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143 BRIGGATE, MARKET STREET ARCADE, LEEDS, WEST YORKSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY
Dendrochronological analysis was undertaken on 10 samples obtained from a series of timbers found during the redevelopment of this site. Of these10 samples, three could be combined to form a single dated site chronology. Interpretation of the sapwood on these dated samples indicates that at least one timber, a main bridging beam of a floor frame, was felled in AD 1574. Two other floor frame timbers, both joists, could also have been felled at this time, but it is possible that they were felled at any time in the period AD 1571–96. Seven further samples remain ungrouped and undated.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Nottingham Tree-ring Dating Laboratory would like to thank the building contractors working on the Briggate construction site, and especially Asim Qureshi, for their unstinting cooperation and help during sampling. We would also like to thank Elizabeth Chamberlin, Senior Historic Buildings Officer of West Yorkshire Archaeology Advisory Service, for her helpful explanation and discussion about the possible phasing of the timbers, for providing drawings, and for arranging sampling. The Laboratory must also acknowledge the efforts of Richard Jaques and Kathryn Gibson of English Heritage in requesting the provision of dendrochronology on this site, and to Dr Peter Marshall (English Heritage Scientific Dating Team) and Cathy Tyers (Sheffield University Dendrochronology Laboratory), for commissioning this programme of analysis.

ARCHIVE LOCATION
West Yorkshire Historic Environment Record
Registry of Deeds
Newstead Road
Wakefield
West Yorkshire WF1 2DE

DATE OF INVESTIGATION
2011

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INTRODUCTION

During commercial redevelopment works of the Market Street Arcade in Leeds (SE 3025 3345, Figs 1 and 2), a section of timber-framing was uncovered in the north wall at 143 Briggate. This timber-framing comprises two vertical posts with two parallel, pegged and tenoned, rails running horizontally between them. This timber-framing is now in-filled with brick, forming a partition wall between 143 Briggate and the next building to its north (Fig 3a). Since the find was unexpected, there was no condition on the planning consent for building recording and whilst the timber-framing will be retained it will be covered over again during redevelopment. Emergency building recording was therefore undertaken by West Yorkshire Archaeology Advisory Service.

A further horizontal timber was also found at first floor level in the south wall of 143 Briggate (Fig 3b). Although there is no clear evidence that it is related to the timber-framed north partition wall, it is possible that it is from the same phase of building, perhaps acting as a wall plate.

In addition to the surviving, clearly *in situ*, timber-frame of the north partition wall and the horizontal timber of the south wall, a number of apparently re-used timbers were recovered from elsewhere within the building. These appear to have been used as a main bridging beam and common joists for a first-floor frame (Figs 4a-e). The positions of these timbers have been recorded prior to being removed and stored on site. These also appeared to have been formerly part of a timber-framed structure although there is no certainty that they of the same phase as the wall-framing.

SAMPLING

Sampling and analysis by dendrochronology of the timbers discovered at 143 Briggate were requested by Richard Jaques and Kathryn Gibson, from English Heritage Yorkshire and Humber Region. Surviving evidence of *in situ* timber-framing in buildings is very rare in Leeds, so the primary purpose of this analysis was to provide a date and context for this unusual survival.

Thus from the timbers available a total of 10 samples was obtained, five by coring the timbers still remaining *in situ,* and five by the removal of cross-sectional slices from the *ex situ*. Each sample was given the code LEE-B (for Leeds, site 'B') and numbered 01–10. A photographic record of the sliced samples was made (see Figs 4a-e) and the locations of the samples removed from the *in situ* north partition wall timbers were noted at the time of coring, and subsequently marked on the drawing produced and provided given here as Figure 5. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

Each of the 10 samples obtained was prepared by sanding and polishing, and the widths of their annual growth rings were measured, the data of these measurements being given at the end of this report. The data of the 10 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing a single group of three cross-matching samples to be formed at a minimum value of *t*=4.5, the three samples cross-matching with each other as shown in Figure 6. These three samples were combined at their indicated offset positions to form site chronology LEEBSQ01, a site chronology with an overall length of 108 rings.

Site chronology LEEBSQ01 was then compared with an extensive series of reference chronologies for oak, this indicating a satisfactory cross-match when the date of its first ring is AD 1467 and a last measured ring date of AD 1574. The evidence for this dating is given in Table 2.

Site chronology LEEBSQ01was then compared to the seven remaining ungrouped samples, but there was no further satisfactory cross-matching. The seven remaining ungrouped samples were then compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and all seven must remain undated.

DISCUSSION AND CONCLUSION

Analysis by dendrochronology of 10 cores from the timbers discovered within143 Briggate has produced a single dated site chronology comprising three samples, its 108 rings spanning the years AD 1467–1574.

One of the three samples, LEE-B06, from a main bridging beam removed from the building, retains complete sapwood, the outermost ring being the last ring produced by the tree from which the sampled beam was derived before it was cut down (Fig 6; Table 1). This last sapwood ring, and thus the felling of the tree represented, is dated to AD 1574.

The heartwood/sapwood boundary on sample LEE-B07, the second sample in site chronology LEEBSQ01 (Fig 6; Table 1), is at relative position 90 (AD 1556), some 21 years later than that on sample LEE-B06. Using the usual 95% confidence limit of 15–40 rings for the amount of sapwood the tree represented by LEE-B07 had would give it an estimated felling date in the range AD 1571–96. It is thus possible that the tree represented by sample LEE-B07 was also felled in AD 1574, but this cannot be proven, and it is equally possible that it was felled a year or two earlier or a number of years later.

The third and final sample, LEE-B08, in site chronology LEEBSQ01, has no trace of sapwood, and thus it is not possible to provide an estimated felling date range for the timber, although, with a last, heartwood ring date of AD 1553, and using a 95% confidence limit of a minimum of 15 sapwood rings, this is unlikely to have been before AD 1568. However, given that sample LEE-B08 cross-matches particularly highly with sample LEE-B07, with a value of *t*=9.9, it is possible that the two timbers represented are in fact derived from the same tree and are thus of a single felling date. Both samples LEE-B07 and B08 represent *ex situ* common joists.

Seven other samples remain ungrouped and undated. In the majority of cases it is possible that this is a result of the samples having low numbers of annual growth-rings (Table 1). It is also possible that the sampled timbers are of a particular time period and/or location which, given the paucity of buildings in the immediate area that have been sampled, is not yet sufficiently well represented by the currently available corpus of reference material, although this seems relatively unlikely. Although this lack of success is particularly disappointing for the *in situ* material, the data is now archived and it is possible that, when further relevant data from the area is obtained in the future, the currently undated samples will be dated. However the lack of intra-site cross-matching does suggest that the chances of successful dating in the future may be somewhat lower than usual.

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TABLES

Table 1: Details of tree-ring samples from 143 Briggate, Market Street Arcade, Leeds

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
LEE-B01	Ground floor, cross-rail (lower), north wall	100	24	------	------	------
LEE-B02	Front (west) main wall post, north wall	50	h/s	------	------	------
LEE-B03	ground-floor, cross rail (upper), north wall	54	h/s	------	------	------
LEE-B04	Rear (east) main wall post, north wall	80	no h/s	------	------	------
LEE-B05	First floor, plate to south wall	54	13	------	------	------
LEE-B06	Loose timber 1 (bressumer/bridging beam?)	108	39C	1467	1535	1574
LEE-B07	Loose timber 2 (common joist?)	60	h/s	1497	1556	1556
LEE-B08	Loose timber 3 (common joist?)	66	no h/s	1488	------	1553
LEE-B09	Loose timber 4 (common joist?)	54	h/s	------	------	------
LEE-B10	Loose timber 5 (common joist?)	56	h/s	------	------	------

*h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Table 2: Results of the cross-matching of site sequence LEEBSQ01 and relevant reference chronologies when the first-ring date is AD 1467 and the last-ring date is AD 1574

Reference chronology	Span of chronology	*t-value*	Reference
Headley Hall Farm, Upper Headley, West Yorkshire	AD 1381–1604	8.2	(Tyers 2001)
Hallgarth, Pittington, Co Durham	AD 1336–1624	7.1	(Howard *et al* 2001)
Oakwell House, Birstall, West Yorkshire	AD 1380–1583	6.7	(Howard *et al* 1991)
Sandiacre Tithe Barn, Derbyshire	AD 1426–1611	6.3	(Howard 2004 unpubl)
Thorpe Prebend House, Ripon, North Yorkshire	AD 1356–1583	6.3	(Boswijk1998)
Manorial barn, Whiston, Rotherham, South Yorkshire	AD 1374–1622	6.1	(Tyers 2002)
Grange Farm, Norton, Sheffield, South Yorkshire	AD 1436–1599	5.7	(Arnold and Howard 2007)
Low Bishopley, Frosterley, Weardale, Co Durham	AD 1401–1575	5.7	(Arnold and Howard 2011)

FIGURES

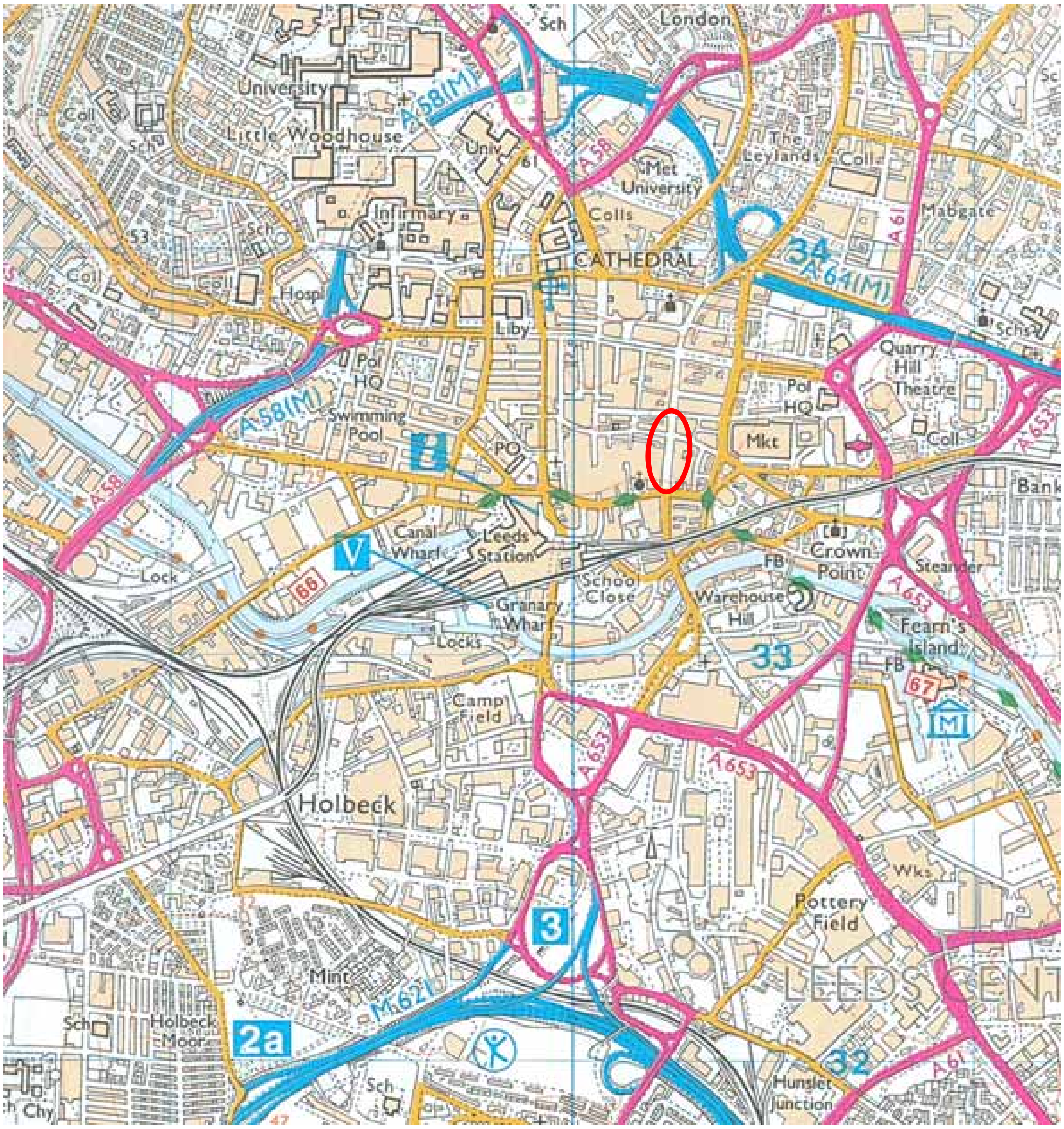


Figure 1: Map to show the location of 143 Briggate, Leeds.

Figure 2: Plan to show the location of 143 Briggate. © Crown Copyright. All rights reserved. English Heritage 100019088. 2012

Figure 3a/b: View of the framing to the north wall (top) and the single horizontal timber of the south wall (bottom), cut off to allow for the insertion of the steel joist, sampled as LEE-B05

Figure 4a/b: Ex situ timbers sampled as LEE-B06 (top) and LEE-B07 (bottom)

Figure 4c/d: Ex situ timbers sampled as LEE-B08 (top) and LEE-B09 (bottom)

Figure 4e: Ex situ timber sampled as LEE-B10

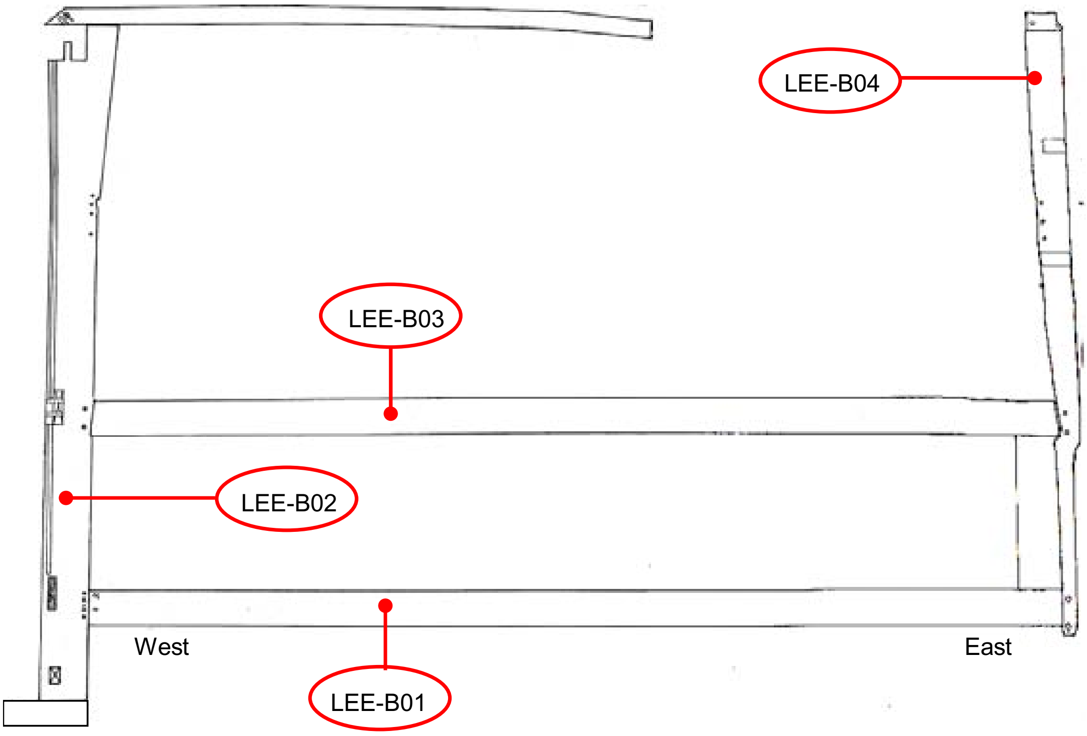
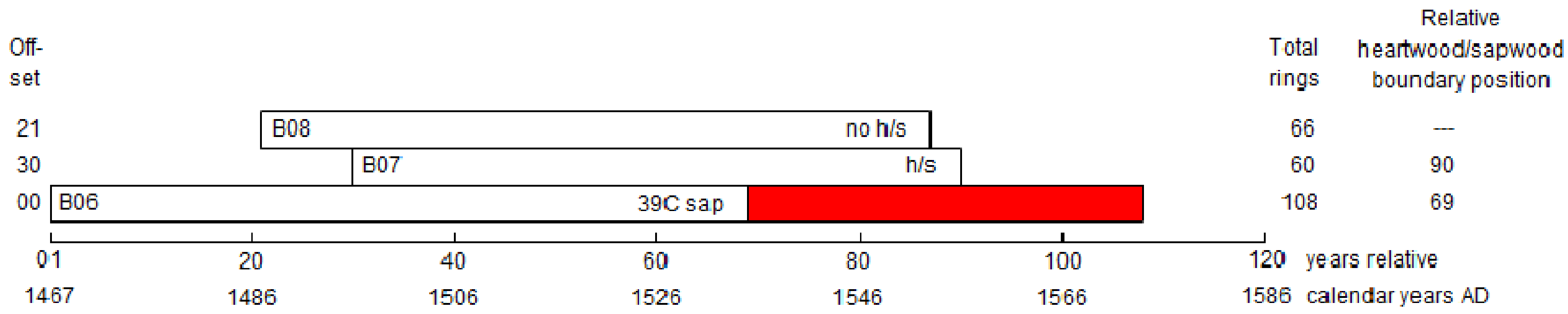


Figure 5: Long-section of the north partition wall to locate sampled timbers (after Elizabeth Chamberlin, West Yorkshire Archaeological Advisory Service)



white bars =heartwood rings, red bar = sapwood rings
h/s = heartwood/sapwood boundary
C = complete sapwood retained on the sample; the last measured ring date is the felling date of the tree

Figure 6: Bar diagram of the samples in site chronology LEEBSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LEE-B01A 100
210 356 240 285 245 200 181 142 200 239 255 364 473 436 427 369 309 264 280 292
355 444 469 420 421 468 408 490 395 391 100 95 128 245 251 249 273 301 320 302
321 288 278 268 213 183 224 210 186 197 221 240 95 94 65 83 79 70 72 82
80 68 69 66 66 63 92 109 80 77 79 90 85 61 83 97 103 126 110 118
112 91 63 66 46 58 95 145 110 110 84 89 61 56 51 74 69 41 40 49
LEE-B01B 100
270 352 251 315 260 199 193 143 191 241 285 341 449 446 435 417 322 265 259 291
355 452 469 412 408 512 389 526 398 395 85 101 128 243 251 255 268 296 330 301
337 285 280 275 212 193 225 200 180 192 211 239 106 97 63 87 69 83 73 88
65 67 69 62 68 60 90 103 87 71 78 93 74 69 77 108 104 119 112 115
112 97 61 64 51 53 94 134 115 105 89 81 68 52 52 73 62 48 49 54
LEE-B02A 50
219 179 181 128 119 124 136 187 184 211 168 100 116 117 139 129 100 158 79 57
49 65 82 124 130 105 105 106 111 128 101 56 71 81 85 102 112 105 95 63
149 120 113 170 134 100 122 105 103 108
LEE-B02B 50
220 175 182 127 117 125 145 186 181 217 164 106 125 118 122 111 100 162 78 45
42 77 76 118 128 102 105 104 103 122 113 55 78 84 93 100 125 114 89 59
145 150 109 174 133 98 126 109 104 109
LEE-B03A 54
144 166 186 96 124 291 189 128 219 198 130 174 219 218 187 228 237 222 185 158
116 130 125 158 152 117 139 137 137 143 133 110 127 170 144 97 98 124 107 83
120 95 147 154 142 120 107 95 110 158 176 197 180 195
LEE-B03B 54
163 161 181 103 144 270 186 107 216 199 106 179 215 217 203 225 221 219 182 174
119 118 129 158 149 112 139 132 139 151 130 112 129 165 147 98 100 129 102 97
124 96 145 150 137 121 107 99 114 156 186 199 176 194
LEE-B04A 80
552 502 551 559 501 501 463 536 386 384 400 425 370 356 282 538 301 456 188 362
334 329 336 382 404 173 171 148 260 201 182 210 195 282 222 161 171 158 181 317
350 225 103 73 129 209 184 165 292 226 256 358 215 168 173 126 119 94 138 178
116 89 234 157 207 203 116 102 107 60 62 103 210 243 187 263 217 118 138 266
LEE-B04B 80
542 472 558 566 510 510 436 569 405 339 399 430 395 354 258 540 293 443 191 364
333 328 351 389 413 182 172 144 271 199 183 234 221 281 240 160 183 172 172 262
357 211 102 84 133 207 187 179 275 251 275 315 228 163 183 136 113 85 160 229
125 100 242 158 194 211 121 110 97 56 61 98 227 226 188 258 218 114 138 266
LEE-B05A 54
322 202 181 166 160 225 297 312 169 231 230 255 205 232 238 244 210 178 209 246
205 256 211 276 236 183 238 286 267 241 232 130 212 247 191 175 113 101 188 173
201 206 252 207 197 134 172 186 235 287 160 241 219 252
LEE-B05B 54
281 192 176 166 150 201 286 275 217 236 243 250 201 242 228 247 217 177 208 258
201 262 212 270 251 189 244 271 259 261 254 127 223 232 199 189 124 106 183 171
209 204 254 212 202 141 167 183 229 313 152 245 235 230
LEE-B06A 108
265 274 234 318 407 423 332 338 333 340 303 255 301 313 285 232 367 358 393 385

427 441 156 58 56 87 137 155 220 262 195 169 148 185 169 214 198 249 238 237
179 221 269 229 249 230 197 298 275 277 189 225 118 74 74 96 94 131 117 117
121 153 139 140 163 133 150 97 161 215 200 157 175 166 71 57 70 78 84 96
98 90 72 108 129 125 104 116 151 116 70 49 71 96 110 120 119 130 131 75
55 37 57 96 109 99 118 118
LEE-B06B 108
258 292 205 334 414 426 314 339 335 321 314 262 289 318 281 236 371 355 383 394
424 428 137 67 65 80 147 157 236 293 184 156 148 188 201 229 192 244 218 237
170 213 259 249 276 235 205 297 261 287 172 231 115 67 71 90 89 122 113 110
120 153 147 132 176 135 147 107 157 208 199 165 179 173 98 48 67 82 78 105
94 95 72 112 117 130 108 115 163 108 71 65 60 87 100 116 123 124 112 73
50 43 48 93 119 93 125 123
LEE-B07A 60
264 292 291 269 298 319 266 337 356 286 209 231 329 299 289 194 186 162 171 198
216 281 269 216 209 227 150 236 203 209 201 163 183 179 197 172 172 137 149 163
168 166 198 244 141 108 125 141 215 193 181 197 149 160 191 155 173 160 248 210
LEE-B07B 60
274 306 285 268 287 309 311 320 292 282 199 203 321 295 300 213 239 194 167 200
217 323 257 212 224 236 147 238 202 206 201 152 184 188 180 174 177 137 135 163
170 165 198 252 142 93 130 146 222 195 195 194 150 161 180 165 170 168 245 202
LEE-B08A 66
168 156 217 183 286 307 370 384 366 341 353 353 229 257 277 207 212 245 200 181
169 232 220 210 194 190 170 171 205 167 251 233 186 200 201 155 233 195 201 219
200 206 231 236 214 214 165 177 170 184 168 207 258 201 121 184 224 230 176 163
180 140 150 196 180 208
LEE-B08B 66
170 159 212 184 283 319 367 385 376 335 354 339 332 264 301 199 215 223 199 186
165 225 220 217 197 189 171 169 199 171 239 226 184 210 204 157 261 185 224 230
202 205 225 240 209 212 164 176 174 181 164 202 264 208 131 189 219 223 175 165
167 152 142 201 184 207
LEE-B09A 54
79 98 124 66 49 73 77 84 59 72 80 69 83 77 73 92 80 75 53 67
110 92 104 87 90 47 72 59 73 95 88 53 80 54 58 72 50 48 36 43
34 41 45 29 36 67 63 47 63 26 38 50 57 89
LEE-B09B 54
82 87 120 61 53 81 83 87 57 85 86 67 85 76 80 99 82 77 50 66
114 89 100 89 92 47 74 63 71 94 87 54 85 54 57 75 48 47 37 41
34 42 44 31 40 68 68 46 59 23 48 52 59 92
LEE-B10A 56
51 53 82 46 58 39 52 50 51 50 69 57 57 61 34 45 45 42 56 38
93 110 84 63 57 47 46 45 33 76 88 85 81 53 73 61 59 71 51 97
70 64 79 81 61 97 66 52 67 68 62 65 57 51 79 88
LEE-B10B 56
50 56 80 41 60 40 54 52 49 47 69 55 57 59 29 48 47 40 59 31
90 115 80 59 55 41 43 42 35 70 83 81 85 54 69 60 57 69 49 90
65 61 77 79 60 100 69 49 70 64 59 61 51 41 77 83

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

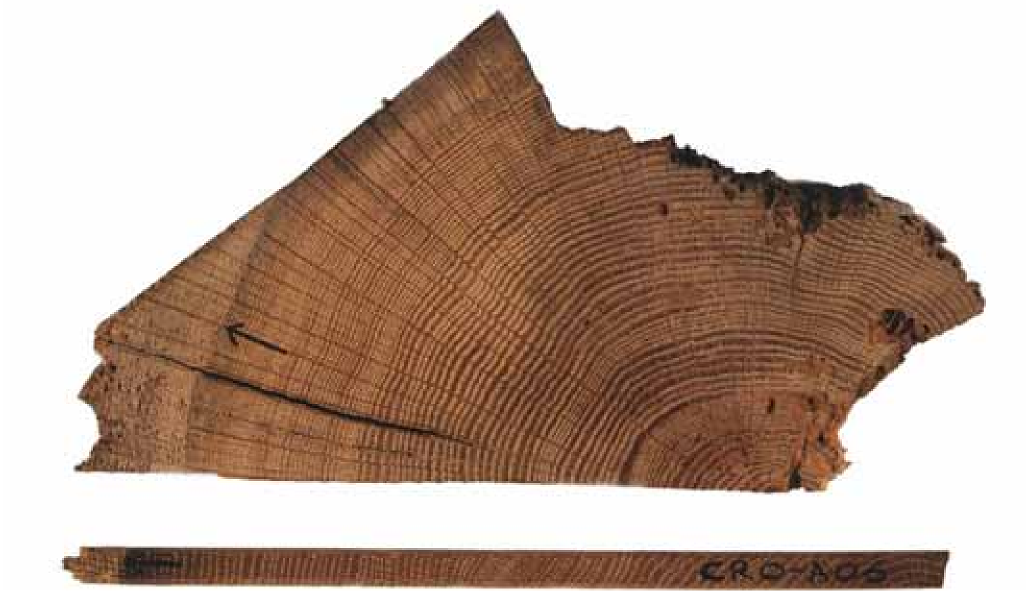


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

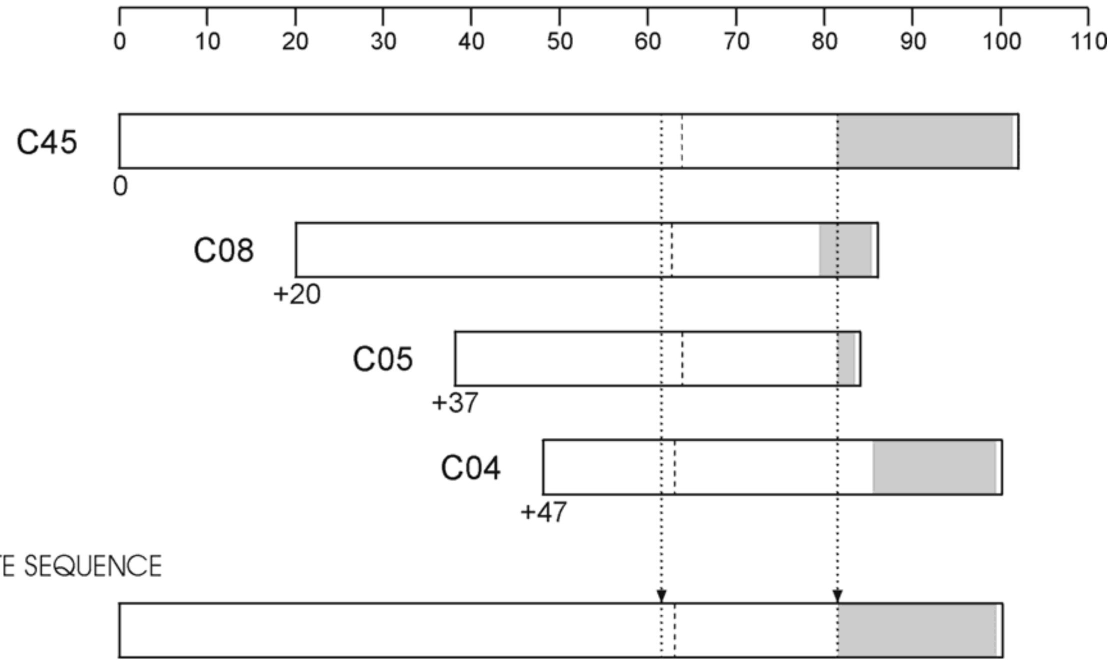


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

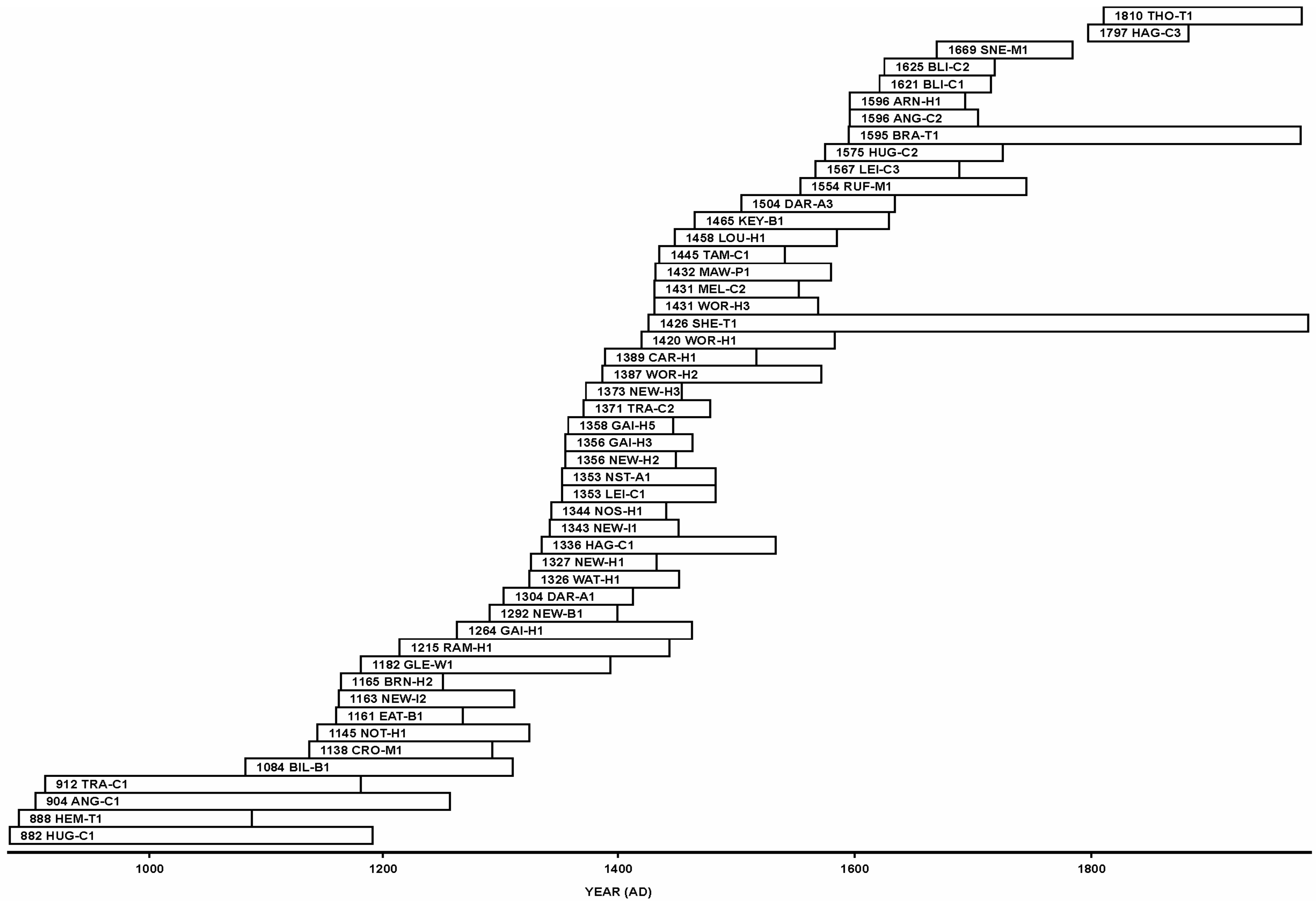
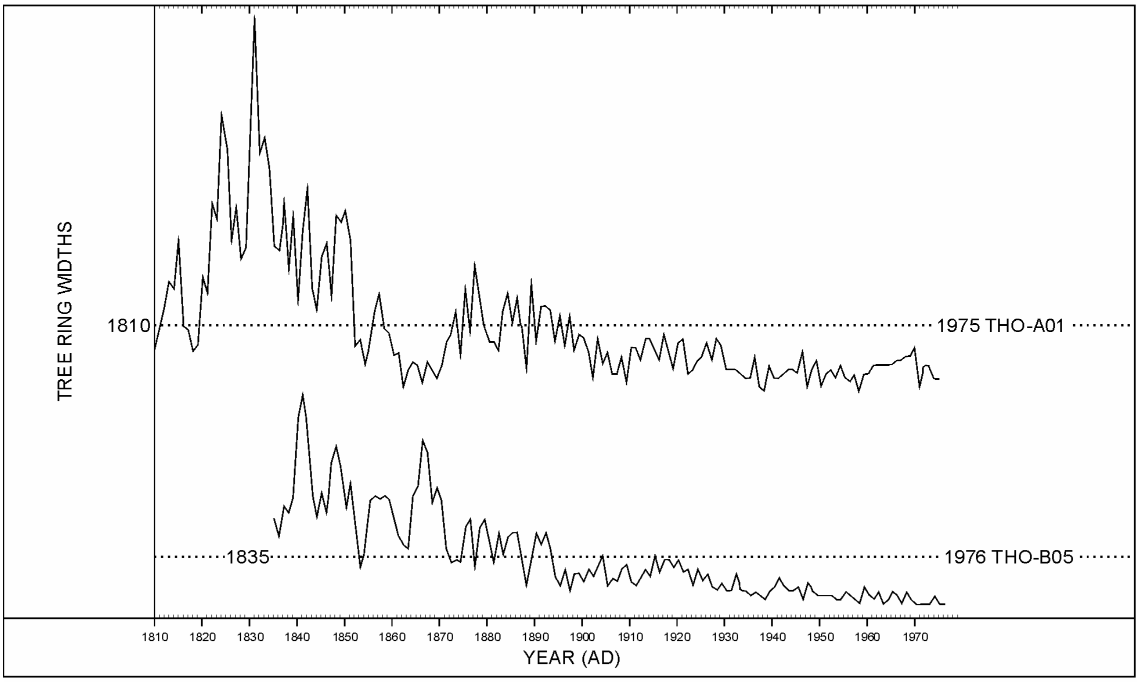


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

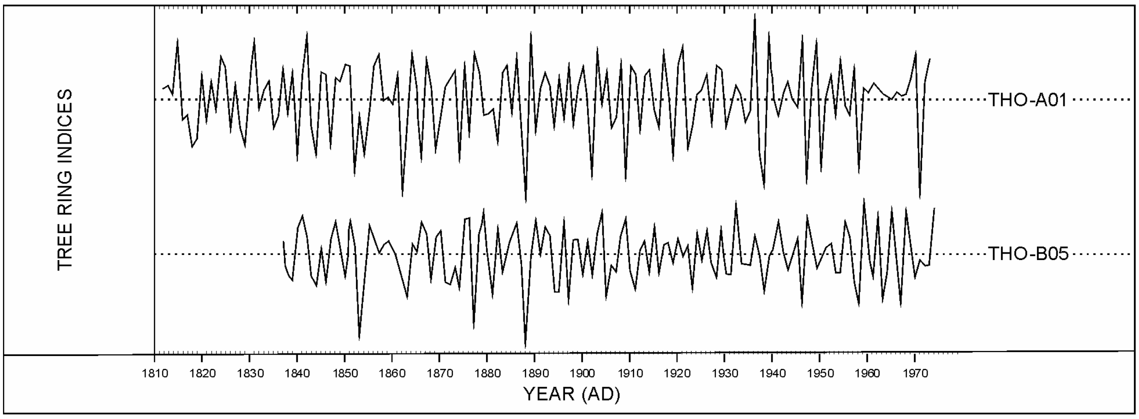


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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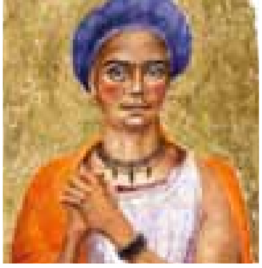


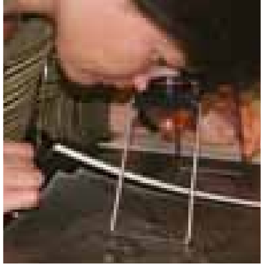


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