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Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

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NGR: SK 57044 39910

ISSN 2059-4453 (Online)

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SUMMARY
Samples taken from the roof and floor frames within the main range of this building resulted in the successful dating of 16 timbers. Roof timbers and main floor beams from this range have been dated to a felling of AD 1747, and are thought likely to be primary to the original construction of the building in the early AD 1750s. In addition, two common floor joists have been individually dated with *terminus post quem* dates for felling of AD 1549 and AD 1652, and are thought likely to represent the timbers reused in their current locations.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank Melanie Duffill-Jeffs, Library Director, for facilitating access and the contractors, Ackroyds, for their assistance during assessment and sampling. We would also like to thank Peter Rogan at Peter Rogan & Associates Limited for permission to reproduce drawings used in this report. Amanda White, Historic England Heritage at Risk Surveyor requested the work and Shahina Farid (Historic England Scientific Dating Team) commissioned and facilitated this programme of dendrochronological analysis.

ARCHIVE LOCATION
Nottingham City Historic Environment Record
Brewhouse Yard Museum
Castle Boulevard
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DATE OF INVESTIGATION
2019

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INTRODUCTION

This Grade II* (List Entry Number: 1246247) former Georgian town house and banking hall is currently on the Heritage at Risk register. It is located on Angel Row in Nottingham (Fig 1), and was built in AD 1752 for George Smith, banker and grandson of the founder of Smith's Bank. It was converted to a subscription library in the early AD 1820s with shopfronts inserted in *c* AD 1929 with further alterations being undertaken in the late-twentieth century. The building is of three storeys plus attics and cellars, and is of L-plan with a rear wing (the garden wing), to the south-west. The roof over the main block is of double-pile construction with four trusses to each side. Each truss consisted of principal rafters, tiebeam, and king post (Fig 2), although some of these elements are now missing.

The history of the site pre-AD 1752 is very vague. There were certainly earlier buildings on the site and it is possible that parts of the garden wing pre-date the main block. There is also a cellar under the garden, which must have had a building over it at one stage.

SAMPLING

Dendrochronological analysis was requested by Amanda White, Historic England Heritage at Risk Surveyor, to provide independent dating evidence to inform the programme of repairs being undertaken.

Twenty-two oak (*Quercus* spp) timbers associated with the roof and floor structure in the main range were sampled by the removal of cores. Each sample was given the code NOT-L and numbered 01–22. Further details relating to the samples can be found in Table 1. The location of sampled timbers has been indicated on Figures 3–5. Trusses and main beams (north side) were numbered from east to west and main beams (south side) from north to south.

The roof of the garden wing was also assessed for its suitability for tree-ring dating but this was found to be a mixture of metal trusses and relatively modern softwood common rafters and purlins, and was, therefore, rejected prior to sampling.

ANALYSIS AND RESULTS

Two of the roof samples had less that 45 rings and so were deemed to have too few rings for secure dating. These were therefore rejected prior to measurement. The remaining 20 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. The data of these samples were compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 14 samples matching each other at a minimum *t*-value of 4.3.

These 14 samples were combined at the relative offset positions to form NOTLSQ01, a site sequence of 96 rings (Fig 6). This site sequence was compared against an extensive series of reference chronologies for oak and cross-matched consistently and securely at a first-measured ring date of AD 1652 and a last-measured ring date of AD 1747 (Table 2).

The remaining ungrouped samples were also compared to the reference chronologies. This resulted in NOT-L13 being found to span the period AD 1537–1637 and NOT-L21 to the period AD 1441–1534 (Tables 3 and 4). The remaining samples could not be consistently and securely matched, and hence remain undated.

INTERPRETATION

Analysis has resulted in the successful dating of 16 samples, ten from the roof timbers and six from the floor frames (Fig 7). Felling date ranges, where quoted, have been calculated using the estimate that 95% of mature oak trees from the area have between 15 and 40 sapwood rings.

Roof

Samples from ten of the roof timbers have been dated, all of which have the heartwood/sapwood boundary. The heartwood/sapwood boundary dates range from AD 1722 (NOT-L04) to AD 1733 (NOT-L01 and NOT-L08). These are clearly broadly contemporary, varying by only 11-years, and are suggestive of a single programme of felling. The average heartwood/sapwood boundary ring date is AD 1729, allowing an estimated felling date to be calculated for the timbers represented to within the range AD 1747–69. This allows for sample NOT-L01 having a last-measured ring date of AD 1746 with incomplete sapwood.

Floor frames

Six of the samples taken from the floor frame have been dated. Two of these, NOT-L10 and NOT-L20 have complete sapwood and the last-measured ring date of AD 1747, the felling date of the timbers represented. Two further samples have similar heartwood/sapwood boundary ring dates suggestive of a single felling event. The average heartwood/sapwood boundary ring date for these two samples is AD 1731, allowing an estimated felling date to be calculated for the two timbers represented to within the range AD 1746–71, consistent with these timbers also being felled in, or around, AD 1747.

The other two dated samples do not have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be calculated for them, except to say that with last-measured ring dates of AD 1534 (NOT-L21) and AD 1637 (NOT-L13) these would be estimated to be after AD 1549 and AD 1652, respectively.

DISCUSSION

The dendrochronology has dated a number of the timbers of the roof and floor of the main range of this building to a felling date of in, or around, AD 1747. With documentary sources placing construction of the building in AD 1752, this dating demonstrates that not only are these elements coeval but that they represent the primary construction. The intra-site matching between roof and floor samples represented within site sequence NOTLSQ01 is generally good, with the majority of the samples matching at a minimum value of $t = 6.5$. This is of a level one would expect between a coherent group of trees felled at the same time, although in this instance no possible same-tree derivations for timbers were indicated.

Two of the common floor joists, NOT-L13 and NOT-L21, have *terminus post quem* dates for felling somewhat earlier (AD 1652 and AD 1549 respectively) than the rest of the dated timbers. It is a possibility that these two timbers represent the inner portions of heavily trimmed trees and they were actually felled at the same time as the rest of the timber. However, this would suggest that the trees from which they were cut were extremely long-lived (more than 300 years old in the case of NOT-L21). It is perhaps more likely they represent the use of reused material from the sixteenth and seventeenth century within the floor frame. During sampling it was noted that the common joists varied in size and appearance, and that some looked more historic than others. It was also seen that different jointing into the main beams was utilised, which might demonstrate repairs and/or replacement. Whether these timbers are reused from earlier structures on the site or from an unrelated building (or buildings) is unknown.

The lack of conclusive dating for four of the beams from the floor frame does not necessarily indicate that they represent yet another phase, or phases, of felling. The ring series derived from NOT-L14 is rather short for dating individually against reference chronologies but the other three series are of sufficient length and don't show any clear growth anomalies. It is, however, a common feature in tree-ring analysis to find that some samples remain undated for no apparent reason. In this respect, the analysis at Bromley House has been successful in dating 16 out of the 20 samples considered suitable for reliable dating purposes, thus achieving the broadly expected success rate of 70–80% for timbers from historic standing buildings.

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TABLES

Table 1: Details of tree-ring samples taken from Bromley House Library, 13, 14, & 15 Angel Row, The Park, Nottingham

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
NOT-L01	North side, north principal rafter, truss 1	55	13	1692	1733	1746
NOT-L02	North side, north principal rafter, truss 3	50	10	1691	1730	1740
NOT-L03	North side, south principal rafter, truss 3	68	07	1668	1728	1735
NOT-L04	North side, south principal rafter, truss 4	75	22	1670	1722	1744
NOT-L05	North side, king post, truss 4	50	05	1688	1732	1737
N0T-L06	North side, north principal rafter, truss 4	61	09	1678	1729	1738
NOT-L07	North side, south purlin, truss 2-3	65	h/s	1668	1732	1732
NOT-L08	North side, south purlin, truss 4-west wall	57	04	1681	1733	1737
NOT-L15	South side, south principal rafter, truss 4	67	06	1667	1727	1733
NOT-L16	South side, tiebeam, truss 4	66	06	1669	1728	1734
NOT-L17	South side, king post, truss 4	NM	--	----	----	----
NOT-L18	South side, south purlin, truss 3-4	NM	--	----	----	----
Floor frame						
NOT-L09	North side, north-south main floor beam 1	72	h/s	1656	1727	1727
NOT-L10	North side, north-south main floor beam 2	84	16C	1664	1731	1747
NOT-L11	North side, joist 2E off beam 1	75	--	----	----	----
NOT-L12	North side, joist 2W off beam 2	100	--	----	----	----
NOT-L13	North side, joist 4E off beam 2	101	--	1537	----	1637
NOT-L14	North side, joist 5W off beam 2	48	22C	----	----	----
NOT-L19	South side, east-west main floor beam 1	54	h/s	1682	1735	1735
NOT-L20	South side, east-west main floor beam 2	96	32C	1652	1715	1747
NOT-L21	South side, joist 7N off beam 2	94	--	1441	----	1534
NOT-L22	South side, joist 8N off beam 2	98	--	----	----	----

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

Table 2: Results of the cross-matching of site sequence NOTLSQ01 and example reference chronologies when the first-ring date is AD 1652 and a last-measured ring date of AD 1747

Reference chronology	*t* – value	Span of chronology (AD)	Reference
Green's Mill, Sneinton, Nottinghamshire	8.5	1664–1787	Laxton *et al* 1982
Bingham, Nottinghamshire	7.8	1445–1752	Arnold and Howard 2013a
Ragnall House (barn), Ragnall, Nottinghamshire	7.1	1607–1717	Howard *et al* 1997
Middleton Hall, Middleton, Warwickshire	6.9	1636–1713	Arnold *et al* 2006
Church of St Peter, Barton upon Humber, Lincolnshire	6.6	1680–1759	Tyers 2001
Coombe Warren, Coventry, Warwickshire	6.4	1666–1761	Arnold and Howard 2015 unpubl
Old Abbey Farm, Risley, Cheshire	6.0	1667–1753	Nayling 1998
Fairfield House, Stogursey, Somerset	6.0	1682–1778	Arnold and Howard 2013b
St Firmin Church, Thurlby, Lincolnshire	5.9	1599–1792	Arnold and Howard 2010
Somerton Castle, Lincolnshire	5.7	1650–1760	Arnold and Howard 2016

Table 3: Results of sample NOT-L13 and example reference chronologies when the first-ring date of AD 1537 and the last-measured ring date of AD 1637

Reference chronology	*t* – value	Span of chronology (AD)	Reference
Black Ladies, Brewood, Staffordshire	6.1	1372–1671	Tyers 1999
Langford Manor, Nottinghamshire	6.0	1467–1632	Esling *et al* 1989
Alcester Town Hall, Alcester, Warwickshire	5.9	1374–1625	Arnold and Howard 2014
Ravens Farm, Misterton, Nottinghamshire	5.8	1482–1634	Arnold *et al* 2002
Ash House Farm, Myrtle Road, Sheffield, South Yorkshire	5.8	1390–1663	Tyers 2004
Flore's House, Oakham, Rutland	5.7	1408–1591	Hurford *et al* 2008
Aston Hall, Birmingham, West Midlands	5.6	1457–1624	Howard 2005
Bentley Hall, Hungry Bentley, Derbyshire	5.6	1444–1675	Arnold and Howard 2009
Sherwood Trees, Nottinghamshire	5.5	1426–1981	Laxton and Litton 1988
Weston Hall, Weston upon Trent, Nottinghamshire	5.5	1480–1628	Arnold *et al* 2020

Table 4: Results of sample NOT-L21 and example reference chronologies when the first-ring date of AD 1441 and the last-measured ring date of AD 1534

Reference chronology	*t* – value	Span of chronology (AD)	Reference
Langhold by Holme, Nottinghamshire	9.1	1451–1608	Howard *et al* 1995
Church of St Swithins, Kirklington, Nottinghamshire	8.1	1404–1669	Arnold *et al* 2016
Church of St Nicholas, Askham, Nottinghamshire	7.1	1407–1588	Arnold *et al* 2016
Old Hall Farmhouse, Mayfield, Staffordshire	6.8	1437–1622	Arnold and Howard 2006
Low Farmhouse, Maplebeck, Nottinghamshire	6.7	1429–1570	Arnold *et al* 2008
Hardwick Old Hall, Doe Lane, nr Chesterfield, Derbyshire	6.5	1375–1590	Howard *et al* 2002
Manor House, Kneesall, Nottinghamshire	6.4	1411–1510	Howard *et al* 1988
Mansfield Woodhouse Priory, Nottinghamshire	6.3	1432–1579	Howard *et al* 1987
Hempshill Hall, Nottinghamshire	6.1	1315–1500	Arnold and Howard 2007
Creswell Mill, Derbyshire	5.8	1405–1529	Hillam 1991 unpubl

FIGURES

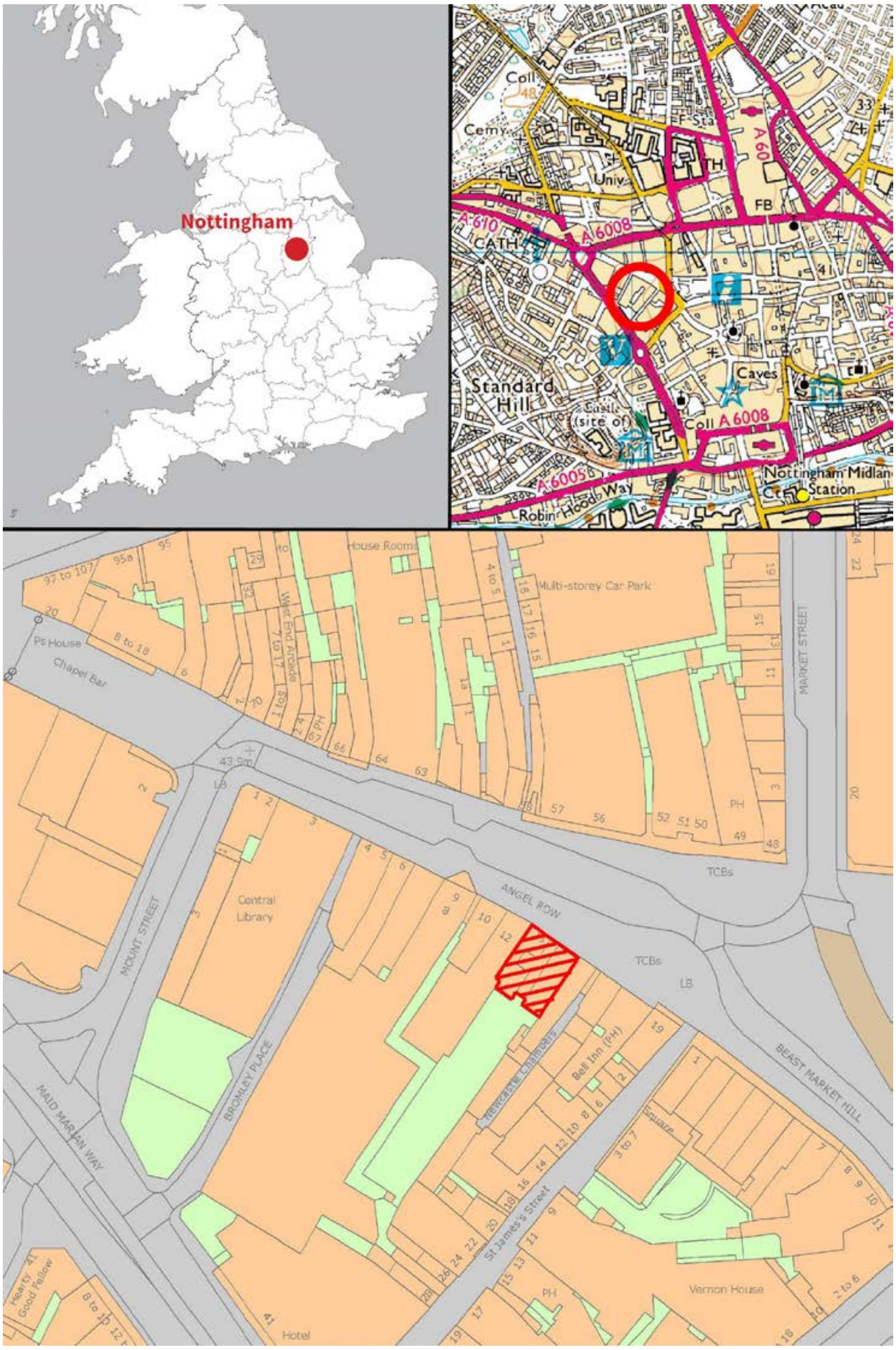

Figure 1: Maps to show the location of Bromley House Library in Nottingham, marked in red. Scale: top right 1:15000; bottom 1:1250. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

Figure 2: North side, truss 4, photograph taken from the south (Alison Arnold)

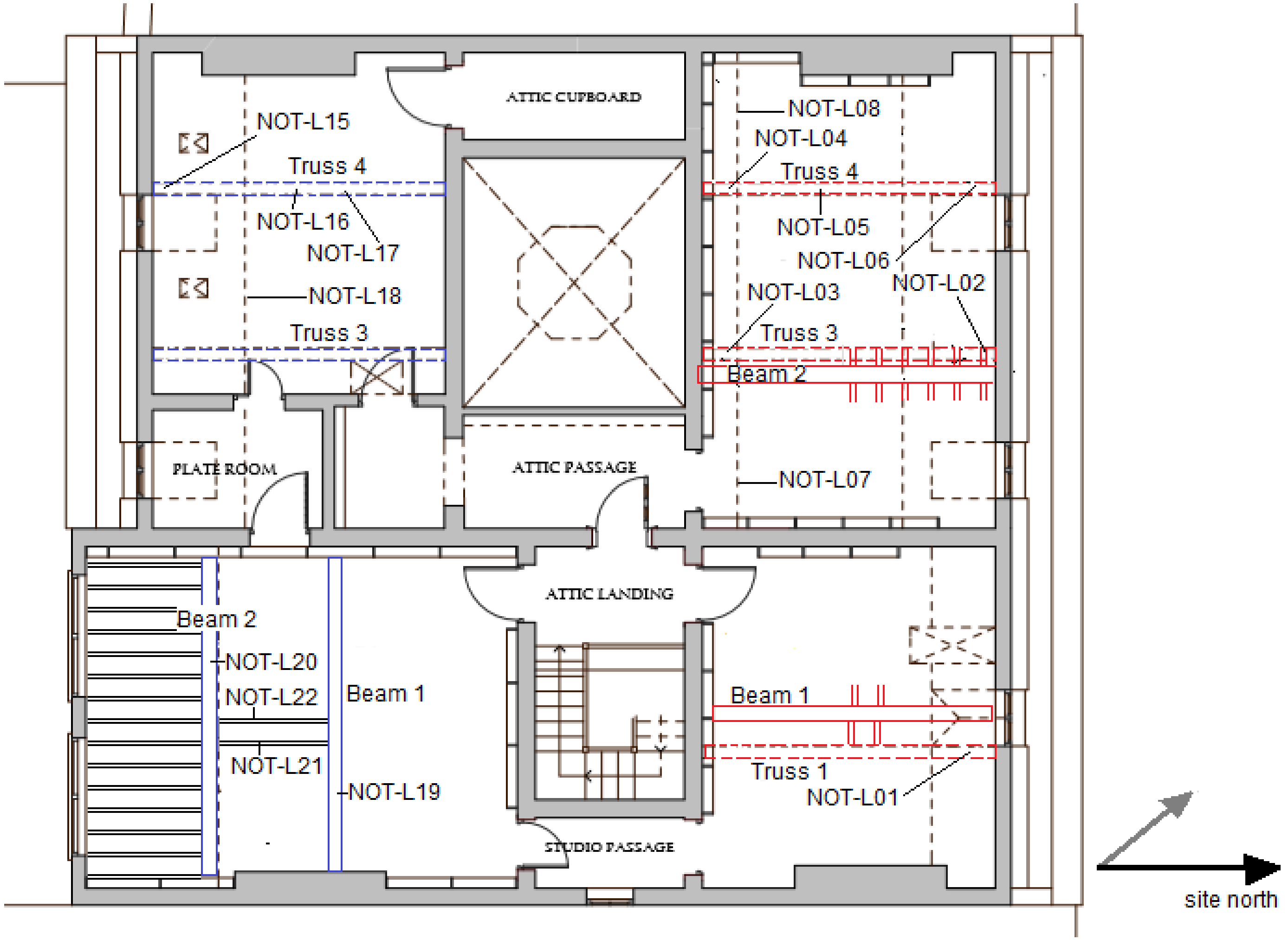

Figure 3: Plan at third-floor level, showing truss and beam positions and the location of samples NOT-L01-8, and NOT-L15-22 (after Peter Rogan & Associates Ltd 2012)

Figure 4: Photograph of some of the exposed floor frame on the north side, showing the location of samples NOT-L09 and NOT-L11, photograph taken from the north (Alison Arnold)

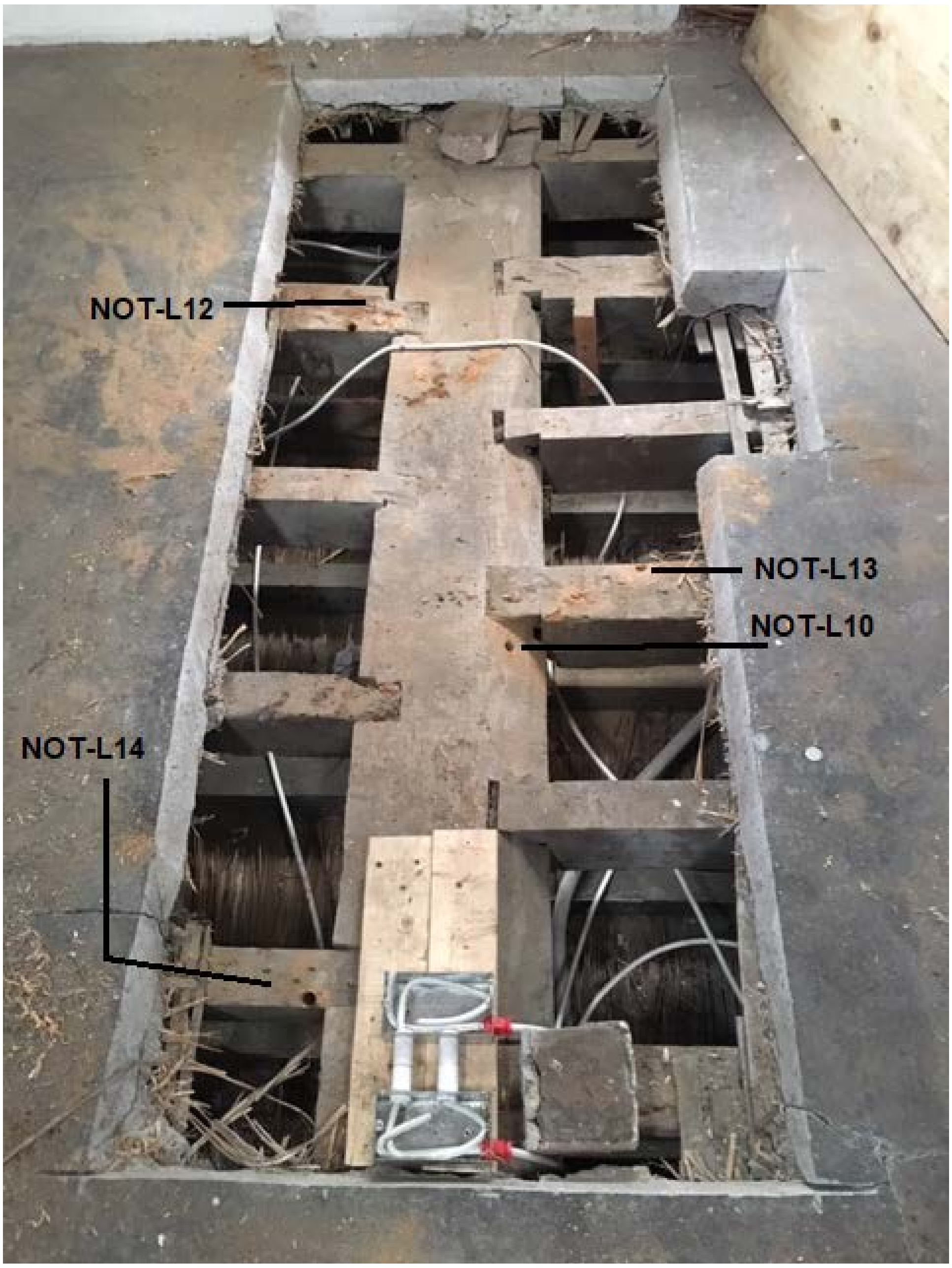

Figure 5: Photograph of some of the exposed floor frame on the north side, showing the location of samples NOT-L10, and NOT-L12-14, photograph taken from the south (Alison Arnold)

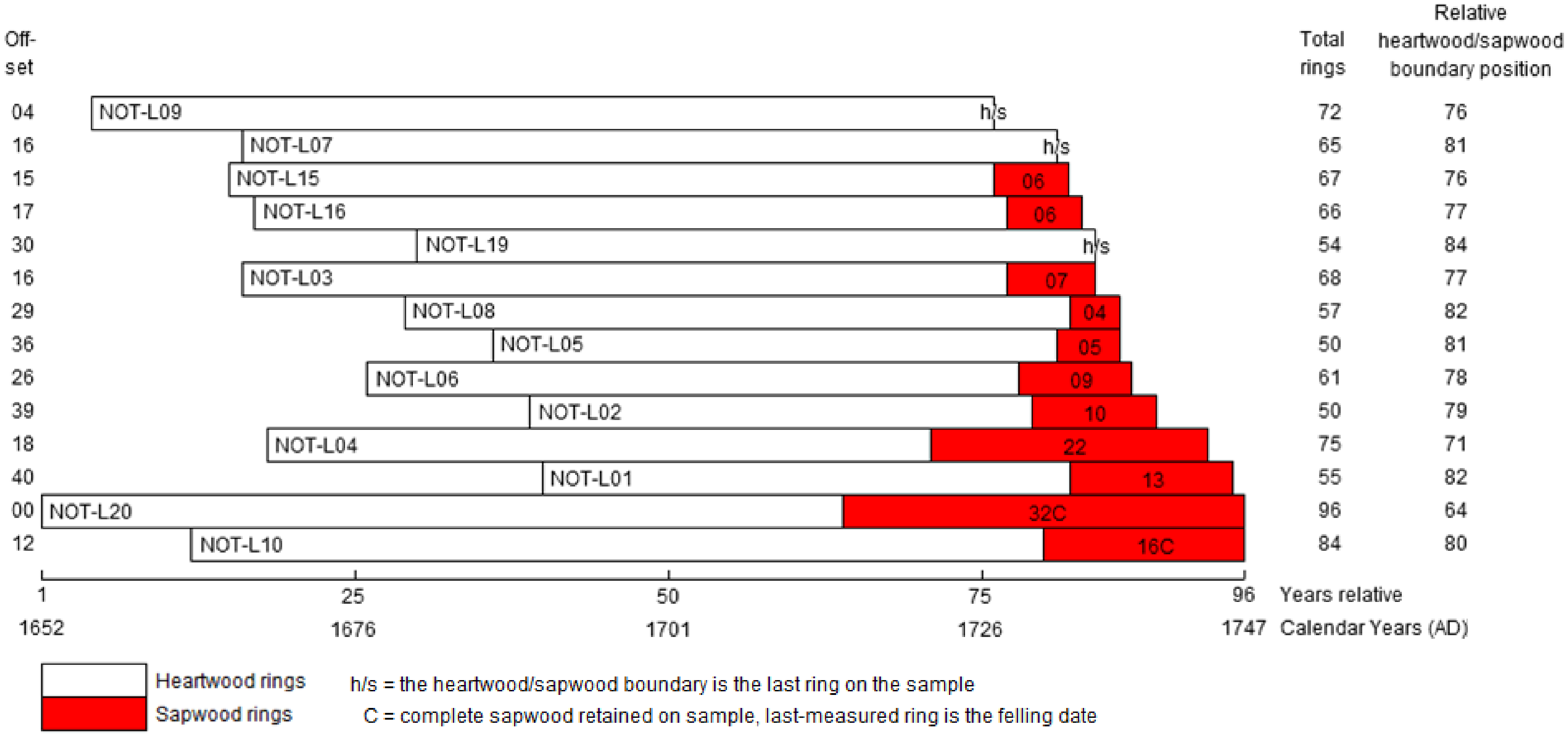

Figure 6: Bar diagram of showing the relative positions of samples in site sequence NOTLSQ01

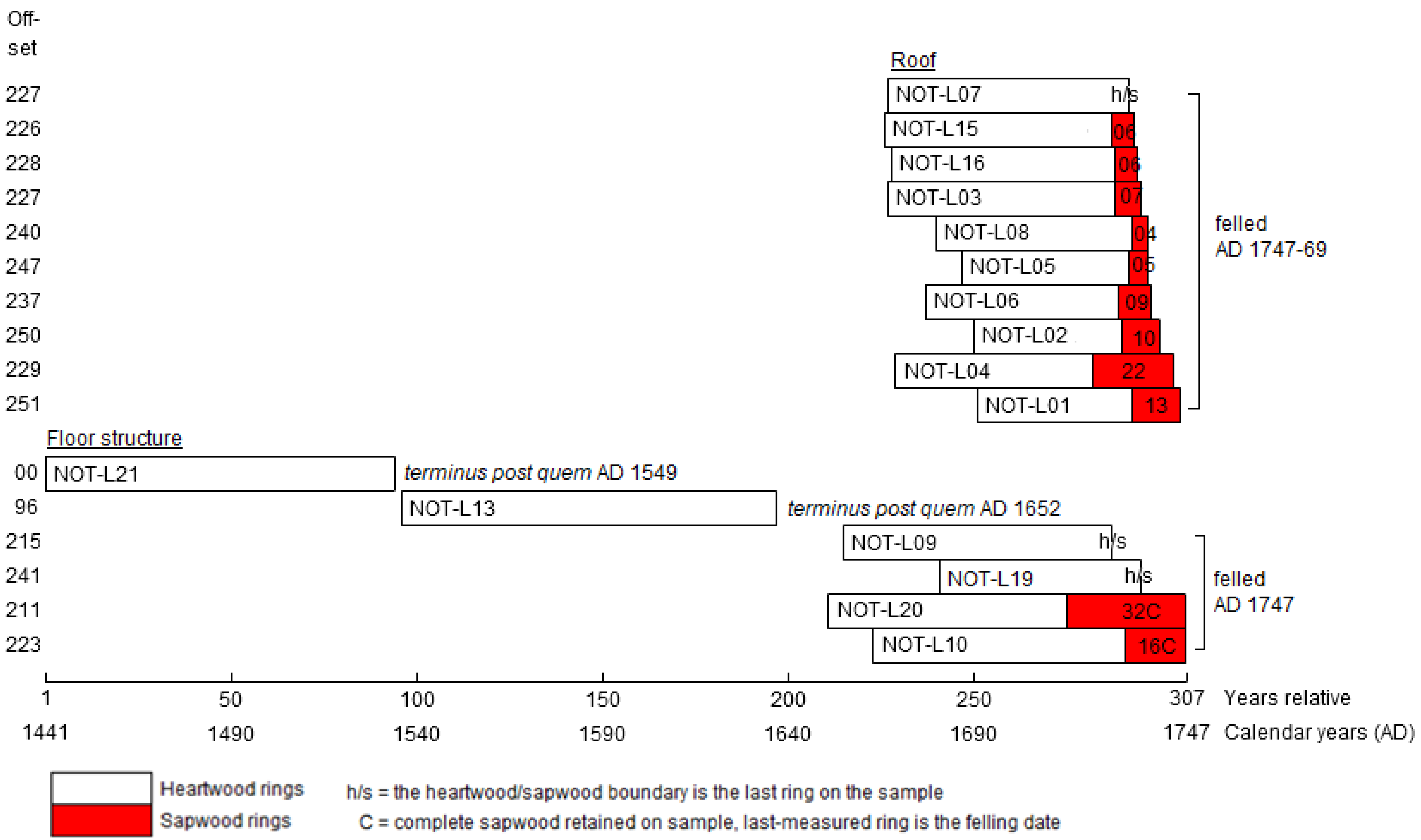

Figure 7: Bar diagram of all dated samples and felling date/ranges, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

NOT-L01A 55
44 92 100 100 143 144 258 258 272 245 277 298 330 309 314 294 349 277 197 240
356 388 434 387 334 254 198 283 303 289 296 289 346 182 257 306 258 332 290 303
256 212 165 241 240 206 254 238 181 173 110 162 151 175 116
NOT-L01B 55
31 85 92 100 138 134 255 245 267 234 276 285 328 315 308 305 339 274 247 236
339 399 422 389 312 241 194 276 292 270 304 287 344 173 267 298 251 316 284 297
252 212 162 238 248 185 263 231 181 182 116 160 157 188 121
NOT-L02A 50
361 230 414 394 328 392 344 330 329 367 377 415 431 504 387 526 441 377 298 192
222 231 296 257 371 199 178 189 266 260 295 284 163 239 163 243 330 382 305 240
192 261 271 269 250 200 200 293 317 221
NOT-L02B 50
363 220 405 390 331 398 339 332 333 375 350 435 463 499 361 536 437 368 296 189
212 233 284 259 380 193 164 198 281 289 289 290 165 239 157 243 316 367 310 257
181 255 279 270 264 200 194 272 318 254
NOT-L03A 68
227 228 223 288 241 269 224 168 240 269 281 341 338 238 291 169 126 69 115 160
142 117 88 81 94 111 138 139 107 157 134 115 89 115 107 127 157 95 141 166
130 126 54 72 81 70 83 74 67 52 73 119 129 144 128 99 107 89 159 127
163 161 152 169 175 124 135 106
NOT-L03B 68
229 223 225 294 237 288 205 169 242 267 289 350 318 244 280 159 123 89 109 157
147 147 100 81 96 110 148 147 109 167 133 115 86 108 103 128 165 100 130 168
139 129 55 72 98 70 72 73 70 54 63 110 125 145 129 101 109 95 160 128
160 160 149 173 175 122 136 102
NOT-L04A 75
231 319 316 246 120 94 123 201 157 250 363 300 361 229 148 123 143 270 266 301
282 250 129 218 215 183 185 199 178 148 144 154 130 194 183 117 142 147 148 158
72 125 88 125 177 194 174 117 128 226 178 166 222 214 181 123 149 243 242 255
219 216 206 175 140 179 189 147 179 234 127 98 121 105 169
NOT-L04B 75
236 336 326 248 121 79 138 186 150 254 388 316 362 243 135 116 140 250 258 282
250 248 127 221 220 189 183 203 180 148 150 147 127 201 178 110 135 156 155 151
90 113 96 120 186 198 173 123 121 226 183 158 221 206 186 124 145 242 237 253
216 228 199 176 140 179 185 149 182 240 134 97 121 98 171
NOT-L05A 50
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511 315 130 111 100 72 79 109 202 132 67 241 316 259 227 207 330 176 146 126
273 357 254 250 361 304 298 380 252 193
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461 290 117 110 91 70 62 109 202 129 67 243 322 253 235 210 331 173 150 125
275 345 249 263 372 310 302 375 251 193
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128 162 330 197 200 149 52 66 195 221 309 279 270 390 204 302 323 287 313 289
221 190 195 255 316 287 348 274 310 252 271 222 152 173 197 235 229 297 156 127
204 266 215 300 249 180 216 162 177 201 337 316 252 203 222 283 284 321 220 212
273

NOT-L06B 61
113 161 316 187 207 168 53 63 188 215 312 276 276 369 185 307 317 285 309 293
224 186 194 253 316 273 337 267 285 274 259 214 147 180 206 227 252 289 159 138
204 263 216 276 258 175 221 158 183 203 338 328 246 204 232 280 293 310 224 207
248
NOT-L07A 65
225 281 243 211 189 214 186 201 169 224 215 227 260 157 205 156 137 126 173 200
221 229 207 276 135 245 233 205 154 139 101 95 101 158 132 257 239 125 146 148
122 114 79 91 76 89 86 120 118 92 94 117 132 95 116 107 122 84 97 124
176 198 161 147 142
NOT-L07B 65
225 273 247 201 181 214 183 204 183 177 202 237 266 177 189 150 135 119 166 187
236 246 233 269 140 244 234 206 152 138 98 96 105 157 123 262 240 106 138 150
123 116 77 97 74 89 86 119 112 86 86 128 131 99 131 111 120 88 89 119
191 198 154 150 147
NOT-L08A 57
221 311 345 228 174 299 302 290 256 247 288 165 220 216 176 223 181 154 132 178
204 275 246 376 220 206 194 166 209 93 131 115 118 165 310 197 142 131 162 206
246 273 267 217 162 99 147 173 174 176 191 243 244 285 265 233 146
NOT-L08B 57
198 310 344 227 182 301 298 283 258 253 289 166 216 235 174 241 179 147 125 187
209 272 249 379 215 254 208 208 198 103 109 119 98 142 283 176 108 121 134 190
247 273 267 220 160 95 148 171 176 177 194 234 240 285 275 213 158
NOT-L09A 72
355 344 327 231 279 221 196 314 255 187 219 260 320 299 268 293 206 253 109 120
209 296 327 303 333 282 401 342 177 124 313 338 348 302 249 195 191 184 254 283
362 273 310 161 196 207 260 328 358 269 251 259 214 240 116 104 122 112 214 299
246 170 182 224 294 323 260 254 258 168 162 146
NOT-L09B 72
374 386 377 227 281 212 190 305 247 187 209 262 325 295 267 281 212 261 139 109
203 288 322 312 332 248 311 332 188 146 318 328 345 319 252 203 198 190 262 277
384 259 316 177 207 220 242 329 364 267 242 256 217 247 112 111 120 105 218 302
248 174 175 222 294 314 274 241 263 165 165 158
NOT-L10A 84
324 242 237 347 324 291 356 327 266 262 201 155 213 248 296 390 367 290 422 238
239 180 229 325 329 265 232 197 152 120 185 231 267 299 464 212 231 286 296 395
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255 121 186 306 252 278 206 205 238 147 162 114 271 154 137 172 154 114 93 113
154 153 186 185
NOT-L10B 84
338 260 238 358 318 307 363 332 272 257 198 157 221 249 296 407 364 297 421 226
237 163 238 316 329 267 225 204 140 120 189 227 254 290 462 210 236 280 293 403
359 235 278 264 311 355 241 210 256 365 333 371 375 250 231 329 274 260 230 257
246 133 185 307 248 279 207 209 247 143 133 118 290 161 130 170 148 127 97 112
165 180 209 189
NOT-L11A 75
379 382 381 409 375 394 330 308 318 303 329 330 324 422 339 272 392 314 359 247
228 367 273 264 161 228 168 164 161 173 186 122 118 139 156 151 139 90 88 94
96 74 60 67 60 61 69 73 101 81 88 98 59 100 157 152 177 156 164 182
130 121 116 115 97 93 84 67 81 101 94 95 61 67 67
NOT-L11B 75
377 371 396 401 393 392 346 305 313 316 302 305 313 402 368 271 396 317 350 240
232 368 276 260 167 217 167 168 165 167 193 122 119 138 158 147 136 92 88 94

88 76 72 55 68 64 66 73 99 83 91 102 59 96 154 152 177 139 163 160
109 115 98 118 102 85 76 73 83 97 102 85 54 73 69
NOT-L12A 100
320 346 564 500 316 276 489 304 348 343 164 276 279 281 223 273 259 204 215 177
93 149 165 143 161 216 114 71 80 69 165 225 132 143 179 203 240 171 102 152
219 153 146 135 138 140 130 109 150 69 187 145 224 124 156 80 96 151 146 122
170 104 103 104 68 79 56 75 70 62 45 47 61 81 54 75 69 93 72 53
54 68 40 51 64 42 64 46 48 58 55 56 81 78 86 76 73 57 69 100
NOT-L12B 100
315 347 553 502 317 273 441 311 346 347 165 271 272 285 194 272 241 226 202 193
95 167 167 145 160 217 114 70 84 71 165 238 125 142 179 195 248 162 100 138
207 145 134 136 130 134 137 106 143 76 182 135 223 117 161 85 98 148 136 146
182 97 101 106 67 78 64 70 72 58 45 50 56 80 60 63 72 96 64 55
54 71 39 48 63 46 63 51 48 59 55 56 82 73 80 83 77 51 75 88
NOT-L13A 101
315 370 247 223 219 227 264 202 168 101 59 95 109 96 110 70 74 71 90 88
90 135 120 165 175 177 130 123 111 81 76 102 101 146 120 103 105 84 55 102
94 103 121 136 104 64 75 87 104 100 81 69 65 49 52 57 67 77 82 61
53 63 52 62 57 63 53 61 64 90 97 89 111 74 70 55 64 44 44 47
59 98 89 111 116 122 90 66 68 54 200 379 462 258 336 325 254 185 195 102
103
NOT-L13B 101
313 359 257 227 222 222 258 209 171 99 55 98 106 100 105 78 71 70 92 84
93 129 129 166 173 177 136 124 105 81 80 100 96 151 129 105 103 82 55 93
88 92 101 137 92 61 76 89 98 98 84 68 65 53 42 55 78 78 81 73
44 60 50 56 64 66 52 59 57 81 106 90 106 74 72 57 58 47 42 51
62 94 90 112 109 125 84 72 69 55 214 367 469 273 335 326 259 176 190 98
112
NOT-L14A 48
206 353 319 205 237 280 255 398 364 281 329 228 262 213 207 236 217 212 208 216
215 207 212 317 300 268 173 197 166 158 139 155 176 175 248 203 281 218 165 181
143 147 158 157 135 101 115 67
NOT-L14B 48
206 330 327 191 267 280 249 389 348 283 328 228 259 213 214 227 221 216 204 215
210 203 213 324 300 265 174 194 170 155 134 142 176 166 245 201 268 233 160 185
143 146 163 150 139 102 113 73
NOT-L15A 67
193 335 270 256 348 295 381 307 298 228 284 356 493 474 376 343 259 136 114 173
169 218 309 233 276 110 178 269 247 249 185 118 86 100 149 182 184 196 108 150
144 107 118 83 73 56 76 104 140 140 80 84 94 89 116 145 109 104 75 84
93 201 219 161 123 111 145
NOT-L15B 67
165 326 276 260 345 293 386 307 298 229 280 357 490 476 356 366 256 124 103 159
166 204 278 236 270 117 175 267 243 254 182 124 92 95 148 187 186 196 99 160
139 112 118 81 71 62 78 107 139 137 80 89 101 93 128 138 112 115 79 82
93 190 221 172 128 105 154
NOT-L16A 66
329 335 375 328 377 317 189 255 294 249 277 244 230 331 354 243 186 262 319 196
205 167 188 188 131 210 235 251 350 370 313 265 266 234 231 254 192 174 222 204
192 118 129 159 155 256 219 269 158 164 160 207 169 169 161 146 135 121 160 157
179 183 199 156 138 114
NOT-L16B 66
343 363 396 329 380 311 192 254 294 244 271 254 218 342 363 259 199 293 311 197

198 166 194 185 129 212 234 254 349 374 312 278 265 234 237 265 188 170 218 207
191 111 147 155 146 256 235 266 162 162 157 212 162 177 151 157 134 120 155 164
178 179 205 154 137 100
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450 576 208 174 397 366 310 327 358 447 243 329 339 319 337 403 459 367 317 347
345 361 416 263 297 338 350 361 242 229 268 407 395 512 457 304 319 406 298 333
318 329 376 257 309 305 375 349 304 299 274 239 224 324
NOT-L19B 54
436 579 210 176 399 378 307 325 380 442 237 312 349 303 340 411 466 364 325 350
373 398 403 278 299 340 342 356 247 251 249 409 400 501 462 284 311 409 290 342
317 327 377 250 316 301 370 353 308 304 274 244 228 331
NOT-L20A 96
162 288 398 319 378 414 301 360 414 262 258 210 229 305 273 294 325 293 218 336
276 368 221 139 212 257 235 229 201 195 309 252 177 182 268 305 244 215 218 275
136 219 266 200 219 267 319 204 201 270 254 297 347 173 246 261 209 194 115 109
93 123 211 205 193 109 99 188 130 92 100 89 78 57 44 69 69 83 90 81
54 59 53 93 70 61 77 101 63 55 47 65 93 96 144 103
NOT-L20B 96
169 288 395 323 291 417 308 359 391 260 260 220 233 284 264 293 336 293 224 333
291 368 222 138 214 249 243 241 202 193 298 239 176 180 260 315 240 215 222 263
133 228 268 214 221 267 317 207 201 271 264 296 336 174 247 254 204 205 100 121
89 124 216 206 187 111 106 193 125 98 93 97 65 53 47 72 67 87 89 79
60 62 56 80 72 65 86 88 65 55 47 69 93 96 138 112
NOT-L21A 94
245 194 205 184 148 110 105 76 206 225 188 165 145 143 110 84 104 52 49 131
153 126 140 114 105 122 184 201 195 206 213 167 167 209 345 304 214 176 233 143
177 114 90 211 158 245 242 164 84 100 97 173 145 140 228 271 152 126 125 138
116 83 107 152 229 239 150 80 86 94 157 132 110 113 95 124 97 99 86 99
107 71 64 96 55 127 122 133 140 116 135 139 148 156
NOT-L21B 94
253 192 212 192 144 110 103 87 194 227 196 160 149 154 102 85 115 49 52 118
162 122 137 117 109 119 180 198 215 200 223 166 162 211 334 308 212 175 238 139
176 129 83 213 155 246 243 158 85 98 91 178 147 141 222 273 157 119 125 142
114 83 105 153 231 236 153 85 81 95 153 132 114 111 99 125 97 98 86 99
103 70 66 86 65 121 121 130 142 111 132 134 149 161
NOT-L22A 98
141 218 369 341 287 292 240 355 274 219 356 313 227 396 349 267 248 278 332 251
217 241 286 201 287 289 269 105 77 44 100 126 144 158 145 139 107 141 205 143
167 157 125 120 162 206 180 135 112 160 186 191 136 134 154 227 179 179 114 133
106 72 79 71 111 156 163 97 75 85 54 113 148 142 149 90 103 84 88 143
185 181 165 151 139 84 105 65 106 163 129 154 105 129 117 125 128 114
NOT-L22B 98
155 217 362 343 293 298 247 361 270 224 364 311 226 398 336 267 239 271 304 257
216 242 286 210 296 302 266 110 66 47 102 127 147 163 140 139 108 138 207 141
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108 71 73 79 110 163 161 96 79 74 59 111 148 141 144 87 104 83 93 128
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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 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	

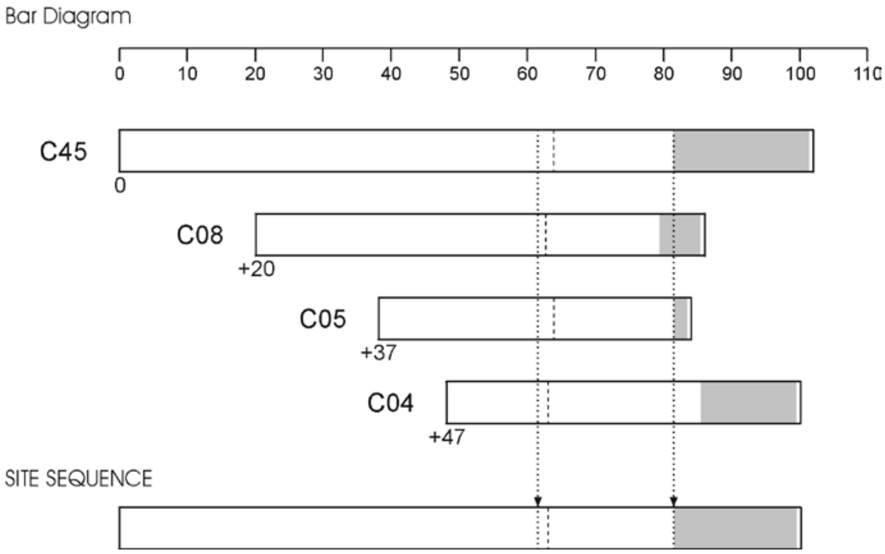


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

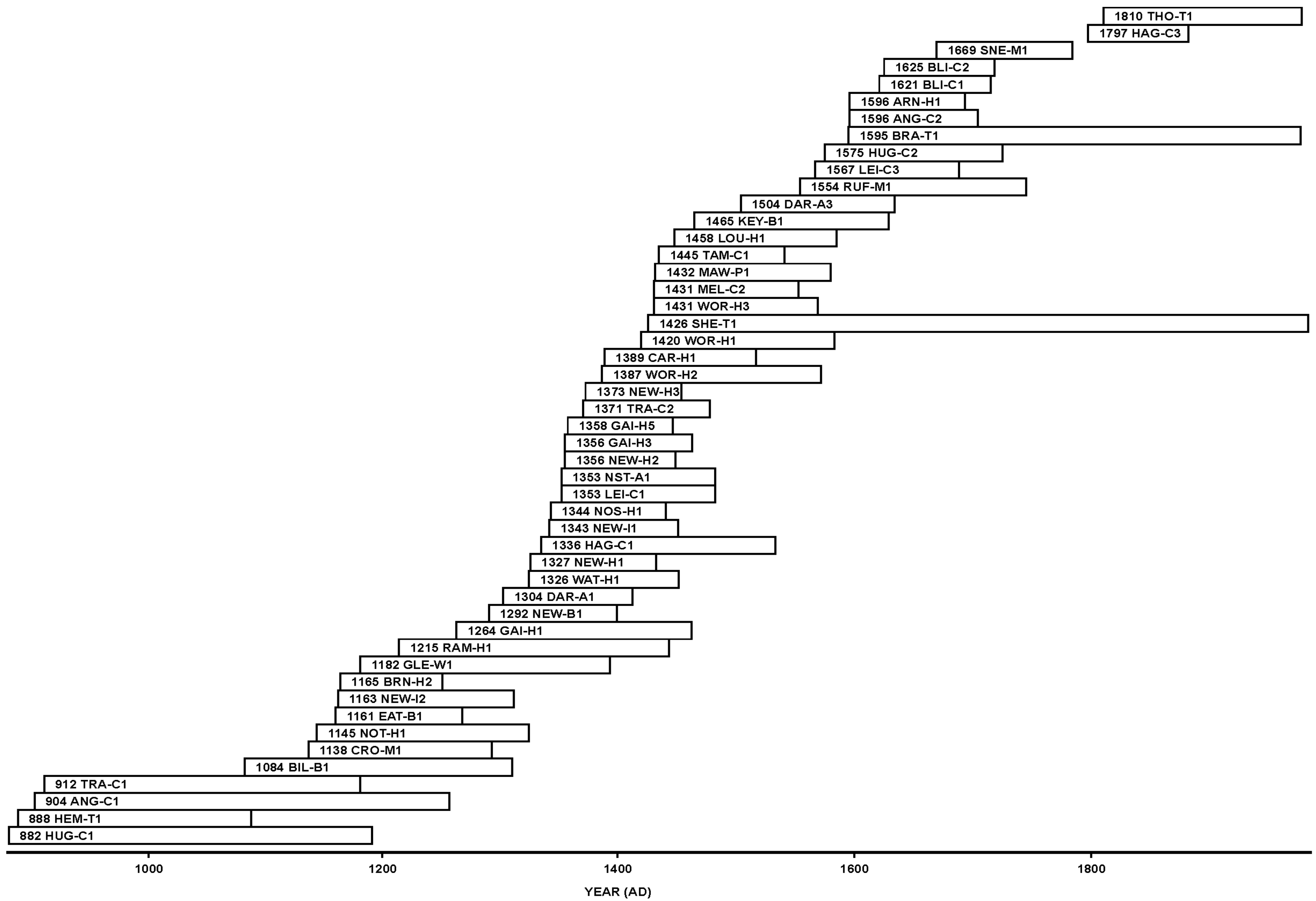
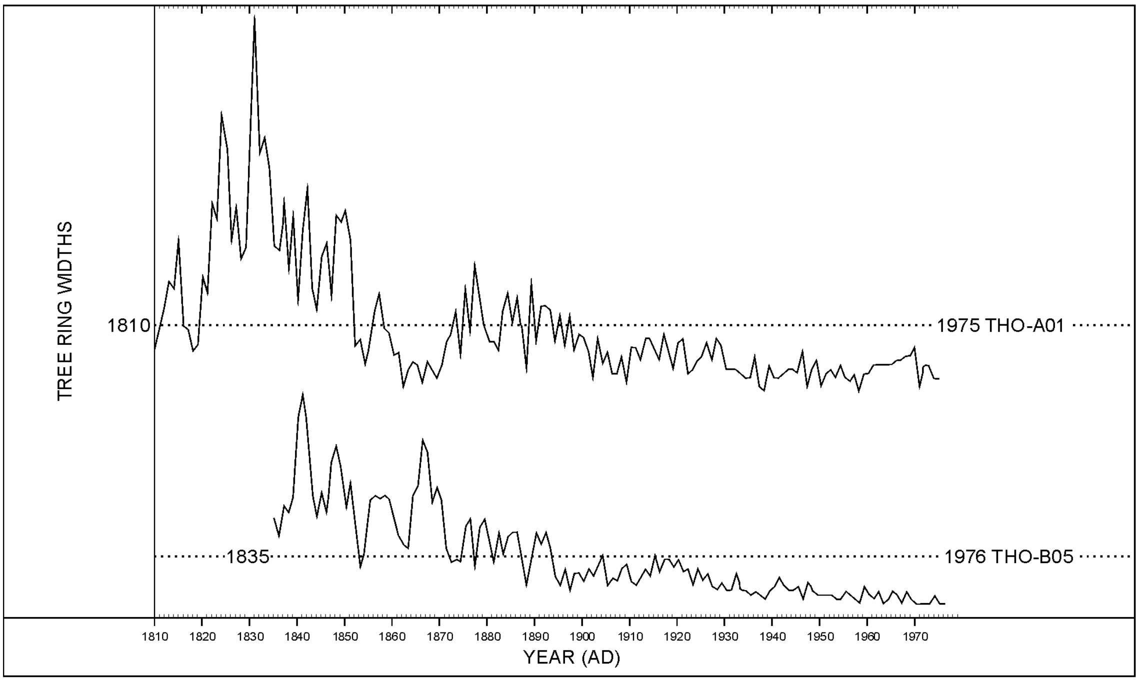


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

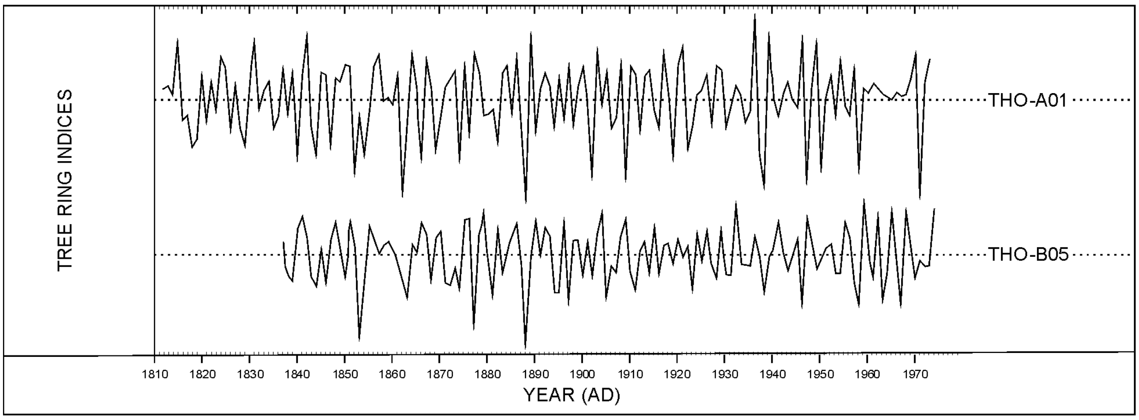


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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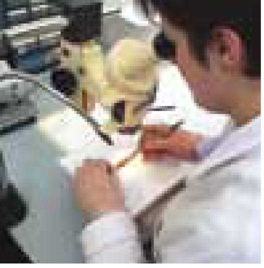
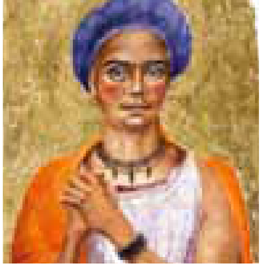


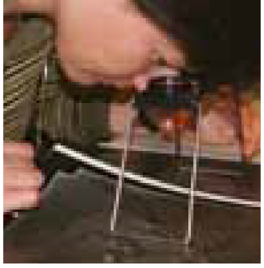


Historic England Research and the Historic Environment

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

Historic England works to improve care, understanding and public enjoyment of the historic environment. We undertake and sponsor authoritative research. We develop new approaches to interpreting and protecting heritage and provide high quality expert advice and training.

We make the results of our work available through the Historic England Research Report Series, and through journal publications and monographs. Our online magazine Historic England Research which appears twice a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.HistoricEngland.org.uk/researchreports

Some of these reports are interim reports, making the results of specialist investigations available in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation.

Where no final project report is available, you should consult the author before citing these reports in any publication. Opinions expressed in these reports are those of the author(s) and are not necessarily those of Historic England.

The Research Reports' database replaces the former:

Ancient Monuments Laboratory (AML) Reports Series
The Centre for Archaeology (CfA) Reports Series
The Archaeological Investigation Report Series and
The Architectural Investigation Reports Series.

ISSN 2059-4453 (Online)