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KING JOHN'S HUNTING LODGE, LACOCK, WILTSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Matt Hurford, Martin Bridge and Cathy Tyers

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SUMMARY

Dendrochronological analysis was undertaken on 11 samples taken from the extant remains of the medieval open-hall core of King John's Hunting Lodge. This resulted in the production of a single site chronology, LCKJSQ01 which comprises nine samples with an overall length of 171 rings dating to the years AD 1148–1318. The results identified that the dated timbers used in the construction of the open-hall probably represent a single programme of felling in the AD 1320s.

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INTRODUCTION

In 2009 the Wiltshire Buildings Record successfully obtained support through the English Heritage Historic Environment Enabling Programme for their project 'Wiltshire cruck buildings and other archaic roof types'. The detailed aims and objectives of the project are set out in the Project Design (Lloyd 2009). The overall aim is to establish a typological chronology of archaic roof types and hence elucidate the development of carpentry techniques in the county. This will then facilitate detailed comparison with other counties allowing Wiltshire to be placed in the regional context. Investigation of these late-medieval buildings (*c* AD 1200 – *c* AD 1550) will combine building survey, historical research, and dendrochronological analysis.

A series of buildings identified by the Wiltshire Buildings Record as having the potential to contribute to the aims and objectives of the project was assessed for dendrochronological suitability during 2009. In order to maximise the potential, these detailed dendrochronological assessments and the WBR's assessments of the significance of the buildings within the project informed the selection of the buildings subsequently subjected to detailed study.

A single final report produced by the Wiltshire Buildings Record (forthcoming a) will summarise the overall results from the project. However, each building included in the project will have an associated individual report produced by the WBR (forthcoming b), whilst the primary archive of the dendrochronological analysis is the English Heritage Research Department Report Series.

A brief introduction to dendrochronology can be found in the Appendix. However, further details can be found in the guidelines published by English Heritage (1998) which are also available on the English Heritage website (http://www.english-heritage.org.uk/publications/dendrochronology-guidelines/).

King John's Hunting Lodge

This grade II* listed building is located immediately to the west of St. Cyriac's Church in Lacock (ST 9166 6857; Figs 1 and 2) with its north elevation fronting onto Church Street. The following information is summarised from the Wiltshire Buildings Record report (forthcoming b) on King John's Hunting Lodge and the listed building record (http://lbonline.english-heritage.org.uk).

The earliest extant fabric, thought to be thirteenth-century in date, survives from an earlier building. This includes a single two-centred arched doorway, originally one of a pair, and a series of timbers that were retained as part of the screens passage in the presumed early fourteenth-century rebuilding of the house with a two-bay open hall (Fig 3). The house was extended to the rear with the addition of the south-east wing (Fig 4), probably during the early eighteenth century. The encasing of the building in rubble stone may also date to this period.

The focus of this investigation was primarily on the extant remains of the open hall structure comprising two trusses, A and B (Figs 5 and 6). The presence of an incomplete plain-chamfered windbrace extending westwards of truss A, towards a post-medieval softwood truss, implies that this bay was also part of the medieval open hall, which is therefore thought to have originally comprised three bays. This screens passage and open-hall structure were of raised-cruck construction. Trusses A and B both have slightly cranked collars; truss A was originally a double-collar truss, though the lower collar is no longer extant. There is a single pair of plain-chamfered windbraces in bay 2 and the extant arch braces have hollow-chamfer mouldings with run-out stops. There is a single row of purlins and a diagonally set ridge piece. Both trusses have saddles but on truss A an apex block above the saddle takes the ridge piece whereas on truss B the saddle is notched to take the ridge piece directly. Ten original common rafters are present, five in each of the two extant bays. The opposing pairs of common rafters between trusses A and B have original side-lapped and pegged fixings for a former louvre. Smoke-blackening of the timbers associated with the original open-hall house is apparent throughout the roof space.

The dendrochronological potential of the south-east wing was also investigated at this stage, as this had not been feasible during the initial pre-sampling assessment of the building due to access being severely restricted. The roof is of two bays and incorporates three trusses. It is a principal-rafter roof with tiebeams and threaded purlins (Fig 7). The principals are connected with a staggered haunch joint at the apex and there is a diagonally set ridge piece. Numerous original common rafters survive. The tiebeam was visible on northernmost of these trusses (Fig 7) and in the gable wall truss; both of these trusses also had a number of original studs.

SAMPLING

The assessment of the timbers in the south-east wing indicated that these were all elm (*Ulmus* spp.) and hence would have been excluded from this project regardless of date. Sampling and analysis by tree-ring dating of the timbers associated with the medieval open hall were commissioned by English Heritage. It was hoped to provide independent dating evidence for the construction of this element of the building and hence inform the overall objectives of the *Wiltshire cruck buildings and other archaic roof types* project. The dendrochronological study also formed part of the English Heritage-funded training programme for the first author.

A total of 13 oak (*Quercus* spp.) timbers associated with the extant remains of the medieval open hall were sampled by coring. Each sample was given the code LCK-J (for Lacock, King John's) and numbered 01–13. The sampling encompassed as wide a range of elements as possible, whilst focussing on those timbers with the best dendrochronological potential. Unfortunately no samples were taken from the common rafters in Bay 1, as they were derived from fast-grown trees and were considered highly unlikely to provide samples with sufficient numbers of rings for reliable dendrochronological analysis.

The location of the samples was noted at the time of coring and marked on the drawings subsequently provided by the Wiltshire Buildings Record, these being reproduced here as Figures 8–10. Further details relating to the samples can be found in Table 1. In this table the timbers have been located and numbered following the scheme on the drawings provided with the trusses and bays being labelled from west to east.

ANALYSIS AND RESULTS

Each of the 13 samples was prepared by sanding and polishing. It was seen at this point that one sample, LCK-J03, had too few rings for reliable dating and one, LCK-J05, was elm, and so these were rejected from this programme of analysis. The annual growth rings of the remaining 11 samples were measured, the data of these measurements being given at the end of this report.

The ring sequences derived from these 11 samples were initially compared with each other by the Litton/Zainodin grouping procedure (see Appendix) allowing a single group of nine series to be formed, the samples of this group cross-matching with each other as shown in the bar diagram (Fig 11). The analytical process was aided by the use of software written by Tyers (2004).

The nine grouped series were combined at their indicated offsets to form site chronology LCKJSQ01. Intra-site cross-matching (see below) indicated the possibility that some timbers may have been derived from the same tree as suggested by *t*-values in excess of 10.0. However, to maintain consistency between all of the dendrochronological reports on individual buildings within this project, these potential same-tree series were not combined prior to incorporation into the site chronology, thus following the Nottingham Tree-Ring Dating Laboratory standard practice. This site master was then compared to an extensive range of reference chronologies for oak, indicating repeated cross-matching when the first ring in the sequence is AD 1148 and the last ring date is AD 1318. The evidence for this is given in Table 2.

The site chronology was compared with the remaining two ungrouped samples but there was no further satisfactory cross-matching. The two ungrouped samples were then compared individually with the reference chronologies, but there was no conclusive cross-matching and these samples must, therefore, remain undated.

The analysis can be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span (where dated)
LCKJSQ01	9	171	AD 1148–1318
	2	---	undated
	2	---	unmeasured

INTERPRETATION

For consistency the sapwood estimate used in all of the dendrochronological reports on individual buildings within this project is the Nottingham Tree-Ring Dating Laboratory estimate of 15-40 (95% confidence) rings. This is used to calculate felling date ranges for samples with incomplete sapwood or felled-after dates for samples which are heartwood only.

The medieval core of King John's Hunting Lodge is represented by nine dated timbers associated with the roof structure (Fig 11). A full complement of sapwood was present on one of the dated timbers, LCK-J11, but due to its highly friable state, approximately 1–5mm of sapwood, including the bark edge, was lost during sample preparation prior to measurement. The average ring width of this entire sequence is 0.69mm (Table 1) but the overall growth trend is towards narrower rings, the outer 10 measured rings having an average ring width of 0.51mm. This suggests that approximately 2–10 rings have been lost. Thus, with a last measured ring date of AD 1318, it is likely that the felling date is in the AD 1320s.

Two of the other dated samples retained their heartwood/sapwood boundary ring. Sample LCK-J01 has a heartwood/sapwood boundary ring of AD 1307 and hence an estimated felling date in the range of AD 1322–1347. Sample LCK-J02 has a heartwood/sapwood boundary ring of AD 1290 and hence an estimated felling date in the range of AD 1305–1330. However, allowing for the outermost measured ring, this can be truncated to AD 1319–30.

The remaining six dated samples in site chronology LCKJSQ01 have no trace of sapwood and thus it is not possible to calculate their likely felling date ranges. Five of these samples have final-ring dates within six years of each other, ranging from AD 1301 to AD 1307, with the remaining one having a last-ring date of AD 1276.

All the dated samples are therefore clearly broadly coeval. The three retaining sapwood or heartwood/sapwood boundary have overlapping felling dates or felling date ranges and hence could represent a single felling, although the variation in heartwood/sapwood date could suggest that they represent a single programme of felling that may have spanned a number of years in the AD 1320s. This interpretation is supported by the overall level of cross-matching between the individual series (Table 3) which includes some *t*-values sufficiently high (>10) to suggest the possibility that the timbers could have been derived from a single tree.

DISCUSSION AND CONCLUSION

Tree-ring analysis has confirmed that the extant remains of the former three-bay open-hall core of King John's Hunting Lodge is of early fourteenth-century date, as previously thought based on other evidence. The trees used in the construction of the open hall roof appear likely to have been felled as part of a single programme of felling in the AD 1320s, with construction following shortly afterwards. The dated timbers represent both extant trusses and the intervening bay, bay 2. It is unfortunate that no timbers could be dated from bay 1, with the common rafters proving to have too few rings and the ridge proving to be elm. However, given the structural integrity of the remains and the consistent level of smoke blackening, it appears likely, but unproven by dendrochronological analysis, that the timbers present in bay 1 are coeval with those from the rest of the roof. However, it cannot be entirely ruled out that they could be reused timbers salvaged from the thirteenth-century structure.

The high overall level of intra-site cross-matching, with many of the *t*-values in excess of 5.0 (Table 3) suggests that these timbers probably originated from the same woodland source. The average ring widths of the timbers analysed varies from 0.65 to 1.71mm, suggesting that some of the timbers were derived from quite dense woodland containing slow-growing trees. The site chronology, LCKJSQ01, generally produces the highest *t*-values, and thus shows the greatest degree of similarity, with reference chronologies from Wiltshire and the surrounding counties (Table 2). This suggests that it is likely that the timbers were derived from a relatively local woodland source.

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TABLES

Table 1: Details of tree-ring samples from King John's Hunting Lodge, Lacock, Wiltshire

Sample number	Sample location	Total rings	Sapwood rings	Average ring width (mm)	Cross-section dimensions (mm)	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
LCK-J01	Truss A collar	152	h/s	1.00	160x320	1156	1307	1307
LCK-J02	Truss A north principal	170	28	1.27	150x280	1149	1290	1318
LCK-J03	Truss A south principal	nm	--	--	250x300	--	--	--
LCK-J04	Truss A saddle	157	no h/s	1.71	150x340	1148	--	1304
LCK-J05	Bay 1 ridge - elm	nm	--	--	120x130	--	--	--
LCK-J06	Bay 2 south common rafter 1	128	no h/s	0.91	90x110	1180	--	1307
LCK-J07	Bay 2 north common rafter 1	56	h/s	1.43	90x100	--	--	--
LCK-J08	Bay 2 north common rafter 2	54	no h/s	0.75	90x90	--	--	--
LCK-J09	Bay 2 north common rafter 3	78	no h/s	0.65	90x100	1224	--	1301
LCK-J10	Bay 2 north common rafter 4	86	no h/s	1.07	90x100	1191	--	1276
LCK-J11	Truss B north principal	120	24c (1–5mm sap lost)	0.69	140x220	1199	1294	1318
LCK-J12	Truss B south principal	147	no h/s	1.22	140x380	1160	--	1306
LCK-J13	Truss B collar	82	no h/s	1.06	150x310	1226	--	1307

nm = not measured
h/s = the heartwood/sapwood ring is the last ring on the sample
c = complete sapwood was present on the timber but some was lost during coring/sample preparation

Table 2: Results of the cross-matching of site sequence LCKJSQ01 and relevant reference chronologies when the first-ring date is AD 1148 and the last-ring date is AD 1318

Reference chronology	*t*-value	Span of chronology	Reference
Abbey Barn, Glastonbury, Somerset	10.0	AD 1095–1334	(Bridge 2001)
Exeter Cathedral, Exeter, Devon	9.9	AD 1132–1315	(Howard *et al* 2001)
Wick Farm Cottage, Heddington Wick, Wiltshire	9.4	AD 1158–1335	(Hurford *et al* forthcoming a)
Dauntsey House, Dauntsey, Wiltshire	9.1	AD 1122–1355	(Hurford *et al* forthcoming b)
Rudge, Morchard Bishop, Devon	9.0	AD 1124–1315	(Groves 2005)
Manor Farmhouse, Meare, Somerset	8.8	AD 1156–1315	(Bridge 2002)
Church of St John the Baptist, Bradworthy, Devon	8.8	AD 1125–1367	(Tyers 2003)
Great Coxwell barn, Oxfordshire	8.8	AD 1043–1267	(Siebenlist-Kerner *et al* 1978)

Table 3: Matrix showing the t-values obtained between the individual ring sequences in site chronology LCKJSQ01; - indicates t-values less than 3.00

	lck-j02	lck-j04	lck-j06	lck-j09	lck-j10	lck-j11	lck-j12	lck-j13
lck-j01	5.16	8.20	9.20	7.79	3.22	6.36	5.46	10.65
lck-j02		6.57	4.28	-	3.91	5.23	5.74	3.53
lck-j04			8.13	4.27	3.64	3.97	5.48	7.04
lck-j06				7.68	4.02	5.75	3.10	7.95
lck-j09					3.74	4.24	3.30	8.60
lck-j10						-	3.17	3.01
lck-j11							10.17	4.62
lck-j12								3.02

FIGURES

Figure 1: Map to show the location of King John's Hunting Lodge, Lacock, Wiltshire (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 King John's Hunting Lodge, Lacock, Wiltshire (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright

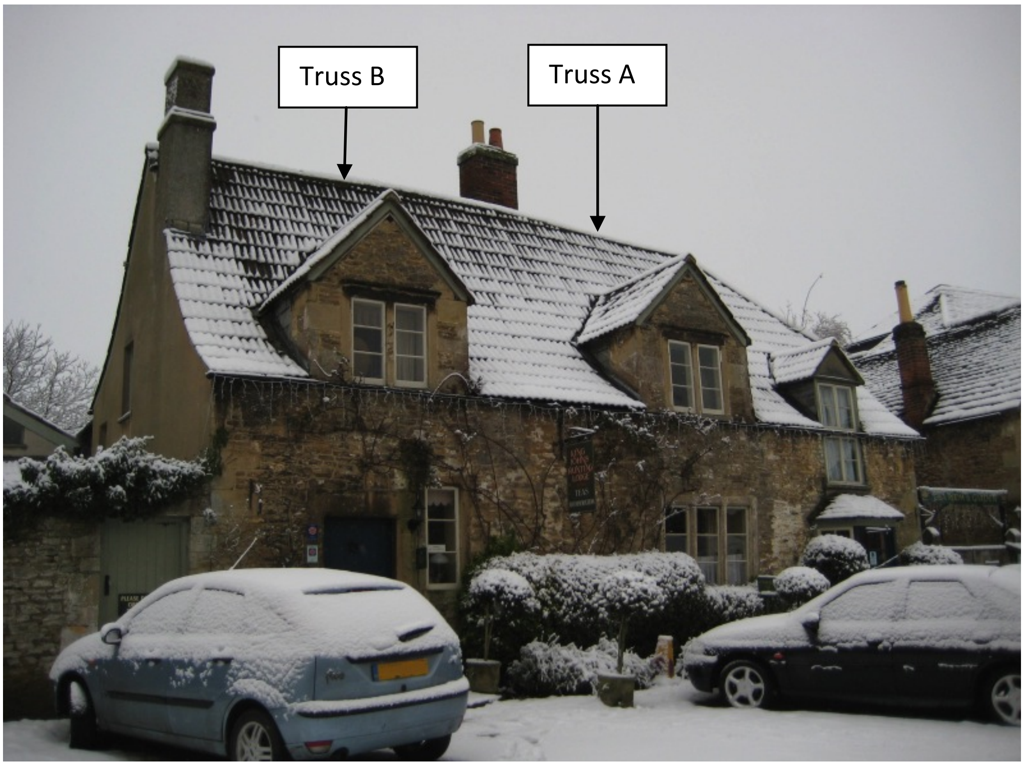


Figure 3: The north elevation of King John's Hunting Lodge viewed looking south-west showing the approximate truss locations

Figure 4: The south-east wing gable of King John's Hunting Lodge viewed looking north

Figure 5: East face of truss A

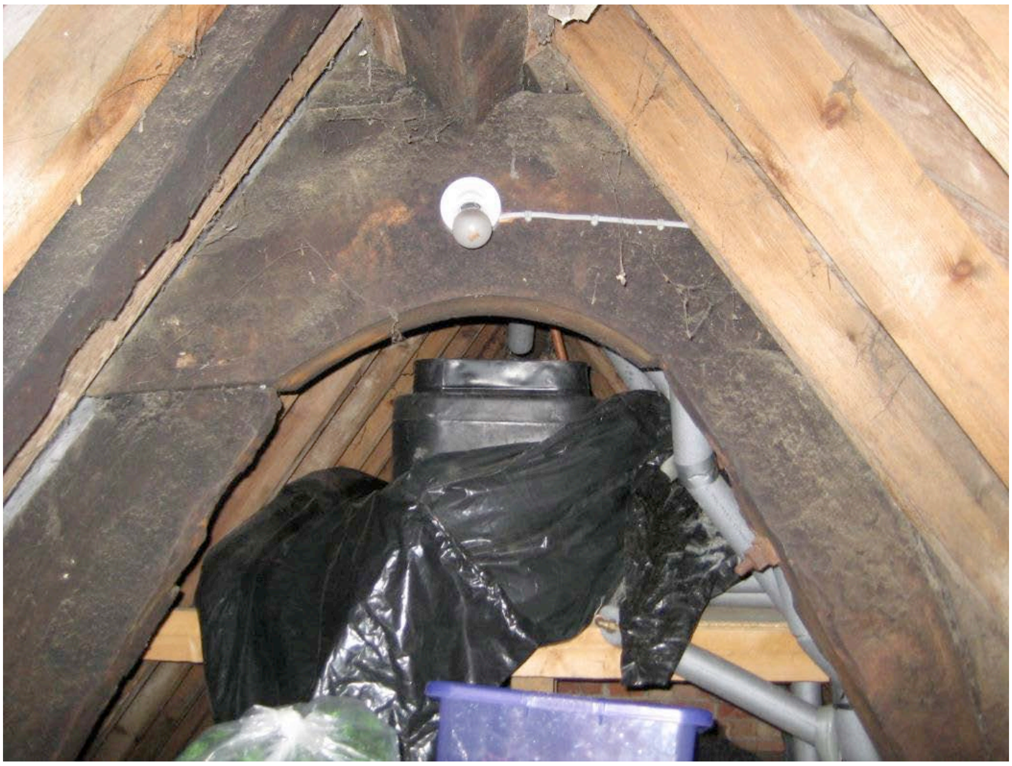


Figure 6: West face of truss B

Figure 7: North face of the northernmost truss of the south-east wing

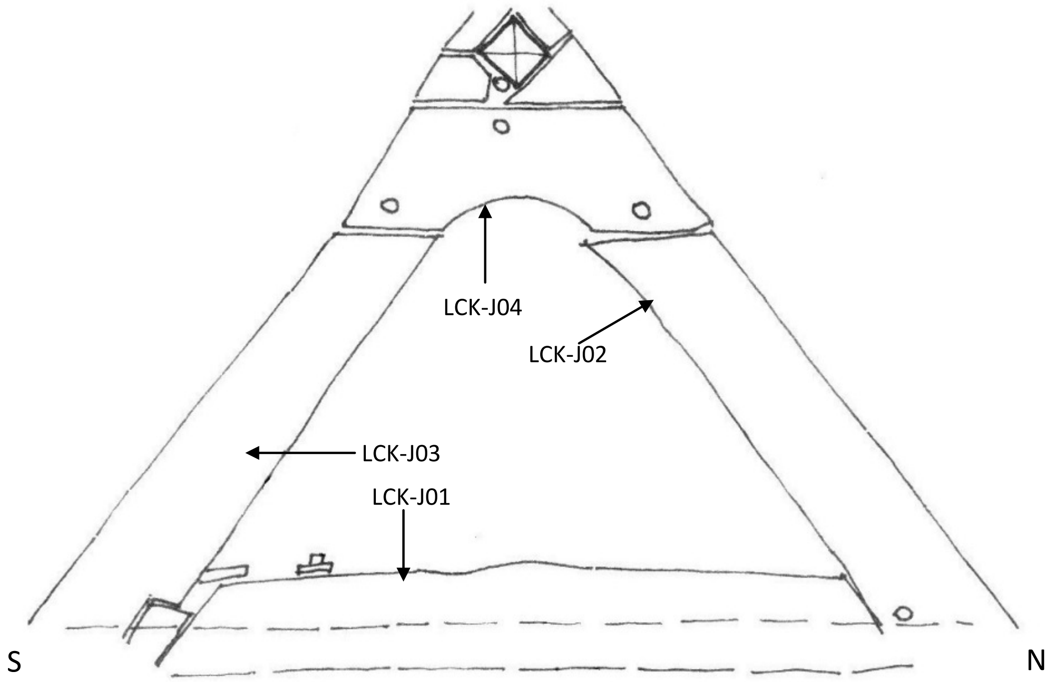


Figure 8: East face of truss A

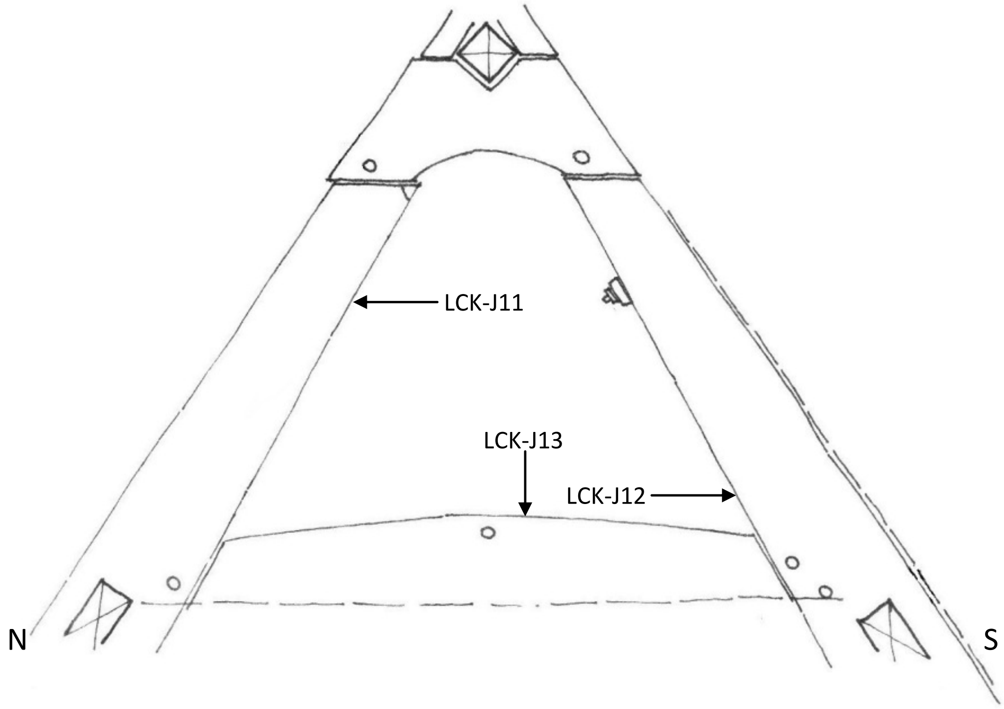


Figure 9: West face of truss B

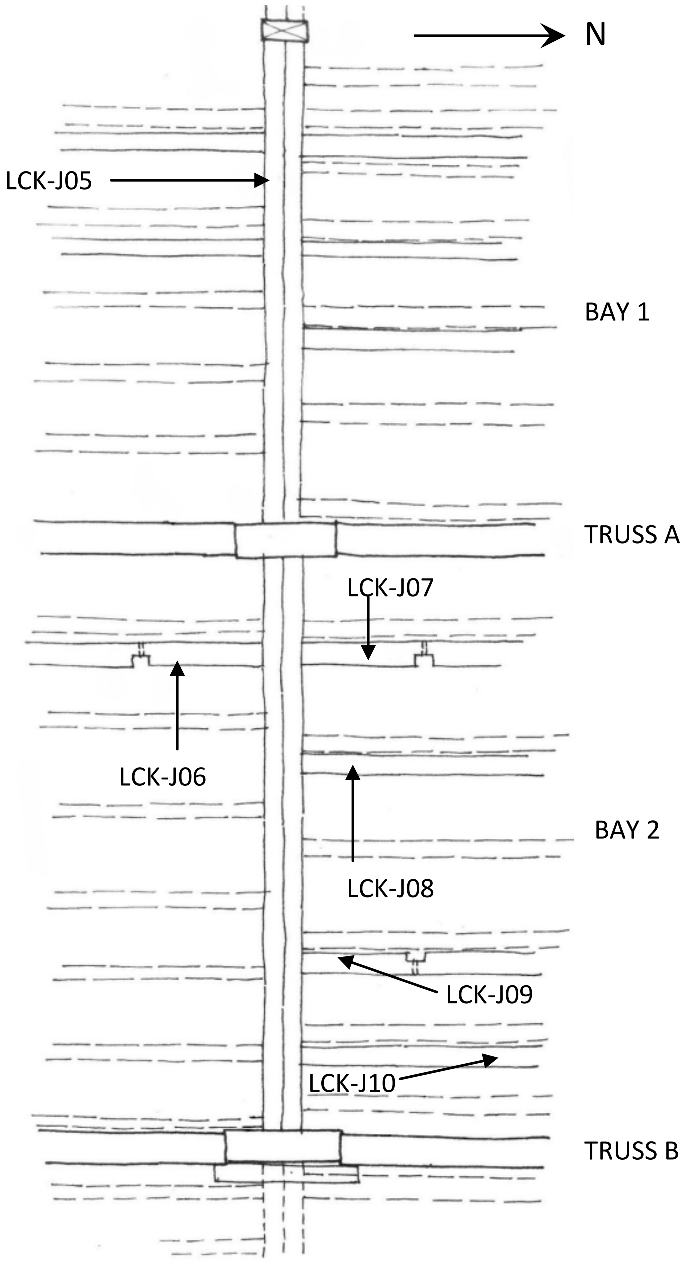
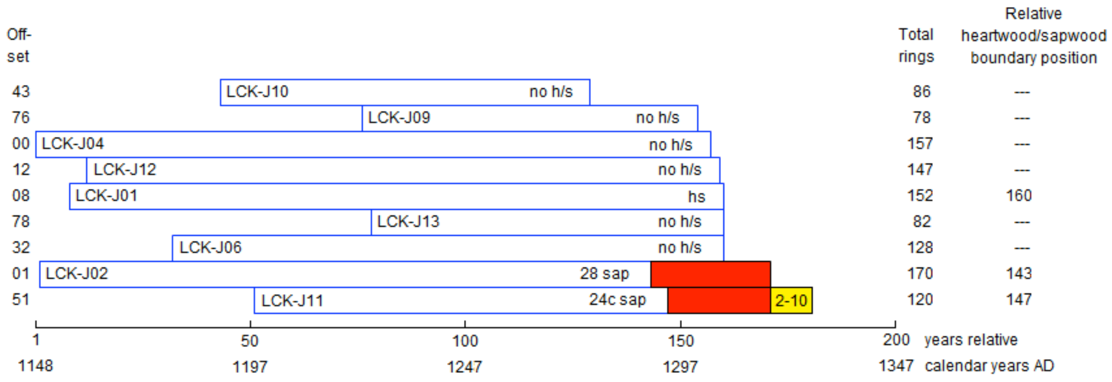


Figure 10: Sample location plan (later replacement rafters are shown dashed in)



White bars = heartwood rings;
filled bars = sapwood rings
estimated number of lost sapwood rings to bark edge
h/s = the last ring of the sample is at the heartwood/sapwood boundary
c= complete sapwood exists on the timber but part of the sapwood on the sample has been lost during preperation

Figure 11: Bar diagram of the samples in site chronology LCKJSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LCK-J01A 152
265 311 284 288 276 285 325 238 314 299 270 164 206 178 139 132 121 107 112 80
91 59 53 57 63 61 46 60 61 50 44 85 60 76 69 56 47 73 80 83
81 76 60 59 57 54 47 61 41 62 41 37 40 58 74 65 53 66 65 49
57 71 89 96 77 73 37 35 26 53 73 56 79 88 68 66 61 65 54 82
57 86 91 84 62 67 83 74 49 47 60 80 84 85 91 65 67 86 129 114
53 55 60 107 105 95 104 78 55 112 95 69 71 75 70 137 83 86 83 82
101 76 81 79 100 84 87 79 57 78 88 110 88 228 219 127 146 144 103 82
76 86 82 132 206 170 175 163 118 145 158 189
LCK-J01B 152
266 316 265 282 271 288 323 235 313 306 266 166 203 246 139 132 123 101 109 84
89 57 60 72 54 63 47 62 53 44 48 91 56 78 69 54 46 76 77 84
78 82 54 60 55 57 40 60 44 53 41 37 33 59 77 60 49 75 57 49
55 74 87 98 80 66 36 34 28 53 70 60 70 89 70 64 61 62 58 81
53 81 89 83 67 63 88 70 48 55 52 74 84 82 91 68 71 80 125 123
48 59 65 95 108 98 115 74 60 108 93 67 65 82 68 130 85 77 82 84
99 78 80 82 92 82 92 80 58 75 86 107 86 224 218 128 145 138 109 73
88 87 78 128 218 168 177 165 118 146 153 187
LCK-J02A 170
497 306 295 219 381 323 230 212 248 217 215 232 206 301 290 386 537 303 286 297
408 254 328 294 303 396 257 183 91 108 116 61 88 80 145 92 124 138 222 83
98 172 111 92 132 134 105 76 69 55 56 76 85 82 92 112 154 101 51 83
64 130 77 94 111 66 70 96 84 118 137 136 182 128 109 101 145 162 113 192
265 99 76 57 70 101 122 57 122 130 134 106 100 152 148 89 63 78 68 65
119 113 93 85 120 88 131 86 78 78 65 69 102 89 66 41 46 73 75 83
88 56 86 77 134 86 53 56 73 69 77 74 88 90 50 37 39 54 62 40
52 83 89 103 65 103 56 73 72 61 54 63 94 93 79 87 94 114 104 98
63 94 51 51 86 113 194 108 77 57
LCK-J02B 170
485 313 275 217 374 330 232 208 235 219 219 227 204 304 286 394 533 302 286 299
406 259 321 290 304 394 254 175 89 100 117 59 92 78 150 87 122 137 223 83
102 163 118 88 137 133 109 73 71 57 53 78 74 78 107 111 156 98 49 83
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262 103 86 53 62 111 114 67 120 127 137 110 100 153 139 92 65 79 66 58
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70 86 54 54 84 117 192 104 75 64
LCK-J04A 157
284 410 286 327 260 277 349 263 301 418 276 314 278 205 306 252 417 475 361 216
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126 198 228 203 244 196 276 203 243 209 159 253 311 424 371 365 412
LCK-J04B 157
283 400 281 326 276 299 346 252 311 395 283 315 269 209 310 255 408 479 363 211
297 376 300 395 382 381 330 174 216 99 81 114 67 72 59 95 70 55 54 94

47 72 69 53 27 58 85 64 49 59 57 63 66 55 51 68 42 54 48 37
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157 177 183 356 180 201 182 154 171 160 204 148 180 176 198 113 121 112 172 231
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LCK-J06A 128
121 138 66 88 66 58 51 118 66 68 87 79 44 101 107 79 63 80 76 101
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125 96 47 44 35 39 44 45 39 45 38 31 45 38 39 38 34 53 50 65
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149 203 172 139 92 120 168 92 80 87 109 141 113 111 103 147 134 89 117 112
142 83 104 76 54 67 61 95 80 193 162 81 127 101 120 68 120 111 103 167
177 210 203 197 136 162 202 238
LCK-J06B 128
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180 207 193 187 127 159 202 242
LCK-J07A 56
100 164 168 151 149 145 161 308 283 232 155 171 194 257 174 175 139 156 130 159
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LCK-J07B 56
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79 80 82 86 76 83 87 84 65 48 39 38 36 43 45 48 66 56 56 52
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LCK-J09A 78
18 18 31 25 35 43 35 31 33 35 46 56 50 71 81 80 54 67 57 107
54 53 52 55 56 81 77 73 52 64 53 65 45 32 53 60 58 45 69 38
47 68 83 49 39 48 58 85 43 64 66 97 68 55 55 67 102 71 48 35
41 60 55 66 42 116 124 64 118 99 87 65 67 72 84 89 178 250
LCK-J09B 78
15 20 30 23 37 47 31 32 31 36 51 52 48 77 76 87 55 67 61 106
65 48 54 54 58 78 79 69 53 60 52 66 45 36 47 66 53 49 69 42
45 69 81 49 42 47 55 88 43 66 66 95 68 59 55 68 98 64 43 44
40 54 61 61 46 127 123 72 115 102 88 63 69 78 86 92 183 250
LCK-J10A 86
70 129 79 94 83 53 66 67 88 121 93 52 44 73 86 58 91 66 84 83
87 83 133 80 95 60 58 77 100 74 109 67 44 66 111 105 76 86 100 94
57 60 100 76 111 74 133 114 119 98 101 114 174 194 152 82 112 133 197 163
143 120 158 107 161 99 107 140 94 105 162 169 108 128 156 112 96 129 119 169
231 151 190 154 130 102

LCK-J10B 86
67 131 87 93 78 56 61 63 101 134 80 60 38 87 79 56 91 64 83 94
97 78 138 76 92 62 61 75 98 76 115 66 45 71 106 107 77 84 95 92
57 65 96 77 117 65 143 112 118 99 102 112 173 195 150 86 112 127 200 161
149 114 159 108 168 102 110 141 96 110 165 167 111 116 147 112 96 128 119 166
241 158 181 153 126 106
LCK-J11A 120
108 106 93 53 139 81 122 100 63 148 105 111 179 104 101 70 69 84 96 94
136 102 103 59 47 39 107 116 104 80 93 61 61 49 57 68 111 52 105 98
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50 62 54 57 38 43 38 58 47 39 80 56 38 83 68 67 50 36 42 31
34 49 56 40 40 32 56 61 54 54 45 43 66 35 64 47 48 47 52 53
LCK-J11B 120
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44 85 107 92 67 48 49 62 69 57 42 34 64 53 50 45 53 43 63 54
55 60 54 56 39 40 41 58 46 39 77 62 36 86 66 69 43 42 41 30
35 52 48 44 36 34 57 59 54 46 42 43 65 33 68 50 48 48 49 55
LCK-J12A 147
352 328 278 239 308 399 290 243 414 398 332 339 400 361 442 323 345 179 221 290
173 218 334 213 110 228 181 250 151 292 241 157 164 174 235 194 141 132 78 95
175 161 89 125 71 155 127 69 180 140 141 150 100 135 96 95 113 128 141 144
154 142 86 70 51 122 116 116 138 108 69 79 64 64 65 91 74 101 90 104
63 52 55 76 53 50 51 78 62 78 75 80 53 52 69 57 41 67 61 36
63 79 88 49 44 44 52 50 45 40 31 60 36 21 18 25 14 21 29 28
27 33 32 27 32 37 52 46 39 46 69 39 76 56 59 33 42 39 32 39
45 48 61 63 80 53 79
LCK-J12B 147
352 326 278 238 325 392 284 239 415 401 327 334 400 366 432 319 349 163 222 287
169 217 336 209 111 227 183 252 148 294 251 159 164 173 242 200 142 126 75 96
165 164 94 125 69 160 120 70 178 142 144 147 102 141 91 111 102 129 138 150
153 137 86 69 50 116 127 120 135 108 70 73 63 72 62 94 66 114 84 106
63 49 58 73 56 55 41 82 64 76 78 75 56 58 63 61 41 56 69 35
59 82 84 51 50 41 45 57 44 39 31 63 34 16 16 24 15 22 28 28
28 32 34 25 34 37 51 50 38 46 65 43 74 54 55 35 39 39 37 38
47 50 64 61 79 65 71
LCK-J13A 82
44 27 60 98 49 59 52 50 78 65 59 98 105 169 111 109 117 141 91 83
79 94 145 187 156 172 122 157 172 184 61 87 75 154 135 106 119 71 74 78
105 51 44 52 42 132 50 69 65 54 54 60 39 57 80 47 51 54 33 36
53 78 36 158 140 100 127 111 128 113 137 175 109 149 231 239 206 265 191 178
273 332
LCK-J13B 82
38 43 50 100 49 48 54 59 67 81 51 97 96 154 118 104 119 142 81 71
60 102 141 186 160 169 120 156 172 186 66 84 83 139 131 109 122 72 72 83
101 51 43 48 47 131 60 80 65 54 66 56 41 41 79 51 50 52 36 32
43 81 43 156 137 89 120 111 119 112 122 174 112 142 217 242 201 260 179 179
279 323

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

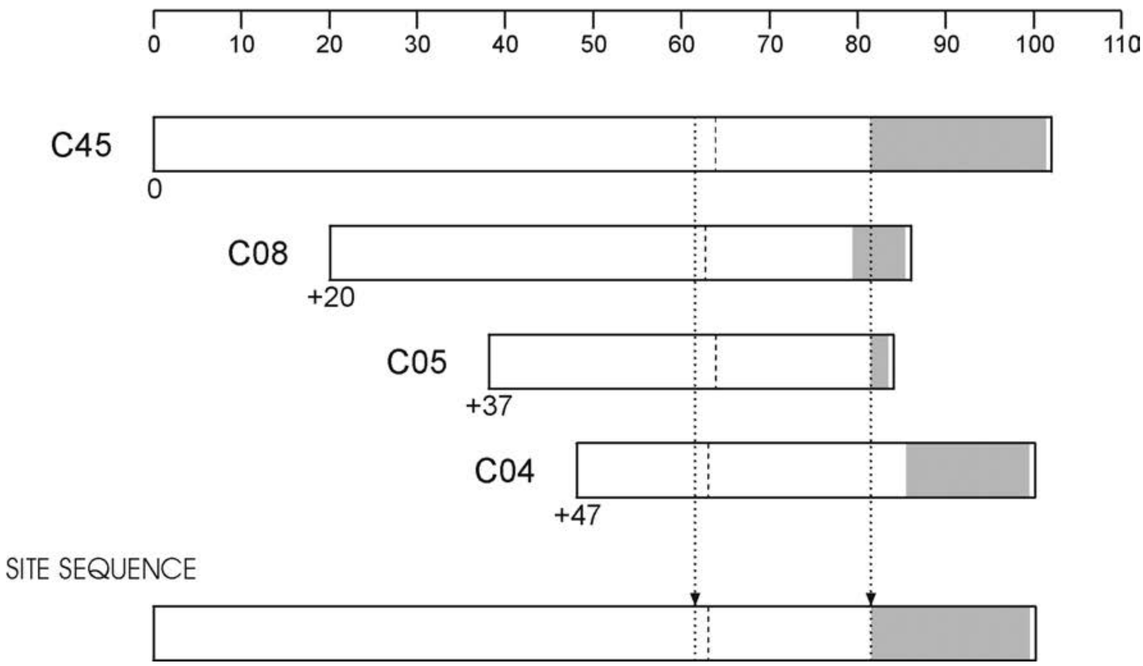


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

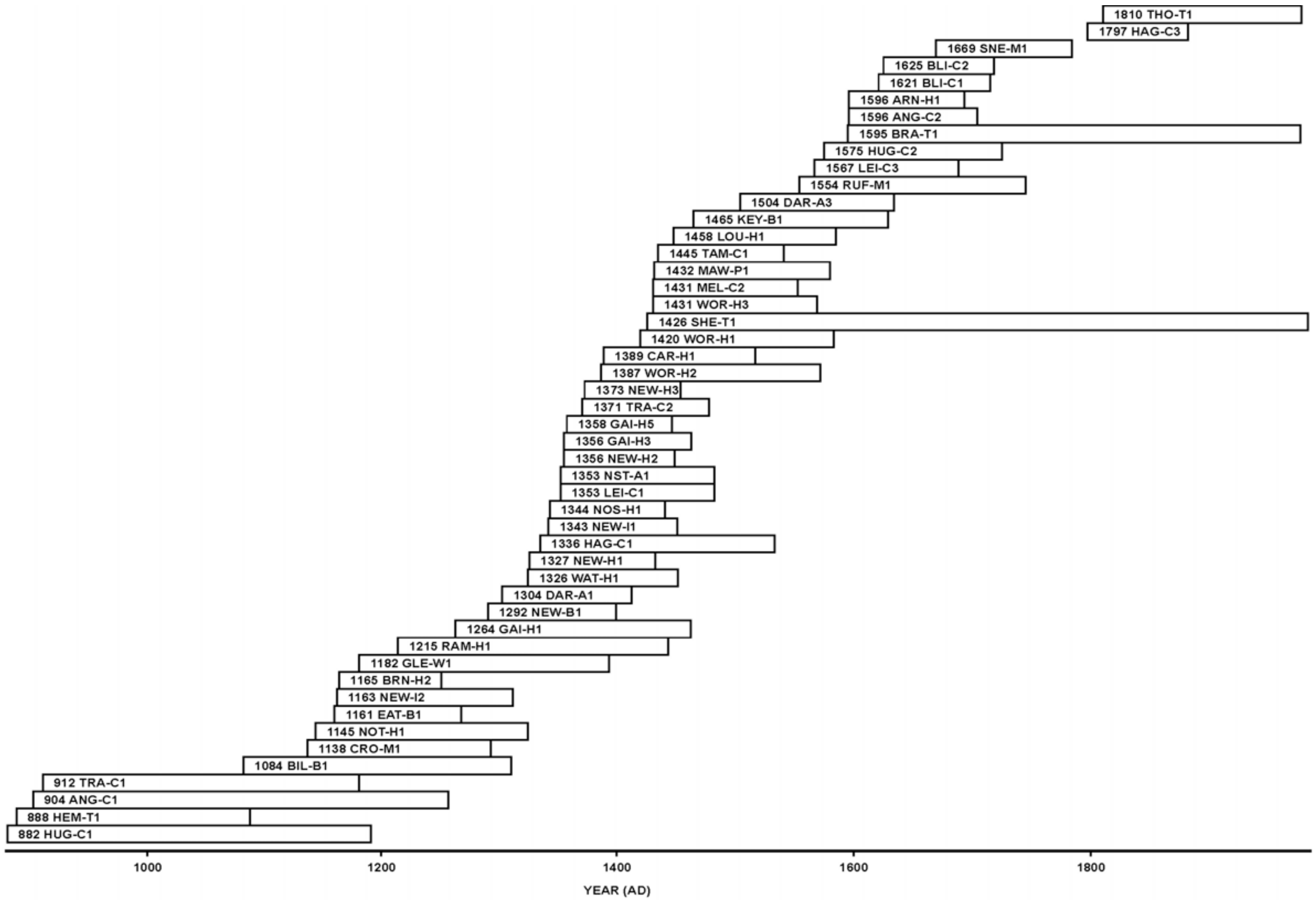
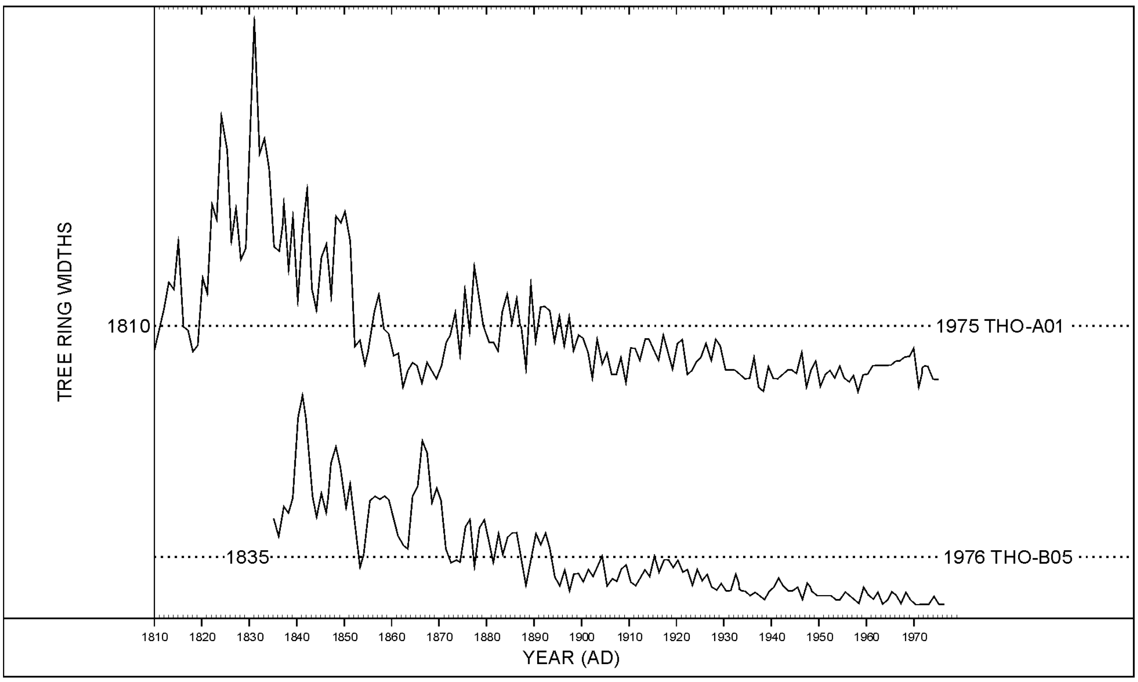


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

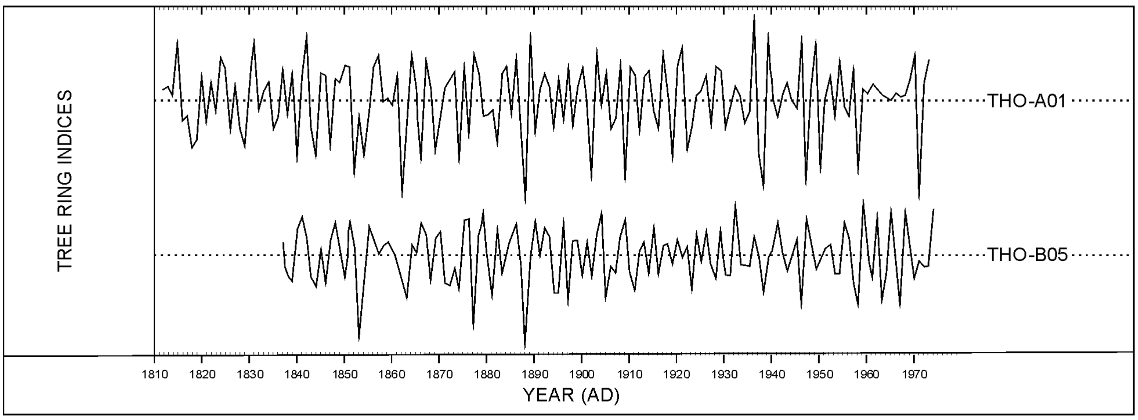


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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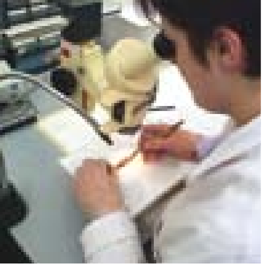
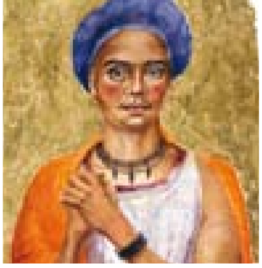



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