RESEARCH DEPARTMENT REPORT SERIES NO 101-2007 ISSN 1749-8775

WARREN FARM QUARRY, LOCKINGTON, LEICESTERSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison J Arnold, Robert E Howard, and Cliff D Litton

ARCHAEOLOGICAL
SCIENCE

ENGLISH HERITAGE

Research Department Report Series 101-2007

WARREN FARM QUARRY, LOCKINGTON, LEICESTERSHIRE

TREE-RING ANALYSIS OF TIMBERS

Alison J Arnold, Robert E Howard, and Cliff D Litton

NGR SK 477 302

ISSN 1749-8775

The Research Department Report Series, incorporates reports from all the specialist teams within the English Heritage Research Department: Archaeological Science; Archaeological Archives; Historic Interiors Research and Conservation; Archaeological Projects; Aerial Survey and Investigation; Archaeological Survey and Investigation; Architectural Investigation; Imaging, Graphics and Survey; and the Survey of London. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, and the Architectural Investigation Report Series.

Many of these are interim reports which make available the results of specialist investigations 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, readers are advised to consult the author before citing these reports in any publication. Opinions expressed in Research Department Reports are those of the author(s) and are not necessarily those of English Heritage.

Requests for further hard copies, after the initial print run, can be made by emailing: Res.reports@english-heritage.org.uk., or by writing to
English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD
Please note that a charge will be made to cover printing and postage.

SUMMARY

Sliced samples were obtained from eight different timbers (some possibly derived from the same tree) at the Warren Farm Quarry site at Lockington, on the Derbyshire / Leicestershire border.

Analysis of these samples produced a single site chronology comprising six samples, with an overall length of 300 rings. These rings were dated as spanning the years 2928–2629 BC. A further sample was dated individually, its 105 rings spanning the years 2623 BC to 2519 BC. A final sample, with 83 rings, remains undated.

CONTRIBUTORS

Alison J Arnold, Robert E Howard, and Dr Cliff D Litton

ACKNOWLEDGEMENTS

Tree-ring dating was funded by the Aggregates Levy Sustainability Fund, administered by English Heritage, through a grant to project 3357 ('Predictive Modelling of Multi-Period Geoarchaeological Resources at a River Confluence'). The principal investigator was Prof Tony Brown, then of the University of Exeter. The Nottingham Tree-Ring Dating Laboratory would also like to acknowledge the assistance provided by Cathy Tyers of the University of Sheffield Dendrochronology Laboratory in cross-matching the site data discussed here against a number of unpublished reference chronologies.

ARCHIVE LOCATION

Leicestershire and Rutland Historic Environment Record
Historic & Natural Environment Team
Room 500, County Hall
Leicester Road
Glenfield LE3 8TE

DATE OF INVESTIGATION

2006

CONTACT DETAILS

Nottingham Tree-Ring Dating Laboratory
20 Hillcrest Grove
Nottingham NG5 1FT

INTRODUCTION

Forming part of the border between the counties of Derbyshire, Leicestershire, and Nottinghamshire in the locality of Aston-on-Trent and Shardlow, the river Trent has deposited substantial areas of sand and gravel in this region as if flows eastwards to join the river Humber. The extraction of aggregates from these deposits has, over the years, exposed a considerable number of archaeological sites and provided quantities of palaeoenvironmental data. Of particular interest to this programme of analysis are a number of tree-trunks, or the partial remains of trees, exposed during quarrying in early 2006.

SAMPLING

Sampling and analysis by tree-ring dating of a selection of the timbers found at the quarry site were requested by Dr Andrew Howard of the Birmingham University Archaeological Unit. For some time the Unit has been responsible for undertaking watching briefs at the quarry site and for conducting archaeological excavations on any remains discovered. Dr Howard, an expert in palaeo-riverine conditions, has been responsible for examining the palaeoecology of the prehistoric River Trent.

The purpose of analysis was to establish, if possible, the absolute date of the recently exposed trees at the Warren Farm Quarry, Lockington, Leicestershire (centred on NGR SK 477 302; Figs 1 and 2) in order to provide some possible dating evidence for the flow channels and depositional context in which they were found. It was further hoped that any tree-ring data obtained would help strengthen and possibly extend the prehistoric tree-ring chronology which already exists for this area. Although the established tree-ring chronology is viable, it is, to a certain extent, limited in both the numbers of samples it contains, as well as in its temporal and geographic applicability.

The Warren Farm quarry site presented several prone whole or partial tree-trunks and branches of varying sizes. Nearly all such trees were wholly or partially buried, with only parts being exposed above the surface of the surrounding gravel and water. From this number, a selection was made of eight timbers possibly suitable for samplings. Areas around the timbers were cleared and, where possible, complete cross-sectional slices were taken from the limbs using a chainsaw (Fig 3). Where it was not possible to take cross-sections, half, or quarter radii were obtained instead.

The radii were then reduced in size to produce manageable sliced samples. Each sample was given the code LOK-Q (for Warren Farm Quarry, Lockington) and numbered 01–08. Given their proximity to each other, it is possible that at least two or, possibly, three timbers, and hence the slices and their resultant samples, may be derived from the same tree, and that, in effect, only six different trees are represented by these samples. Such timbers may be represented by samples LOK-Q02 and Q04, and possibly by sample LOK-Q05 as well. Details of the samples are given in Table 1.

ANALYSIS

Each sample thus obtained was initially prepared by freezing to stabilize it. Once hardened enough, the sample surfaces were prepared using a surform and plane. A scalpel or a Stanley knife blade was then used to clean the surfaces to increase the visibility of the rings, which were then measured in the usual way (the data of these measurements are given at the end of the report). The growth-ring widths of all eight samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a minimum *t*-value of 6.0 a single group, comprising six samples, could be formed, cross-matching as shown in the bar diagram Figure 4. The six samples were combined at these relative positions to form site chronology LOKQSQ01, this having an overall length of 300 rings. It may be of interest to note that samples LOK-Q02 and C04 cross-match with each other with a value of *t*-10.7, suggesting that the timbers they represent are from the same tree.

Site chronology LOKQSQ01 was then compared to the available reference chronologies for prehistoric oak, cross-matching with a number of these, including a previous chronology derived from timbers at Shardlow (Tyers 1999) and other local site chronologies from Langford and Colwick in Nottinghamshire. The cross-matching indicates at date span of 2928 BC to 2629 BC for this site chronology. Evidence for this dating is given in Table 2.

Site chronology LOKQSQ01 was compared with the two remaining samples but there was no further cross-matching. Each of the two remaining individual samples was, therefore, compared individually with the full range of reference chronologies. This indicated a cross-match and date for only one further sample, LOK-Q06, its 105 rings dated as spanning the years 2623 BC to 2519 BC. Evidence for this dating is given in Table 3.

The final individual sample, LOK-Q01, remains undated. There appears to be no problem with the ring sequence of this samples, such as distorted or compacted rings, which would make cross-matching and dating difficult. It is possible, though of course this has not been proven by tree-ring analysis, that the sample data represents a time period or area (the tree possibly having been washed to this deposition site from somewhere else) for which little or no reference material exists.

CONCLUSION

Tree-ring analysis of timbers uncovered during gravel extraction has produced a single site chronology, LOKQSQ01, comprising 6 samples, and dated one sample individually. A final sample remains undated. The 300 rings of site chronology LOKQSQ01 span 2928 BC to 2629 BC. The 105 rings of the individually dated sample span 2623 BC to 2519 BC.

Given that none of the dated samples had sapwood, or the heartwood/sapwood boundary, on them, it is not possible to be certain as to the precise dates of death of the trees represented. As is often the case with such timbers, this had been lost through rapid drying and decay as the once waterlogged trees were left exposed to the air. It was possible to see, however, that some of the trees themselves, as opposed to the actual samples, did have a possible heartwood/sapwood edge to them. Unfortunately, given the positions of the trees in the ground, it was not possible to sample at these points safely. It is thus very likely that the last measured rings are within 10–20 years of the heartwood/sapwood boundary, and that the date of death lies within an approximately 15–50 year period thereafter.

REFERENCES

Hillam, J, 1994 *The dating of oak timbers from the Wootton Quarry Survey, Isle of Wight*, Anc Mon Lab Rep, 10/1994

Tyers, I, 1999 *Tree-ring analysis of naturally deposited timbers from Shardlow Gravel Pit, Derbyshire*, ARCUS, 425

Table 1: Details of samples from Warren Farm Quarry, Lockington, Leicestershire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
LOK-Q01	Quarry oak	84	Close to h/s?	------	------	------
LOK-Q02	Quarry oak	202	Close to h/s?	2871 BC	------	2670 BC
LOK-Q03	Quarry oak	165	Close to h/s?	2818 BC	------	2654 BC
LOK-Q04	Quarry oak	102	Close to h/s?	2790 BC	------	2689 BC
LOK-Q05	Quarry oak	188	Close to h/s?	2883 BC	------	2696 BC
LOK-Q06	Quarry oak	105	Close to h/s?	2623 BC	------	2519 BC
LOK-Q07	Quarry oak	107	Close to h/s?	2735 BC	------	2629 BC
LOK-Q08	Quarry oak	118	no h/s	2928 BC	------	2811 BC

*h/s? = the last ring on the sample is at or approaching the heartwood/sapwood boundary

Table 2: Results of the cross-matching of site chronology LOKQSQ01 and relevant reference chronologies when first ring date is 2928 BC and last ring date is 2629 BC

Reference chronology	Span of chronology	*t*-value	Reference
England National	4989–1681 BC	12.5	(Hillam pers comm)
Shardlow Quarry (1), Derbyshire	2942–2610 BC	10.9	(Tyers 1999)
Wicken Fen, Cambridgeshire	3088–2585 BC	8.6	(Brown pers comm)
Langford Quarry, Nottinghamshire	2979–2125 BC	7.9	(Hillam and Howard unpubl)
Holme Fen, Cambridgeshire	3141–1868 BC	7.3	(Brown pers comm)
Colwick Hall (1), Nottinghamshire	3054–2697 BC	6.7	(Brown pers comm)

Table 3: Results of the cross-matching of sample LOK-Q06 and relevant reference chronologies when first ring date is 2623 BC and last ring date is 2519 BC

Reference chronology	Span of chronology	*t*-value	Reference
Wootton Quarry, Isle of Wight	3463–2557 BC	6.0	(Hillam 1994)
England National	4989–1681 BC	5.8	(Hillam pers comm)
East Anglia: Regional	3196–1681 BC	5.0	(Brown pers comm)
Langford Quarry, Nottinghamshire	2979–2125 BC	5.4	(Hillam and Howard unpubl)
Whittlesey Mere, Cambridgeshire	2701–2476 BC	4.8	(Brown pers comm)
Holme Fen, Cambridgeshire	3141–1868 BC	4.7	(Brown pers comm)

Figure 1: Map showing the general location of the site and the Trent-Soar confluence.

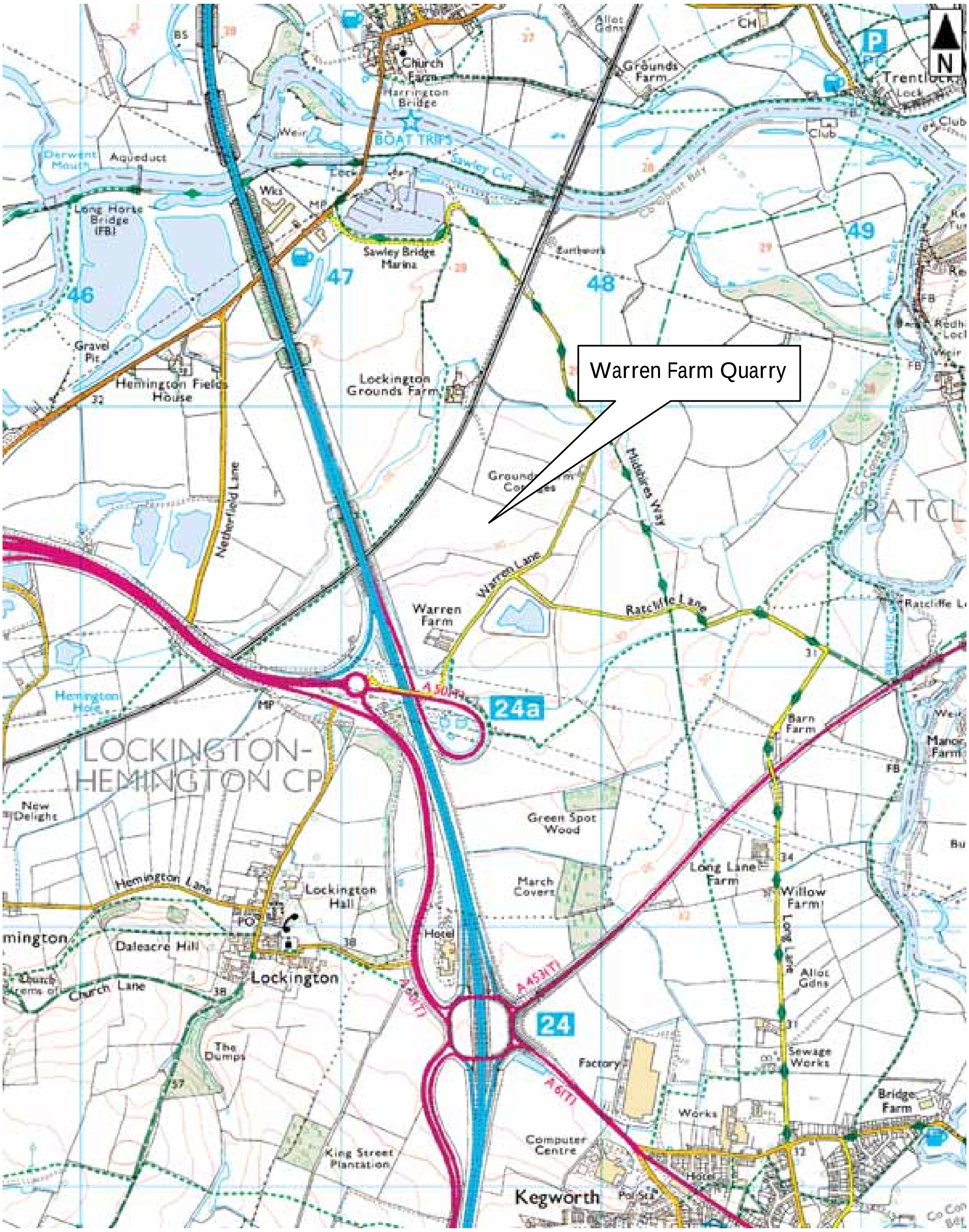


Figure 2: Location map of Warren Farm Quarry, Lockington, Leicestershire.

Figure 3: Sampling at Warren Farm Quarry, Lockington (photo: Andy Howard)

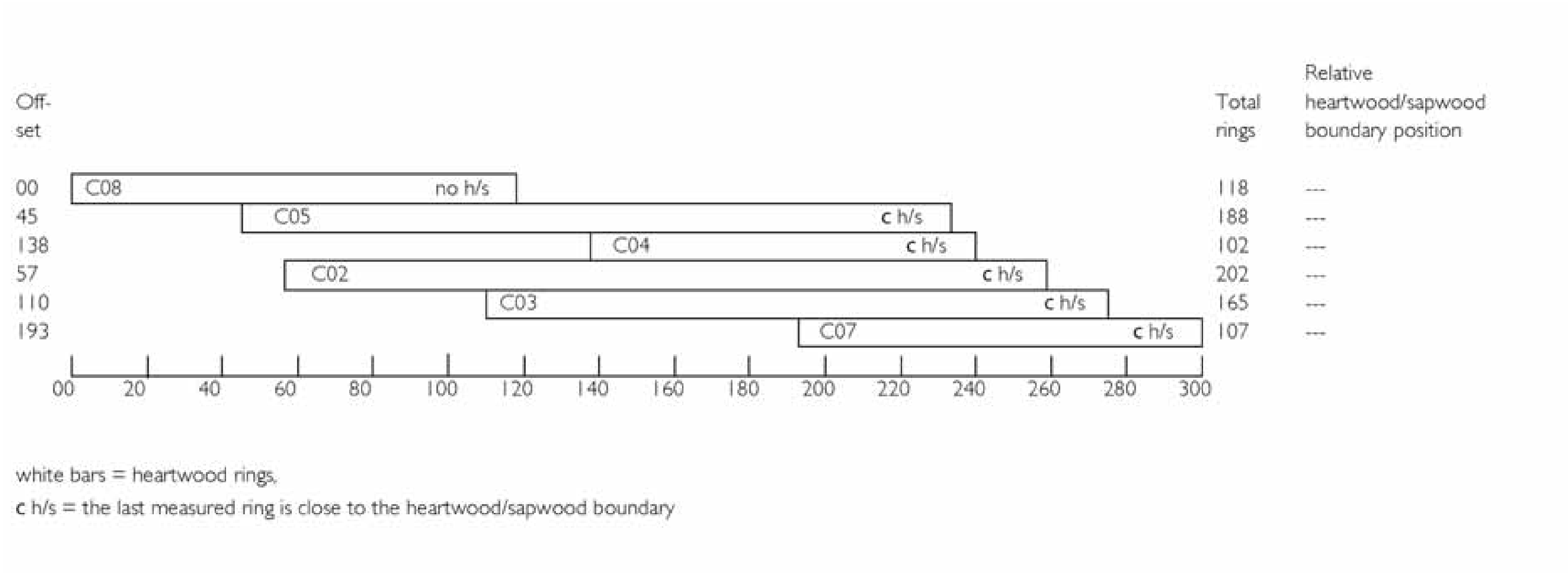


Figure 4: Bar diagram of the samples in site chronology LOKQ sequence 1

MEASUREMENTS IN 0.01MM UNITS

LOK-Q01A 83
214 244 192 215 289 539 363 417 432 300 265 411 257 185 191 272 207 119 68 31
45 68 51 47 62 70 62 69 66 130 134 116 143 146 115 229 178 213 201 173
181 178 158 102 90 85 131 106 99 165 126 165 160 278 195 201 153 147 117 150
130 129 84 93 109 93 126 138 109 102 76 113 103 89 79 135 98 103 105 132
78 103 167
LOK-Q01B 83
215 272 370 315 554 427 399 417 334 244 419 254 193 194 274 194 146 55 41 52
41 43 42 61 57 42 68 55 112 118 144 159 147 131 180 174 194 221 166 190
171 161 110 94 82 136 118 92 160 119 144 162 281 196 197 153 150 104 168 131
131 173 59 96 107 130 126 115 110 73 115 99 84 87 134 101 93 103 107 98
99 95 159
LOK-Q02A 143
94 160 109 98 99 88 68 85 82 113 71 81 61 135 99 110 147 83 58 60
104 92 101 80 140 69 89 68 60 64 99 64 64 81 78 58 69 109 67 41
66 56 63 64 55 74 86 69 100 69 92 73 111 48 66 81 85 86 155 155
137 71 98 136 56 31 52 56 55 36 51 52 69 74 52 62 74 50 50 60
58 49 50 56 70 70 63 103 114 90 131 148 73 60 89 100 70 88 112 111
62 70 87 57 62 105 107 89 135 109 92 84 78 73 82 87 91 72 70 108
125 145 118 58 67 80 89 140 117 90 95 63 83 81 111 107 75 51 54 61
51 63 83
LOK-Q02B 123
188 160 120 167 148 182 181 76 145 223 190 152 117 132 114 66 85 96 84 83
48 73 97 131 70 127 60 72 140 86 123 144 158 96 69 125 54 74 57 140
143 112 150 128 120 80 76 163 166 162 152 155 116 86 77 81 125 80 98 110
129 109 85 99 94 79 68 83 152 94 74 79 133 95 111 171 90 55 54 96
89 86 98 108 72 82 77 61 63 79 61 77 65 82 51 53 94 71 62 60
82 61 65 74 82 73 58 98 72 73 85 74 42 62 63 64 83 128 137 111
89 84 141
LOK-Q03A 165
133 142 160 230 122 173 182 171 160 146 133 148 108 123 126 263 135 161 112 123
116 90 136 118 153 257 245 152 163 242 90 162 297 65 58 54 49 69 84 111
90 172 211 161 104 170 164 167 80 153 179 155 114 76 75 146 185 198 156 93
200 160 173 257 241 260 265 153 167 209 86 71 82 86 85 115 97 137 149 161
143 88 202 122 136 146 139 90 95 145 113 121 105 139 111 158 149 109 72 114
101 121 97 116 168 169 110 140 133 133 75 153 114 134 150 157 111 109 140 105
121 137 106 118 161 186 143 169 148 124 131 186 224 232 204 120 149 165 166 142
212 261 187 171 124 122 74 76 39 80 93 131 94 108 121 99 105 79 167 120
110 81 75 100 173
LOK-Q03B 165
173 158 173 218 122 167 172 190 168 126 157 141 97 144 134 260 118 137 117 123
112 85 149 127 156 262 224 148 177 224 103 192 237 114 60 52 78 147 51 61
86 156 157 162 111 151 169 173 72 131 181 152 126 78 73 140 204 184 213 95
172 153 183 262 244 270 382 123 168 212 66 75 85 78 104 110 108 123 144 162
146 103 174 131 136 141 140 85 122 143 126 124 85 147 127 144 136 115 76 104
124 125 97 121 173 172 106 139 131 128 75 140 99 143 147 133 153 105 112 120
110 135 127 101 161 173 142 169 157 136 106 200 236 210 213 126 128 160 169 133
247 225 186 153 132 128 63 69 59 68 74 138 106 97 136 120 82 87 181 195
105 71 85 101 106
LOK-Q04A 102
149 161 160 111 90 98 70 62 89 60 79 66 78 53 79 98 64 53 95 104
55 63 75 88 90 66 111 98 101 125 91 66 84 84 90 106 151 163 149 117
121 178 82 53 49 42 46 67 69 63 96 86 67 66 108 92 72 68 75 50
47 78 153 101 80 116 123 174 198 232 99 61 107 125 105 111 131 169 102 97
75 100 64 99 98 140 162 119 99 83 86 84 81 114 82 85 82 116 175 135
125 83

LOK-Q04B 100
98 147 183 105 96 92 67 76 82 64 61 83 74 62 71 84 68 61 103 62
65 73 77 91 84 72 99 86 109 115 110 59 89 83 100 91 152 168 154 113
117 157 96 42 37 39 58 59 63 66 123 66 72 71 98 103 66 84 60 63
46 85 127 112 85 120 106 198 205 241 103 70 96 132 114 115 119 169 107 102
99 81 63 108 98 127 160 118 105 75 88 81 103 86 94 74 101 120 120 158
LOK-Q05A 135
211 286 214 83 120 234 100 143 94 247 165 147 111 87 81 78 88 169 115 150
182 135 141 106 117 133 134 110 197 118 148 112 113 135 102 148 102 162 255 68
106 91 196 94 161 128 84 108 93 122 117 130 150 141 135 253 175 93 132 241
127 112 122 138 115 122 168 145 97 209 158 159 110 124 162 114 88 135 115 135
104 140 94 145 137 123 178 181 170 152 86 111 205 146 163 127 95 114 136 140
96 192 164 129 118 211 139 107 147 122 68 84 98 134 90 91 107 108 103 117
150 97 94 209 211 135 199 204 175 150 129 137 199 123 180
LOK-Q05B 188
186 194 216 164 145 120 159 200 138 114 201 397 211 203 125 148 125 186 170 97
210 350 298 193 139 153 289 175 275 202 127 193 137 220 207 180 128 246 157 267
313 179 448 342 296 125 153 247 125 200 89 251 159 190 152 127 142 101 89 258
154 188 221 147 169 115 123 129 142 103 239 122 164 108 143 160 103 127 104 101
159 72 67 77 146 85 87 109 50 71 71 63 72 65 60 56 50 97 55 46
65 102 65 54 59 70 47 77 104 69 83 87 113 105 97 115 129 115 106 136
122 123 122 137 100 206 117 146 173 191 187 138 101 142 216 131 129 85 71 105
155 151 77 121 105 78 87 121 82 91 139 104 49 77 76 91 91 70 105 93
108 103 122 79 72 113 159 105 101 148 139 91 107 117 156 89 207 114 148 162
193 108 172 304 406 276 242 193
LOK-Q06A 105
181 130 120 144 156 250 170 171 172 108 160 146 218 309 215 314 307 307 274 375
288 508 624 590 376 305 316 267 173 213 219 279 309 402 336 330 200 364 321 332
138 169 156 216 195 191 112 238 272 302 294 275 249 196 171 218 251 188 190 193
180 213 281 313 219 134 81 109 171 159 109 172 149 101 91 115 136 137 150 184
130 138 112 116 102 76 107 131 183 171 85 137 126 107 95 97 98 100 105 139
98 155 148 133 160
LOK-Q06B 105
156 118 129 145 154 231 174 174 143 112 137 143 260 307 217 321 313 310 284 378
296 512 628 576 330 276 286 272 175 217 245 273 294 401 339 321 220 356 345 302
164 172 160 201 195 180 123 208 249 298 346 302 239 202 155 208 265 179 188 209
154 200 268 324 230 123 88 104 163 158 130 150 145 112 81 118 149 141 173 154
128 111 132 101 108 79 106 130 163 187 111 126 106 117 100 84 108 103 107 143
112 138 164 134 144
LOK-Q07A 107
502 395 435 644 383 364 565 787 448 331 442 384 325 501 372 217 149 400 382 234
273 360 305 176 268 367 308 167 306 233 386 310 360 229 143 239 182 250 324 214
249 265 395 360 242 298 193 173 297 298 260 270 151 183 208 160 118 209 252 240
335 311 310 189 139 79 140 108 146 145 124 174 165 178 295 385 177 414 262 217
332 232 192 198 210 338 114 162 260 167 129 132 131 118 144 145 124 115 110 83
90 62 76 137 85 137 156
LOK-Q07B 107
462 392 505 635 366 417 573 753 425 321 466 382 343 531 414 178 176 412 331 203
314 373 267 144 205 316 275 177 296 243 405 323 337 234 140 264 190 241 312 243
254 252 379 352 264 280 218 189 308 288 277 261 178 165 217 135 137 216 295 261
308 336 318 181 164 104 116 84 179 140 136 173 173 162 300 390 172 442 244 229
364 264 210 187 210 357 135 146 240 209 122 160 110 105 151 133 130 105 119 77
76 86 81 125 88 121 146
LOK-Q08A 118
337 385 413 227 224 329 312 208 330 258 197 223 314 244 380 364 202 175 264 300
267 264 268 318 272 310 196 182 250 333 287 193 183 144 127 152 157 128 194 280
225 224 133 128 87 106 116 176 139 193 152 128 111 155 86 173 156 187 192 147
128 133 125 165 89 145 170 111 138 146 110 237 78 92 123 126 124 112 157 163
133 114 114 101 129 210 108 125 161 177 95 81 167 68 62 52 139 155 129 90
89 107 87 86 142 132 152 161 118 122 103 86 81 106 87 159 109 182

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,

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	

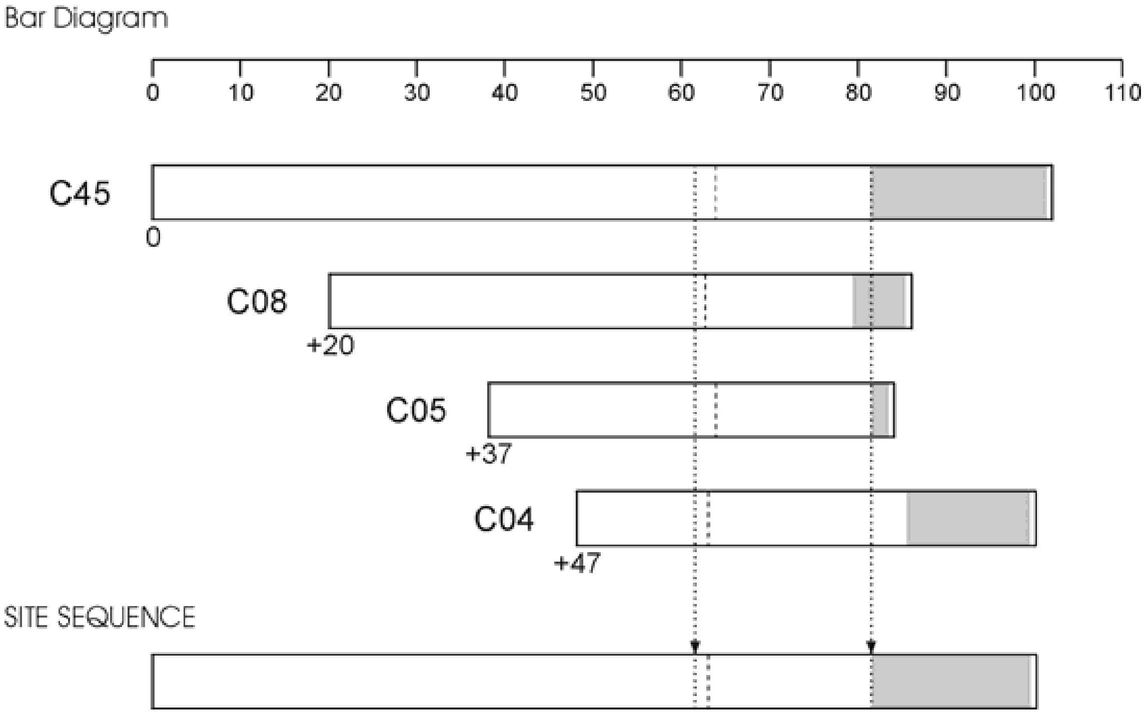


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

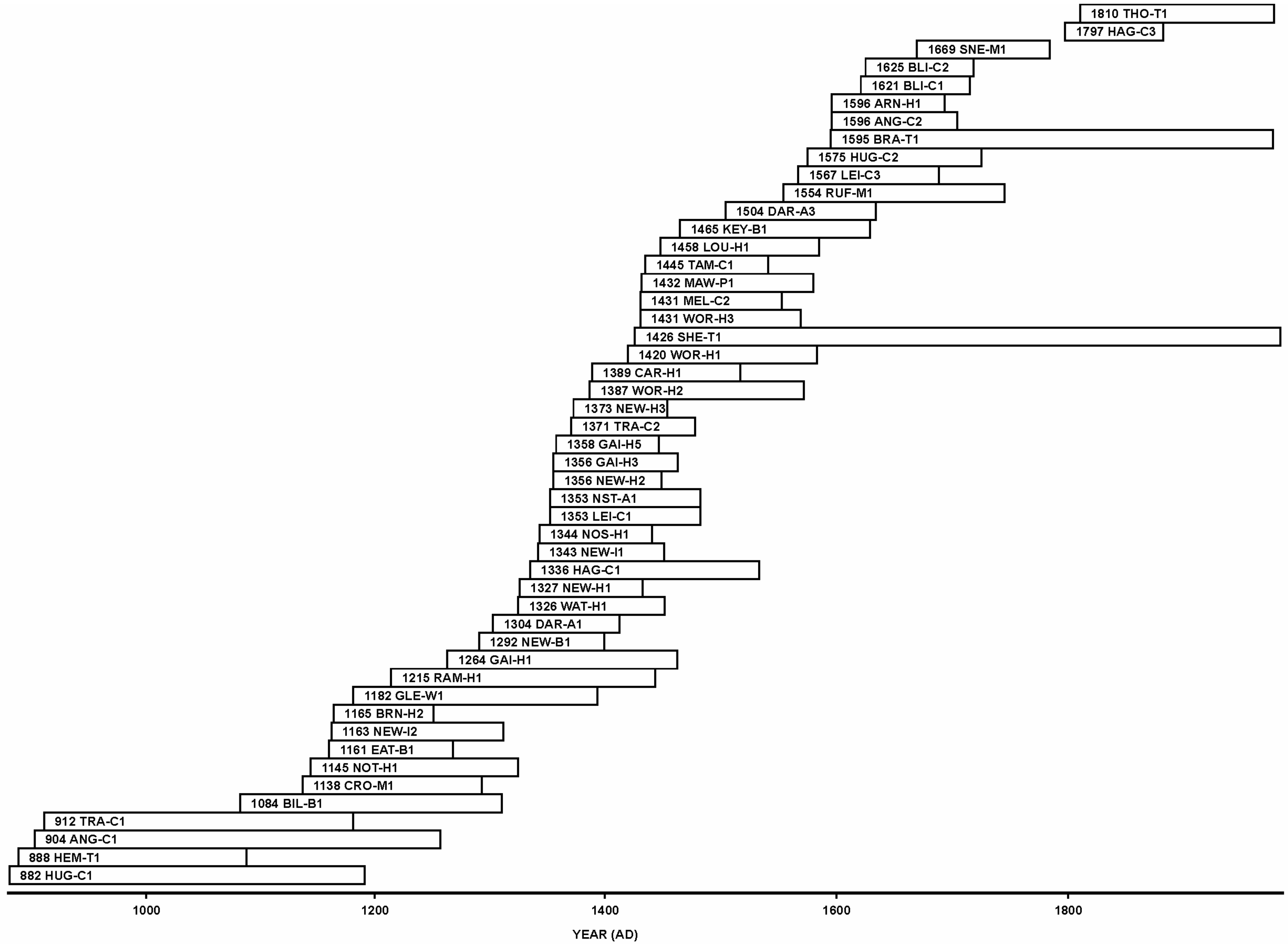
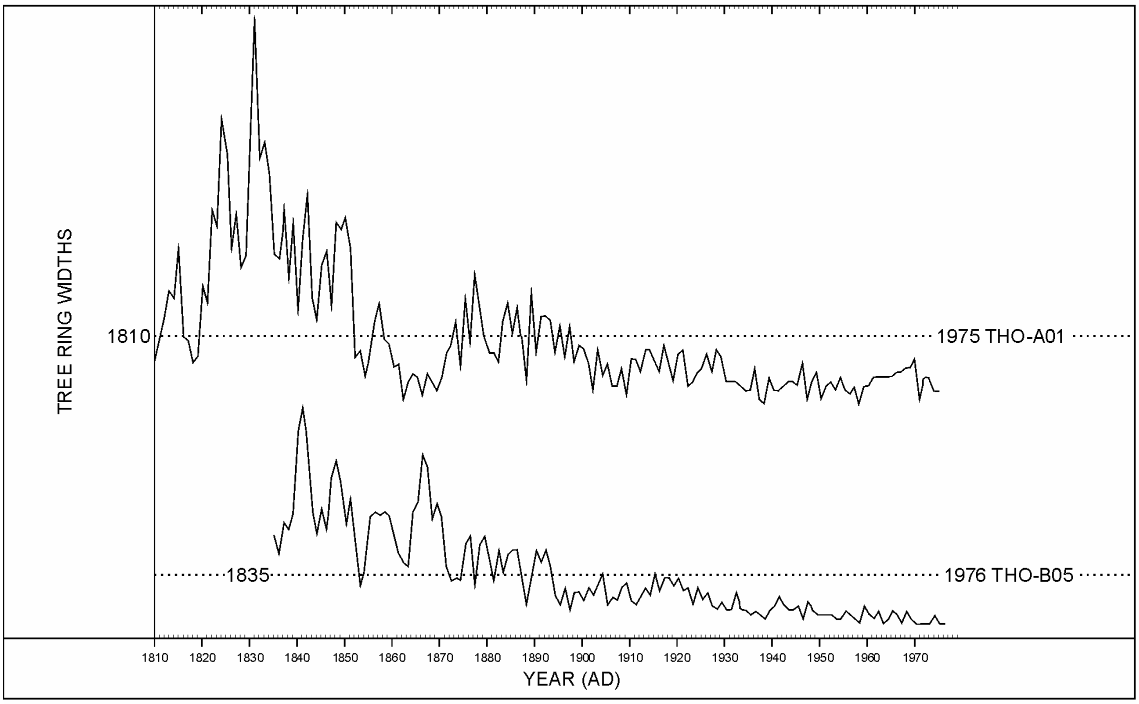


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

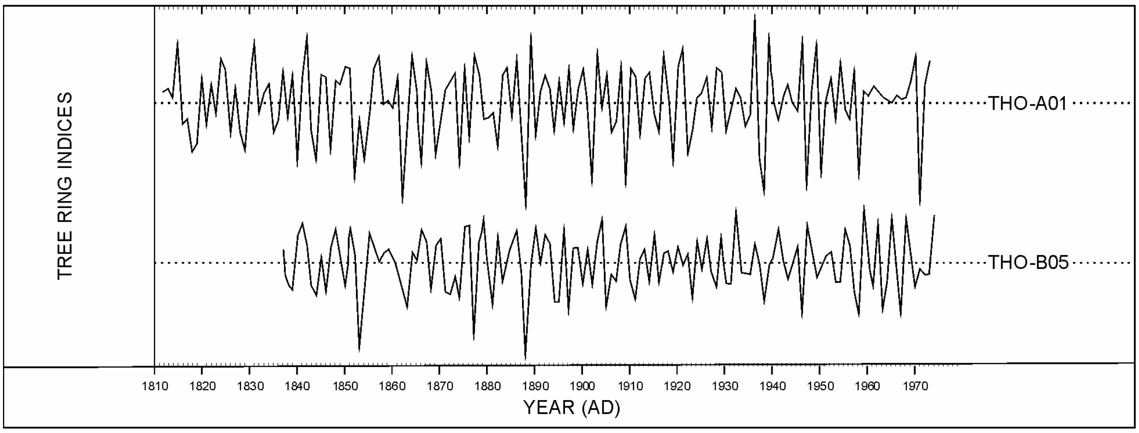


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

Appendix References

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

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

Hillam, J, Morgan, R A, and Tyers, I, 1987 Sapwood estimates and the dating of short ring sequences, *Applications of Tree-Ring Studies*, BAR Int Ser, **3**, 165–85

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

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, **8**, 381–90

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

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

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

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

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

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

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

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

This report has been prepared for use on the internet and the images within it have been down-sampled to optimise downloading and printing speeds.

Please note that as a result of this down-sampling the images are not of the highest quality and some of the fine detail may be lost. Any person wishing to obtain a high resolution copy of this report should refer to the ordering information on the following page.

ENGLISH HERITAGE RESEARCH DEPARTMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for sustainable management, and to promote the widest access, appreciation and enjoyment of our heritage.

The Research Department provides English Heritage with this capacity in the fields of buildings history, archaeology, and landscape history. It brings together seven teams with complementary investigative and analytical skills to provide integrated research expertise across the range of the historic environment. These are:

* *Aerial Survey and Investigation*
* *Archaeological Projects (excavation)*
* *Archaeological Science*
* *Archaeological Survey and Investigation (landscape analysis)*
* *Architectural Investigation*
* *Imaging, Graphics and Survey (including measured and metric survey, and photography)*
* *Survey of London*

The Research Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support outreach and education activities and build these in to our projects and programmes wherever possible.

We make the results of our work available through the Research Department Report Series, and through journal publications and monographs. Our publication Research News, which appears three times 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 Department Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

For further information visit www.english-heritage.org.uk

ENGLISH HERITAGE