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ALL SAINTS' CHURCH, NORTH SCARLE, LINCOLNSHIRE
TREE-RING ANALYSIS OF TIMBERS OF THE BELLFRAME AND BELFRY FLOOR

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

ALL SAINTS' CHURCH, NORTH SCARLE, LINCOLNSHIRE

TREE-RING ANALYSIS OF TIMBERS OF THE BELLFRAME AND BELFRY FLOOR

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SUMMARY
Samples were taken from the timbers of the bellframe and belfry floor.
Nine bellframe samples grouped and were combined to form NSCBSQ01, a site sequence of 115 rings. This was found to span the period AD 1602–1716, with the timbers represented being felled in AD 1716.
Two of the belfry floor timbers were combined to form site sequence NSCBSQ01. This was dated to the period AD 1331–1482, with both beams being felled in AD 1482.
Two further site sequences are undated.

CONTRIBUTORS
Alison Arnold and Robert Howard

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INTRODUCTION

All Saints' Church, located in the Lincolnshire village of North Scarle (Figs 1–3; SK 8482 6674) is grade II listed, and originally dates from the twelfth century, undergoing subsequent work in the thirteenth, fifteenth, and nineteenth centuries. It consists of west tower, nave, north and south aisles, south porch, and chancel (www.lbonline.english-heritage.org.uk).

Bellframe and Belfry Floor

The current bellframe holds three bells in three parallel pits, aligned east-west (Fig 4). It is of long-headed type; the four main east-west trusses have braces from sill to head and jack braces from brace to head (Fig 5). The three bells hanging in the frame date from AD 1616 to AD 1733, with the frame itself thought to date to the seventeenth century.

The bells have not been rung for ten years, thought to be most likely due to the poor condition of the belfry floor. This consists of four east-west beams and two north-south bearers, one against the west wall and one against the east wall. The middle two of the east-west beams are split, perhaps weakened by being trimmed back to allow the bells to pass, and the east bearer is hollow at its midpoint (Fig 6).

SAMPLING

Sampling was requested by Graham Pledger to inform an application for the removal of the bellframe and belfry floor. The parish have decided they would like to increase the current three bells to six, and investigations into how best to achieve this have suggested the removal of these structures. It is hoped that tree-ring dating will provide precise dates for both elements, thereby informing decisions to be made on their importance.

A total of 16 timbers was sampled. Each sample was given the code NSC-B (for North Scarle) and numbered 01–16. Ten of the samples were taken from the bellframe (NSC-B01–10) and six from the belfry floor beams (NSC-B11–16). The location of samples was noted at the time of sampling and has been marked on figures 7–13. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

At this stage it was noted that one of the bellframe samples (NSC-B05) had too few rings to make secure dating a possibility and so it was discarded prior to analysis. The remaining 15 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

Bellframe and Belfry Floor

All nine remaining bellframe samples matched each other at a value of *t*=5.0. These series were combined at the relevant offset positions to form NSCBSQ01, a site sequence of 115 rings (Fig 14). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1602 and a last-measured ring date of AD 1716. The evidence for this dating is given in Table 2. One of these samples (NSC-B08) has complete sapwood and the last-measured ring date of AD 1716, the felling date of the timber represented. A further five samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1696, which allows an estimated felling date to be calculated for the five timbers represented to the range AD 1714–36 (this allows for sample NSC-B10 having a last-measured ring date of AD 1713 with incomplete sapwood), consistent with a felling of AD 1716. The other three dated samples do not have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be calculated, except to say with last-measured ring dates ranging from AD 1666 (NSC-B02) to AD 1691 (NSC-B04) it is possible that these timbers were also felled in AD 1716.

Two samples taken from the belfry floor timbers matched each other and were combined at the relevant offset position to form NSCBSQ02, a site sequence of 152 rings (Fig 15). Attempts to date this site sequence by comparing it against the reference material resulted in it being found to span the period AD 1331–1482. The evidence for this dating is given by the *t*-values in Table 3. One of these samples (NSC-B13) has complete sapwood and the last-measured ring date of AD 1482, the felling date of the timber represented. The other sample (NSC-B16) has the heartwood/sapwood boundary ring date of AD 1443, which allows an estimated felling date to be calculated for the timber represented to AD 1458–83, consistent with a felling date of AD 1482.

Two further site sequences were constructed from the remaining four samples (Figs 16 and 17) but attempts to date these by comparing them against the reference chronologies were unsuccessful and they remain undated.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees in this area have between 15 and 40 sapwood rings.

DISCUSSION

Prior to tree-ring analysis being undertaken the bellframe was believed, on the basis of its height, moulded heads, and end bearers, to date to the seventeenth century. It is now known to be constructed from timber felled in AD 1716, dating it to the first quarter of the eighteenth century, hence slightly later than expected.

Analysis of the six timbers of the belfry floor resulted in the construction of three site sequences, only one of which could be dated. The dated site sequence indicates that two of the east-west beams of this floor were felled in AD 1482. However, with the other four beams remaining undated, it cannot be stated categorically that the floor dates to AD 1482 on the basis of these two timbers. Although there were no obvious signs that these timbers had been used previously, or inserted later, these are still possibilities.

Although undated, the other two site sequences from the belfry floor demonstrate that in both cases, the two samples represented were felled contemporaneously. This can be seen by their relative heartwood/sapwood boundary ring positions (Figs 16 and 17). Unfortunately, it cannot be said whether all four beams were felled at the same time or whether either pair also dates to AD 1482. Indeed, it may be that the analysis produced three separate site sequences because three different felling dates are represented within the belfry floor. Equally, it may be due to the timbers utilised being from varying woodland sources, or other non-climatic factors significant to the trees themselves. Interestingly, both of the trees represented by the samples in site sequence NSCBSQ04 have experienced periods of restricted growth, occurrences which may have unduly affected their growth pattern and so, hampered the matching against both the other samples and the reference chronologies.

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TABLES

Table 1: Details of tree-ring samples from the bellframe and belfry floor at All Saints' Church, North Scarle, Lincolnshire

Sample Number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Bellframe						
NSC-B01	Truss 1, east brace	76	11	1636	1700	1711
NSC-B02	Truss 2, head	65	--	1602	----	1666
NSC-B03	Truss 3, sill	67	--	1621	----	1687
NSC-B04	Truss 4, head	70	--	1622	----	1691
NSC-B05	Truss 4, west jack brace	NM	--	----	----	----
NSC-B06	East return, north brace	86	12	1623	1696	1708
NSC-B07	East return, north jack brace	58	07	1641	1691	1698
NSC-B08	West return, north jack brace	59	14C	1658	1702	1716
NSC-B09	West return, north brace	74	14	1639	1698	1712
NSC-B10	West return, south jack brace	75	16	1639	1697	1713
Belfry floor						
NSC-B11	East bearer	120	h/s	----	----	----
NSC-B12	West bearer	111	h/s	----	----	----
NSC-B13	Beam 4	116	41C	1367	1441	1482
NSC-B14	Beam 3	56	16	----	----	----
NSC-B15	Beam 2	45	04	----	----	----
NSC-B16	Beam 1	139	26	1331	1443	1469

*NM = not measured; **h/s = heartwood/sapwood boundary is the last-measured ring; C = complete sapwood retained on sample, last-measured ring date is the felling date

Table 2: Results of the cross-matching of site sequence NSCBSQ01 and relevant reference chronologies when the first-ring date is AD 1602 and the last-measured ring date is AD 1716

Reference chronology	*t*-value	Span of chronology	Reference
Lincoln Cathedral (St Hugh's Choir) Lincs	10.5	AD 1575–1724	Laxton *et al* 1984
Lincoln Cathedral (Angel Choir roof), Lincs	7.7	AD 1596–1703	Howard *et al* 1985
Castle House, Melbourne, Derbys	6.1	AD 1583–1720	Arnold and Howard 2009
Kibworth Harcourt Mill, Leics	5.9	AD 1582–1773	Arnold *et al* 2004
Potterdike House, Lombard Street, Newark, Notts	5.8	AD 1603–1740	Arnold *et al* 2002
Bolsover Castle (Riding House), Derbys	5.7	AD 1494–1744	Arnold *et al* 2005
De Grey Mausoleum, Flitton, Beds	5.8	AD 1510–1726	Arnold *et al* 2003a

Table 3: Results of the cross-matching of site sequence NSCBSQ02 and relevant reference chronologies when the first-ring date is AD 1331 and the last-measured ring date is AD 1482

Reference chronology	t-value	Span of chronology	Reference
Nostell Priory, Wakefield, West Yorks	7.4	AD1263–1536	Tyers 1998
Boughton Hall, Boughton, Northants	6.9	AD 1355–1509	Brown *pers comm*
Ulverscroft Priory, Leics	6.7	AD 1219–1463	Arnold *et al* 2008
Lincoln Cathedral (south-west transept roof), Lincs	6.4	AD 1372–1477	Laxton and Litton 1988
Green Farm, Bradgate Road, Anstey, Leics	6.3	AD 1254–1449	Alcock *et al* 1990
Hagworthingham Church, Lincs	6.0	AD 1336–1533	Laxton *et al* 1984
Kingswood Abbey, Gatehouse, Glos	6.0	AD 1307–1428	Arnold *et al* 2003b

FIGURES

Figure 1: Map to show the general location of North Scarle (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

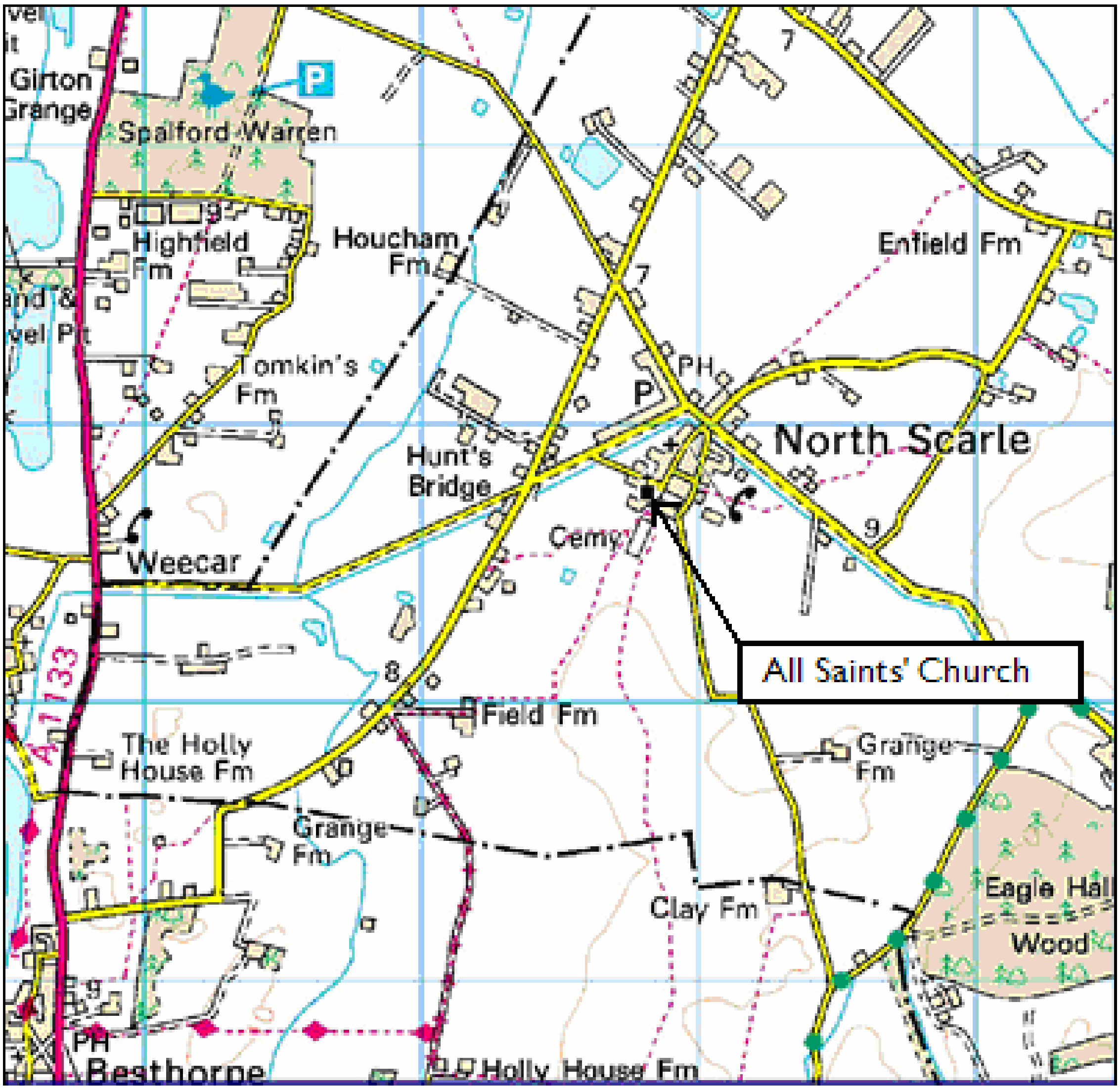

Figure 2: Map to show the general location of All Saints' Church, North Scarle (based on the Ordnance Survey map with permission of Her Majesty's Stationery Office, ©Crown Copyright)

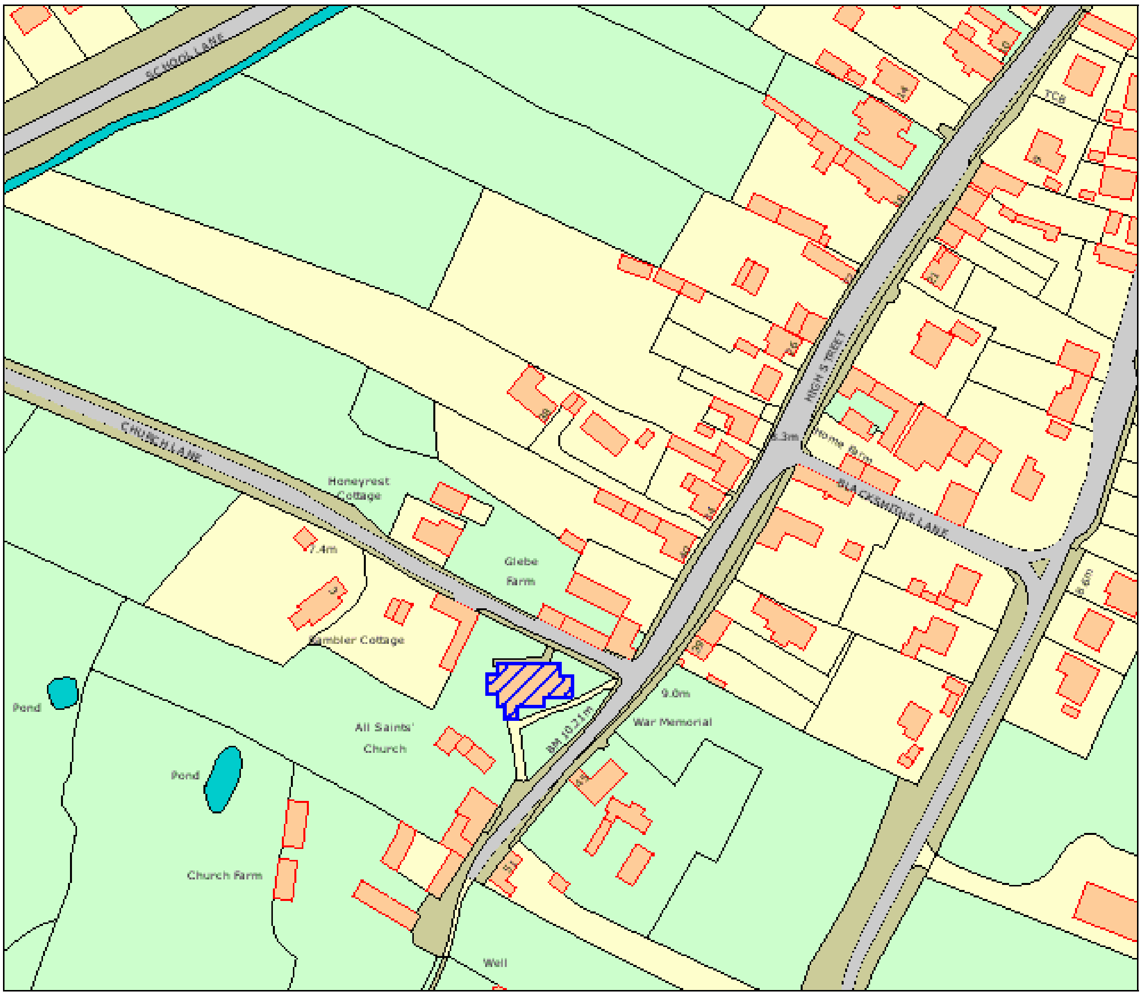

Figure 3: Map to show the location of All Saints' Church, North Scarle, outlined and hashed in blue (based on the Ordnance Survey (map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

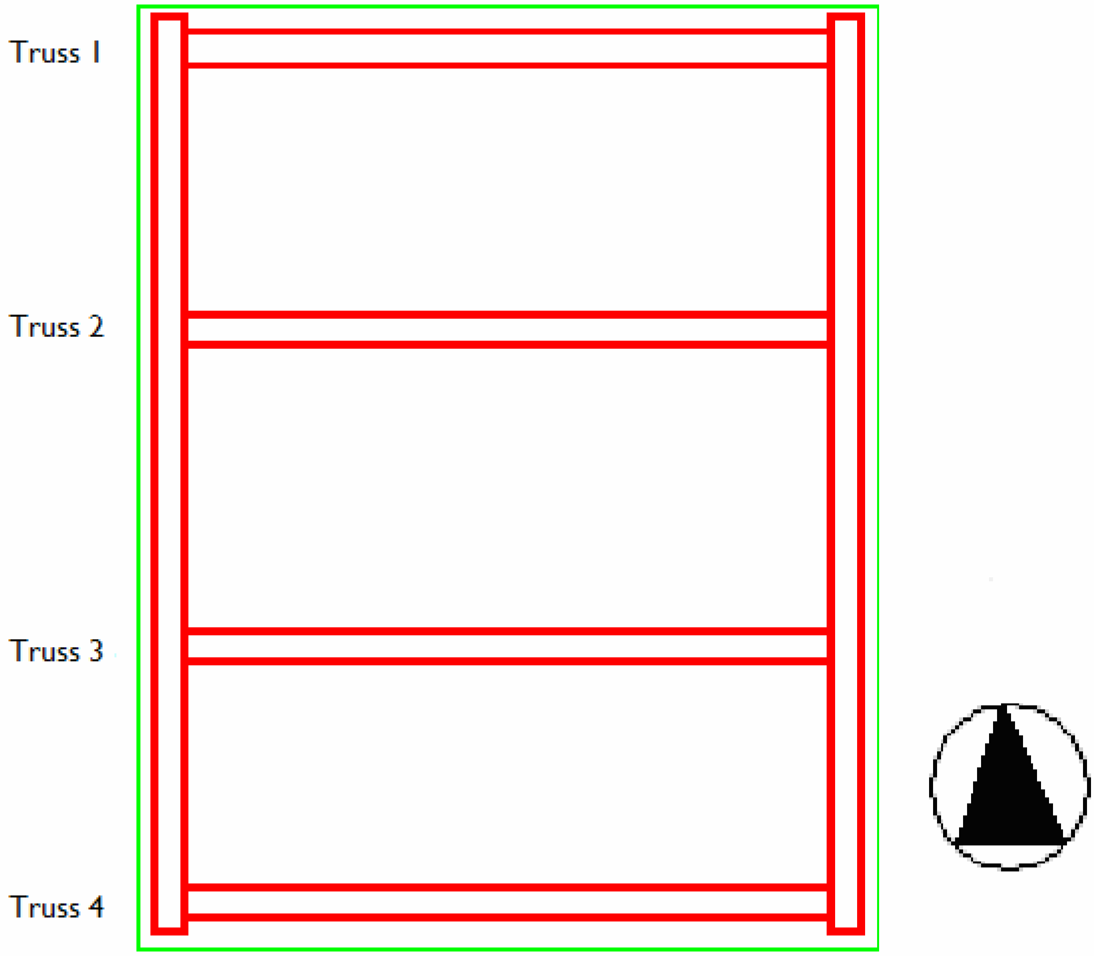

Figure 4: Plan of bellframe (Graham Pledger)

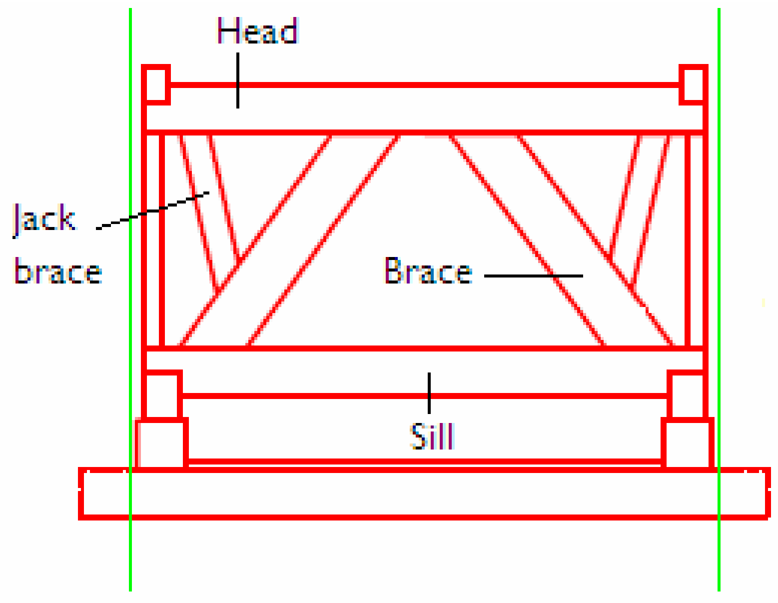

Figure 5: Main east-west truss (Graham Pledger)

Figure 6: Belfry floor, beam 4 to far left and west bearer in towards the rear

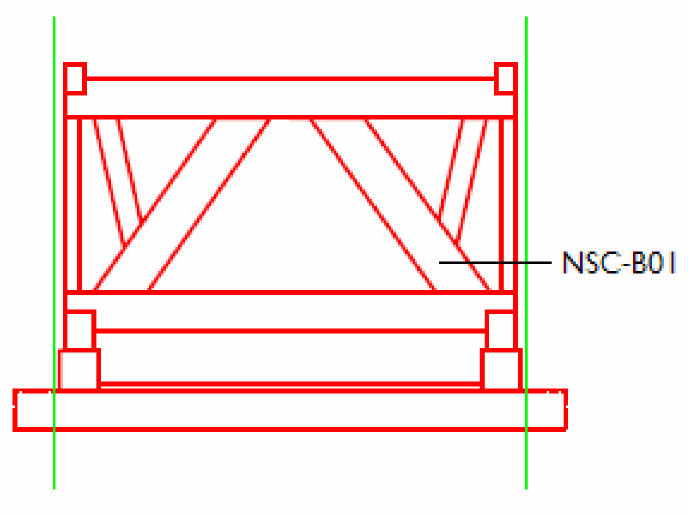

Figure 7: Truss 1, showing the location of sample NSC-B01 (Graham Pledger)

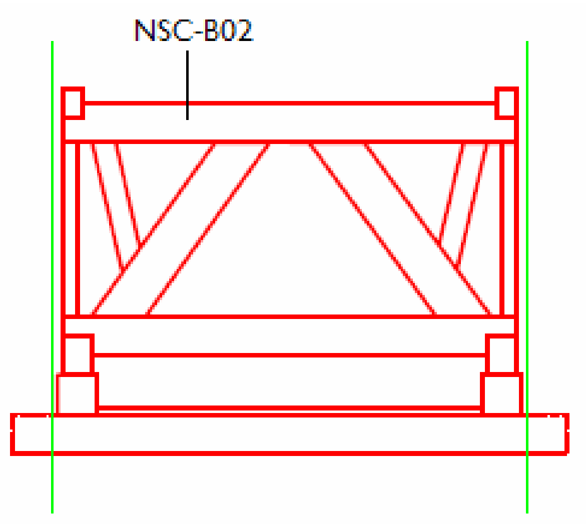

Figure 8: Truss 2, showing the location of sample NSC-B02 (Graham Pledger)

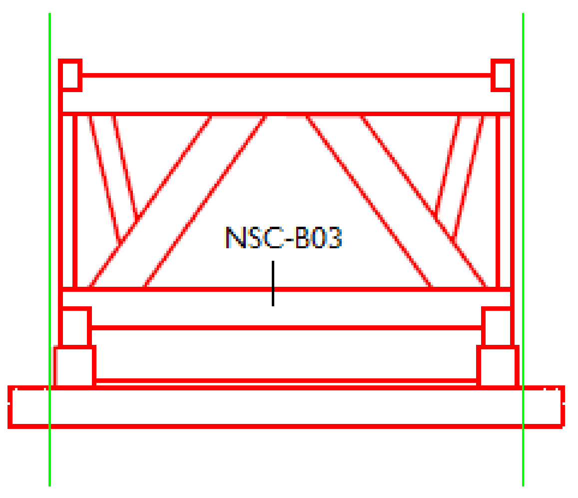

Figure 9: Truss 3, showing the location of sample NSC-B03 (Graham Pledger)

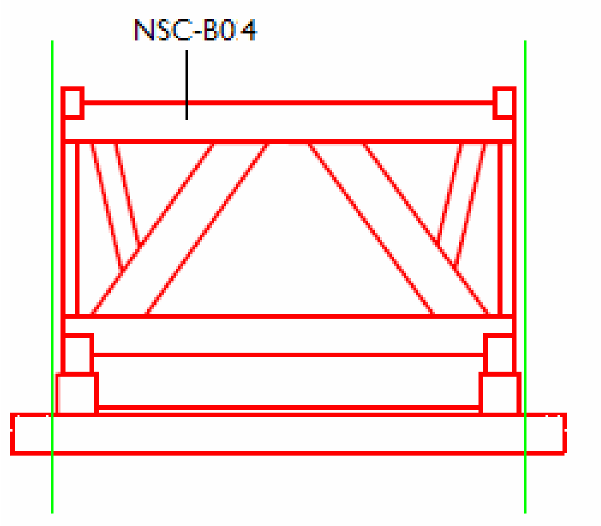

Figure 10: Truss 4, showing the location of sample NSC-B04 (Graham Pledger)

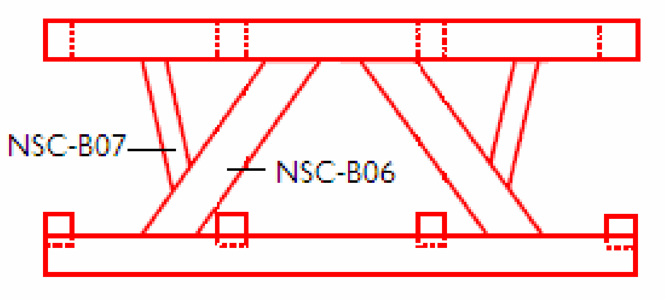

Figure 11: East return, showing the location of samples NSC-B06 and NSC-B07

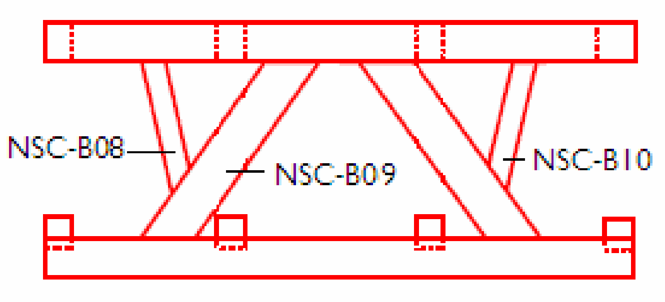

Figure 12: West return, showing the location of samples NSC-B08–10

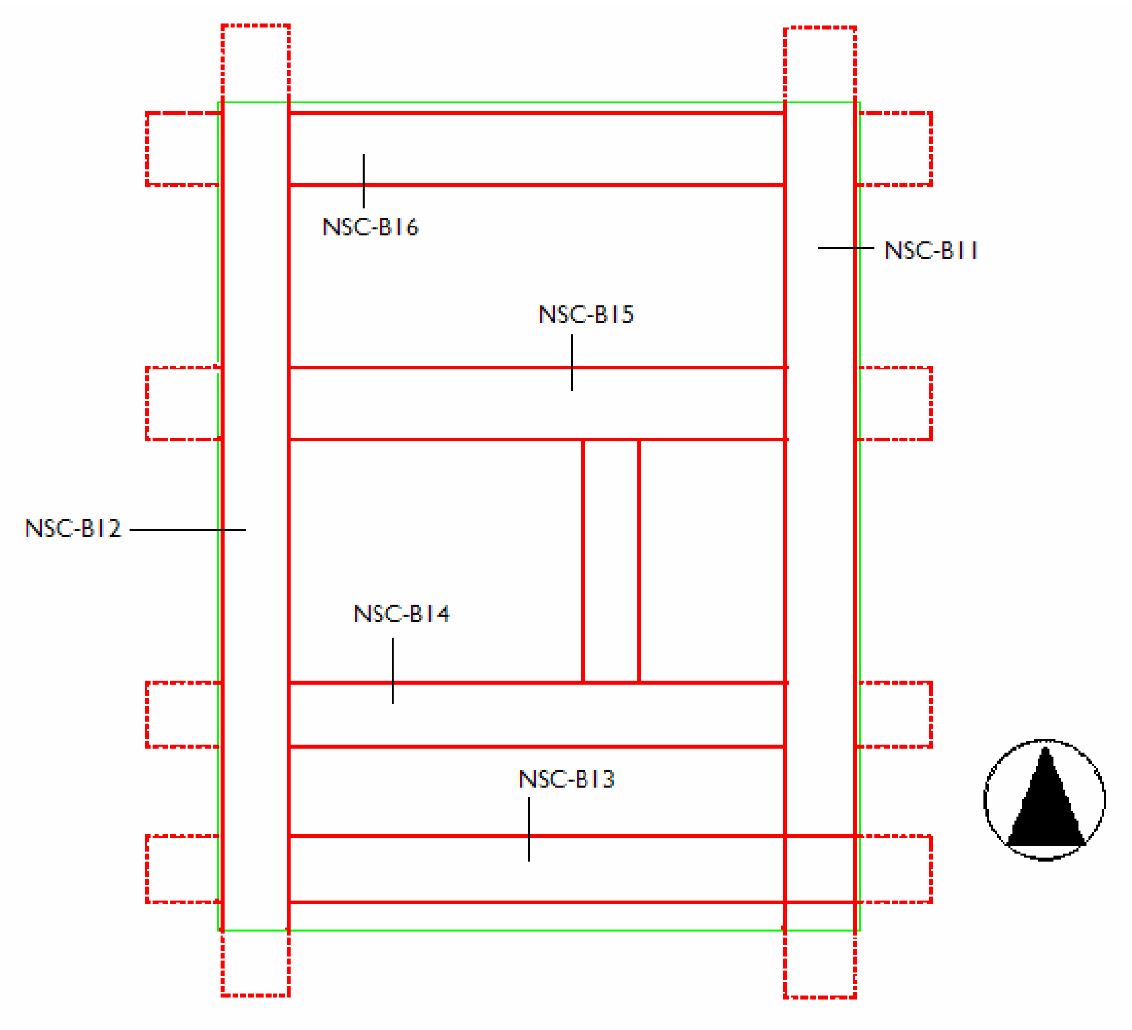

Figure 13: Plan of belfry beams, showing the location of samples NSC-B11–16 (after Graham Pledger)

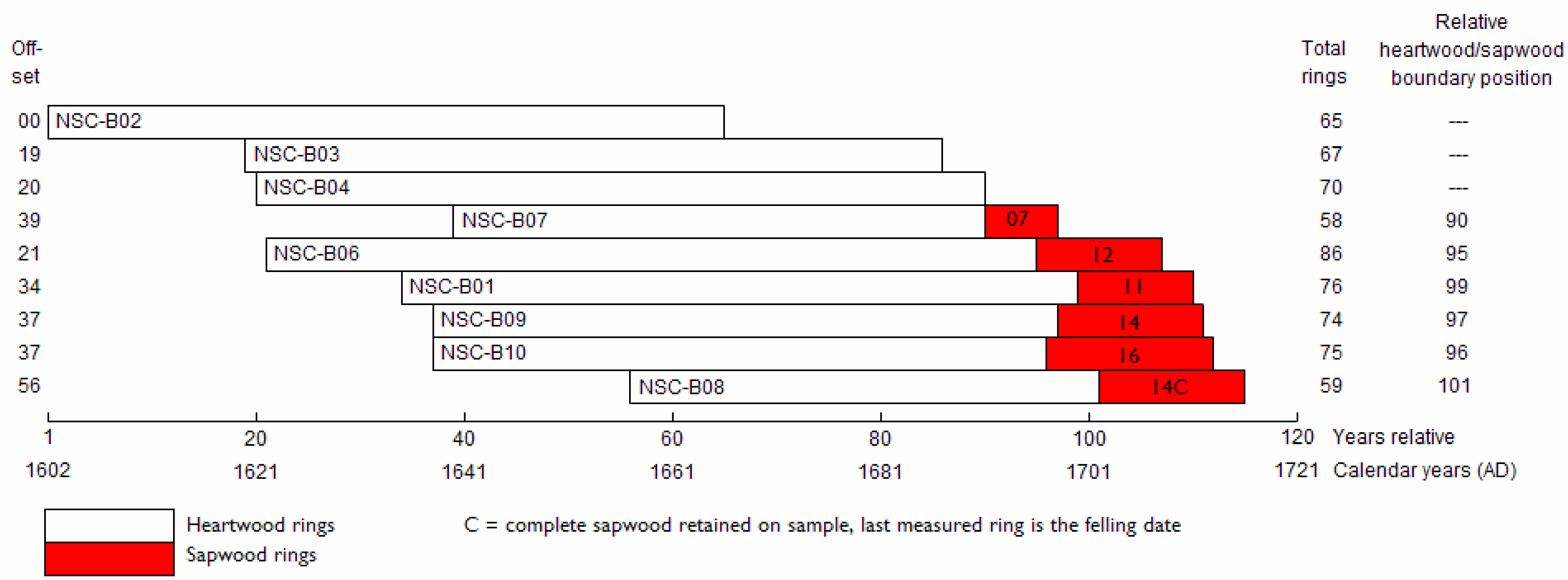

Figure 14: Bar diagram of samples in site sequence NSCBSQ01

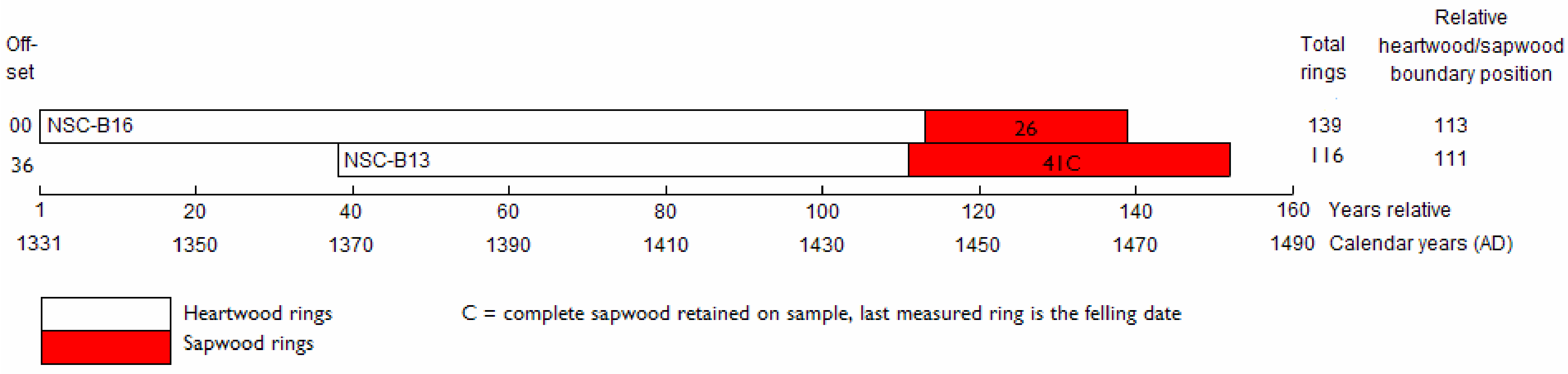

Figure 15: Bar diagram of samples in site sequence NSCBSQ02

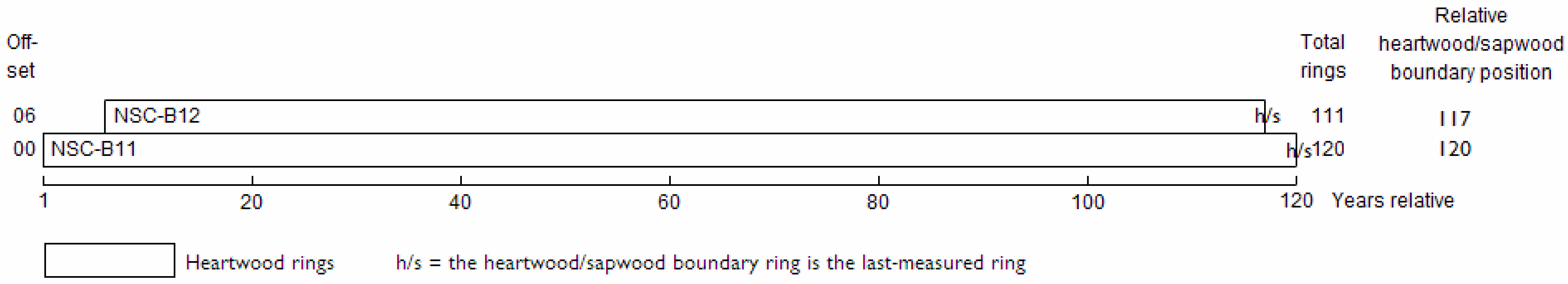

Figure 16: Bar diagram of samples in site sequence NSCBSQ03

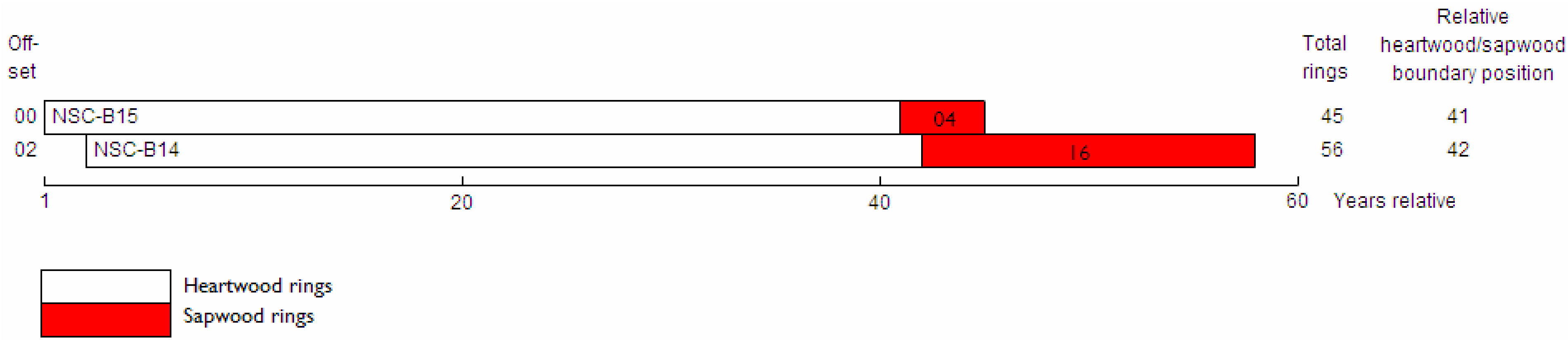

Figure 17: Bar diagram of samples in site sequence NSCBSQ04

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

NSC-B01A 76
587 353 512 524 393 412 170 234 270 317 369 165 232 109 125 241 261 335 481 566
485 374 278 388 234 181 204 210 240 185 172 171 201 240 339 296 267 223 180 142
148 225 192 240 194 202 285 232 225 175 272 299 142 105 129 153 212 198 146 144
94 99 92 110 148 175 176 135 188 187 194 201 193 151 197 236
NSC-B01B 76
561 339 520 521 401 406 169 227 260 310 367 161 237 102 121 243 259 337 480 562
490 371 249 390 232 183 204 213 240 168 167 197 210 257 324 298 261 231 177 145
163 223 200 252 190 207 291 244 217 171 262 291 133 94 137 175 219 196 156 140
95 97 96 104 148 161 188 132 183 187 194 196 197 146 199 244
NSC-B02A 65
628 903 773 385 729 880 569 385 284 312 513 561 388 316 474 582 601 559 462 451
635 625 497 407 436 419 440 453 357 313 375 310 201 276 341 242 427 484 352 376
223 238 270 305 352 251 358 222 144 165 138 161 236 304 308 291 399 363 284 157
176 210 210 184 152
NSC-B02B 65
626 942 767 391 734 935 574 382 274 314 509 577 407 319 476 581 604 563 488 456
622 628 493 380 419 416 429 454 349 292 371 308 203 274 325 237 426 486 351 341
200 242 269 302 352 254 339 235 146 157 138 164 237 312 316 293 404 363 275 160
169 216 213 192 159
NSC-B03A 67
678 453 371 339 276 451 617 396 485 311 326 350 456 231 400 668 411 600 589 439
450 297 340 340 404 448 236 306 138 168 296 290 431 567 579 561 369 217 361 211
207 295 179 237 201 189 210 290 254 353 264 265 215 203 174 211 260 187 288 248
222 261 248 200 204 262 215
NSC-B03B 67
682 468 376 325 276 475 612 392 489 303 331 352 456 235 396 675 425 603 594 441
448 293 338 347 402 452 235 303 146 175 298 267 428 573 579 548 369 222 356 213
214 288 183 243 208 193 207 291 257 344 263 269 219 198 175 208 261 188 284 250
211 270 251 206 202 268 223
NSC-B04A 70
132 119 92 71 152 199 247 248 159 151 231 376 121 205 320 302 420 425 256 343
141 236 223 346 331 182 277 138 195 220 228 416 536 617 523 437 311 362 261 267
196 158 94 105 106 157 246 220 331 343 308 292 230 178 233 293 152 233 241 219
343 348 229 177 268 278 166 151 169 200
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102 114 95 70 134 194 233 266 161 117 258 368 129 187 331 294 417 412 262 336
132 239 217 360 323 184 267 137 195 220 229 417 517 617 516 439 312 362 262 271
202 149 94 114 110 152 251 221 329 338 308 291 226 181 236 287 155 231 240 222
341 342 225 175 269 284 167 148 171 204
NSC-B06A 86
467 357 269 362 614 614 574 320 199 308 411 232 247 364 295 427 412 333 496 355
330 409 453 602 325 352 254 234 248 253 265 203 282 289 264 266 317 258 246 305
322 262 344 284 205 266 290 316 382 264 294 180 178 164 427 262 258 297 170 339
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219 142 76 108 171 159

NSC-B06B 86
461 359 281 356 606 590 549 335 189 311 427 244 231 352 293 428 408 330 493 364
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317 246 328 277 198 269 286 317 401 265 282 222 171 165 425 260 269 302 161 332
247 231 209 240 248 222 200 142 161 203 233 142 175 246 231 256 192 177 175 155
214 140 75 141 131 156
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391 236 294 391 519 526 319 466 276 228 258 219 221 285 295 327 293 395 418 370
177 189 242 209 239 214 243 270 274 236 271 239 201 227 197 171 288 446 326 268
204 356 252 292 185 256 200 176 162 150 193 218 198 134 148 140 189 212
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370 231 280 389 515 536 311 457 279 233 260 222 217 280 308 325 285 406 431 369
177 192 235 193 242 217 245 262 284 238 303 241 199 224 195 174 293 444 316 267
194 357 255 290 175 241 207 172 164 162 186 221 201 142 151 141 195 202
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295 470 243 203 251 217 123 99 113 182 198 229 349 301 297 214 232 186 146 257
174 243 230 273 417 326 269 214 256 256 229 163 218 262 238 343 198 210 173 169
171 194 236 277 275 356 425 286 387 316 307 263 227 279 273 158 233 324 291
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173 198 233 272 280 360 422 289 385 309 288 268 239 269 273 173 218 303 229
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285 315 153 282 309 243 264 314 301 281 224 164 186 264 331 191 176 271 250 218
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NSC-B10B 75
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236 210 242 350 297 257 216 288 234 175 175 191 238 218 253 179 173 157 237 198
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NSC-B11A 120
304 247 415 266 263 275 326 282 213 136 101 100 109 126 92 198 240 205 247 163
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NSC-B11B 120
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NSC-B12B 111
330 529 543 250 163 150 152 173 134 231 317 346 356 212 204 283 207 201 235 289
214 143 141 197 160 220 195 198 213 153 169 193 228 199 193 166 129 177 178 132
99 70 69 71 45 62 49 50 58 55 95 95 86 110 89 90 74 49 75 106
119 153 93 116 193 161 149 124 140 169 174 103 89 87 105 102 105 119 113 118
143 134 97 110 147 151 119 118 144 137 149 127 165 187 172 133 136 138 118 103
97 106 156 136 104 122 116 126 102 117 114
NSC-B13A 112
134 90 75 101 119 94 93 85 72 65 55 71 82 78 37 71 70 71 72 61
56 48 73 61 37 59 43 32 40 64 71 75 51 60 56 39 67 55 55 56
48 53 47 45 51 67 56 53 61 66 67 67 64 82 74 55 52 75 59 89
55 68 86 70 65 61 58 68 55 96 87 73 60 98 59 86 53 77 72 58
55 83 74 72 42 64 101 68 91 81 111 85 57 67 72 109 94 81 63 78
93 73 77 76 83 117 73 108 74 98 103 80
NSC-B13B 116
100 150 183 157 101 76 107 133 128 108 90 117 72 71 77 103 80 59 95 71
79 78 70 57 45 77 62 44 47 50 31 38 67 68 71 41 61 56 46 66
55 57 51 52 56 59 53 61 69 61 56 59 62 76 67 87 95 80 56 49
79 64 108 57 93 93 78 69 69 70 56 60 101 92 67 59 105 67 75 63
71 63 60 46 90 63 73 35 69 102 77 92 83 115 91 64 71 73 97 79
76 51 78 101 80 67 78 72 101 66 81 69 94 70 82 93
NSC-B14A 56
351 289 352 321 451 316 391 430 352 387 320 172 89 129 149 171 165 196 240 179
223 385 367 395 368 371 352 291 225 271 374 430 233 283 469 388 355 267 340 140
108 102 133 124 102 140 139 186 180 202 216 166 140 146 76 141
NSC-B14B 56
340 302 339 311 422 313 384 446 314 417 325 172 88 134 153 173 167 187 238 171
221 392 378 397 362 362 360 300 227 270 372 442 209 285 459 378 357 276 354 149
104 109 137 112 116 143 141 173 182 197 224 177 119 156 88 135
NSC-B15A 45
637 683 756 706 576 507 521 499 516 589 436 617 607 365 218 246 215 225 328 254
270 175 236 369 307 280 272 346 369 241 238 285 349 238 184 326 441 436 302 310
316 136 70 85 106
NSC-B15B 45
649 700 754 703 580 510 535 491 513 587 435 628 600 362 217 263 209 246 330 259
261 175 230 381 307 274 272 346 371 239 231 286 348 238 185 325 447 428 306 313
321 137 76 79 109

NSC-B16A 139
214 277 195 172 195 140 151 148 150 144 138 193 131 108 112 128 135 171 144 143
144 94 91 101 40 41 71 40 54 63 66 88 103 81 67 77 87 114 115 109
71 59 56 96 86 87 104 95 112 78 86 99 71 56 70 71 77 87 61 70
61 78 71 60 59 74 49 57 75 95 74 58 75 52 52 61 51 56 68 54
69 61 66 52 54 44 42 69 71 61 64 63 79 67 56 52 82 88 87 68
83 121 96 83 87 88 105 87 112 88 107 68 134 89 79 71 92 87 80 61
97 93 91 60 81 100 102 102 102 124 118 92 90 100 116 103 85 67 92
NSC-B16B 139
217 280 202 173 200 137 156 152 147 146 148 188 136 115 122 133 143 176 133 131
152 94 90 99 42 51 57 41 66 51 68 82 106 80 64 85 85 109 120 104
67 59 54 98 88 91 100 95 110 76 83 99 69 52 78 65 85 80 73 65
65 73 75 68 53 68 56 53 80 98 79 55 75 59 53 60 56 55 65 57
61 65 69 52 52 44 42 66 72 57 67 65 75 74 54 54 79 89 90 66
81 111 94 77 90 89 109 85 104 83 111 66 130 87 81 79 83 85 80 65
94 89 93 56 93 90 102 102 114 116 107 105 73 102 104 99 89 73 95

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 A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

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

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

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

6. **Master Chronological Sequences.** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. **Ring-Width Indices.** Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

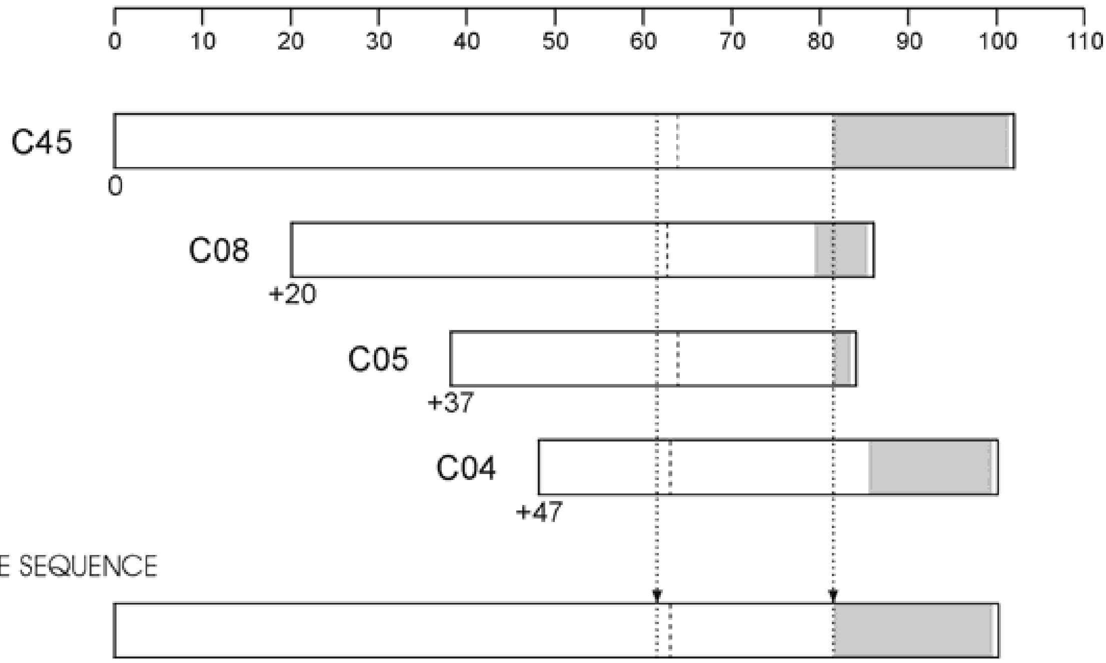


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width

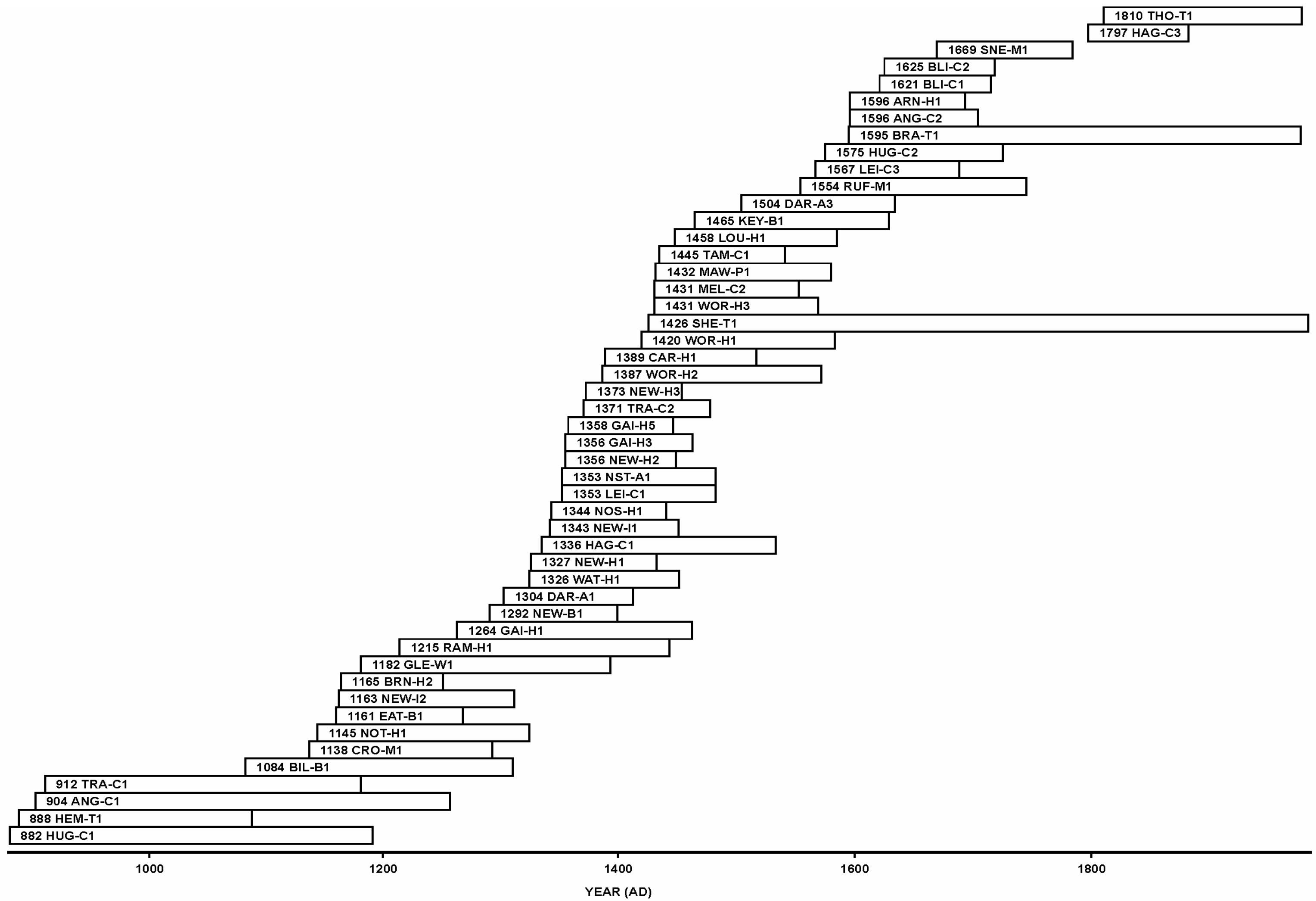
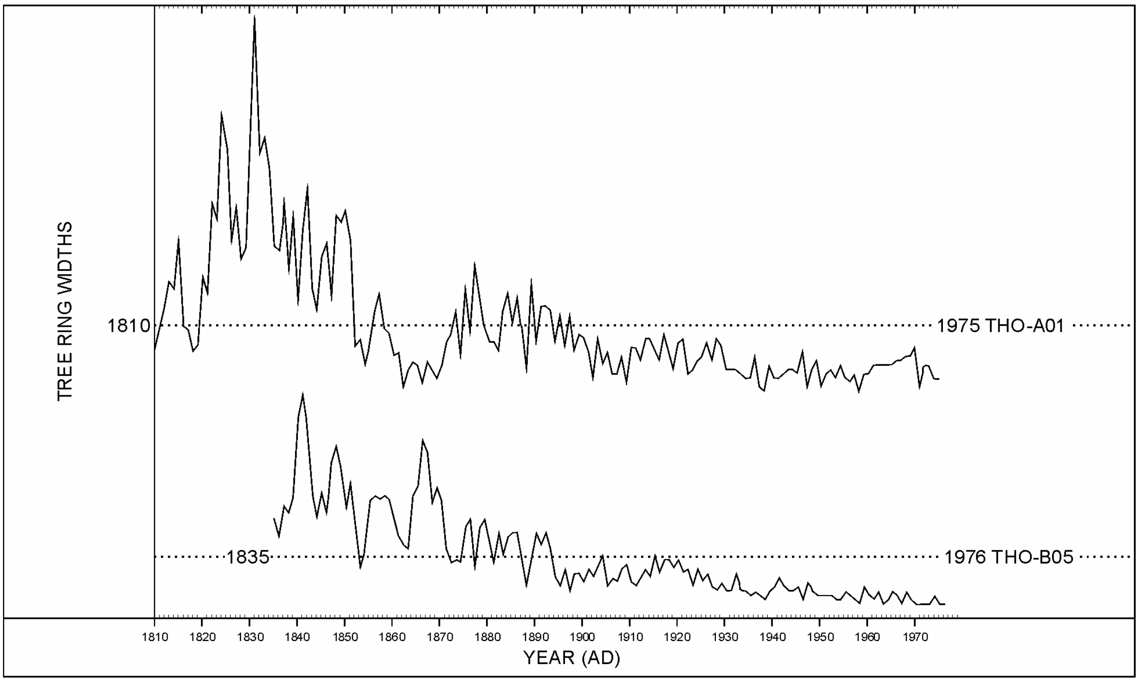


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

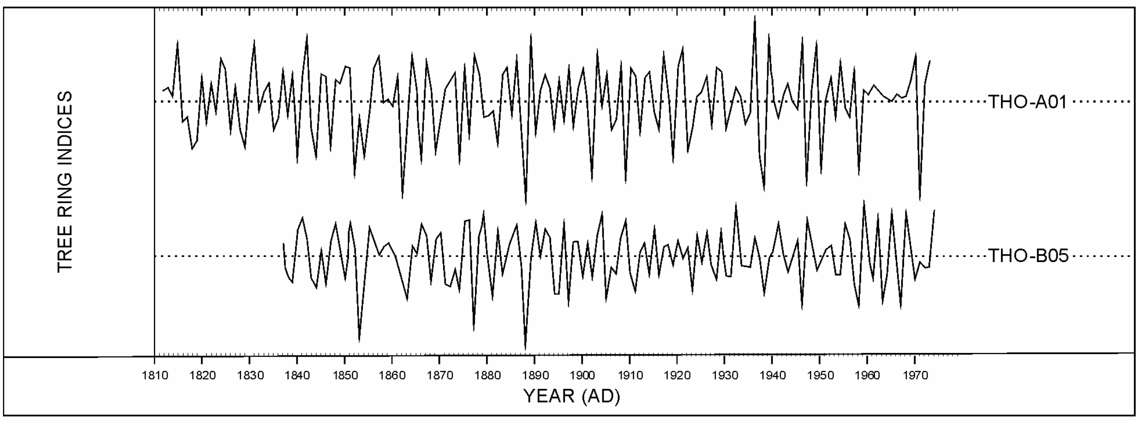


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

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

The growth trends have been removed completely

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