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Church of St Mary, Alton Barnes, Wiltshire

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

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CHURCH OF ST MARY, ALTON BARNES, WILTSHIRE

TREE-RING ANALYSIS OF OAK TIMBERS

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SUMMARY
Analysis was undertaken on a series of samples from timbers in the nave roof, resulting in the construction of a single site sequence. Site sequence ALTBSQ01 contains 14 samples and spans the period AD 1203–1372. Interpretation of surviving heartwood/sapwood boundary ring dates gives a likely felling date for all 14 dated timbers within the range AD 1380–1405.

CONTRIBUTORS
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ARCHIVE LOCATION
Wiltshire & Swindon Historic Environment Record
Wiltshire Archaeology Service
The Wiltshire and Swindon History Centre
Cocklebury Road
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2016

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CONTENTS

INTRODUCTION

The grade I listed Church of St Mary, located in the village of Alton Barnes (Figs 1 and 2), is thought to have its origins in the tenth and eleventh centuries, with other works dating to the fourteenth century and AD 1748. It was altered in AD 1832 and then restored firstly in AD 1875 and then again in 1904 by C E Ponting. The church comprises a nave and chancel (Fig 3). The two-bay nave is rendered on three elevations with late Saxon half-height stone pilaster strips and limestone quoins. The roof is of stone slate and has raised gable walls with limestone copings. The chancel was rebuilt for Nicolas Preston in AD 1748. It has recently been added to the Heritage at Risk Register.

Nave roof

The roof is described in the listing (www.historicengland.org.uk/listing/the-list/list-entry/1364707) as consisting of three quasi-raised cruck trusses. There are chamfered tiebeams, cranked collars, and arch braces. It has a square set ridge and long curved wind braces which rise from the cruck blades to a single set of surviving threaded purlins (Fig 4). Empty mortices in the cruck blades reveal there were originally further purlins. The surviving purlins are a mixture of timbers with an historic appearance and ones of much more modern appearance. The purlins that are of historic appearance are ill-fitting in their mortices and thus potentially also replacements (Fig 5). Previous documentary research had suggested that the roof might be mid-seventeenth century in date but recent visual inspection of the roof has pointed to a somewhat earlier date.

SAMPLING

Dendrochronological analysis was requested by Sarah Ball to provide precise independent dating evidence for the roof. It was hoped that this would inform advice and enhance understanding, and hence inform the programme of urgent repairs to the roofs funded by the Heritage Lottery Fund under the Grants for Places of Worship scheme.

Sixteen core samples were taken from timbers of the nave roof. Each sample was given the code ALT-B and numbered 01–16. Samples ALT-B15 and ALT-B16 are from two purlins, both of which were thought possibly to be later insertions, though not modern insertions. Further details relating to all samples can be found in Table 1. The location of each sample has been marked on Figures 6–9. Trusses were numbered from east to west (Fig 3).

ANALYSIS AND RESULTS

One of the samples, ALT-B07, taken from a collar, had too few rings for reliable dating and so was rejected prior to measurement. The remaining 15 samples were prepared by sanding and polishing and their growth ring widths measured; the raw ring-width data are given at the end of the report. These ring-width series were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 14 samples matching to form a single group.

The 14 matching samples were combined at their relative offset positions to form ALTBSQ01, a site sequence of 170 rings (Fig 10). This site sequence was compared against a series of relevant reference chronologies where it was found to match consistently and securely at a first-ring date of AD 1203 and a last-measured ring date of AD 1372. The evidence for this dating is given in Table 2.

Attempts to date the remaining ungrouped sample, ALT-B10, by comparing it individually against the reference material were unsuccessful and it remains undated.

INTERPRETATION

Analysis has resulted in the successful dating of 14 timbers. Unfortunately, none of these samples have complete sapwood and so a precise felling date cannot be given. However, eight of them do have the heartwood/sapwood boundary ring. In all cases this is broadly contemporary, ranging from AD 1356 (ALT-B09) to AD 1372 (ALT-B04), and suggestive of a single period of felling. The average heartwood/sapwood boundary ring date is AD 1365, allowing an estimated felling date to be calculated for the eight timbers represented to within the range AD 1380–1405.

The other six dated timbers do not have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be calculated for them. They are, however, clearly broadly coeval and the overall level of cross-matching between all 14 dated sequences suggests that these six timbers are also likely to have been felled in the range AD 1380–1405. This interpretation is supported by the fact that the heartwood/sapwood boundary was present on some of these timbers, notably the purlins and the north cruck blade of truss 3. However, the location of mortices and other timbers constrained sampling and it was not possible to access this heartwood/sapwood boundary ring, but it is known that the outermost ring on the sample is likely to have been within a few rings of the heartwood/sapwood boundary.

Felling date ranges have been calculated using the estimate that 95% of mature oak trees in this region have 15–40 sapwood rings.

DISCUSSION

This analysis has demonstrated that the nave roof utilises timber felled in AD 1380–1405, with construction likely to have followed shortly after felling. The late fourteenth/early fifteenth century date obtained for this roof is substantially earlier than the previously assumed mid-seventeenth century date but clearly supports the recent reappraisal of the roof made possible by the repair works.

The analysis also demonstrates that the two sampled purlins that were thought to potentially be later replacements due their ill-fit within the mortices are in fact coeval in date with the rest of the dated timbers from the roof. Thus it may be that they have simply been reset at some point.

Samples ALT-B11 (outermost measured ring at AD 1349) and ALT-B12 (outermost measured ring at AD 1298) match each other at t = 10.6, a level high enough to suggest that both timbers may have been cut from the same tree and hence felled at the same time. The timber represented by ALT-B12 has clearly been much more heavily trimmed at the point of coring than the timber represented by ALT-B11.

The overall intra-site cross-matching between the 14 dated ring series is sufficient to suggest that the timbers were all derived from a single woodland source. Site sequence ALTBSQ01 can be seen to cross-match very well against some references chronologies from other Wiltshire sites, especially Bremhill Court approximately 21km to the north-west and Dauntsey House some 36km to the south-east. However, it can also be seen to have a high level of similarity with references from Devon and the Midlands (Table 2), suggesting that the trees utilised at Alton Barnes church are responding to a generic climatic signal rather than a strong regional one but are nevertheless likely to have come from a relatively local woodland source.

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TABLES

Table 1: Details of samples taken from the Church of St Mary, Alton Barnes, Wiltshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
ALT-B01	Tiebeam, truss 1	80	h/s	1285	1364	1364
ALT-B02	North blade, truss 1	115	h/s	1256	1370	1370
ALT-B03	South blade, truss 1	73	h/s	1292	1364	1364
ALT-B04	West brace, truss 1, south side	53	h/s	1320	1372	1372
ALT-B05	North blade, truss 2	142	h/s	1225	1366	1366
ALT-B06	South blade, truss 2	164	h/s	1203	1366	1366
ALT-B07	Collar, truss 2	NM	--	----	----	----
ALT-B08	North brace, truss 2	121	--	1229	----	1349
ALT-B09	South brace, truss 2	131	h/s	1226	1356	1356
ALT-B10	Tiebeam, truss 2	77	h/s	----	----	----
ALT-B11	North blade, truss 3	109	--	1241	----	1349
ALT-B12	South blade, truss 3	88	--	1211	----	1298
ALT-B13	Collar, truss 3	80	--	1262	----	1341
ALT-B14	South wall plate, truss 1–2	129	h/s	1235	1363	1363
ALT-B15	North purlin, truss 1–2	65	--	1291	----	1355
ALT-B16	South purlin, truss 1–2	48	--	1308	----	1355

Table 2: Results of the cross-matching of site sequence ALTBSQ01 and relevant reference chronologies when the first-ring date is AD 1203 and the last-measured ring date is AD 1372

Reference chronology	*t*-value	Span of chronology	Reference
Bremhill Court, Bremhill, Wiltshire	8.4	AD 1111–1323	Hurford *et al* 2010
Reading Waterfront, Berkshire	8.0	AD 1160–1407	Groves *et al* 1997
Ulverscroft Priory, Ulverscroft, Leicestershire	7.9	AD 1219–1463	Arnold *et al* 2008
Exeter Cathedral, Exeter, Devon	7.5	AD 1137–1332	Mills 1988
Exeter Cathedral, Exeter, Devon	7.4	AD 1132–1337	Arnold *et al* 2003
Polesworth Abbey (gatehouse), Warwickshire	7.3	AD 1095–1342	Arnold and Howard 2007
Wadhayes, Awliscombe, Devon	7.2	AD 1179–1331	Tyers *et al* forthcoming
Dauntsey House, Dauntsey, Wiltshire	7.1	AD 1122–1355	Bridge *et al* 2014

FIGURES

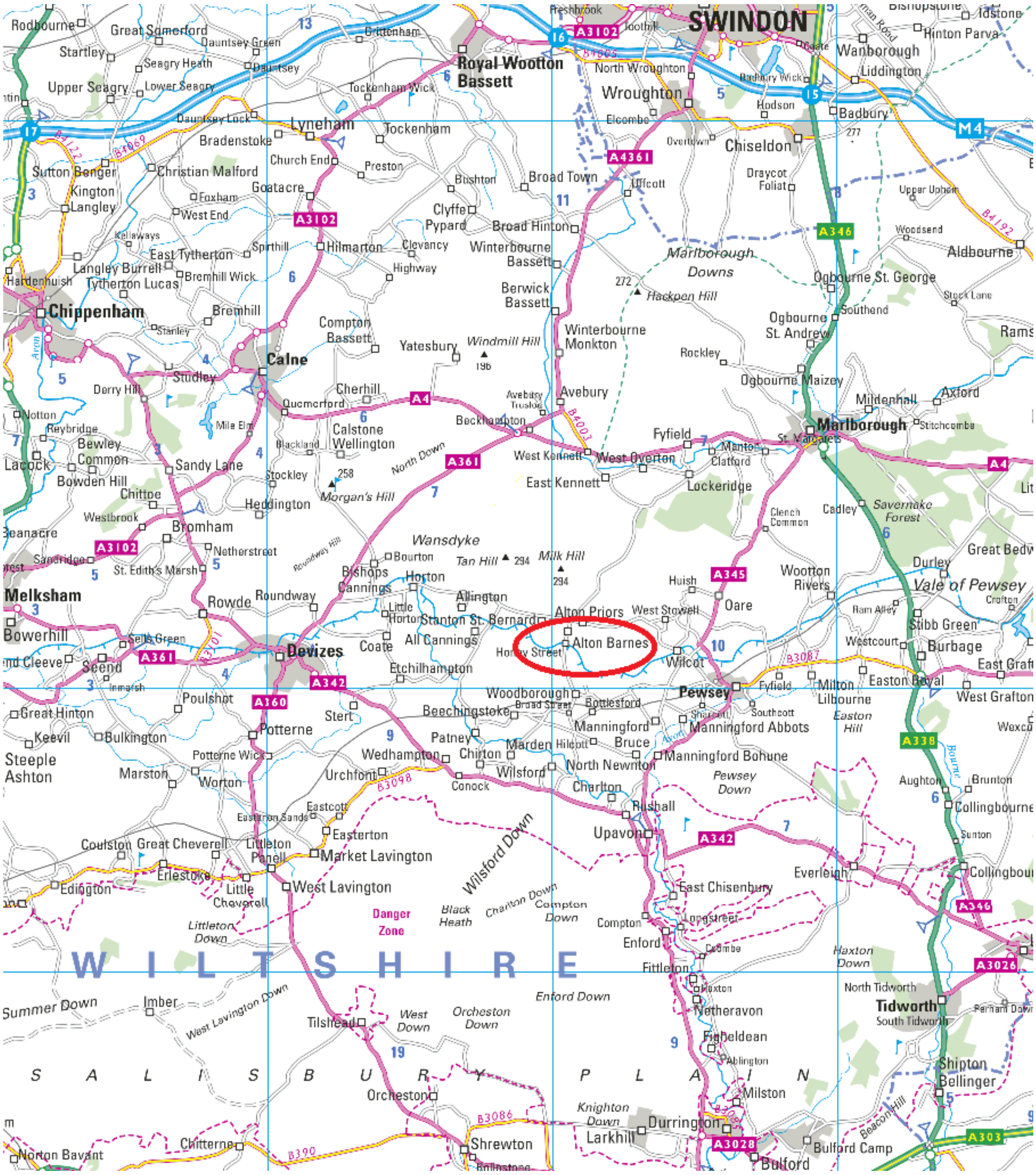

Figure 1: Map to show the general location of Alton Barnes, circled. ©Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show St Mary's Church, hashed. ©Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

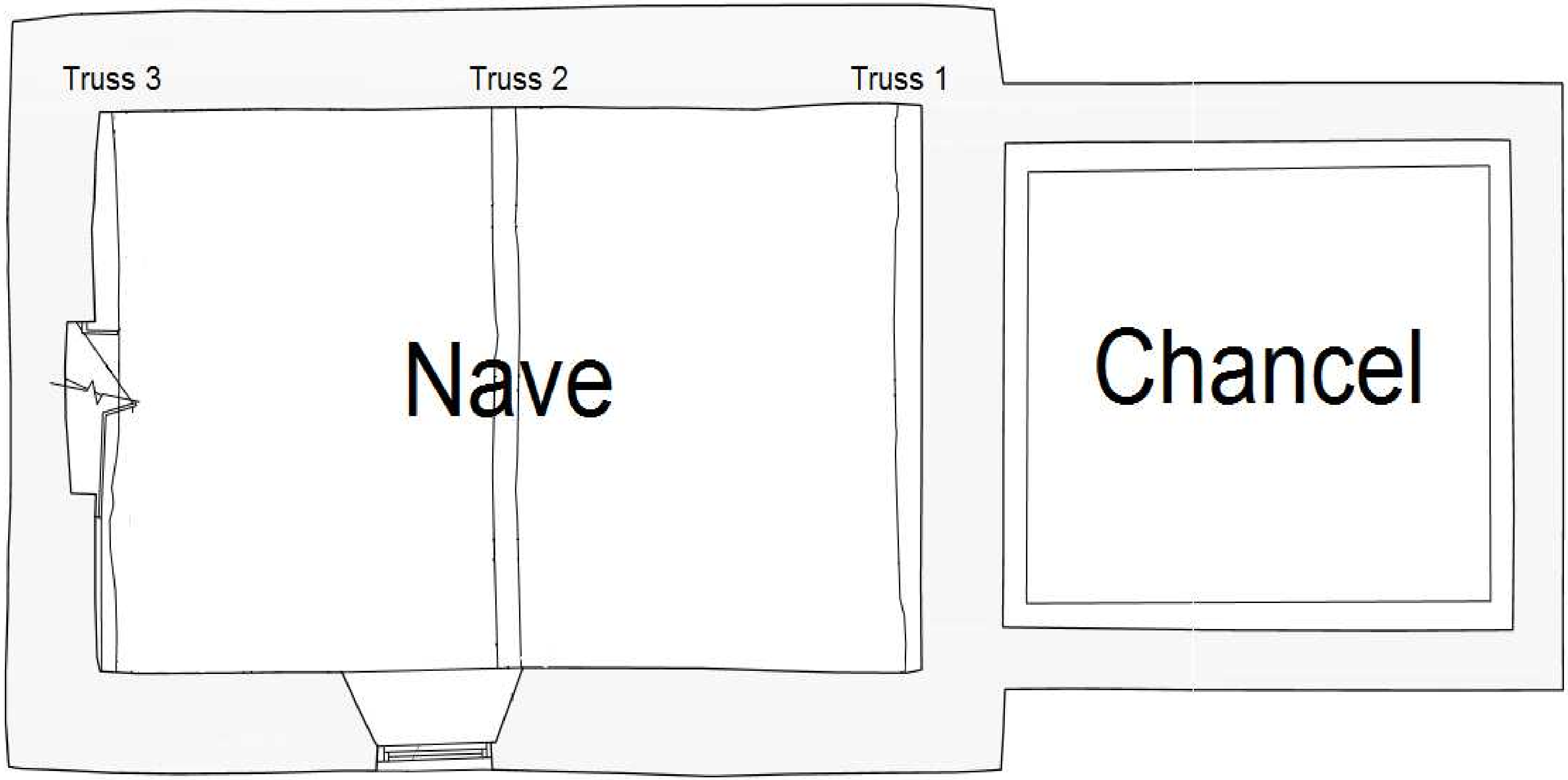

Figure 3: Plan of the church with truss positions marked (after Donald Insall Associates)

Figure 4: Nave roof, photograph taken from the east (Alison Arnold)

Figure 5: Photograph to show one of the blocked mortices which presumably once housed another purlin and the ill-fitting surviving purlin, photograph taken from the north-east (Alison Arnold)

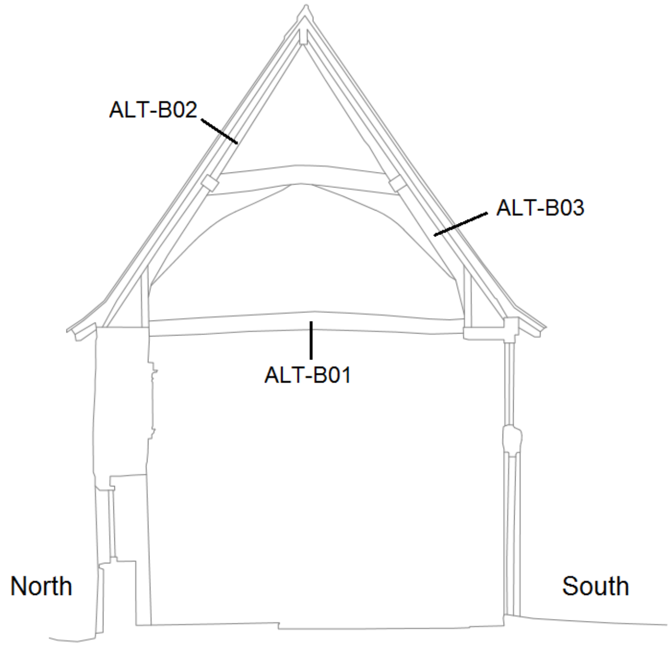

Figure 6: Truss 1, showing the location of samples ALT-B01–03 (after Donald Insall Associates)

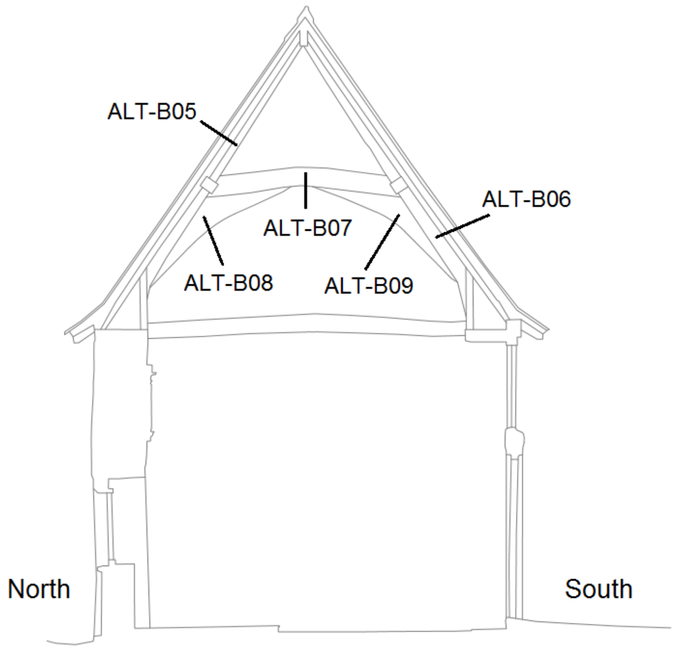

Figure 7: Truss 2, showing the location of samples ALT-B05–09 (after Donald Insall Associates)

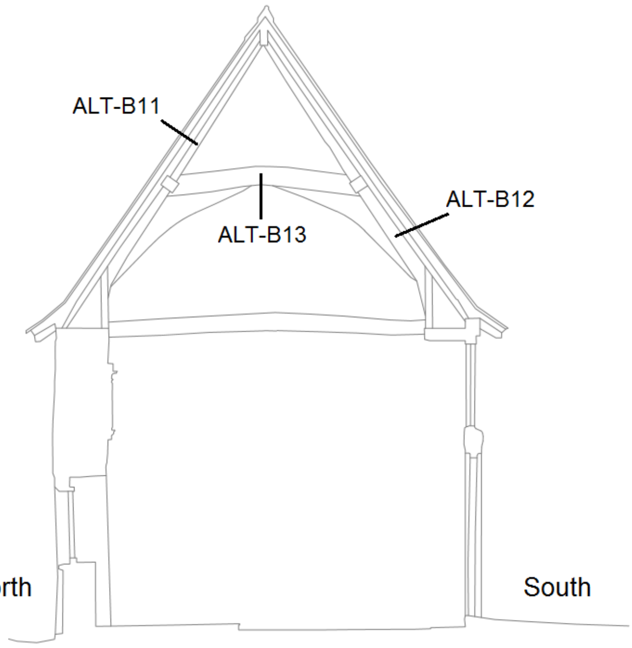

Figure 8: Truss 3, showing the location of samples ALT-B11–13 (after Donald Insall Associates)

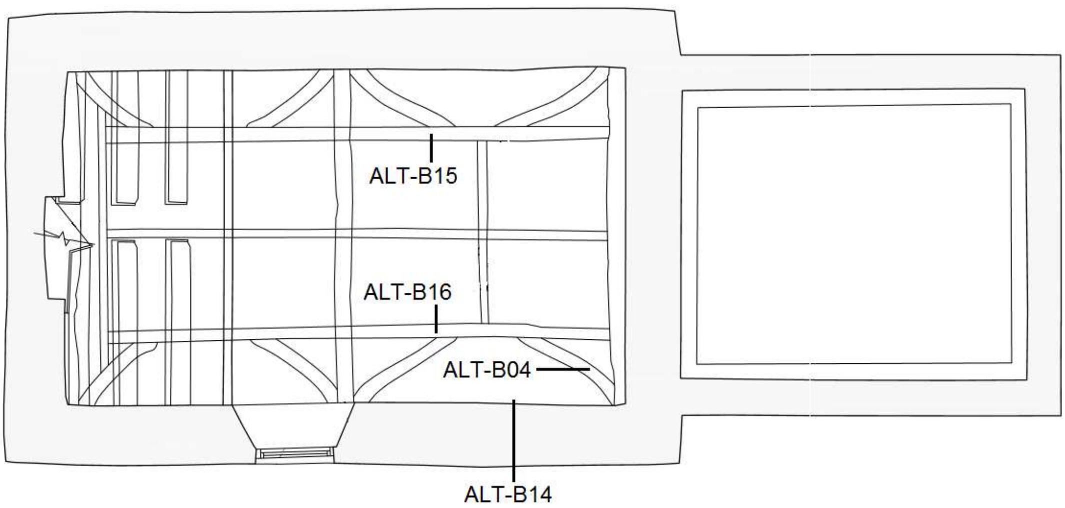

Figure 9: Plan, showing the location of samples ALT-B04 and ALT-B14–16 (after Donald Insall Associates)

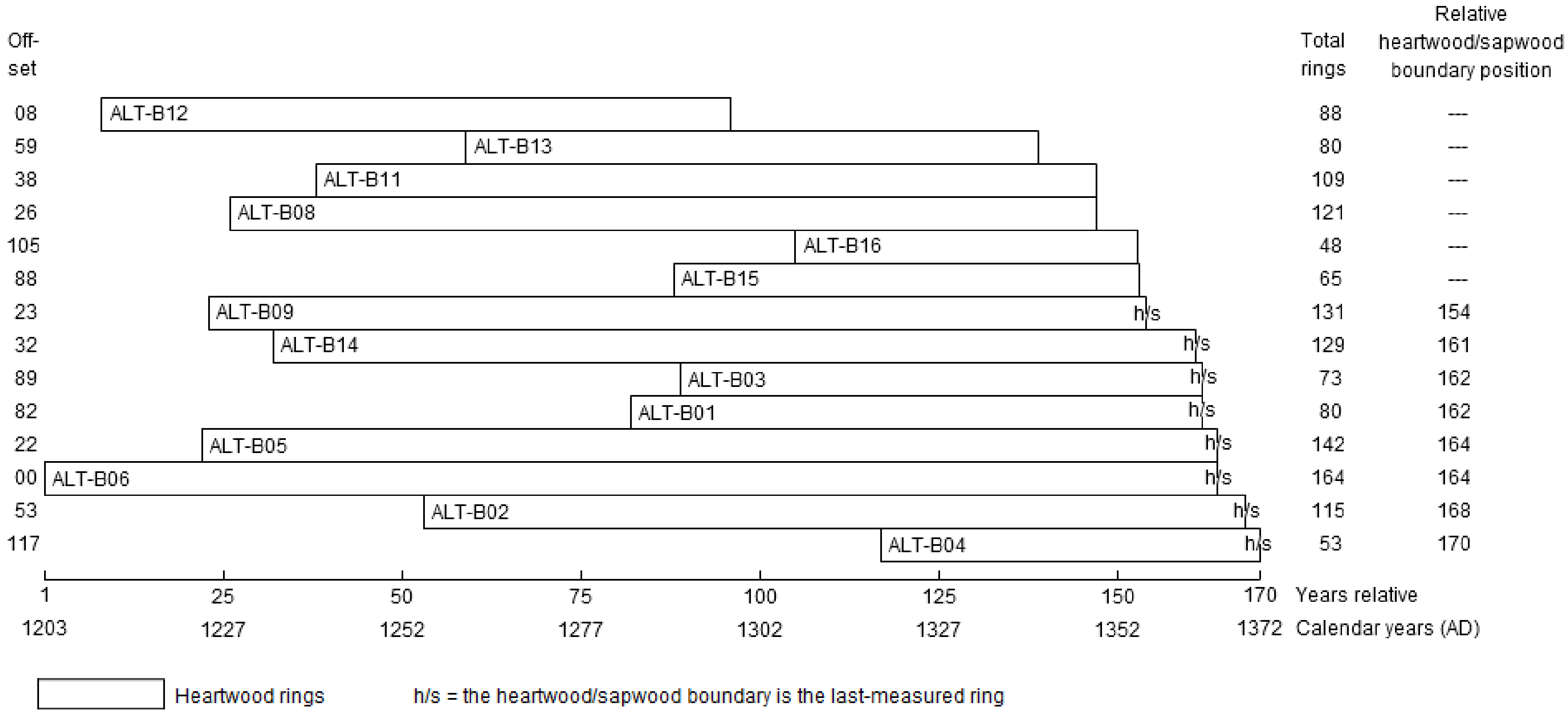

Figure 10: Bar diagram to show the relative position of samples in site sequence ALTBSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

ALT-B01A 80
139 160 109 97 112 147 208 213 225 118 73 72 46 48 46 74 132 181 86 70
135 179 208 251 200 188 75 65 60 130 227 292 226 226 111 191 221 93 58 70
129 103 185 197 191 173 212 158 141 191 164 221 208 143 207 124 128 98 114 125
137 151 148 119 153 207 198 107 64 80 53 149 89 64 81 87 102 241 141 135
ALT-B01B 80
139 152 107 89 130 140 208 214 222 129 66 76 53 46 58 69 129 180 85 74
132 174 213 230 201 188 78 59 61 136 231 294 227 226 115 196 200 82 82 81
127 70 213 190 191 175 216 161 142 174 161 231 217 157 229 123 123 106 119 119
139 149 148 125 146 204 191 105 68 84 70 136 80 68 82 83 107 189 142 175
ALT-B02A 115
194 152 192 100 212 322 346 247 254 172 197 277 267 360 322 363 291 363 193 233
157 241 148 214 267 292 297 222 228 295 199 97 90 170 271 301 344 220 136 121
112 135 92 107 155 162 76 39 33 59 91 93 90 90 111 73 60 59 84 69
90 91 77 70 64 78 98 94 73 88 81 120 91 113 87 87 78 85 108 101
73 107 76 85 76 82 65 79 76 78 80 56 68 68 73 72 77 98 93 68
60 101 72 87 44 88 131 135 116 96 81 82 62 115 147
ALT-B02B 115
190 152 188 103 213 312 355 240 237 170 197 280 263 360 317 365 297 359 199 226
162 231 153 211 264 295 290 226 225 297 194 101 97 167 277 315 335 218 137 127
107 131 101 104 150 160 78 40 37 51 92 79 89 91 108 65 70 54 83 52
101 86 79 60 85 67 99 96 73 90 82 115 97 108 101 78 80 81 103 98
75 112 70 83 72 76 71 82 64 78 76 69 65 75 68 74 68 94 95 66
69 88 73 76 71 74 138 148 136 83 93 73 70 98 156
ALT-B03A 73
300 225 141 114 73 92 79 87 148 165 147 78 54 112 154 97 121 120 247 294
146 125 257 236 267 197 128 110 113 109 107 123 69 93 87 260 176 153 130 103
132 111 148 140 127 92 75 125 122 150 99 93 88 80 79 100 93 112 139 150
118 93 67 51 80 78 54 50 56 60 81 77 88
ALT-B03B 73
298 234 138 105 78 91 77 87 158 164 145 85 53 105 160 97 129 117 245 312
141 112 252 238 264 194 119 103 102 103 112 108 60 74 94 227 172 162 125 107
133 154 113 133 121 95 78 121 126 160 105 86 90 82 77 87 98 102 129 146
121 93 82 49 80 79 59 49 51 80 67 83 98
ALT-B04A 53
232 207 179 191 152 214 158 236 254 244 195 115 135 169 185 234 206 236 199 219
210 177 168 146 193 204 217 179 160 264 231 236 192 187 162 142 190 174 143 174
212 241 352 435 452 339 348 451 300 373 376 218 194
ALT-B04B 53
234 212 180 196 147 215 167 222 261 255 203 121 129 160 189 230 209 231 202 219
199 184 168 149 190 203 220 177 170 265 234 233 194 186 160 145 184 168 139 169
207 231 366 431 454 335 344 406 276 428 376 213 192
ALT-B05A 142
310 282 179 185 214 151 142 153 164 224 245 188 357 286 160 125 104 141 117 138
118 135 301 126 115 137 163 241 342 298 305 157 106 97 163 228 283 256 221 146
106 63 69 76 101 111 245 224 230 186 80 70 88 100 130 191 126 187 117 108
164 163 45 34 64 100 135 135 93 71 55 66 72 63 42 74 130 79 111 33
92 140 179 134 171 139 77 69 73 99 182 227 195 128 75 46 49 52 46 46
68 78 111 110 171 128 82 101 103 102 101 142 138 130 131 102 73 65 89 110

117 84 86 79 82 72 100 75 70 71 71 87 107 69 45 78 61 62 50 45
49 58
ALT-B05B 142
267 283 175 186 213 152 143 157 164 227 251 194 359 293 164 118 108 139 100 169
112 162 303 119 120 148 183 211 339 297 334 153 109 114 160 213 282 256 227 140
128 71 69 79 101 129 236 226 222 189 84 73 88 96 127 181 137 205 115 109
173 152 45 34 55 94 138 147 95 63 61 76 65 46 64 90 119 79 86 45
96 158 175 131 171 137 68 66 67 105 169 248 194 115 87 49 46 52 47 45
67 85 108 108 168 125 90 116 117 112 116 148 126 131 143 110 79 65 90 112
110 87 81 89 71 76 104 74 71 71 72 79 101 58 46 81 57 57 55 48
43 57
ALT-B06A 164
362 140 190 175 172 202 200 177 133 89 105 196 240 282 126 201 199 307 314 320
197 129 208 136 59 87 183 200 141 132 162 150 231 156 328 311 164 151 89 118
203 286 181 266 300 192 140 115 109 130 200 239 261 158 89 62 119 169 170 193
134 103 92 64 57 65 72 73 142 136 141 120 68 49 59 50 58 108 113 122
88 86 88 96 46 37 59 90 131 115 93 89 55 53 72 58 48 75 89 68
56 83 93 111 193 140 173 108 61 75 76 108 177 230 178 175 107 117 98 82
122 89 94 82 118 96 111 112 90 62 46 62 69 95 69 64 89 54 43 38
40 31 42 56 33 29 36 27 23 29 34 46 29 37 47 39 41 61 56 36
31 41 58 56
ALT-B06B 164
307 140 190 171 178 206 197 174 134 86 106 202 231 300 117 198 203 291 297 330
198 140 203 134 60 89 180 200 142 131 163 152 226 165 323 315 182 143 99 116
241 268 178 264 285 187 138 114 109 118 208 235 264 158 99 77 111 176 184 206
142 114 91 78 55 60 71 71 133 124 127 120 76 55 48 53 55 121 131 123
96 84 92 91 53 32 60 85 118 116 95 82 48 67 61 65 55 93 104 64
63 69 104 125 170 145 166 103 58 73 90 119 189 221 182 183 106 122 93 83
112 81 97 83 115 94 109 108 81 56 51 69 60 96 74 81 75 57 46 36
42 36 46 49 30 31 25 31 34 35 35 38 32 37 42 32 31 57 56 33
29 34 60 84
ALT-B08A 121
58 98 95 86 68 86 101 56 119 162 151 115 88 109 151 110 63 89 77 60
52 84 85 69 97 83 91 61 40 83 117 95 83 93 67 53 49 48 36 47
57 59 82 65 55 74 46 36 50 48 58 72 61 64 64 66 57 80 63 58
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85 84 65 67 71 85 75 73 70 74 76 58 49 70 60 68 94 68 71 76
93
ALT-B08B 121
69 74 102 90 69 95 89 74 125 150 157 132 101 103 147 111 69 82 77 50
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104 116 82 38 44 44 69 75 67 45 60 57 57 68 84 86 60 69 99 71
95 80 63 64 82 84 76 70 66 67 70 69 54 63 64 86 88 76 67 82
77
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111 46 45 118 150 155 122 129 150 173 109 266 224 179 138 107 93 172 143 119
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91 76 70 81 84 135 122 99 100 90 85 74 67 77 91 82 95 80 69 67
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80 58 85 59 38 42 34 56 61 55 66 54 47 58 61 55 62 56 56 57

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98 55 59 108 142 139 115 154 141 169 113 267 222 190 139 108 94 165 142 114
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71 57 85 53 43 37 34 56 65 62 57 53 54 42 64 53 64 57 63 51
55 58 74 48 48 51 69 123 83 83 74 67 88 73 58 60 53 76 95 68
69 73 93 75 105 80 82 70 89 92 102
ALT-B10A 77
372 408 399 283 263 315 306 294 352 359 396 254 136 148 128 200 227 248 219 154
159 188 117 128 136 135 155 148 192 203 209 170 124 151 100 134 175 189 147 167
132 161 144 113 108 121 178 124 112 106 101 125 111 148 168 126 178 130 215 188
208 140 154 164 150 132 158 144 215 185 176 129 187 132 116 134 105
ALT-B10B 77
371 414 404 300 241 317 303 292 361 364 395 244 143 150 128 198 235 238 220 162
162 177 120 136 142 134 152 143 200 207 208 170 121 134 111 128 190 178 166 163
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193 135 151 154 156 132 165 134 223 186 175 131 182 130 128 139 99
ALT-B11A 109
66 99 118 98 135 157 135 80 87 123 161 114 186 178 244 89 96 125 256 212
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210 264 194 184 166 79 79 58 44 55 131 214 182 162 205 285 366 404 328 333
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267 201 319 105 93 61 96 138 164 175 93 86 123 121 103 96 52 48 66 114
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123 122 103 140 93 90 63
ALT-B16B 48
281 223 303 106 96 67 91 147 171 176 97 94 117 132 96 101 53 46 68 113
81 92 71 55 63 42 66 70 83 123 94 119 118 97 83 110 100 118 118 88
126 132 99 144 102 81 70 63

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can

sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

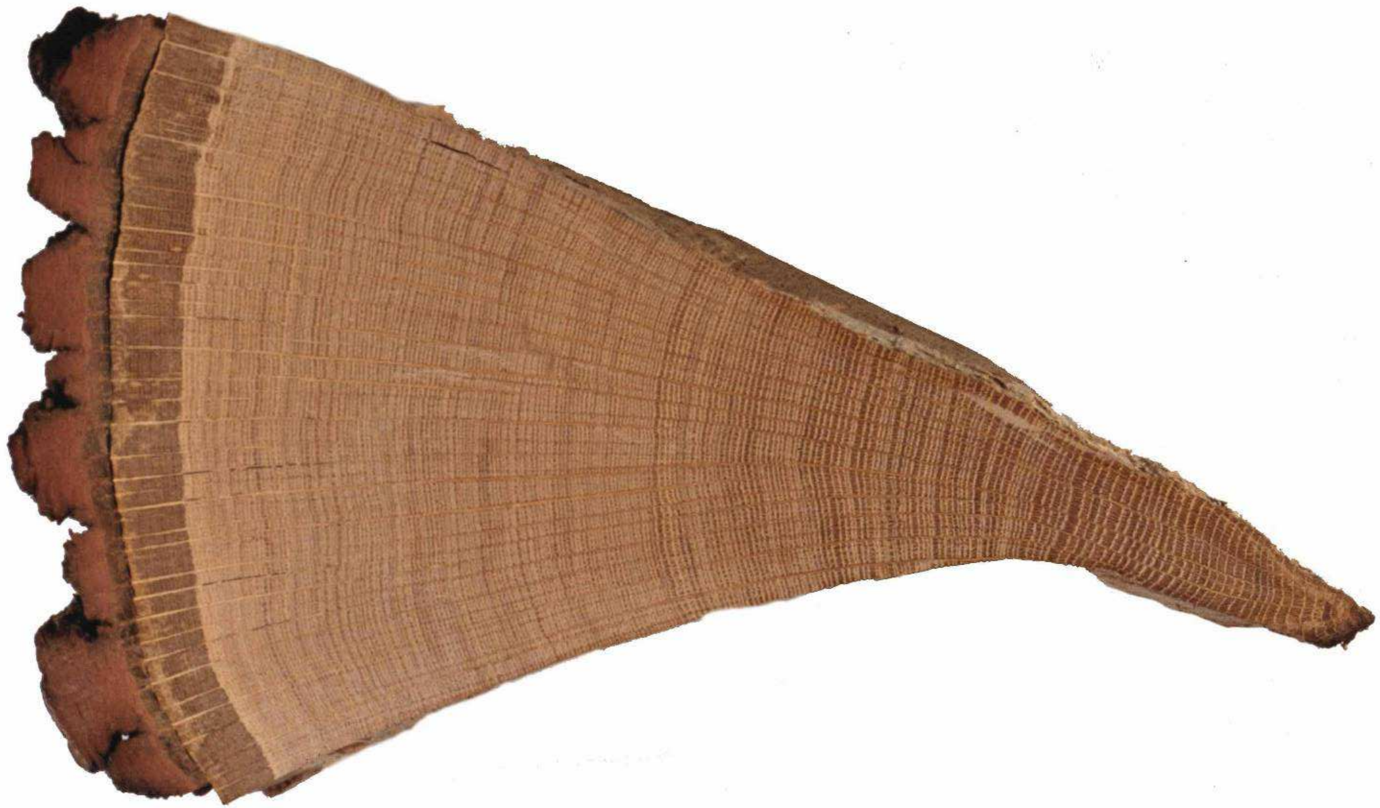


Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

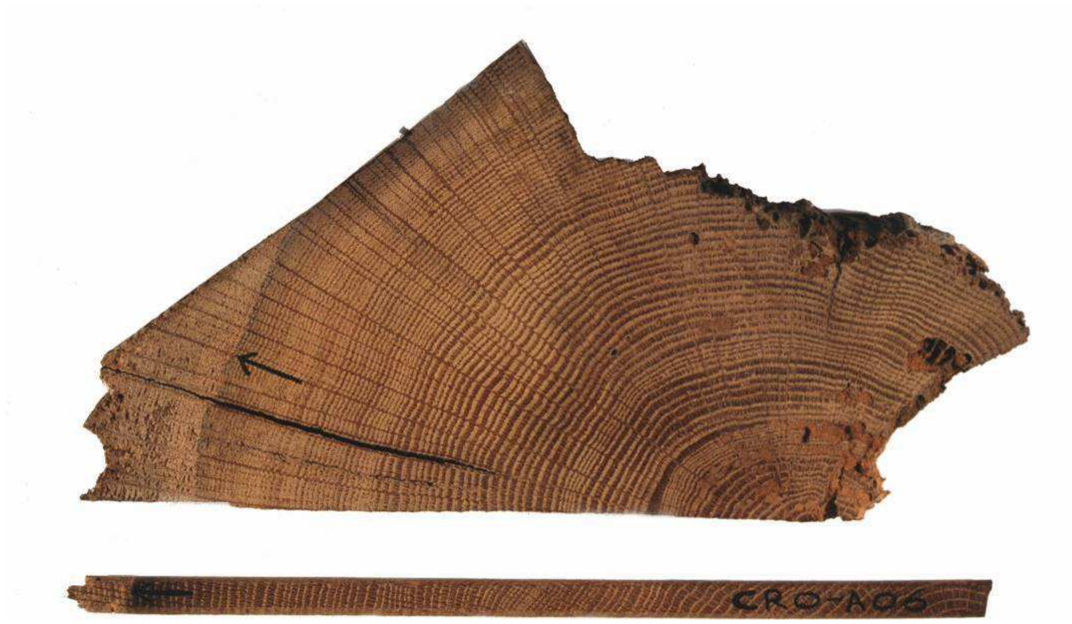


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Figure 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

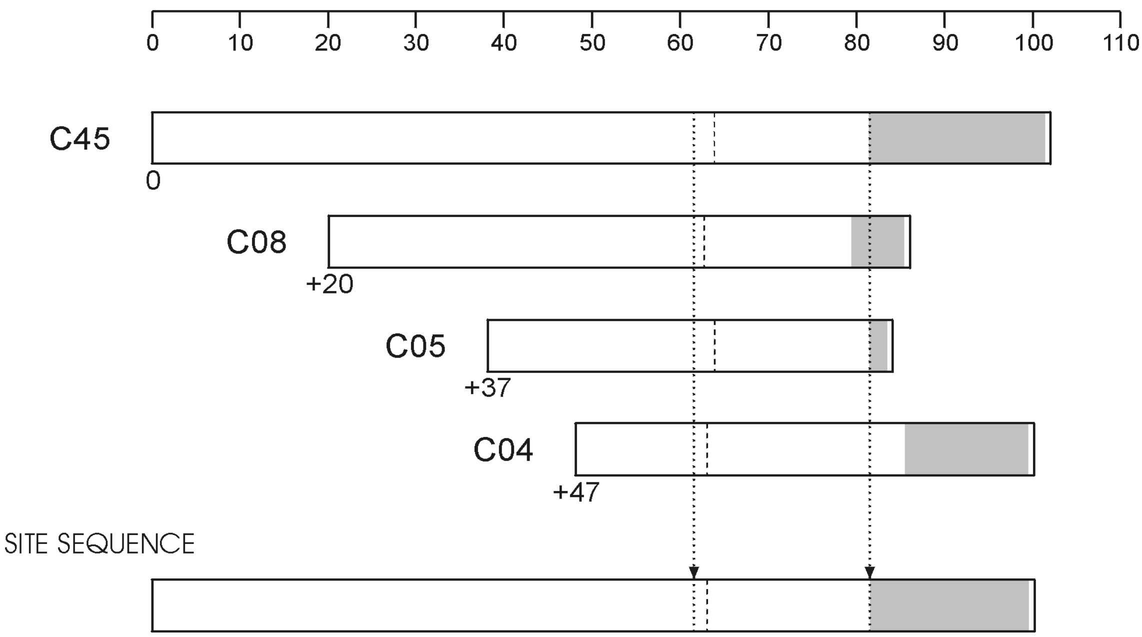


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

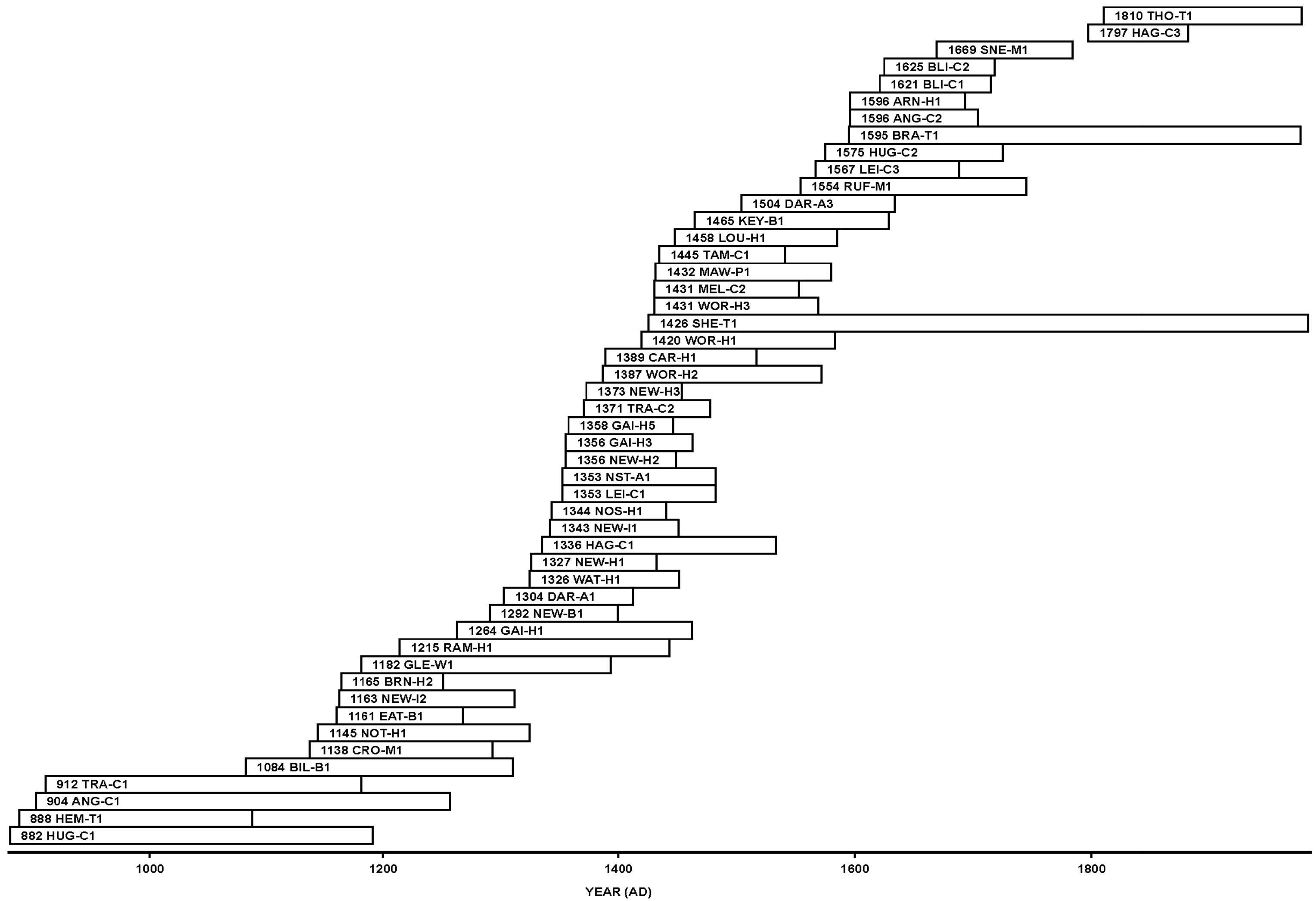
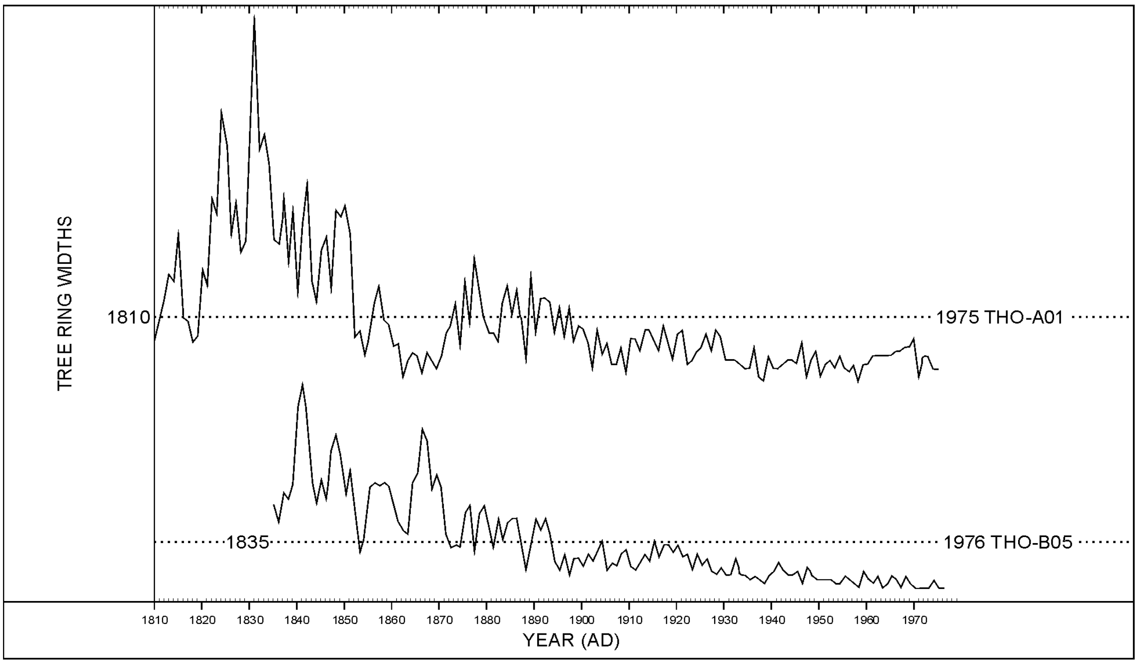


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

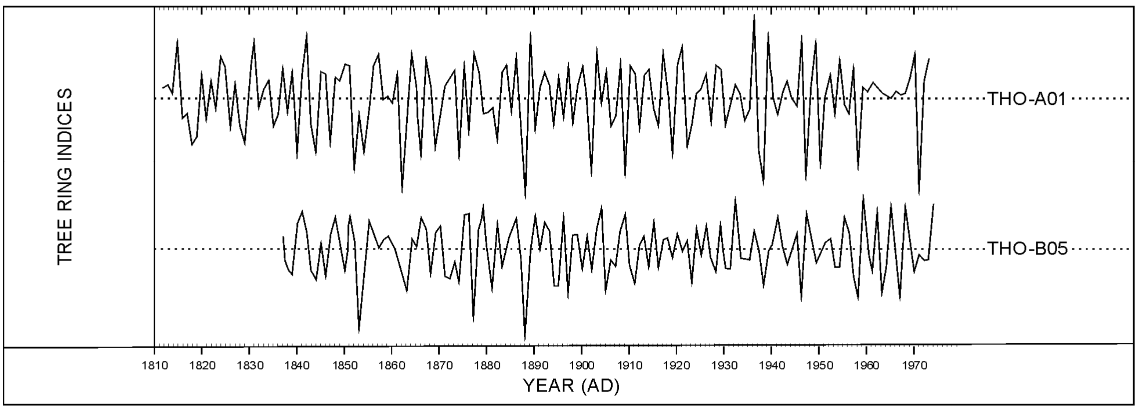


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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