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ST NICHOLAS' CHURCH, POTTER HEIGHAM, NEAR NORWICH, NORFOLK
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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Summary

It is believed that the re-roofing of St Nicholas's Church was funded by a series of bequests made specifically for such work between AD 1479–1535. Analysis of samples obtained from the roof of the north aisle during recent (AD 2006) repair works, however, indicates it is likely that all the timbers sampled were cut as part of a single felling, which is likely to have taken place between AD 1533–58. It is possible, therefore, that whilst the money for the re-roofing was given as late as AD 1535, the work was not necessarily carried out immediately but possibly more than 20 years later.

Keywords

Dendrochronology
Standing Building

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Introduction

The parish church of St Nicholas in Potter Heigham, Norfolk (TG 419 199, Figs 1 and 2), is believed to have its origins in the twelfth century, from which time the tower and chancel remain. The nave, and the north and south aisles, are believed to date to the thirteenth century, though the present roofs to these area are thought to date to c AD1500; Cattermole and Cotton (1983, 260) record that bequests for such works were made between AD 1479–1535, and one will, dated AD 1535, specifically mentions an aisle.

The nave is covered by a very fine hammerbeam roof (Fig 3) with wooden wall posts rising from stone corbels between the windows, the hammerbeams and the principal rafters being supported by arch braces. All such timbers are moulded and decorated, with the spandrels between the braces being filled with delicate wooden tracery.

The north and south aisle roofs comprise nine principal rafter trusses which are supported by aisle plates and arcade plates, these principal trusses alternating between those which are braced, (from the east end, frames 1, 3, 5, 7, and 9), and those which are not (frames 2, 4, 6, and 8), the braces themselves springing from wall posts. The braces springing from the posts of the nave walls are arched (the spandrels of at least the south aisle being filled with decorative tracery), while the braces springing from the posts of the outer walls of the aisle are kneed into the junction between the principal rafter and the wall post. All the principal rafters have roll moulding decoration, there being some moulding on the braces, wall posts, and plates as well. Between each principal rafter runs a single purlin, decorated in a similar manner, this supporting four or five plain common rafters to each bay. The roofs, views of which are given in Figures 4 a/b and 5, project beyond the arcade plates.

Sampling

Sampling and analysis by tree-ring dating of the north aisle roof timbers were commissioned by English Heritage, the purpose of this being to inform a programme of grant-aided repairs. It was hoped that tree-ring dating would confirm the date of this roof and determine the date of any possible repairs. It was anticipated that the dating of this roof might coincide with the dates of the known bequests.

Thus, from the material available a total of 12 samples was obtained by coring. Each sample was given the code PTH-A (for Potter Heigham, site 'A') and numbered 01–12. The positions of these samples are marked on plans made by Nicholas Warns, Architects, Norwich, and provided by English Heritage. These are reproduced here as Figures 6a/b. Details of the samples are given in Table 1. In this Table the bays, trusses and other timbers have been located and numbered from east to west following the schema on the drawings provided

The Laboratory would like to take this opportunity to thank Nicholas Warns for his enthusiasm and help with this programme of tree-ring analysis and for the use of his drawings and plans. We would also like to thank Cathy Tyers for her help in cross-matching sample data against data held by the Sheffield Dendrochronology Laboratory.

Analysis

The 12 samples obtained were prepared by sanding and polishing and their annual growth-rings were measured (the data of these measurements are given at the end of this report). The data of these 12 samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix), allowing four groups to be formed accounting for 10 of the 12 samples obtained (although the *t*-values between the individual components of site chronology PTHASQ02 are slightly below the usual threshold, the cross-matching between them can be confirmed by the fact that the three constituent samples can be dated individually. The position of the samples in each of the four site chronologies is shown in the bar diagrams Figures 7–10.

Each of the four site chronologies was then compared to an extensive series of reference chronologies for oak, this indicating cross-matches and dating for three of them. The four site chronologies were also compared with the two remaining ungrouped samples, but there was no satisfactory cross-matching. Both the remaining ungrouped samples were compared individually with the reference chronologies but again there was no satisfactory cross-matching and these two samples must remain undated. This analysis can be summarised below.

Chronology/ sample	Number of samples	Number of rings	Date span (where dated)
PTHASQ01	3	124	AD 1356–1479
PTHASQ02	3	65	AD 1456–1520
PTHASQ03	2	92	AD 1425–1516
PTHASQ04	2	66	undated
PTH-A09	1	55	undated
PTH-A10	1	56	undated

<u>Interpretation</u>

Analysis by dendrochronology of material from the roof of the north aisle of St Nicholas' Church has produced four site chronologies, accounting for 10 of the 12 samples obtained. Three of these site chronologies, accounting for eight samples, can be dated. One other site chronology remains undated, and two further samples remain ungrouped and undated.

Given the moulded and heavily squared nature of the beams in this roof, none of the timbers retain complete sapwood and thus their precise felling dates cannot be determined. Four of the eight dated samples do, however, retain the heartwood/sapwood boundary, the average date of this transition being AD 1518. The 95% confidence limit for the amount of sapwood the trees might have had is in the range 15–40 rings, such a figure giving the timbers represented an estimated felling date in the range AD 1533–58.

It is likely that all the dated timbers were felled at the same time as part of a single felling operation. This probability is likely despite three of the dated samples, POT-A03, H04, and H08, having first and last measured ring dates that are somewhat earlier than those seen on the other five dated samples, as may be seen in the bar diagram Figure 11, which shows the relative position of all eight dated samples. This difference is possibly due to way that the beams represented by the three earlier samples, all curved braces, have been cut from the original timber, all three probably being cut from near the middle of the same tree (*t*-values as high as 12.0 and 10.6 being found between these samples), whilst the others beams have been cut from the outer portions of their respective trees. It is almost certain that the timbers represented by samples POT-A06 and A07 are derived from the same tree as each other, these samples cross-matching with a *t*-value of 18.3.

Conclusion

It would appear likely, therefore, that the roof of the north aisle is composed of timbers all of which were cut as part of a single programme of felling which is likely to have taken place sometime between AD 1533–58. This is perhaps slightly later than might have been expected, given that bequests were made to the church for such works between AD 1479 and AD 1535. It thus might appear that whilst the money was donated over a period of time, up to as late as AD 1535, it is possible that the work was not actually carried out until some time later, possibly 20 or more years later, with the donations made in earlier years being used to re-roof the nave and the south aisle first. Dendrochronological investigation of the roofs of the nave and south aisle may be able to address whether these three areas are likely to have been re-roofed at the same time, or sequentially over a period of a few years.

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Table 1: Details of samples from the north aisle roof, St Nicholas' Church, Potter Heigham, Norfolk

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
PTH-A01	North aisle plate bay A	64	h/s	AD 1456	AD 1519	AD 1519
PTH-A02	Common rafter 5, bay A	54	h/s	AD 1467	AD 1520	AD 1520
PTH-A03	South brace, truss 3	120	no h/s	AD 1360	------	AD 1479
PTH-A04	South brace, truss 5	119	no h/s	AD 1356	------	AD 1474
PTH-A05	Common rafter 4, bay D	56	no h/s	AD 1459	------	AD 1514
PTH-A06	North aisle plate, bay F	90	h/s	AD 1426	AD 1515	AD 1515
PTH-A07	North wall post, truss 7	92	h/s	AD 1425	AD 1516	AD 1516
PTH-A08	North brace, truss 7	92	no h/s	AD 1372	------	AD 1463
PTH-A09	South brace, truss 7	55	no h/s	------	------	------
PTH-A10	North aisle plate, bay G	56	no h/s	------	------	------
PTH-A11	Principal rafter, truss 8	62	h/s	------	------	------
PTH-A12	Common rafter 3, bay H	63	no h/s	------	------	------

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

Table 2: Results of the cross-matching of site chronology PTHASQ01 and relevant reference chronologies when first ring date is AD 1356 and last ring date is AD 1479

Reference chronology	Span of chronology	*t*-value	
England East Anglia	AD 406–2001	7.7	(Tyers pers comm 2004)
England, Essex	AD 663–2001	7.2	(Tyers pers comm 2004)
Church House, Edenbridge, Kent	AD 1377–1538	6.6	(Howard *et al* 2000)
Chicksands Priory, Beds	AD 1175–1541	6.1	(Howard *et al* 1998)
Sutton House, Hackney, London	AD 1319–1534	5.6	(Tyers 1991)
England London 1659	AD 413–1994	5.4	(Tyers pers comm 2004)
England Kent	AD 890–1780	5.3	(Tyers pers comm 2004)
Thaxted Church, Essex	AD 1345–1526	5.2	(Tyers 1990)

Table 3: Results of the cross-matching of site chronology PTHASQ02 and relevant reference chronologies when first ring date is AD 1456 and last ring date is AD 1520

Reference chronology	Span of chronology	*t*-value	
Post-mill, Drinkstone, Suffolk	AD 1464–1586	8.4	(Bridge 2001a)
Otley Hall, Suffolk	AD 1380–1555	6.0	(Tyers 2000)
England East Anglia	AD 406–2001	5.8	(Tyers pers comm 2004)
Chiddingly Place, East Sussex	AD 1324–1576	5.6	(Arnold *et al* 2003)
South-east England	AD 435–1811	5.5	(Tyers pers comm 2004)
Priory Barn, Little Wymondly, Herts	AD 1450–1540	5.3	(Bridge 2001b)
Fiddleford Manor, Sturminster Newton, Dorset	AD 1433–1553	5.3	(Bridge 2003)
St Mary's Church, Attleborough, Norfolk	AD 1418–1514	5.3	(Bridge 2004a)

Table 4: Results of the cross-matching of site chronology PTHASQ03 and relevant reference chronologies when first ring date is AD 1425 and last ring date is AD 1516

Reference chronology	Span of chronology	*t*-value	
Abbas Hall, Great Cornard, Suffolk	AD 1421–1548	6.6	(Bridge 2000)
England East Anglia	AD 406–2001	5.9	(Tyers pers comm 2004)
Thames foreshore, Richmond, London	AD 1358–1584	5.3	(Hillam 1997)
St Mary's Church, Strethall, Essex	AD 1347–1511	5.1	(Bridge 2004b)
All Saints Church, Little Totham, Essex	AD 1380–1517	5.0	(Tyers 1996)
Manningtree, Essex	AD 1384–1534	5.0	(Loader pers comm 1996)
White Colne, Essex	AD 1439–1516	5.0	(Tyers pers comm 2002)
Mary Rose timbers, Hants	AD 1372–1535	4.9	(Bridge and Dobbs 1996)

Figure 1: Location of Potter Heigham, Norfolk.

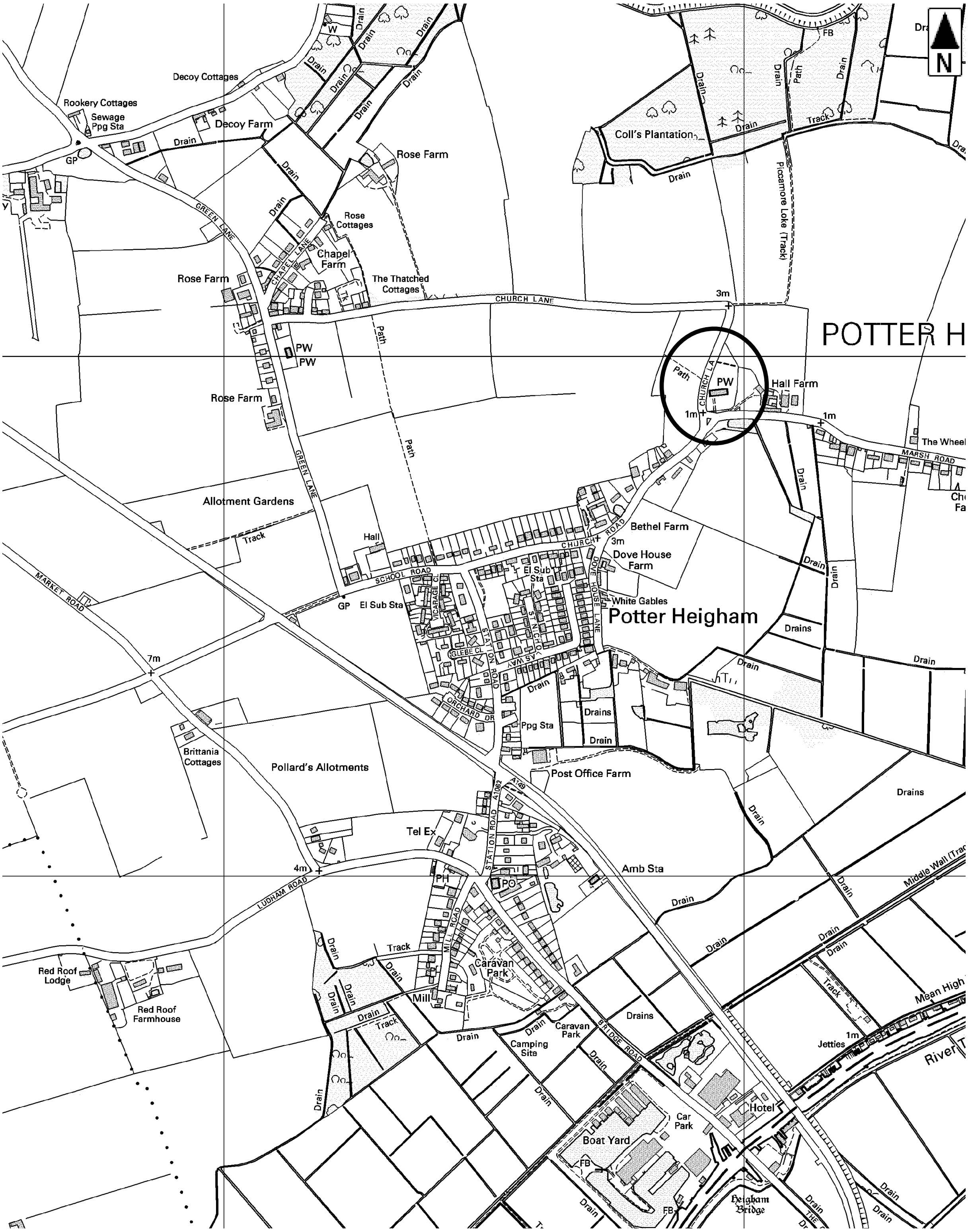

Figure 2: Location of St Nicholas' Church, Potter Heigham.

Figure 3: View of the nave roof viewed from the east looking west

Figure 4a/b: View of the roof of the north aisle, from the west looking east, showing the braces at alternate trusses (top) and the common rafters (below)

Figure 5: View of the south aisle roof looking west to east

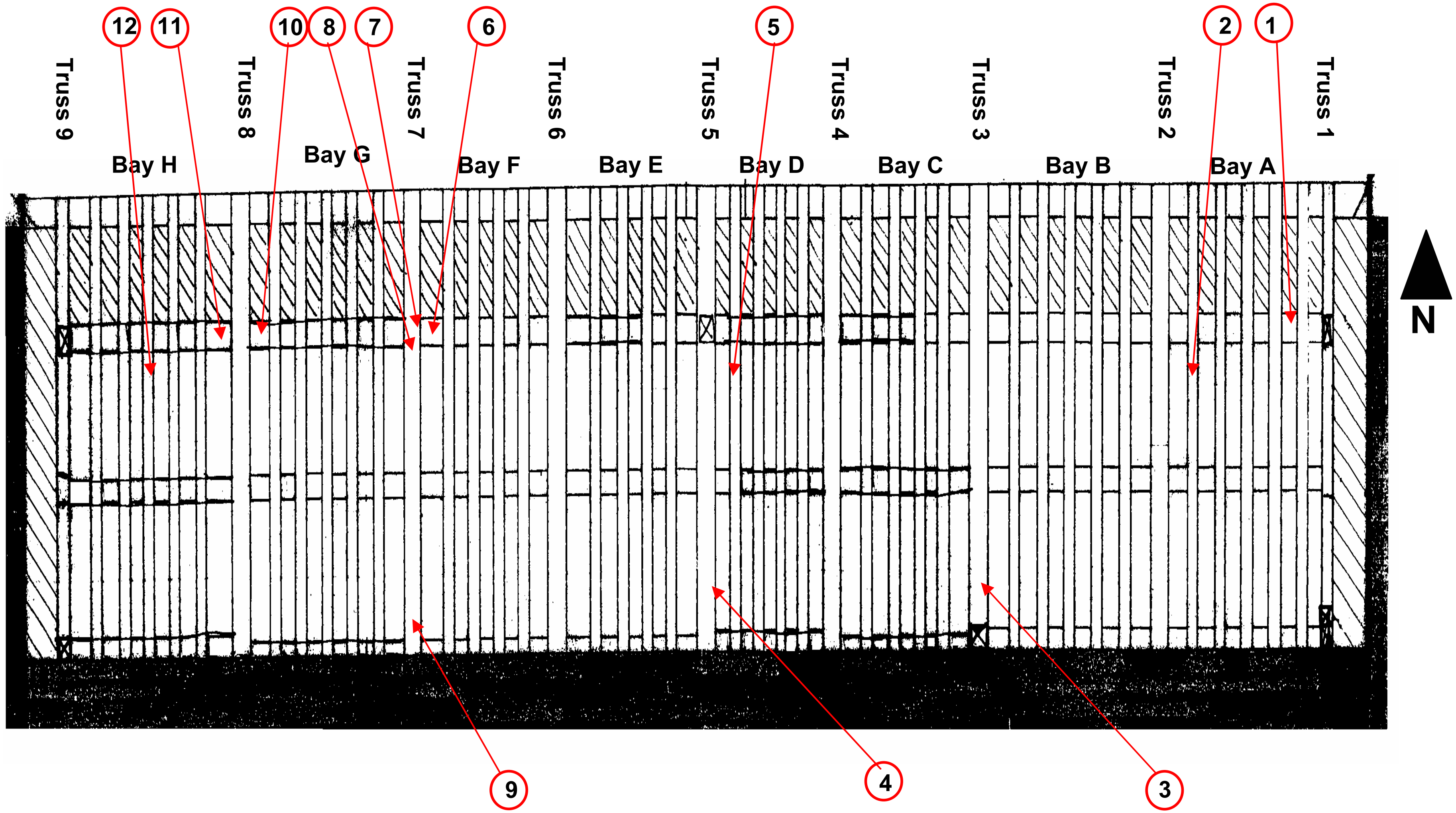

Figure 6a: Plan to show sampled timbers (after Nicholas Warns Architects Ltd, Norwich)

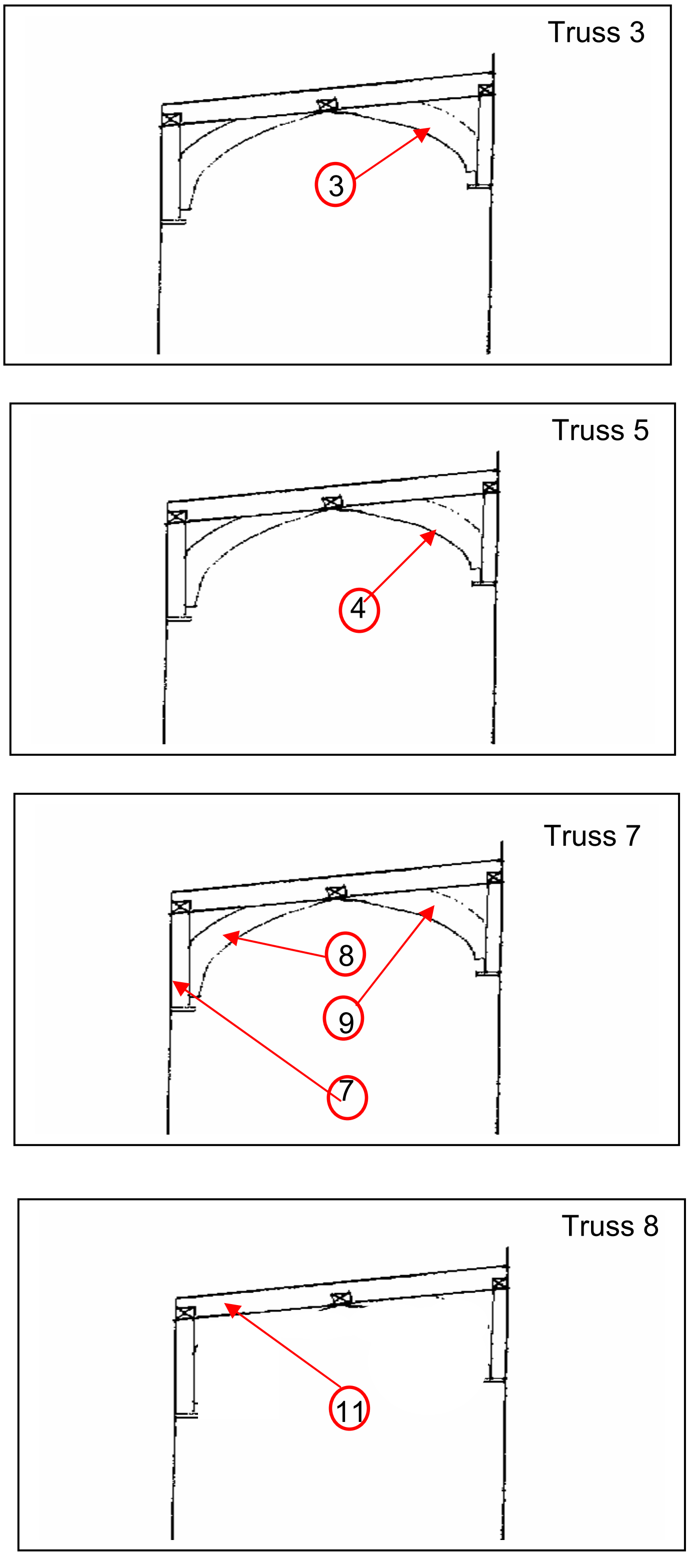

Figure 6b: Cross sections through trusses to show sampled timbers (viewed from the west looking east) (after Nicholas Warns Architects Ltd, Norwich)

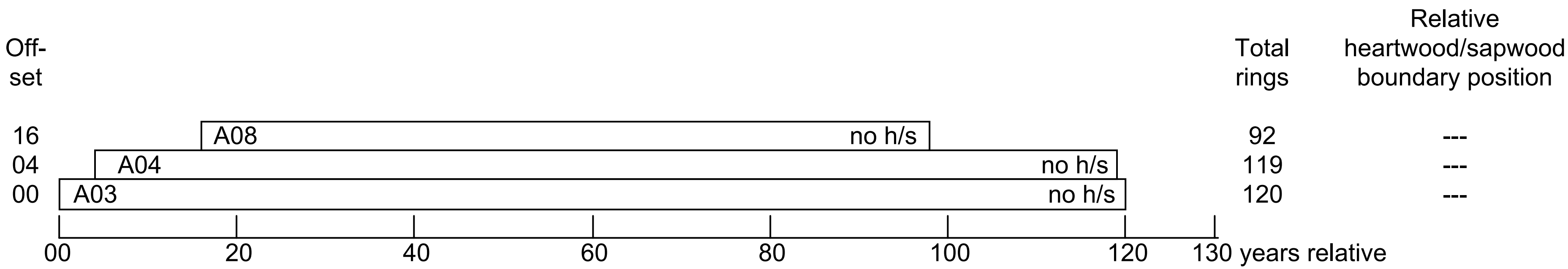

Figure 7: Bar diagram of the samples in site chronology PTHASQ01

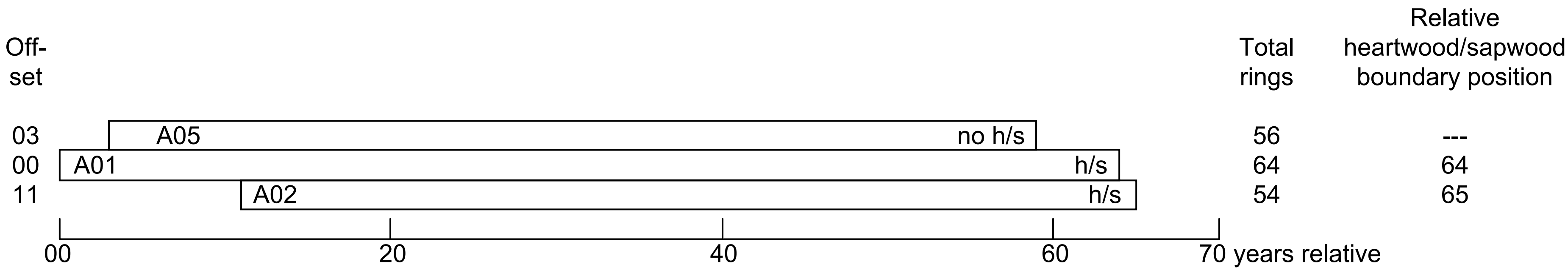

Figure 8: Bar diagram of the samples in site chronology PTHASQ02

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

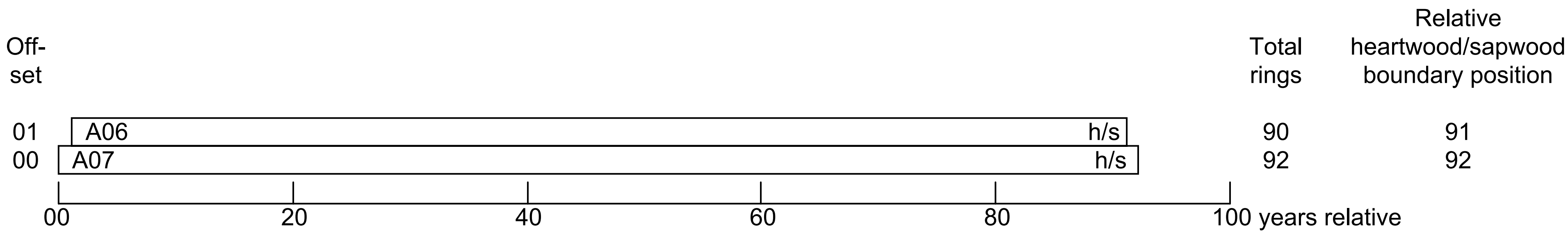

Figure 9: Bar diagram of the samples in site chronology PTHASQ03

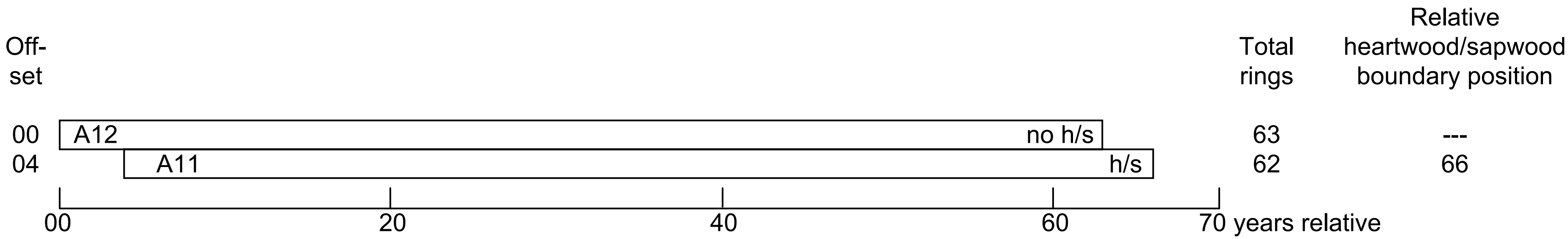

Figure 10: Bar diagram of the samples in site chronology PTHASQ04

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

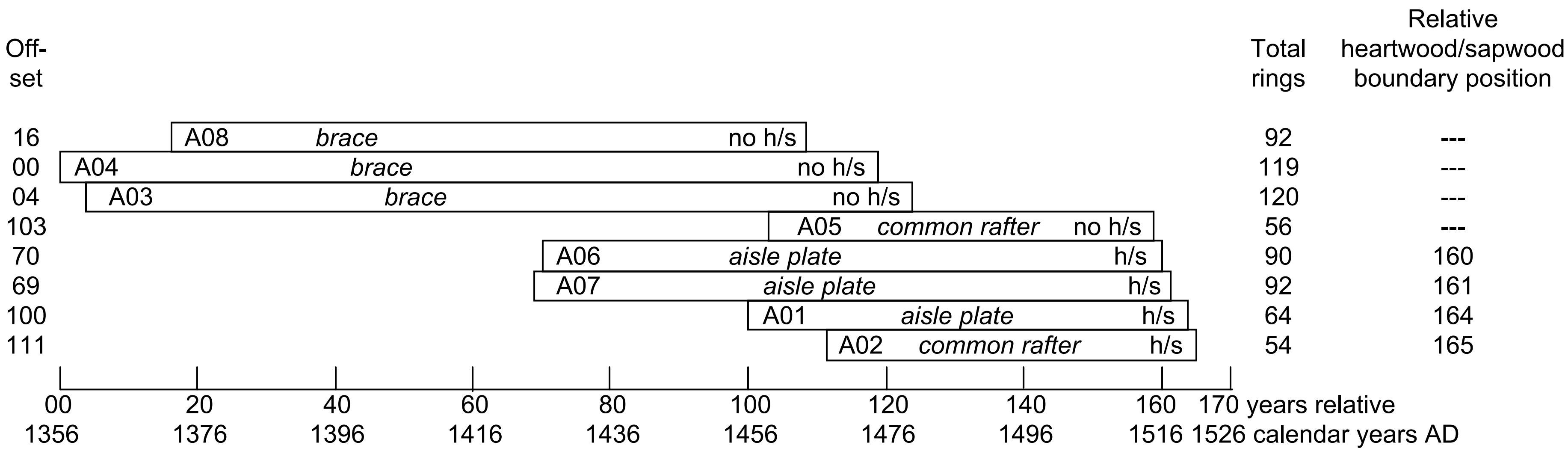

Figure 11: Bar diagram showing the relative positions of all dated samples

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

Data of measured samples – measurements in 0.01 mm units

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PTH-A01A 64
196 182 199 226 174  98 246 297 263 350 436 366 267 359 418 284 384 333 322 327
210 198 215 267 244 270 286 279 221 165 279 316 241 299 248 206 242 231 287 305
362 242 160 161 170 179 303 204 173 168 161 123 234 215 300 219 276 226 172 207
235 188 263 273
PTH-A01B 64
237 196 204 223 169 105 243 294 263 352 405 365 272 352 419 303 386 320 347 332
207 221 213 267 276 260 341 259 214 183 272 325 237 296 246 200 233 248 289 318
358 227 158 151 177 188 305 212 161 167 152 118 235 197 275 230 272 237 180 186
243 191 245 311
PTH-A02A 54
213 363 272 247 279 283 317 249 389 166 150 248 314 320 281 273 244 261 178 236
120  60  70  70  66  75 153 144 305 271 167 179 171 158 139 211 108 111 107 132
 97 134 137 169 146 165 131 134 143 158 159 134 199 195
PTH-A02B 54
263 359 223 234 290 253 271 267 336 190 142 244 305 322 288 306 247 247 177 236
130  70  62  82  63  61 112 123 274 208 194 169 156 148 121 175 100 110  92 137
 99 129 166 165 161 153 135 147 141 157 153 128 200 199
PTH-A03A 120
296 209 363 323 230 291 150 217 265 272 371 262 338 157 244 220 244 236 294 231
217 265 254 304 136 114 203 182 193 146 118 102 112 167 191 137 249 302 307 343
421 403 306 413 468 214 165 176 159 179 235 249 321 255 159 255 357 389 265 345
330 372 393 277 344 304 295 315 322 262 310 238 342 157 173 226 274 171 215 231
199 259 278 271 212 166 152 140 138 150 162 178 145 163 222 242 194 263 105 133
115 232 250 196 225 183 260 192 257 330 230 228 437 279 369 500 333 218 222 391
PTH-A03B 120
302 209 348 370 215 268 142 222 252 270 380 264 337 156 251 217 250 231 302 226
213 266 250 307 145 118 190 188 200 171 128  92 125 174 176 163 222 301 329 349
395 395 336 400 443 221 165 158 146 204 199 241 287 297 165 267 369 310 301 347
325 370 387 279 343 315 300 308 330 260 284 242 345 156 174 222 289 172 213 248
194 246 260 269 226 174 141 145 133 138 182 171 151 169 218 203 196 265  93 145
118 226 244 210 228 196 304 194 223 358 230 233 432 280 357 488 329 187 222 353
PTH-A04A 119
142 161 131 225 226  93 170 212 133 196 167 154 177 258 239 141 233 129 264 276
263 266 322 202 285 326 359 369 184 200 294 320 286 219 266 161 136 234 231 239
421 331 390 446 454 375 346 342 381 283 211 152 143 198 198 202 215 170 135 162
202 275 206 310 321 320 311 311 295 216 217 190 239 306 336 290 404 176 135 209
171 134 169 165 189 187 199 194 209 168 201 149 126 204 224 197 167 192 258 275
309 311 144 156 201 291 308 213 215 187 302 263 427 408 304 278 429 341 380
PTH-A04B 119
117 150 130 211 230  95 169 222 129 206 154 162 192 258 218 157 229 134 269 280
258 266 332 206 263 324 370 381 166 194 296 327 274 233 265 155 156 232 241 230
431 344 397 448 431 418 325 333 385 277 223 151 149 193 191 219 194 169 138 150
212 264 220 295 318 312 282 335 292 234 221 191 232 290 329 335 357 179 144 170
168 150 180 168 170 170 180 190 190 156 195 171 133 199 181 212 161 198 217 273
333 320 142 161 187 279 326 198 211 189 276 249 425 399 309 258 436 340 377
PTH-A05A 56
244 205 258 211 348 221 248 288 322 381 493 456 330 342 312 405 436 376 263 374
407 602 408 301 234 231 161 253 314 143 234 245  98 116 130 169 206 208 169 147
178 133 205 269 189 170 169 192 194 211 238 289 264 216 228 268
PTH-A05B 56
241 316 251 255 311 239 247 289 290 435 503 490 316 358 295 419 443 380 277 384
442 605 452 291 230 211 154 249 305 165 214 237  99 126 127 186 237 219 157 140
154 153 213 229 178 181 184 180 193 242 234 302 285 223 214 258
PTH-A06A 90
168 170 175 181 128 159 150 164 118 161 118 149 130  83 134 137 220 206 113  80
135 172  60  74  54  76  69 108 101 113 139 159  99 103 100 127 140 133 110  91
163 106 162 149 156 153  99  91  96 109  82  64 100 100 129 118 108 115 113 149
143 167 128 153 170 108 116 132 179 158 238 124  80  96 117 126 153 165 151 126
115  96 131 190 177 171 155 154 134 129
PTH-A06B 90
151 115 121 121  81 103 146 154 116 169 125 155 119  84 136 156 222 213 114  70
144 180  59  81  54  70  68 105 108 111 135 162 104  96 103 128 133 132 112 102
158 105 158 155 153 152 100  93  87 105  97  64 100 100 120 119 117 130 120 136
146 157 133 157 163 108 115 126 183 153 234 129  81  94 118 123 157 164 142 124
 93  89 125 198 171 169 157 174 129 126
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PTH-A07A 92
 94 162 146 197 166 133 150 144 149 112 185 123 163 138 106 130 150 225 202 121
 77 165 150  70  67  54  84  72 104 135 119 126 167 111 101 114 163 142 128 122
 99 159 122 171 170 139 152  93  95  87 119  90  83 101 101 134 129 112 113 110
130 138 152 143 174 156 112 111 123 171 139 239 119  94  94 112 124 152 153 148
121 119  73 128 216 216 172 153 239 183 148 192
PTH-A07B 92
116 193 117 182 160 132 159 133 146 126 180 119 173 135 128 135 147 225 208 116
 75 161 187  70  50  79  72  85 125 127 134 130 163 112 106  95 147 135 130 131
 92 160 123 168 166 144 157  90  99  85 117  97  76 100 104 138 120 116 110 118
130 142 154 134 157 173 104 114 119 177 137 237 110 100  99 111 127 141 159 144
125 113  73 138 208 200 176 161 241 191 136 188
PTH-A08A 92
212 143 231 280 363 370 407 328 468 529 526 777 216 269 316 383 353 303 316 256
251 423 396 338 520 587 669 737 829 546 548 486 633 442 311 177 119 147 111 131
161 134  88 181 320 307 350 361 399 371 335 367 354 282 366 273 284 451 305 297
313 186 157 222 131 136 220 206 251 259 298 241 201 133 185 150  92 137 170 153
129 138 178 167 299 398 102 105 114 286 448 382
PTH-A08B 92
247 126 243 273 387 364 400 329 403 541 539 754 207 268 306 370 355 313 327 256
248 445 417 306 569 600 660 748 837 544 546 481 625 451 312 182 123 147 110 121
164 127 105 170 314 303 327 362 389 372 363 360 363 278 367 265 297 446 320 274
376 183 160 210 115 150 197 204 257 240 271 249 196 139 185 139 105 141 167 165
128 133 187 166 312 433 114  94 118 287 464 388
PTH-A09A 55
159 217 190  81  87  95 135 129 124 131 119 122  89 153 136 145 179 190 219 238
362 294 253 170 261 261 316 348 266 379 224 251 379 372 292 254 286 264 240 378
526 415 382 145 305 261 358 181 157 120 106 121 166 151 200
PTH-A09B 55
182 199 198  95  95  88 132 133 122 133 115 114 103 151 138 145 171 178 216 237
350 286 240 192 259 278 297 335 270 392 244 261 369 321 318 232 322 237 287 369
501 406 377 205 318 268 339 175 156 117 104 117 163 150 210
PTH-A10A 56
110 149 187 179 139 137 181 174 200 193 170 136 130 157  89 105 134 144 120 131
 95 192 135 105 126 110 137 118  75  97 236 239 202 218 251 234 272 202 120 121
 92 151 139 151 135 112 130 133 150 189 226 221 172 217 178 220
PTH-A10B 56
121 159 172 183 136 141 170 174 207 210 173 134 124 157  83 115 143 136 127 118
 96 163 160  96 137 111 136 117  75 111 207 242 187 212 240 226 274 206 123 110
100 163 132 146 136 115 132 129 150 184 227 220 177 214 182 218
PTH-A11A 62
432 290 420 373 386 481 354 280 397 389 214 239 320 329 262 142 268 327 297 341
514 463 360 356 383 381 349 352 430 312 322 178 148 149 110 155 134 163 159 204
206 171 219 218 154 178 297 222 154 139 151 135 112 130 133 150 189 226 246 168
139 198
PTH-A11B 62
409 284 329 397 387 456 401 261 404 400 212 252 315 329 271 129 269 333 309 352
527 443 369 381 370 374 357 352 418 349 314 178 126 139  92 174 138 168 169 181
215 177 222 214 142 192 302 218 152 136 146 141 115 132 127 153 194 227 250 180
144 194
PTH-A12A 63
336 416 281 149 316 287 359 428 481 471 508 261 418 612 266 240 274 377 235 155
149 234 208 227 412 304 223 243 200 271 299 215 331 270 237  94  68  72  64 127
106 129 104 133 127  98 117 121 103 106 181 170 138 139 137 131  93 108 132 156
161 162 222
PTH-A12B 63
344 375 286 156 339 283 370 440 474 460 506 252 417 612 274 252 260 384 261 142
133 252 201 217 406 302 224 232 218 254 301 220 325 283 239  97  64  77  64 125
 97 134 107 131 136  84 119 120 105 107 197 162 140 155 120 131 102 103 117 167
157 163 209
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building'* (Laxton and Litton 1988) and*, Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. ***Inspecting the Building and Sampling the Timbers***. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

   To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8 to 10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. (Oak boards quite often come from the Baltic and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56)).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

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

6. ***Master Chronological Sequences***. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well

replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

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

t-value/offset Matrix

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

Bar Diagram

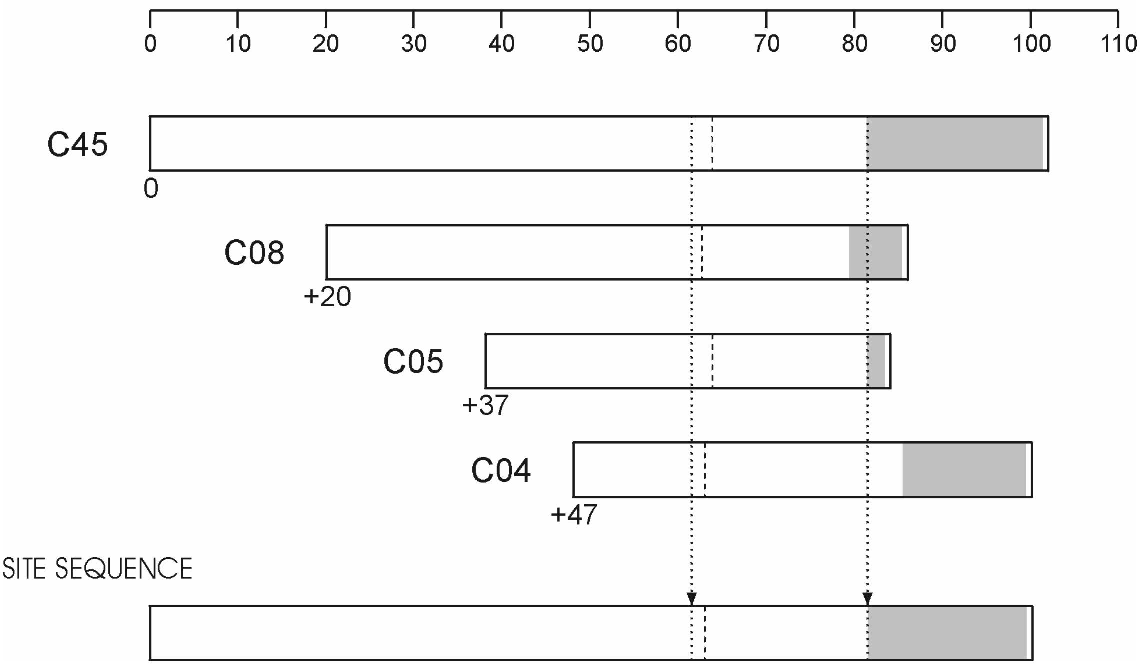

Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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

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

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

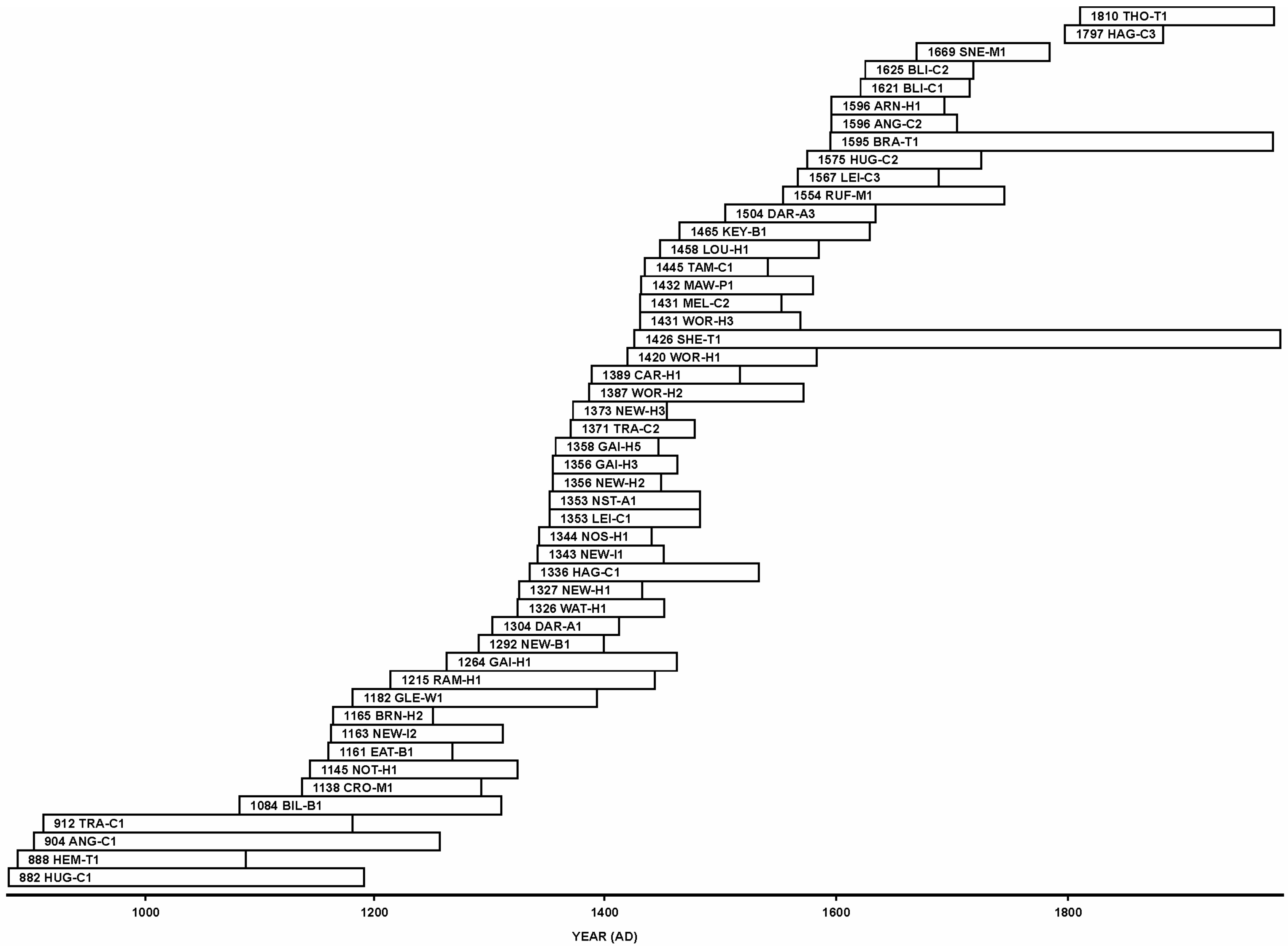

Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

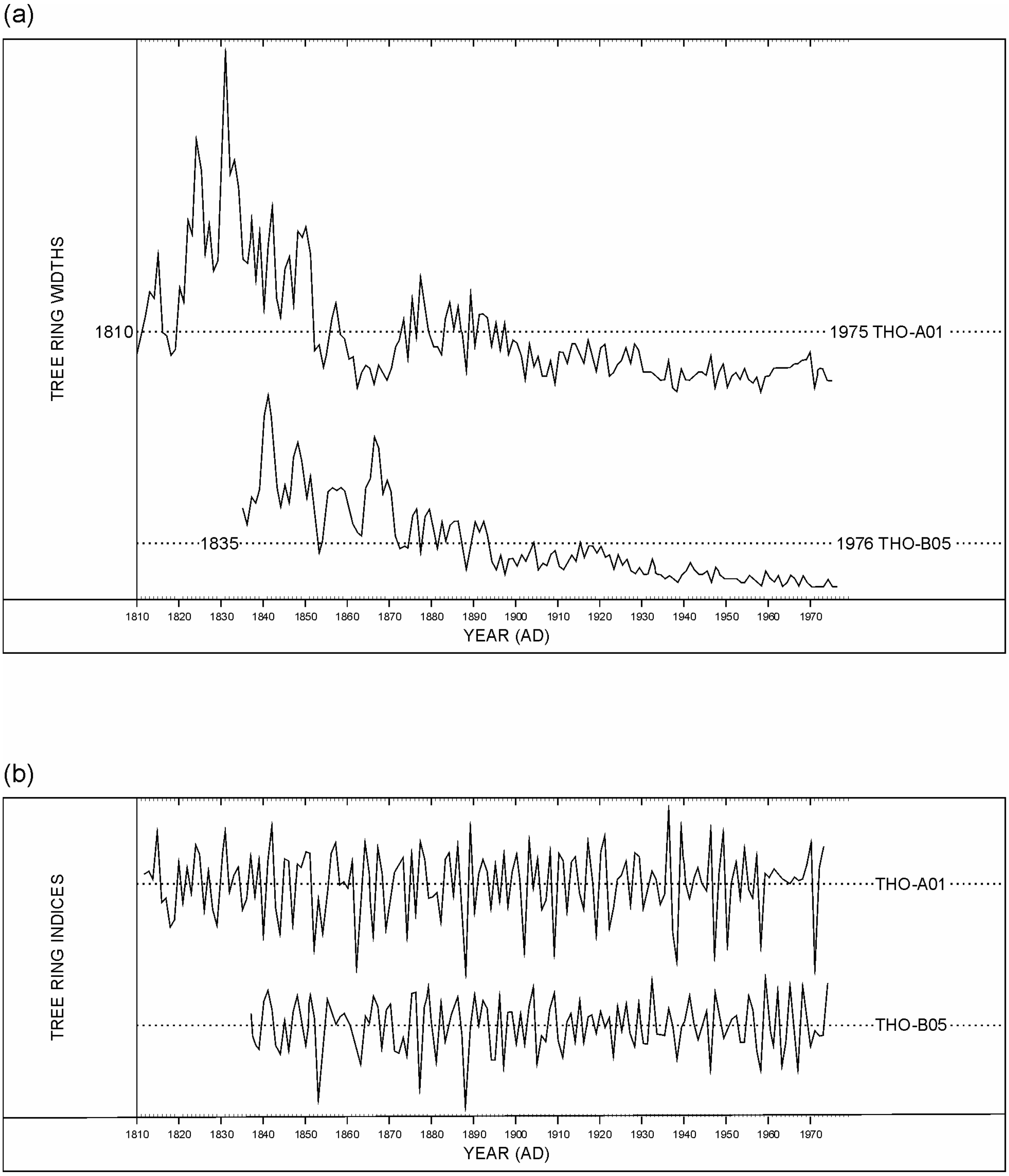

Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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