 92 115 186 263 318 207 218 214 151
131 153 204 214 274
WYM-H09A 54
514 375 522 407 387 389 480 439 272 439 426 378 303 350 284 289 201 293 287 328
282 445 262 182 218 270 257 299 195 223 267 350 204 275 290 320 334 195 206 212
279 223 168 214 229 169 221 147 203 188 327 206 165 125
WYM-H09B 54
482 479 491 370 434 353 478 450 334 386 426 378 315 346 299 276 198 290 239 334
270 468 264 175 246 262 271 303 193 228 257 351 204 290 300 310 340 214 212 246
284 212 173 206 237 154 234 135 209 170 319 200 165 124
WYM-H10A 43
358 368 181 256 289 308 319 283 216 174 114 212 246 252 228 219 239 174 164 388
282 287 285 377 306 168 121 178 156 273 221 162 114 214 216 236 246 235 445 396
555 277 239
WYM-H10B 43
403 380 201 259 273 316 321 297 216 166 125 210 250 245 217 242 254 189 172 389
350 285 332 367 295 179 104 168 200 282 212 173 121 217 224 231 242 240 443 381
545 309 223
WYM-H11A 63
424 468 501 577 430 466 617 419 441 385 326 457 280 355 293 351 256 287 254 300
342 245 212 209 217 264 203 173 204 246 189 299 236 170 115 112 57 50 44 82
87 139 157 160 96 81 87 151 189 240 121 140 78 85 96 148 189 193 226 193
325 190 175
WYM-H11B 63
420 482 471 504 425 482 525 512 410 443 314 449 285 356 289 374 289 293 253 309
320 242 206 218 227 250 226 168 210 247 193 310 225 167 118 104 54 46 50 84
85 145 173 146 98 75 103 148 185 243 145 139 79 90 104 136 187 200 226 201
331 189 180
WYM-H12A 62
210 297 541 495 506 476 496 530 503 401 491 538 521 350 400 337 388 337 387 314
235 370 431 410 342 315 278 279 199 275 300 343 240 318 195 160 134 243 257 214
139 157 162 232 128 150 175 145 209 122 146 138 176 180 118 163 193 171 221 119
171 177
WYM-H12B 62
217 294 586 485 529 469 498 534 521 388 475 543 510 348 400 335 381 337 387 314

243 375 401 409 391 337 271 257 204 294 310 348 224 351 204 159 157 229 277 231
134 162 154 226 131 144 169 152 206 144 150 133 171 179 130 165 184 173 221 125
184 161

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 Buildings* (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	

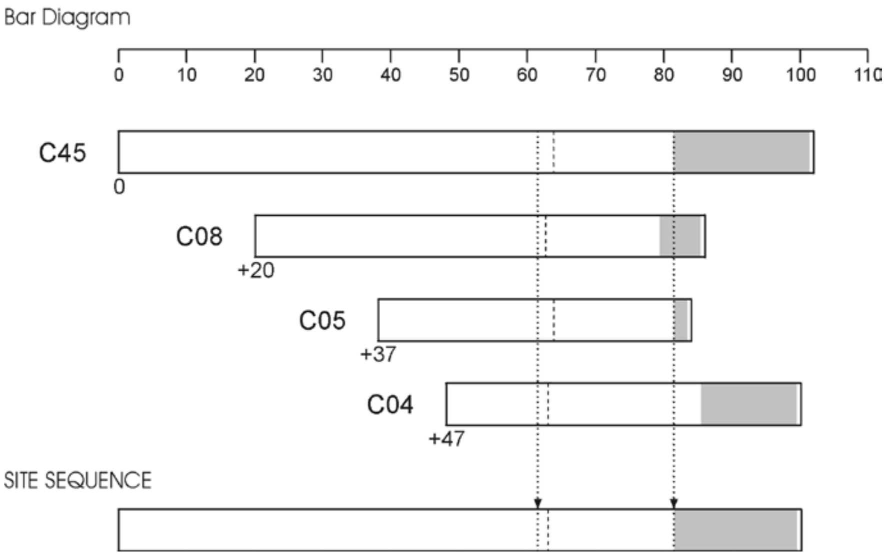


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

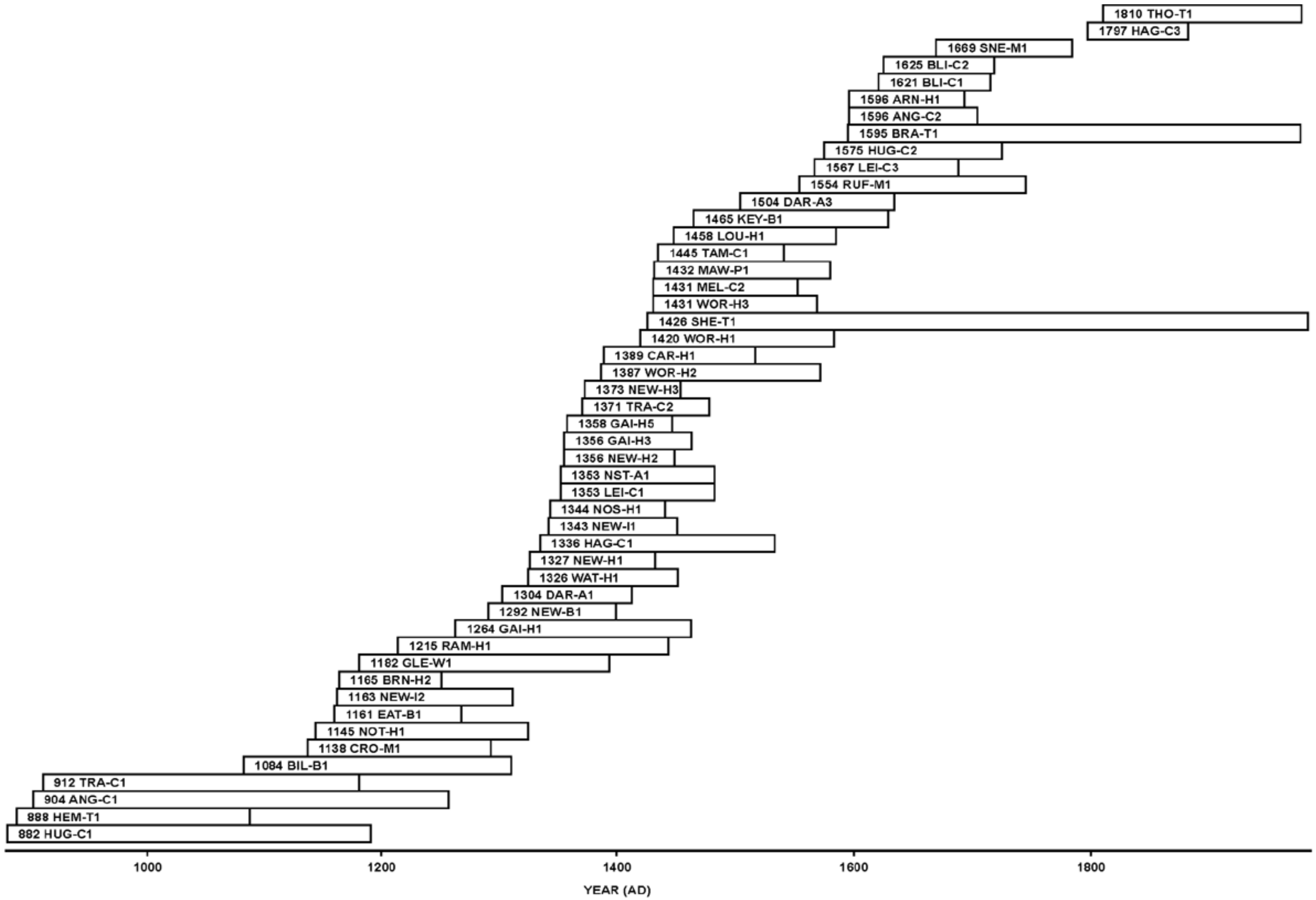
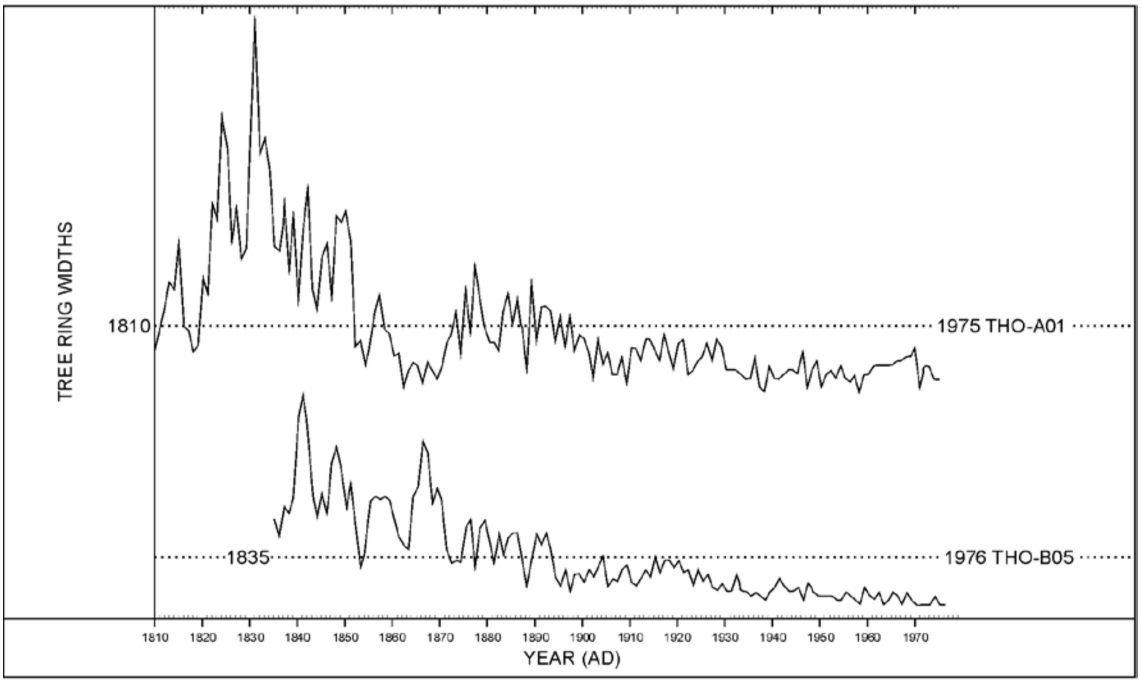


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

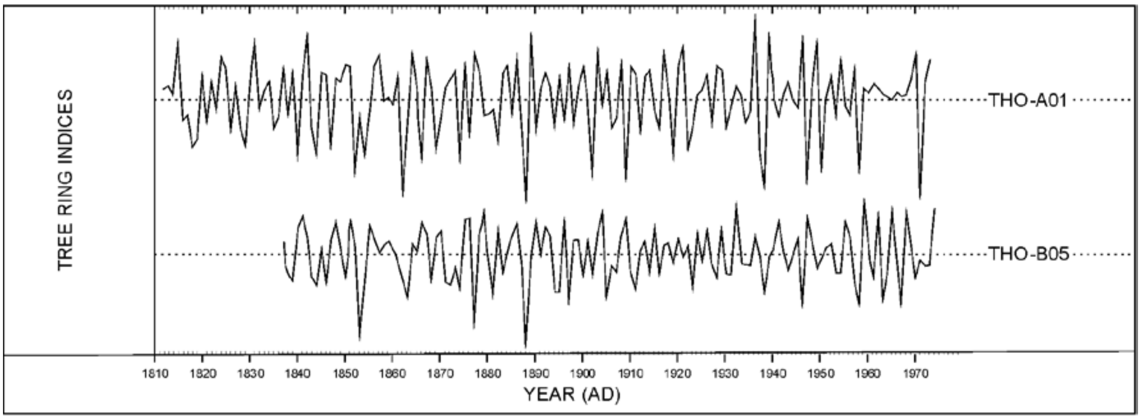


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

References

Baillie, M G L, and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-Ring Bull*, **33**, 7–14

English Heritage, 1998 *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates,* London

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95 Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect,* **15–26**

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, **23**, 51–6.

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series **III**

Laxton, R R, and Litton, C D, 1989 Construction of a Kent master dendrochronological sequence for oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90–8

Laxton, R R, Litton, C D, and Howard, R E, 2001 Timber: *Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, **7**

Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸**18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architect*, **28**, 40–56

Pearson, S, 1995 *The Medieval Houses of Kent, an Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London

Historic England's Research Reports

We are the public body that helps people care for, enjoy and celebrate England's historic environment.

We carry out and fund applied research to support the protection and management of the historic environment. Our research programme is wide-ranging and both national and local in scope, with projects that highlight new discoveries and provide greater understanding, appreciation and enjoyment of our historic places.

More information on our research strategy and agenda is available at HistoricEngland.org.uk/research/agenda.

The Research Report Series replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.

All reports are available at HistoricEngland.org.uk/research/results/reports. There are over 7,000 reports going back over 50 years. You can find out more about the scope of the Series here: HistoricEngland.org.uk/research/results/about-the-research-reports-database.

Keep in touch with our research through our digital magazine *Historic England Research* HistoricEngland.org.uk/whats-new/research.

ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)