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THE DOVECOTE, BREAKSPEAR HOUSE, BREAKSPEAR ROAD NORTH, HAREFIELD, HILLINGDON, LONDON
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY
Dendrochronological analysis of the roof of the dovecote at Breakspear House, has produced a single dated site chronology comprising nine of the 10 samples measured. This site chronology has an overall length of 75 rings, these dated as spanning the years AD 1695–1769. Interpretation of the sapwood on the dated samples, all common rafters, indicates that the roof is composed of timber felled between late summer AD 1769 and very early AD 1770.

A single measured sample remains ungrouped and undated.

CONTRIBUTORS
Alison Arnold and Robert Howard

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ARCHIVE LOCATION
Greater London Historic Environment Record
English Heritage
1 Waterhouse Square
138–142 Holborn Place
London EC1N 2ST

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2011

CONTACT DETAILS
Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
alisonarnold@tree-ringdating.co.uk
roberthoward@tree-ringdating.co.uk

CONTENTS

INTRODUCTION

Breakspear House is a large, Grade I listed, red-brick mansion, standing in its own grounds approximately one kilometre to the south-east of Harefield Village, west London, in the county of Middlesex (TQ 06016 89692, Figs 1 and 2). Although an earlier house, possibly dating from the early- to mid-sixteenth century, may have existed here, the present house contains timber dated by tree-ring analysis to the early-seventeenth century, the late-seventeenth century, and possibly to the early-eighteenth century (Arnold and Howard 2010). The house has been the subject of an archaeological assessment and historic building report (Compass Archaeology Ltd 2009).

Within the grounds, to the north-west of Breakspear House, stands a two-storey dovecote, also the subject of archaeological assessment and survey (Compass Archaeology Ltd, forthcoming). This is a square, red brick building, with a slightly jettied first floor over a moulded string course, with battered angle-buttresses to the ground floor. The dovecote has a pyramidal tiled roof surmounted by a fine bell cupola with clock, the mechanism still retained within the attic. There are 'Tudor' arched entrances on the east and west sides, and a lancet opening in south side. The building is listed as Grade II*. The fabric of the dovecote, and other associated buildings, has experienced such deterioration since the site was abandoned in 1987 that that they are now on the Heritage at Risk register (www.english-heritage.org.uk).

Although constructed of brick, and believed to date in this form from the seventeenth century, the dovecote, following the recent survey, is now thought to have originally been a timber-framed structure, and, like the earlier house on this site, to possibly date from the early- to mid-sixteenth century. Differences in the brickwork to the ground and first-floor levels suggest that any timberwork which might have existed here may have been replaced piecemeal, and at different times, as possible decay of the frame dictated. In this interpretation, although the wall framing has been replaced, the timbers of the roof are possibly still original.

SAMPLING

Sampling and analysis by dendrochronology of the timbers of the dovecote were requested by Kim Stabler, Archaeology Advisor in English Heritage's Greater London Archaeological Advisory Service, and Will Reading, Historic Building and Areas Advisor in English Heritage's London Region Office. This was undertaken in an attempt to more fully understand the history of the dovecote and to determine the extent of survival of the historic fabric. It was hoped that this analysis would inform the historic buildings appraisal being undertaken in advance of potential redevelopment, and inform the associated listed building consent as appropriate.

A thorough assessment of the potential of the dovecote timbers for tree-ring analysis was made prior to sampling. This showed that although there were one or two oak timbers used as lintels to now-blocked ground-floor openings, these were very small, deeply buried in the walls, and apparently derived from fast-grown trees. As such, it was felt very unlikely that they would provide samples with a sufficient number of rings, here deemed to be in excess of 50, for reliable analysis.

A further series of large timber joists were seen forming the ceiling of both the ground and first-floor chambers. These, however, were all deemed to be of some type of softwood, possibly pine, and again to have insufficient rings for reliable analysis.

It was thus only in the, possibly original, roof that a sufficient number of oak timbers could be found, the majority of these being common rafters which, although of slightly small scantling, appeared to have sufficient rings (Fig 3). In addition to the common rafters there were four slightly larger rafters, though hardly principals, at the corners of each pitch of the roof, along with plates to the top of each of the four walls. These last two sets of timbers, however, again appeared to be derived from fast grown timbers and to be generally unsuitable for tree-ring analysis, thus sampling focussed predominantly on the common rafters.

Thus, from the timbers available a total of 11 oak samples was obtained by coring. Each sample was given the code HFD-C (for Harefield, site 'C') and numbered 01–11. The location of the sampled timbers was noted at the time of coring and marked on a plan made by STRUCTA, consulting engineers, and provided by Compass Archaeology Ltd. This is reproduced here as Figure 4. Further details relating to the samples can be found in Table 1.

ANALYSIS

Each of the 11 samples obtained was prepared by sanding and polishing. It was seen at this time that one sample, HFD-C11, had less than the minimum of 50 rings here deemed necessary for reliable dating, and it was rejected from this programme of analysis. The annual growth-ring widths of the remaining 10 samples were, however, 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 nine cross-matching samples to be formed at a particularly high minimum value of t=8.0 (see section on intra-site cross-matching below). The nine samples cross-match as shown in Figure 5. The cross-matching samples of this group were combined at their indicated offset positions to form HFDCSQ01, a site chronology with an overall length of 75 rings.

Site chronology HFDCSQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a number of these when the date of its first ring is AD 1695 and the date of its last measured ring is AD 1769. The evidence for this dating is given in Table 2.

Site chronology HFDCSQ01 was also compared to the single remaining measured but ungrouped sample, but there was no further satisfactory cross-matching. This single remaining sample was then compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and this sample must, therefore, remain undated.

INTERPRETATION AND CONCLUSION

Analysis by dendrochronology of 10 measured samples from this building has produced a single site chronology comprising nine samples, its 75 rings dated as spanning the years AD 1695–1769. As may be seen from Table 1 and the bar diagram, Figure 5, all but two of these nine samples, HFD-C03 and C08, retain complete sapwood (the last ring produced by the tree from which the beam has been derived before it was cut down), this being indicated by upper case 'C' in Table 1 and the bar diagram. In every case, judging by the development of large amounts of summer cell growth for this last year and the lack of any spring cell growth for the following year, the condition of this last, complete, sapwood ring indicates that the trees represented were felled between the late summer of AD 1769 and the spring of AD 1770.

The two other dated samples in this site chronology, HFD-C03 and C08, come from timbers which do have complete sapwood on them. Small amounts of the sapwood, however, have been lost from these samples in coring, this due to the soft and fragile nature of this part of the wood (this is indicated by lower case 'c' in Table 1 and the bar diagram). The average date of the boundary on these two samples is AD 1754. Using a 95% confidence limit of 15–40 rings for the amount of sapwood these trees might have had would give the timbers represented an estimated felling date in the range AD 1769–94. It may be seen that this estimated range brackets the known felling date of seven other timbers suggesting the two timbers in question could have been felled at a very similar, if not identical, time.

It will of course be seen from Table 1 that all the dated timbers are solely common rafters, and it is thus possible that other beams, principal rafters, wall plates, etc, are of a different date. It would perhaps be necessary to undertake a survey of the roof to address whether it is entirely of a single phase of construction, or if older timbers have been reused, or more recent timbers inserted. The undated principal rafter, for example (HFD-C05), provides the sample with the longest ring sequence from the site and is also the fastest grown. This could be taken as some indication that the timber was sourced from a different woodland, and thus could possibly be of a different date. Tree-ring dating of timbers from the main house to the early-seventeenth century, the late-seventeenth century, and possibly to the early-eighteenth century, show that timbers of different dates can be found in the same building.

Apart from dating the timbers, it may be of interest to note that the intra-site cross-matching of the samples of site chronology HFDCSQ01, is such as to suggest that the timbers represented have been derived from a single woodland source, a number of samples cross-matching with each other with values in excess of t=9.0. Indeed, the level of cross-matching between some samples, HFD-C01, C07, and C09, or between HFD-C02, C08, and C10 for example, where values in excess of t=10, t=11.0 and t=12.0 are seen, is sufficiently high as to suggest the possibility that the two or more timbers are derived from the same tree. Such an interpretation is supported by the probability that many of the common rafters appeared to be quarter-trees.

Where this source woodland was cannot be identified precisely by dendrochronology (eg Bridge 2000). However, as may be seen from Table 2, which lists a short selection of the reference chronologies used to date site sequence HFDCSQ01, the majority of better cross-matches tend to be with reference chronologies from north of London and this could be taken as evidence of a possible general source area. In respect of this, the London composite reference chronology is relatively poorly replicated in its latter years, ie, the time relevant to the dovecote. The data obtained from the dovecote and Breakspear House samples are thus welcome additions to the relatively scarce late-seventeenth and eighteenth century London dataset.

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TABLES

Table 1: Details of tree-ring samples from The Dovecote, Breakspear House, Harefield, Hillingdon, London

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
HFD-C01	North pitch, rafter 7 (from east)	75	21C	1695	1748	1769
HFD-C02	South pitch, rafter 4 (from east)	63	20C	1707	1749	1769
HFD-C03	South pitch, rafter 7	63	12c	1702	1752	1764
HFD-C04	South pitch, rafter 8	65	20C	1705	1749	1769
HFD-C05	South east principal rafter	87	2	------	------	------
HFD-C06	East pitch, rafter 9 (from north)	66	15C	1704	1754	1769
HFD-C07	East pitch, rafter 8	66	19C	1704	1750	1769
HFD-C08	West pitch, rafter 5 (from north)	63	8c	1702	1756	1764
HFD-C09	West pitch, rafter 7	68	17C	1702	1752	1769
HFD-C10	West pitch, rafter 8	66	12C	1704	1757	1769
HFD-C11	South wall plate	nm	---	------	------	------

nm = sample not measured

c = complete sapwood is found on the timber, but all or part has been lost from the sample in coring

C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented

Table 2: Results of the cross-matching of site sequence HFDCSQ01 and relevant reference chronologies when the first-ring date is AD 1695 and the last-ring date is AD 1769

Reference chronology	Span of chronology	*t*-value	Reference
Tilbury Fort, Thurrock, Essex	AD 1678–1777	7.9	(Groves 1993)
Ely Cathedral, Ely, Cambs	AD 1678–1828	6.2	(Esling *et al* 1989)
HMS Victory, Greenwich, London	AD 1640–1800	6.2	(Barefoot 1975)
Clothall Bury Farmhouse, Wallingford, Herts	AD 1636–1753	6.1	(Arnold *et al* 2003)
Burghley House, Burghley, Cambs	AD 1686–1809	5.8	(Howard *et al* 1992)
Hampshire county chronology	AD 443–1972	5.7	(Miles 2003)
Manor barn, Great Newstead, Staplehurst, Kent	AD 1670–1780	5.6	(Arnold *et al* 2003)
Cobham Hall, Cobham, Kent	AD 1656–1774	5.5	(Arnold *et al* 2003)

FIGURES

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

Figure 2: Map to show the location of Breakspear House (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 3: The dovecote roof viewed from the south-east

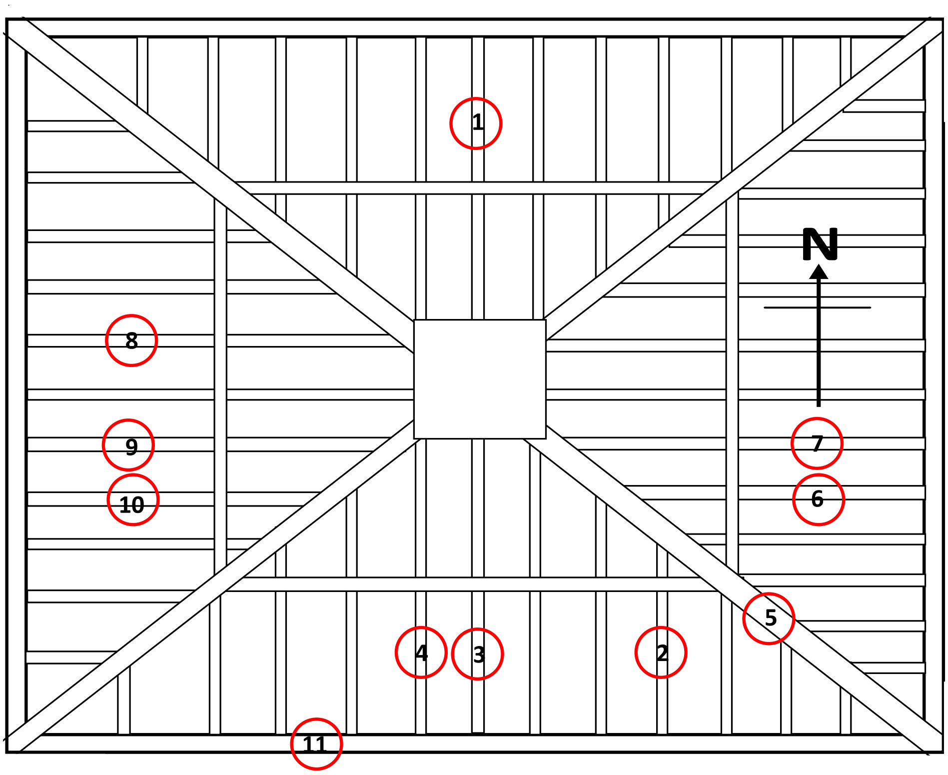
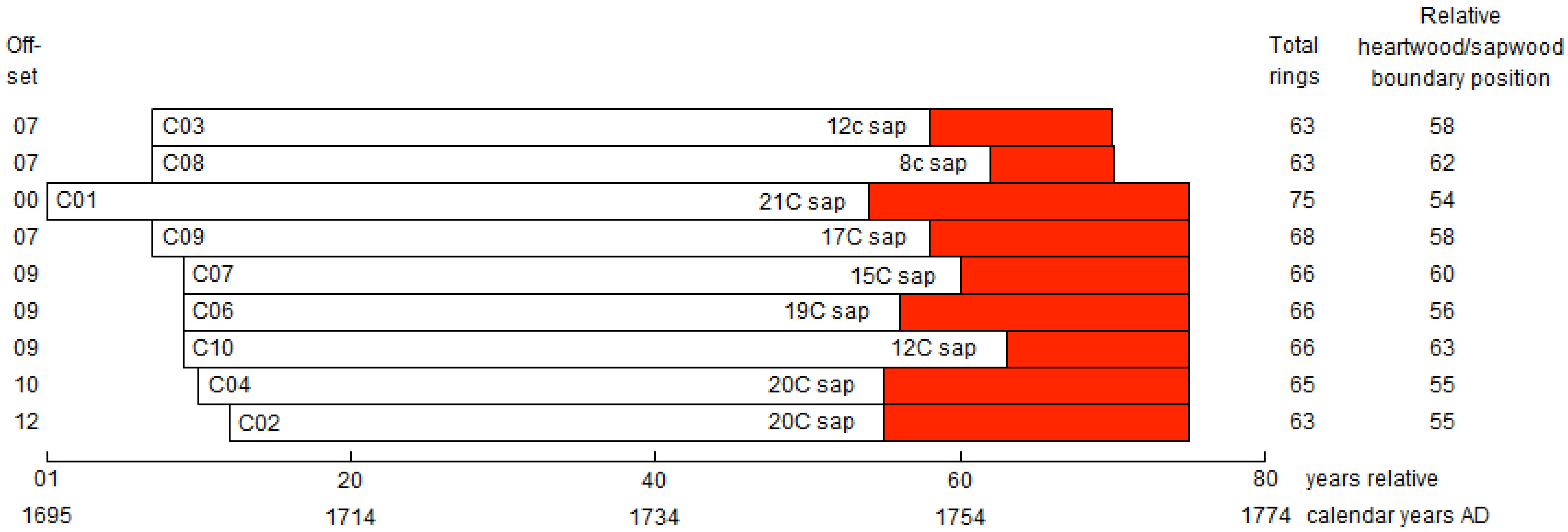


Figure 4: Plan of the dovecote roof to show sampled timbers (after STRUCTA, consulting engineers)



White bars =heartwood rings, shaded area = sapwood rings
c = complete sapwood is found on the timber, but all or part has been lost from the sample in coring
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented

Figure 5: Bar diagram of the samples in site chronology HFDCSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HFD-C01A 75
206 389 291 275 259 213 179 185 259 190 157 198 118 138 189 174 163 220 375 172
276 160 146 88 44 110 192 169 140 111 78 79 139 134 122 136 105 152 105 109
92 97 83 109 116 54 48 47 65 49 50 76 82 70 42 64 80 96 89 102
95 109 73 96 79 91 72 77 120 108 71 103 81 130 88
HFD-C01B 75
209 380 282 258 259 211 187 184 263 188 155 201 105 142 189 176 166 219 382 177
273 176 149 84 48 121 171 176 139 127 90 75 137 135 117 116 116 160 109 117
90 90 82 107 111 57 49 63 61 46 55 75 85 69 38 78 82 94 91 110
98 110 73 94 69 89 79 74 120 103 73 106 88 128 77
HFD-C02A 63
128 154 166 89 114 149 210 116 156 169 121 74 84 111 151 120 164 163 86 83
97 137 138 137 152 175 204 217 193 263 236 287 295 146 129 178 162 106 142 228
240 168 137 170 286 310 218 210 254 264 128 100 115 105 185 184 213 242 211 239
188 215 163
HFD-C02B 63
128 149 170 88 118 135 222 114 160 174 104 68 79 110 154 128 149 160 82 89
111 128 131 143 151 178 221 223 199 260 245 276 293 164 130 158 165 100 130 236
223 176 128 183 273 317 224 226 235 268 126 95 125 112 183 180 209 237 236 225
175 217 169
HFD-C03A 63
163 206 155 191 186 126 115 156 153 187 220 195 183 217 161 141 90 68 126 139
171 163 126 97 115 166 147 159 138 127 221 167 170 156 205 176 243 188 151 128
122 121 74 97 136 137 109 69 101 137 129 100 116 121 167 105 127 88 146 109
102 159 118
HFD-C03B 63
167 207 154 193 177 135 114 158 150 168 211 185 175 211 162 138 85 77 106 149
176 170 126 99 110 175 142 157 136 138 215 173 170 167 194 188 231 202 114 121
116 129 65 93 132 155 104 76 102 117 109 109 125 110 160 98 133 103 136 110
113 161 121
HFD-C04A 65
157 255 137 143 321 182 155 192 241 122 244 185 187 125 114 144 220 117 133 109
119 73 189 218 246 252 197 219 164 128 54 139 130 135 92 108 54 45 55 36
42 99 86 45 40 72 167 163 90 129 111 123 107 90 166 79 84 52 146 112
73 96 126 148 133
HFD-C04B 65
145 260 128 139 329 180 149 199 237 129 236 230 160 118 110 138 213 125 145 108
112 70 199 208 223 252 169 264 159 129 53 142 126 135 88 108 52 41 53 45
40 104 89 49 49 76 162 161 87 140 106 129 102 89 165 79 87 61 136 117
66 100 122 165 122
HFD-C05A 87
311 189 154 134 175 108 184 209 213 331 211 269 252 193 174 223 228 355 288 233
352 339 272 307 293 363 303 243 163 223 228 128 108 184 192 193 165 107 87 60
72 120 142 87 82 110 102 89 119 106 148 126 120 129 87 82 118 87 109 103
115 85 315 403 404 345 447 404 387 384 185 163 342 315 267 345 282 348 430 334
298 309 337 450 322 317 177
HFD-C05B 87
355 195 156 128 173 104 188 202 234 309 216 278 260 180 181 231 219 372 272 242

351 322 276 315 276 371 313 252 153 199 228 126 116 188 187 192 165 110 92 52
72 130 152 90 76 116 90 102 111 105 154 124 113 126 102 87 120 81 108 99
113 78 328 404 409 342 449 408 384 382 185 160 332 324 260 344 294 328 427 310
307 313 327 454 306 345 166
HFD-C06A 66
307 248 224 106 96 211 185 122 157 174 86 155 162 154 94 79 119 212 188 120
111 58 72 72 101 109 85 86 125 115 60 111 82 57 85 111 66 75 65 64
60 63 97 90 63 56 78 387 268 139 294 285 352 175 239 229 168 177 114 263
256 177 205 222 250 210
HFD-C06B 66
303 248 223 95 92 213 167 137 158 178 95 167 169 155 109 62 140 220 172 136
117 61 73 73 98 109 80 87 123 111 70 98 94 53 87 106 76 68 61 70
57 61 102 81 74 61 84 370 266 142 305 275 349 165 232 243 143 175 138 245
261 166 213 209 269 212
HFD-C07A 66
272 234 282 155 150 179 181 169 193 257 157 228 167 179 117 93 179 236 213 177
134 73 95 130 155 132 128 90 126 149 131 126 134 150 188 165 102 80 85 97
44 65 134 159 106 63 123 173 209 158 147 104 138 84 97 69 89 79 87 110
111 111 113 93 110 114
HFD-C07B 66
279 238 273 159 155 175 183 156 195 259 174 233 176 182 118 94 154 209 209 192
137 86 78 136 154 136 121 102 123 134 140 125 139 144 188 154 105 77 89 97
48 61 123 156 103 65 103 186 189 176 140 115 135 85 96 72 87 78 89 115
118 98 127 80 110 113
HFD-C08A 63
132 203 144 108 176 120 116 185 119 203 174 229 140 181 229 187 115 123 158 187
154 169 175 126 114 206 169 191 178 181 186 233 215 205 248 242 255 209 161 141
131 117 96 87 153 168 127 129 129 284 279 179 177 180 181 138 188 156 134 170
122 176 182
HFD-C08B 63
112 218 131 120 170 124 112 189 117 194 161 230 143 185 228 193 109 123 155 191
148 167 183 127 117 207 160 183 188 172 190 219 207 195 247 248 250 217 157 134
137 116 92 94 151 170 130 115 144 278 275 178 174 190 184 156 163 158 132 166
117 180 185
HFD-C09A 68
216 340 294 218 219 143 161 205 184 159 203 297 186 253 211 164 104 92 141 193
214 168 129 114 103 193 156 127 163 137 190 134 162 151 169 172 223 206 156 148
98 115 95 76 113 164 116 59 129 149 208 166 189 125 166 87 112 109 123 143
108 216 135 131 162 131 139 121
HFD-C09B 68
180 344 291 217 217 156 152 205 194 150 203 300 188 265 206 156 106 96 153 197
227 156 128 112 121 171 157 123 157 143 195 128 165 152 160 168 218 213 169 136
101 124 82 83 117 158 118 59 118 158 214 146 181 135 169 91 99 123 128 129
115 210 142 118 164 115 149 130
HFD-C10A 66
183 147 190 155 174 264 190 204 254 325 156 255 228 182 134 136 159 211 152 151
180 134 175 256 222 178 163 170 229 235 255 254 247 230 275 259 178 145 175 196
169 133 278 320 228 158 163 340 339 270 294 282 338 222 205 250 190 253 171 282
267 196 239 172 202 141
HFD-C10B 66
195 125 195 146 168 272 193 212 247 336 156 269 215 186 128 128 163 199 160 169
172 140 169 270 224 163 180 160 235 230 258 246 255 234 273 264 166 149 178 189
174 123 292 306 222 169 166 346 337 265 275 274 344 229 205 249 171 261 188 265

270 203 243 161 208 140

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

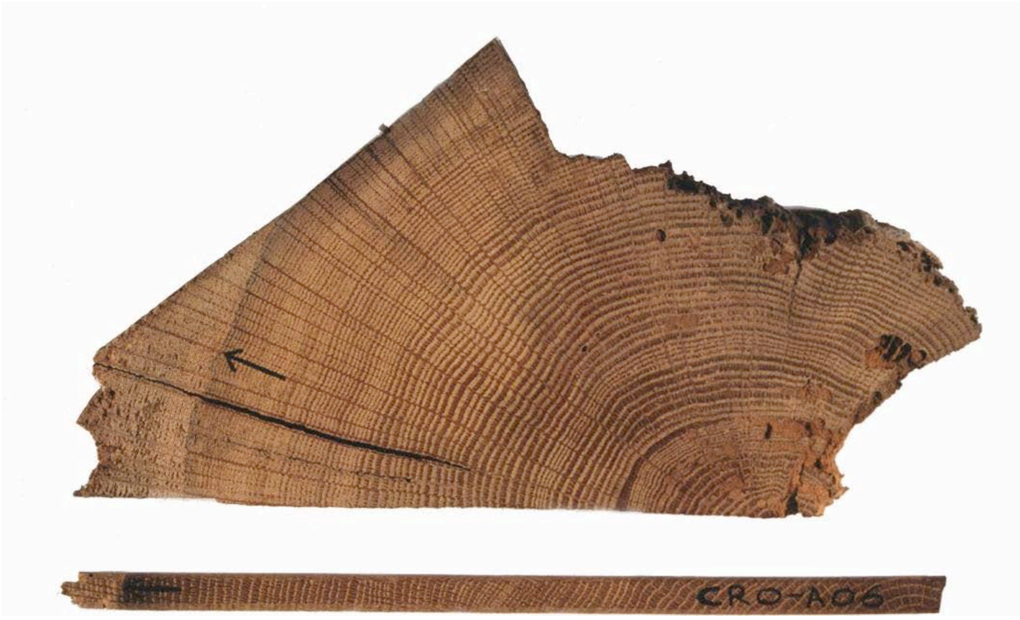


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

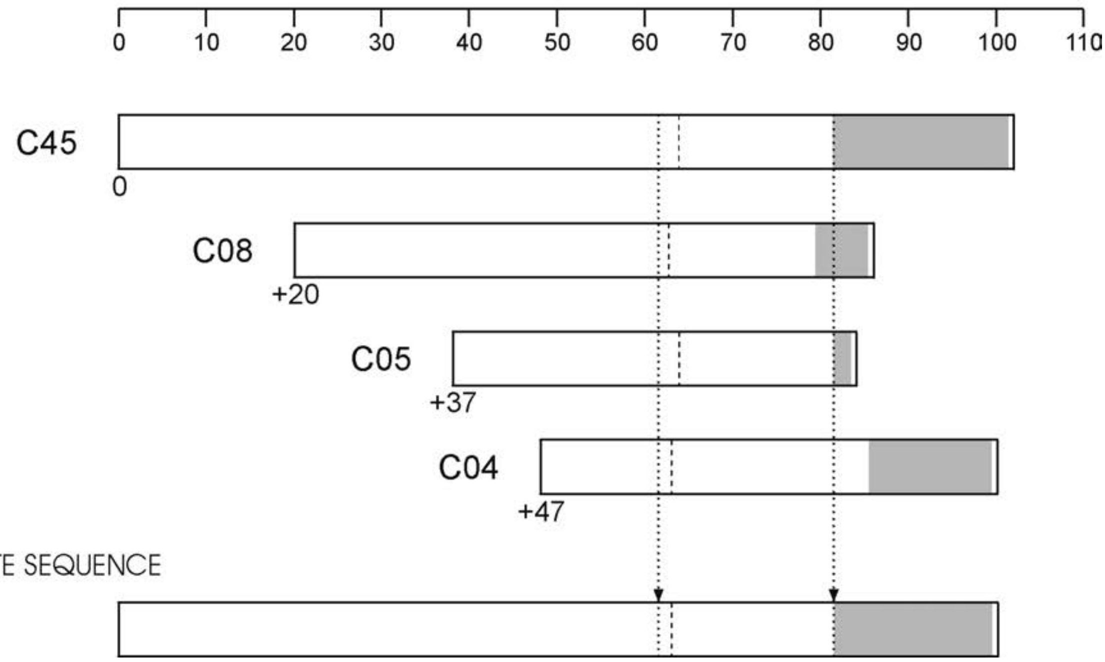


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

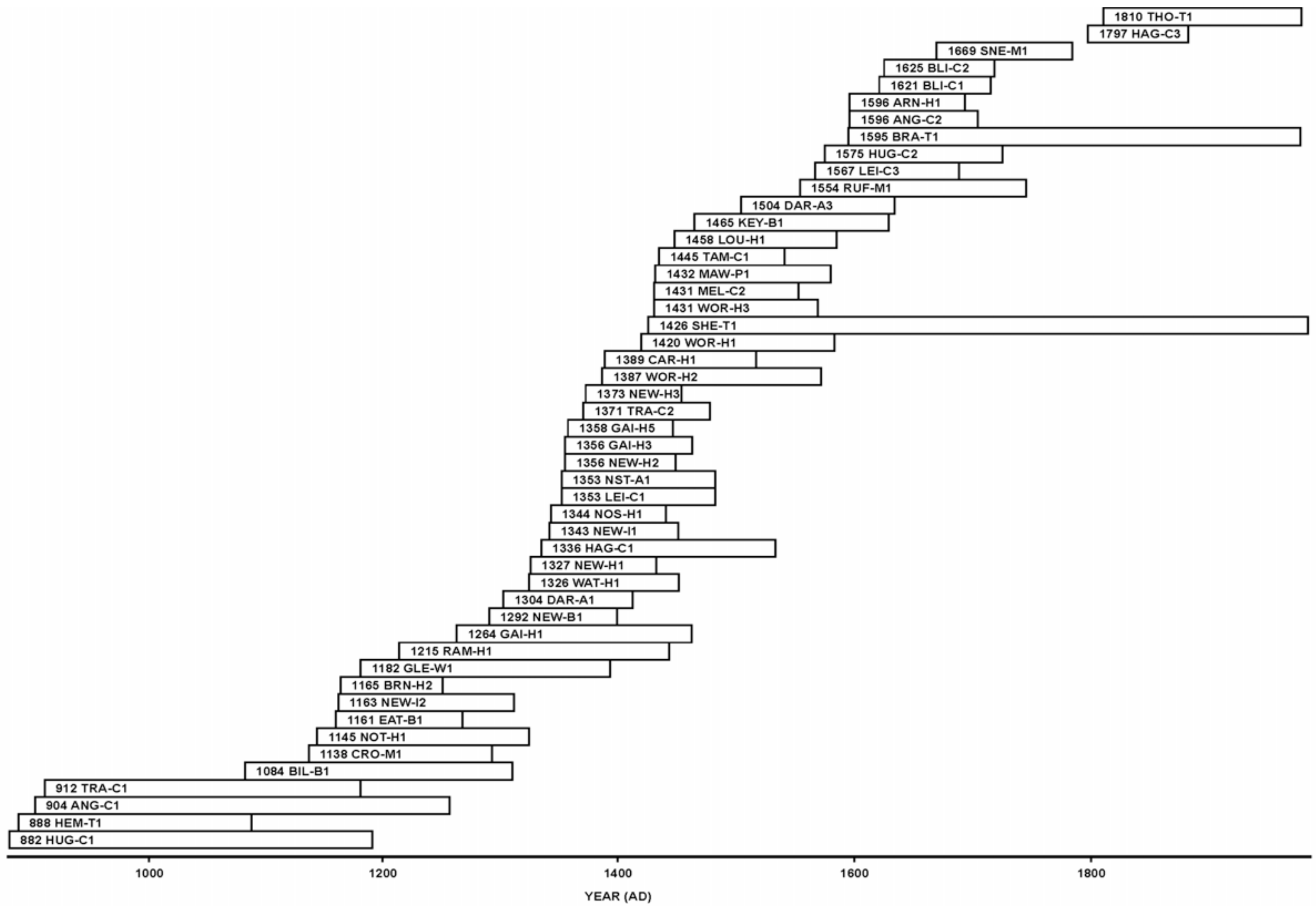
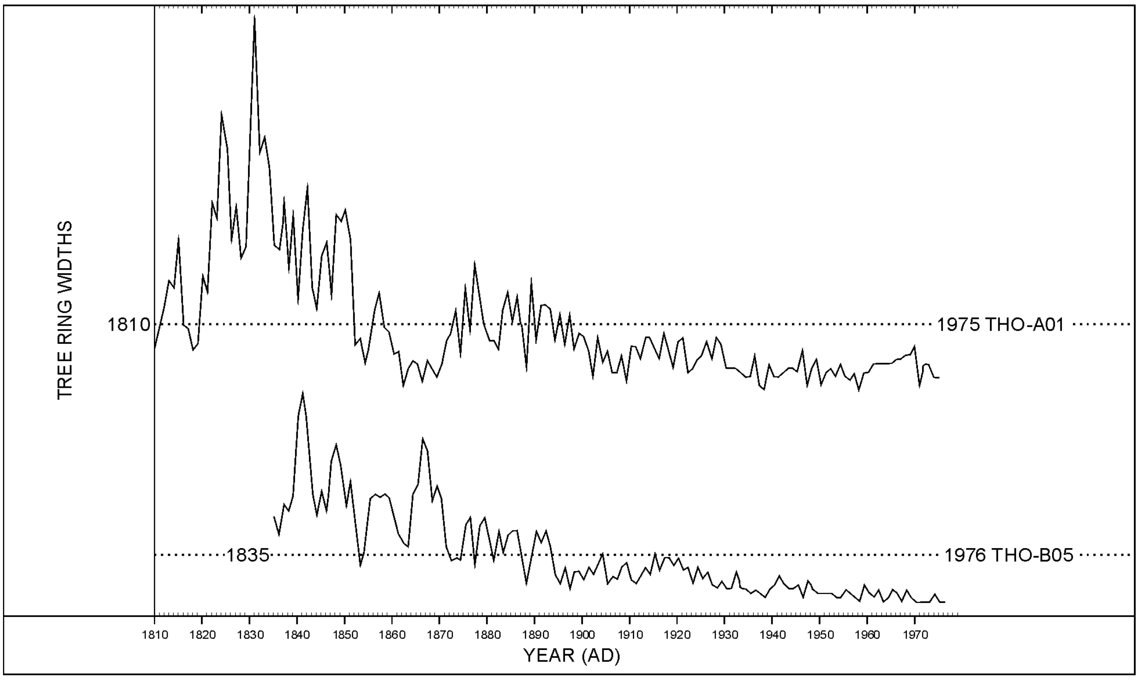


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

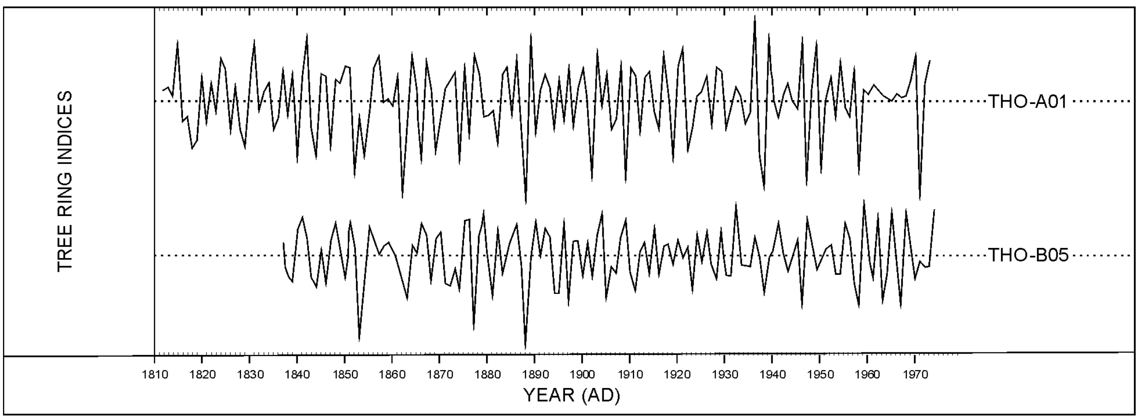


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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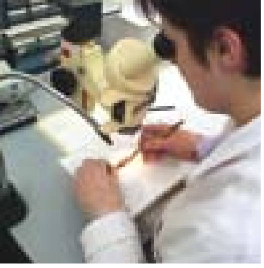
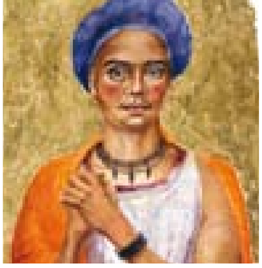



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