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Church of St Julitta Lanteglos Cornwall

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

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Photograph taken pre-repair works (2013) by Chris Miners

Research Report Series 169-2020

CHURCH OF ST JULITTA
LANTEGLOS
CORNWALL

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SUMMARY
Dendrochronological analysis has resulted in the dating of 28 timbers from the roofs of the nave, south aisle, and north transept. Timbers from the south aisle roof have been dated as felled in the period AD 1469–91, whilst those from the nave roof may be coeval but appear more likely to be very slightly later having a felling date range of AD 1483–1508. Two slightly different felling periods have been identified for the timbers in the north transept roof of AD 1464–89 and AD 1485–1510. These two felling date ranges overlap indicating the possibility that the timbers represented are coeval but they appear more likely to represent two different episodes of felling. Thus, this roof can be seen to utilise timber coeval with both the south aisle and the nave roofs perhaps suggesting that the bulk of the timber in this roof was felled at the same time, or within a few years, of the nave but that this roof also incorporates slightly earlier timbers, perhaps surplus from construction of the south aisle roof.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank Jonnie Starr, site manager, and the other contractors on site for their patience and assistance whilst assessment and sampling were undertaken. We would also like to thank Jeremy Chadwick, architect, for his invaluable *on-site* advice and for providing the plans used to locate samples, and Chris Miners, Historic England Architect/Surveyor, who requested the work and for his help with logistical arrangements. Shahina Farid (Historic England Scientific Dating Team) commissioned and facilitated this programme of dendrochronological analysis.

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CONTENTS

INTRODUCTION

The Grade I listed (List Entry Number: 1142729) parish church of St Julitta lies in the hamlet of Lanteglos, just to the south-west of Camelford in north Cornwall (Fig 1). It is thought to have originated in the Norman period and is likely to have been of cruciform plan with a tower added in the fourteenth century and a south aisle added in the fifteenth century, probably along with the south porch. It presently consists of nave, chancel, south aisle, south porch, north transept, and west tower and has Cornish rag slate roofs. It was restored in 1864 and in 1873 by J P St Aubyn. It is currently being monitored for addition to the Heritage at Risk Register due to rain water ingress.

The roofs are of wagon-roof type with common-rafter couples, upper and lower braces, and soulaces. A typical example truss from the south aisle is illustrated in Figure 2. Figures 3–5 show the roofs of the nave, south aisle, and north transept respectively. There is little variation between these roofs but some of the beams in the north transept are moulded. The typology of wagon roofs remains relatively poorly understood (Thorp 2013) but it is thought that these three roofs are likely to be broadly contemporary and date to the fifteenth century. The date of the two large beams located in the valley between the south aisle and nave roofs (Fig 6) is, however, uncertain.

SAMPLING

A Heritage Lottery Fund Grant has been secured and a dendrochronological survey was requested by Chris Miners, Historic England Architect/Surveyor, to provide independent dating evidence in order to understand the significance of the development of the church and inform advice on the repair programme.

Forty-three core samples were taken from timbers of the nave, south aisle, and north transept roofs and from the two valley beams. Additionally, three samples in the form of cross-sectional slices were taken from offcut sections of timbers removed for disposal during the present renovations. Each sample was given the code LNT-G and numbered 01–46. Further details relating to the samples can be found in Table 1. The location of cored timbers, with the exception of the valley beams, has been marked on Figure 7. Trusses and frames have been numbered from east to west (nave and south aisle roofs) and north to south (north transept roof).

The tower was also assessed for its suitability for tree-ring dating but was found to be a relatively recent structure (Fig 8). Also assessed were two pieces of painted wood (Fig 9), thought to be fragments of the rood screen, to see whether it would be possible to measure a combination of exposed rings and grain. However, it was found that one of the pieces had too few rings for secure dating to be a possibility (less than 40), and the other could not be prepared to a standard where the growth rings could be accurately and reliably measured.

ANALYSIS AND RESULTS

Thirteen of the cores (six from the nave roof, two from the south aisle, three from the north transept, and two from the valley beams) had too few rings for secure dating and so were rejected prior to measurement. The remaining 30 cores and the three cross-sectional slices were prepared by sanding and polishing and their growth-ring widths measured. These measurements are given at the end of the report. All measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 30 samples cross-matching to form two groups.

Firstly, 28 samples cross-matched each other (minimum *t*-value of 3.6) and were combined at the relevant offset positions to form LNTGSQ01, a site sequence of 111 rings (Fig 10). This site sequence was compared against an extensive series of relevant reference chronologies for oak. It was found to cross-date securely and consistently at a first-ring date of AD 1366 and a last-ring date of AD 1476 (Table 2), thus allowing each individual component series to be assigned calendar dates (Table 1; Fig 10).

Two other samples also cross-matched each other (*t*-value of 6.8) and were again combined at the relevant offset position to form LNTGSQ02, a site sequence of 71 rings (Fig 11). However, attempts to date this site sequence were unsuccessful and so the two individual component series remain relatively dated only.

The remaining three ungrouped samples also remain undated following comparison to the same extensive series of relevant reference chronologies.

INTERPRETATION

Dendrochronological analysis has resulted in the successful dating of 28 timbers, nine from the nave roof, 11 from the south aisle roof, and eight from the north transept roof, potentially representing at least two different episodes of felling. To aid interpretation, the results are presented area by area below and in Figure 12. In each case, where sapwood is not complete (ie the sample does not have the last ring produced before the tree was felled), the estimated felling date is calculated on the basis that 95% of mature oak trees from this area have between 15 and 40 sapwood rings.

Nave roof

Nine of the samples taken from the timbers of this roof have been successfully dated. These represent four rafters, three arch braces, one collar, and an offcut of unknown function. Seven of these samples have the heartwood/sapwood boundary ring present, the dates of which are broadly contemporary, ranging from AD 1465 (LNT-G02) to AD 1471 (LNT-G03 and LNT-G14), and suggestive of a single episode of felling. The average heartwood/sapwood boundary ring date is AD 1468, allowing an estimated felling date range to be calculated for the seven timbers represented of AD 1483–1508.

The other two dated samples from this roof do not have the heartwood/sapwood boundary and so a felling date range cannot be calculated for either timber but, with last-measured ring dates of AD 1458 (LNT-G07) and AD 1455 (LNT-G17), these have estimated felled after dates of AD 1473 and AD 1470 respectively. These *terminus post quem* dates for felling indicate that it is possible, and likely, that the two timbers were also felled during the period AD 1483–1508.

South aisle roof

Eleven of the samples taken from this roof have been dated. These represent seven rafters, two arch braces, and two offcuts of unknown function. Eight of these samples have the heartwood/sapwood boundary ring present. The dates of these heartwood/sapwood boundary rings are broadly contemporary, ranging from AD 1442 (LNT-G22) to AD 1460 (LNT-G31), and suggestive of a single felling episode. The average heartwood/sapwood boundary ring date is AD 1451, allowing an estimated felling date range to be calculated for the eight timbers represented of AD 1469–91. This allows for sample LNT-G31 having a last-measured ring date of AD 1468 with incomplete sapwood.

The other three dated samples from this roof do not have the heartwood/sapwood boundary and so a felling date range cannot be calculated for them. With last-measured ring dates of AD 1439 (LNT-G21), AD 1437 (LNT-G24), and AD 1436 (LNT-G28), these have estimated felled after dates of AD 1454, AD 1452, and AD 1451. These *terminus post quem* dates for felling suggest it is possible, and likely, that the three timbers represented were also felled during the period AD 1469–91.

North transept roof

Eight of the samples taken from this roof have been dated. These represent four rafters and four arch braces. Five of the dated samples have the heartwood/sapwood boundary, the dates of which suggest two potentially separate felling episodes. Samples LNT-G37 and LNT-G40 have similar heartwood/sapwood boundary ring dates of AD 1450 and AD 1448 respectively. The average of these, AD 1449, allows an estimated felling date range to be calculated for the two timbers represented of AD 1464–89. The heartwood/sapwood boundary ring dates of the other three samples are all slightly later, being of AD 1468 (LNT-G35), AD 1476 (LNT-G41), and AD 1466 (LNT-G43). The average of these is AD 1470, giving an estimated felling date range of AD 1485–1510.

The other three dated samples from this roof do not have the heartwood/sapwood boundary and so a felling date range cannot be calculated for them. With last-measured ring dates of AD 1460 (LNT-G33), AD 1432 (LNT-G39), and AD 1461 (LNT-G42), these have estimated felled after dates of AD 1475, AD 1457, and AD 1476 respectively. Whilst samples LNT-G39 and LNT-G33 could be associated with either of the two felling phases, sample LNT-G42 cross-matches sample LNT-G43 (felled AD 1485–1510) at a t-value high enough (t = 11.0) to suggest that both timbers were cut from the same tree and, therefore, felled at the same time.

DISCUSSION

The tree-ring analysis has dated timbers from the roofs of the nave, the south aisle, and the north transept with the estimated felling date ranges produced indicating that these roofs are broadly coeval, dating to the later fifteenth or very early sixteenth century. However, the felling date ranges obtained suggest the possibility that the south aisle was constructed from timber felled slightly earlier (AD 1469–1491) than the nave (AD 1483–1508), but perhaps by only a couple of decades at most. The north transept roof contains timbers potentially representing two separate felling episodes, the earlier timbers being coeval with the south aisle roof timbers and the later one coeval with the nave roof timbers. This could suggest felling for the bulk of the timbers for the north transept roof occurred at the same time, or within a few years, of the nave but that this roof also incorporates slightly earlier timbers, perhaps representing surplus from the construction of the south aisle roof. All three wagon roofs have, therefore, been dated by dendrochronology towards the latter part of the period to which wagon roofs are generally thought to date, that is the early fifteenth to early sixteenth centuries, although earlier examples are now challenging this common perception (Thorp 2013).

In addition to the potential same-tree match noted between two rafters from the north transept roof mentioned above (LNT-G42 and LNT-G43), a third rafter, LNT-G35, from this roof matches both of these samples at $t = 10.9$, which could suggest that all three timbers were cut from the same tree. Additionally, the two offcuts from the south aisle roof (represented by samples LNT-G31 and LNT-G32) match each other at $t = 12.5$ and are likely to come from the same tree. However, as it is unclear which timbers these are from, it is possible that they are from the same timber.

The site master sequence shows high levels of similarity with reference chronologies from sites in the south-west, west midlands, and north-west but notably also a number of chronologies from sites in Yorkshire (Table 2), a phenomenon that has been noted previously with some chronologies from sites in the south-west and Yorkshire. Thus, the likely source of the timber is difficult to ascertain, although such sites usually use relatively local woodland sources. The overall level of similarity with sites across the south-west and into the west midlands does, however, suggest a relatively local source for the roof timbers.

It is unfortunate that the second site sequence, representing an arch-brace from the nave (LNT-G09) and a rafter from the south aisle (LNT-G26), is undated. The heartwood/sapwood boundary positions of these two samples differ by ten years (Fig 12), which makes it possible that both timbers were felled at the same time, although this remains uncertain.

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TABLES

Table 1: Details of samples taken from the Church of St Julitta, Lanteglos, Cornwall

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Nave						
LNT-G01	South lower archbrace 2, bay 1	NM	--	----	----	----
LNT-G02	North rafter 3, bay 1	67	h/s	1399	1465	1465
LNT-G03	South upper archbrace 1, bay 2	72	03	1403	1471	1474
LNT-G04	South rafter 1, bay 2	NM	--	----	----	----
LNT-G05	North lower archbrace 2, bay 2	64	01	1407	1469	1470
LNT-G06	North upper archbrace 1, bay 4	NM	--	----	----	----
LNT-G07	Collar 2, bay 4	50	--	1409	----	1458
LNT-G08	North rafter 2, bay 4	72	h/s	1396	1467	1467
LNT-G09	South upper archbrace 2, bay 4	58	03	----	----	----
LNT-G10	North rafter 2, bay 5	NM	--	----	----	----
LNT-G11	South rafter 2, bay 5	NM	--	----	----	----
LAN-G12	South rafter 3, bay 5	51	h/s	1420	1470	1470
LNT-G13	North rafter 3, bay 5	59	--	----	----	----
LNT-G14	North lower archbrace 1, bay 5	70	h/s	1402	1471	1471
LNT-G15	North rafter 1, bay 12	68	h/s	1399	1466	1466
LNT-G16	North rafter, truss 13	NM	--	----	----	----
LNT-G17	Offcut	69	--	1387	----	1455
South aisle						
LNT-G18	North rafter 50	49	h/s	1400	1448	1448
LNT-G19	North rafter 47	NM	--	----	----	----
LNT-G20	North rafter 42	84	04	1369	1448	1452
LNT-G21	North rafter 41	68	--	1372	----	1439
LNT-G22	North lower archbrace 41	68	h/s	1375	1442	1442
LNT-G23	North rafter, 39	77	02	1375	1449	1451

Table 1:cont.

LNT-G24	North rafter 37	65	--	1373	----	1437
LNT-G25	North rafter 35	68	--	----	----	----
LNT-G26	North rafter 29	66	26C	----	----	----
LNT-G27	North rafter 27	89	03	1366	1451	1454
LNT-G28	North lower archbrace 16	60	--	1377	----	1436
LNT-G29	North rafter 15	52	03	1406	1454	1457
LNT-G30	North rafter 13	NM	--	----	----	----
LNT-G31	Offcut	61	08	1408	1460	1468
LNT-G32	Offcut	53	h/s	1407	1459	1459
North transept						
LNT-G33	East rafter, truss 1	62	--	1399	----	1460
LNT-G34	West lower archbrace, truss 1	NM	--	----	----	----
LNT-G35	West rafter 3, bay 1	54	02	1417	1468	1470
LNT-G36	East rafter 2, bay 2	59	h/s	----	----	----
LNT-G37	East lower archbrace 2, bay 2	89	04	1366	1450	1454
LNT-G38	East lower archbrace 3, bay 2	NM	--	----	----	----
LNT-G39	East lower archbrace 1, bay 3	64	--	1369	----	1432
LNT-G40	West lower archbrace 1, bay 3	80	02	1371	1448	1450
LNT-G41	East lower archbrace 2, bay 3	48	h/s	1429	1476	1476
LNT-G42	East rafter 3, bay 3	90	--	1372	----	1461
LNT-G43	West rafter 3, bay 3	69	02	1400	1466	1468
LNT-G44	East lower archbrace 3, bay 3	NM	--	----	----	----
Valley beams						
LNT-G45	Valley beam 1	NM	--	----	----	----
LNT-G46	Valley beam 2	NM	--	----	----	----

Key:
NM = not measured;
h/s = the heartwood/sapwood boundary is the last-measured ring
C = complete sapwood retained on sample; last-measured ring is the felling date

Table 2: Results of the cross-matching of site sequence LNTGSQ01 and relevant reference chronologies when the first-measured ring date is AD 1366 and the last-measured ring date is AD 1476

Reference	*t*-value	Span of chronology (AD)	Reference
St John's Walk, Hereford Cathedral, Herefordshire	9.5	1356–1504	Arnold and Howard 2015 unpubl
The Commandery, Worcester, Worcestershire	9.5	1284–1473	Arnold and Howard 2006
Church of St Barnabas, Brampton Bryan, Herefordshire,	9.1	1268–1622	Arnold *et al* forthcoming a
Lower Brockhampton Manor, near Bromyard, Herefordshire	9.1	1304–1505	Arnold and Howard 2014 unpubl
Plowden Hall, Lydbury North, Shropshire	9.1	1330–1453	Miles *et al* 1993
All Hallows' Church, Kirkburton, West Yorkshire	9.1	1306–1633	Arnold and Howard 2007
Wigmore Abbey, nr Adforton, Herefordshire	9.0	1055–1729	Tyers 2006
St Mary's Abbey, Halesowen, West Midlands	8.8	1310–1535	Arnold and Howard 2008
Docton Court, Appledore, Devon	8.7	1440–1581	Arnold and Howard 2012 unpubl
Calverley Old Hall, Calverley, West Yorkshire	8.5	1261–1585	Arnold *et al* forthcoming b
St Andrew's Church, Alwington, Devon	8.3	1342–1490	Arnold and Howard 2009
Mercer's Hall, Gloucester, Gloucestershire	8.3	1289–1541	Howard *et al* 1996

FIGURES

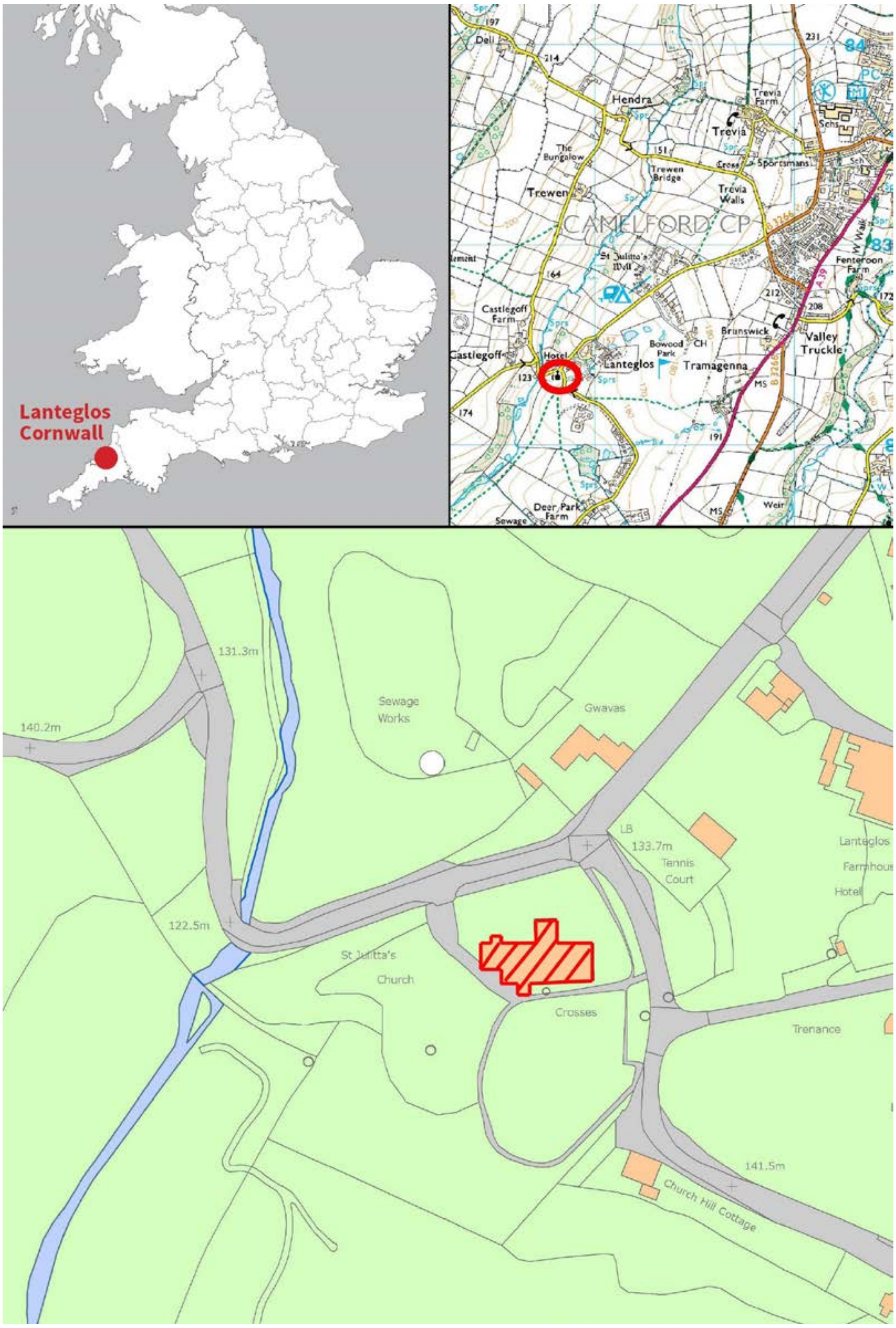

Figure 1: Maps to show the location of the Church of St Julitta, Lanteglos in Cornwall, marked in red. Scale: top right 1:25000; bottom 1:1500. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

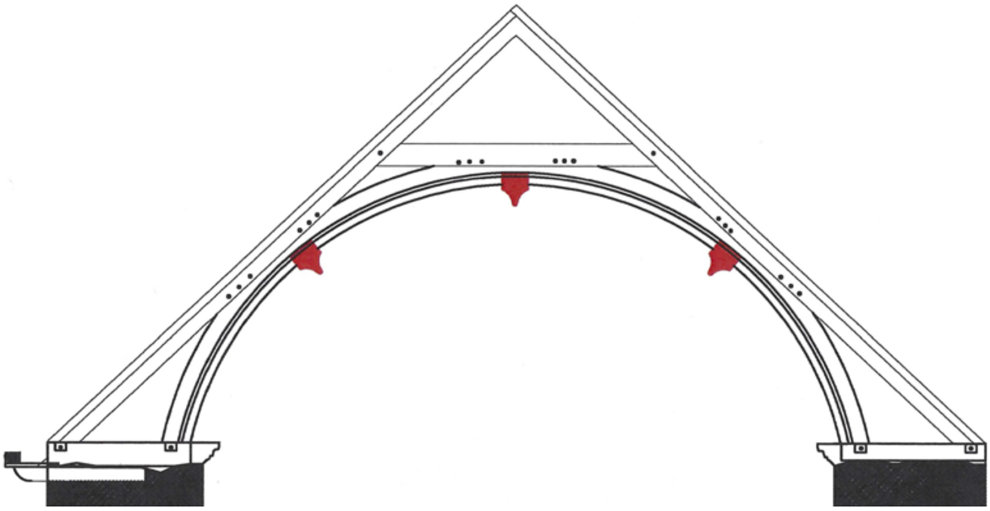

Figure 2: A south aisle roof truss, typical of wagon roofs (after Chadburn Conservation Architect 2015)

Figure 3: Nave roof, photograph taken from the east (Alison Arnold)

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

Figure 5: North transept roof, photograph taken from the north-east (Alison Arnold)

Figure 6: Valley gutter beams, beam 1 to the left and beam 2 to the right (Alison Arnold)

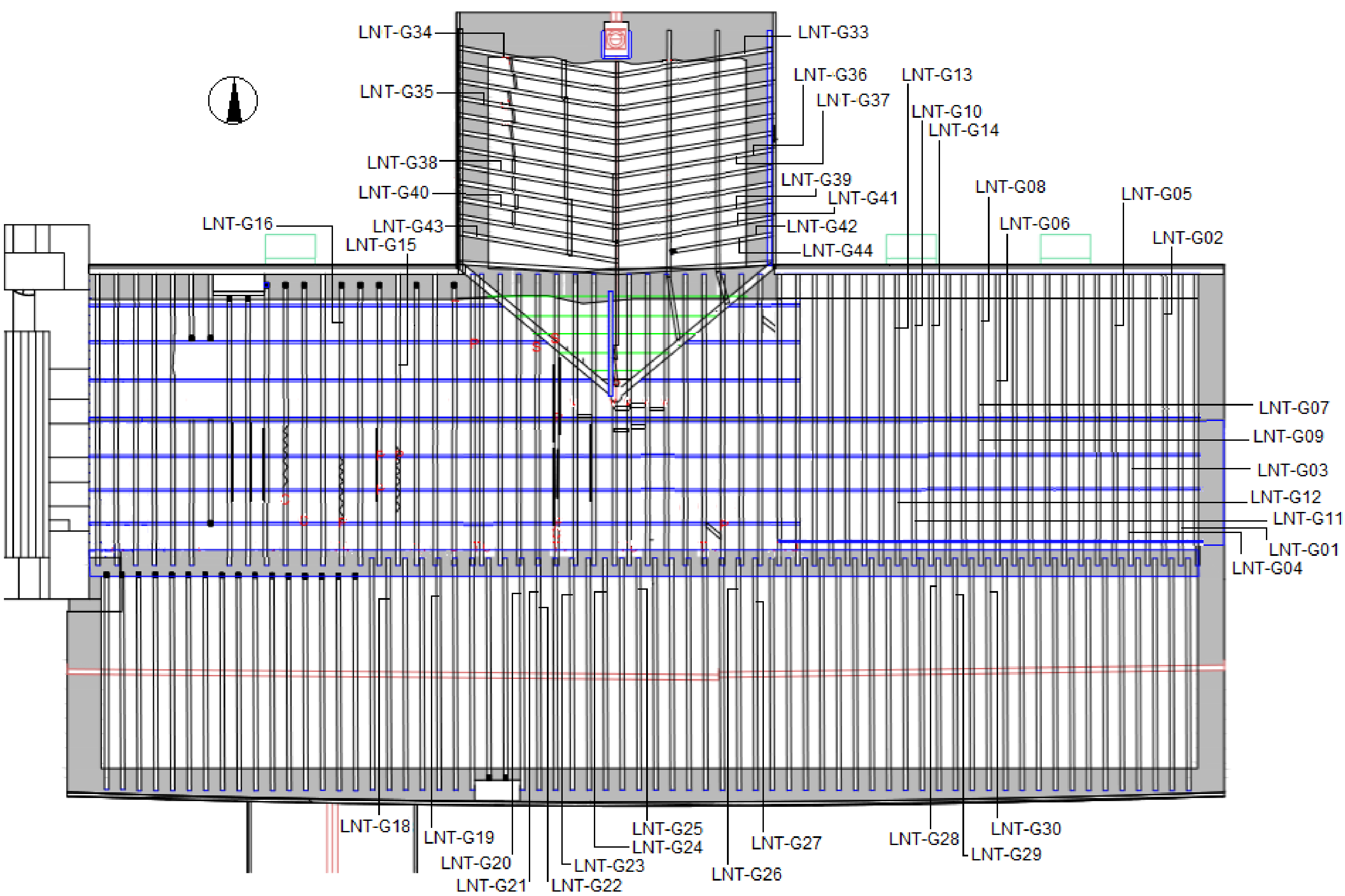

Figure 7: Roof plan, showing the location of sampled timbers LNT-G01–16, LNT-G18–30, and LNT-G33–44 (after Chadburn Conservation Architect 2015)


Figure 8: Tower roof, photograph taken from the east (Alison Arnold)


Figure 9: Painted wooden fragments thought to be from the rood screen (Alison Arnold)

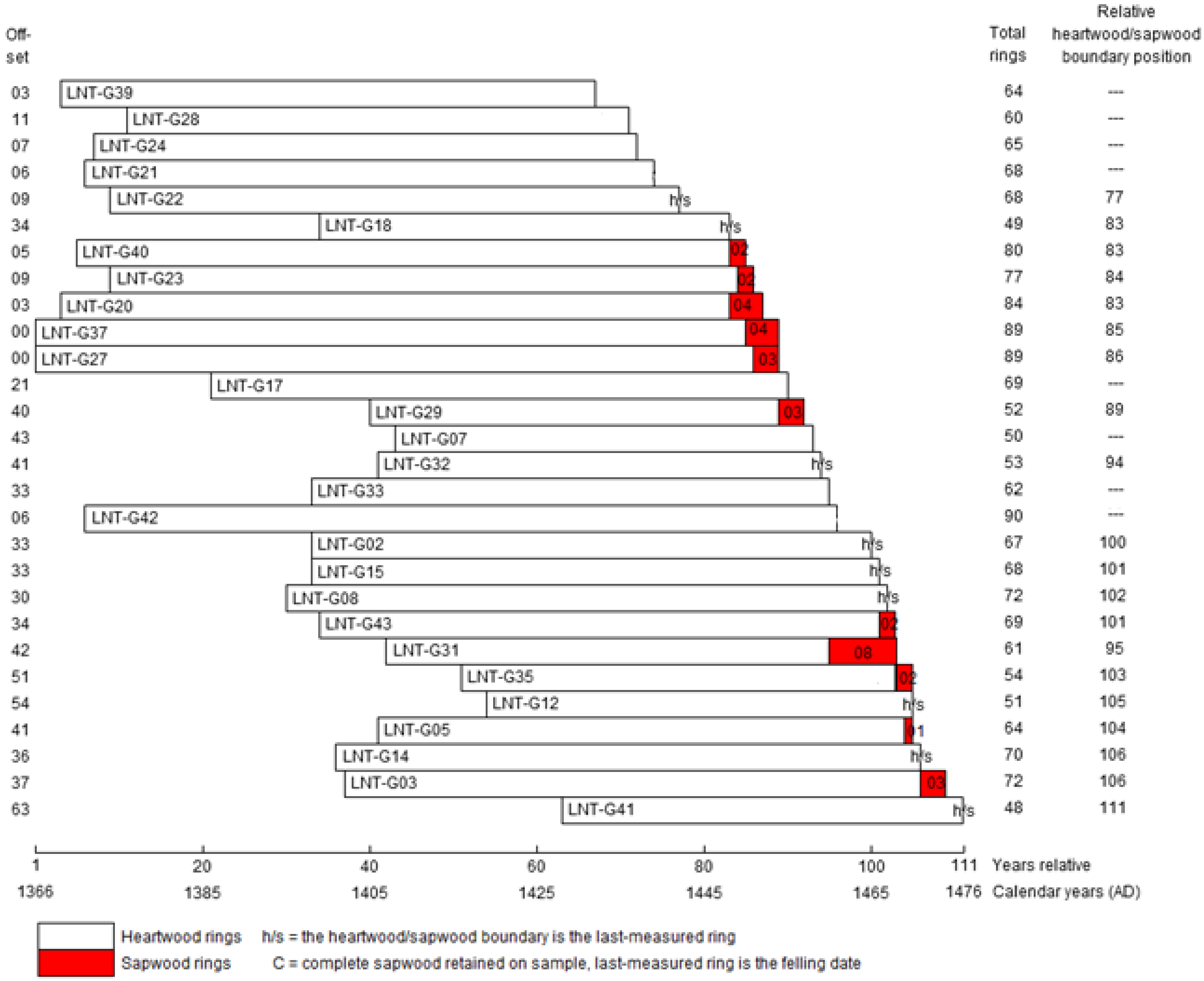

Figure 10: Bar diagram to show the relative position of samples in site sequence LNTGSQ01. The calendar date span for the measured ring series for each sample is given in Table 1

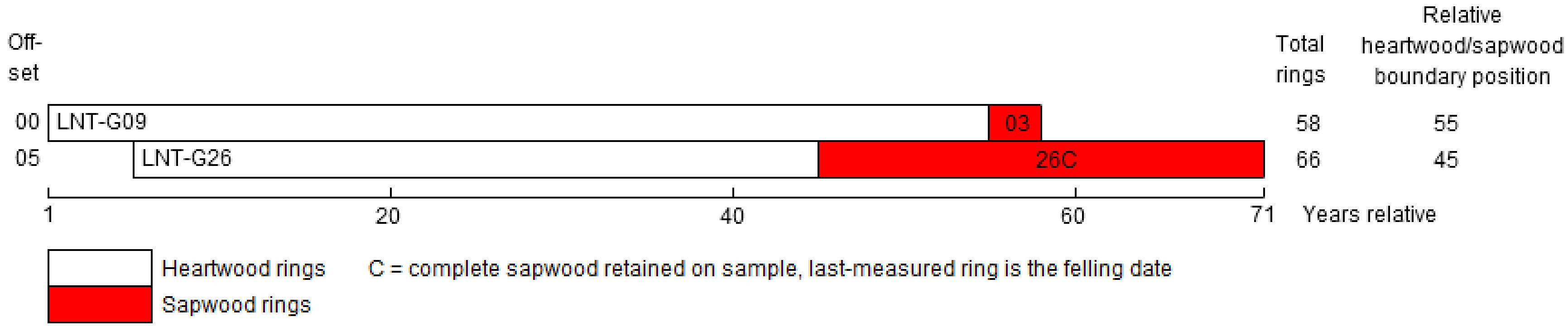

Figure 11: Bar diagram to show the relative position of samples in undated site sequence LNTGSQ02. The relative date span for the measured ring series for these two samples is 1-58 (LNT-G09) and 6-71 (LNT-G26)

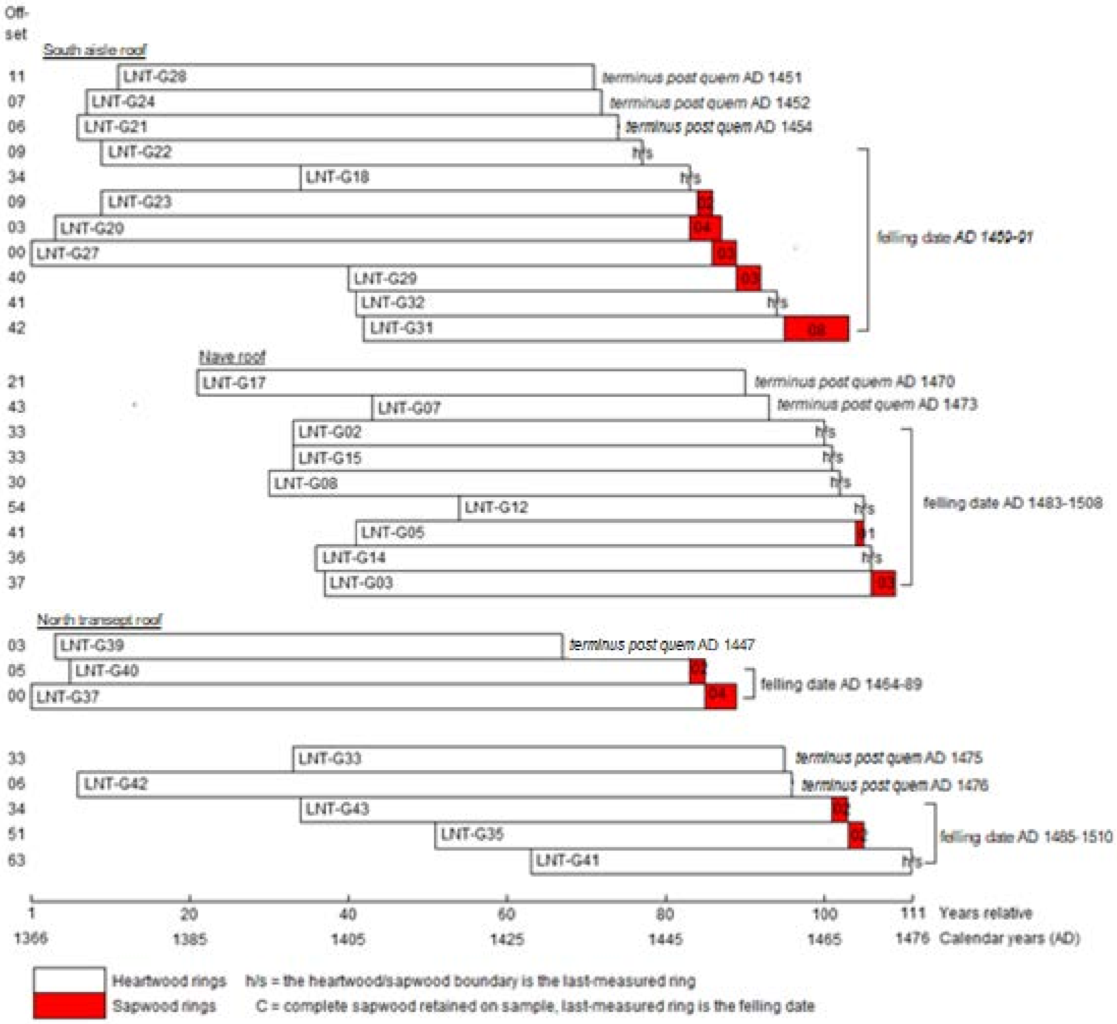

Figure 12: Bar diagram to show the relative position of all dated samples, sorted by area, with felling date ranges or felled after dates indicated. The calendar date span for the measured ring series for each sample is given in Table 1

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LNT-G02A 67
113 177 146 119 154 161 139 162 139 143 135 135 95 125 138 138 132 109 108 98
103 101 109 77 116 118 116 154 138 136 145 130 152 168 129 139 163 139 135 91
63 57 81 106 111 105 142 99 94 119 119 109 110 116 101 85 78 99 90 113
93 117 116 105 112 87 120
LNT-G02B 67
111 179 147 125 150 156 139 159 140 139 138 130 99 124 138 139 138 106 106 93
104 91 115 81 124 114 119 149 140 140 139 134 146 157 141 142 161 139 128 97
57 56 84 104 110 111 142 98 95 116 123 103 114 117 104 78 81 97 94 110
91 118 116 107 107 91 123
LNT-G03A 72
187 173 169 188 76 92 116 71 98 95 75 75 92 77 118 98 74 81 67 78
197 181 119 138 83 143 91 147 167 181 136 146 240 181 211 184 247 337 272 157
248 311 335 355 264 235 261 168 237 292 165 261 226 214 226 207 156 175 209 205
219 156 119 150 256 291 260 278 132 65 153 165
LNT-G03B 72
185 164 173 178 80 89 120 66 102 92 80 66 100 75 140 98 73 92 57 78
176 182 121 146 85 140 94 150 173 181 130 144 243 182 206 179 246 349 274 162
261 320 333 360 260 238 252 161 235 275 161 261 225 212 227 206 157 190 222 213
233 163 121 170 254 292 264 282 131 61 165 165
LNT-G05A 64
311 396 536 366 363 372 327 295 343 270 381 335 213 400 370 214 359 387 376 459
120 122 93 152 214 243 212 210 203 150 166 136 164 166 150 119 182 113 100 121
139 207 189 158 192 199 138 173 160 219 186 289 158 222 152 258 300 216 250 225
307 382 210 238
LNT-G05B 64
323 390 489 374 370 367 326 301 351 294 404 339 207 417 371 207 351 369 401 452
120 125 88 150 213 245 213 210 201 151 167 142 164 168 159 116 187 115 101 106
144 221 185 155 182 210 128 176 159 224 206 268 169 219 149 266 299 217 249 222
317 379 210 258
LNT-G07A 50
354 209 283 337 373 505 411 354 313 279 175 272 240 121 328 276 220 248 135 201
151 155 140 148 131 126 180 169 194 123 81 124 114 87 119 114 115 120 84 105
148 75 87 107 83 112 78 118 87 88
LNT-G07B 50
345 198 305 344 368 506 408 363 311 279 176 273 236 121 326 277 222 246 131 202
153 155 140 150 132 119 182 169 195 129 69 126 117 85 121 116 114 117 95 102
150 77 81 113 86 108 75 114 86 88
LNT-G08A 72
166 132 165 203 173 162 153 191 167 126 90 106 144 131 116 108 130 158 142 142
103 112 156 133 116 134 119 263 196 219 220 134 209 182 178 249 274 205 241 285
223 185 219 214 171 190 156 212 248 184 168 183 242 233 228 346 312 219 233 225
281 256 290 150 178 191 204 204 212 172 142 155
LNT-G08B 72
152 132 168 195 173 157 150 191 172 143 65 112 140 128 109 111 133 155 139 145
102 110 158 123 113 119 123 257 207 211 224 151 204 178 176 252 285 190 255 285
216 193 205 238 166 183 156 223 234 185 158 188 243 238 247 315 322 229 210 212
271 256 285 159 185 173 202 202 213 169 141 151
LNT-G09A 58

271 120 109 121 172 160 115 173 125 136 285 184 127 165 172 167 75 66 167 128
243 160 84 168 187 296 303 342 218 163 298 294 333 248 208 307 206 270 242 133
208 283 138 165 198 172 157 146 153 128 96 110 164 160 170 123 156 137
LNT-G09B 58
271 119 113 118 166 161 113 172 133 117 279 188 132 166 167 164 60 69 164 132
250 156 82 181 190 261 277 294 220 167 298 295 334 257 201 318 211 268 238 129
202 277 140 161 202 168 151 151 151 131 95 111 163 170 160 124 144 124
LNT-G12A 51
163 223 152 283 230 215 244 181 242 202 194 253 276 217 270 362 257 304 245 176
172 176 141 229 233 209 195 202 284 253 207 327 324 255 294 202 236 175 229 132
168 177 199 160 148 176 149 168 179 129 170
LNT-G12B 51
161 202 166 277 224 251 250 169 245 176 196 259 271 201 265 365 256 301 241 180
167 175 138 224 235 212 192 230 288 248 214 323 320 252 294 172 234 176 228 134
166 176 200 164 141 181 143 170 180 125 168
LNT-G13A 59
252 344 195 274 192 195 211 194 165 189 151 240 133 254 205 156 135 111 130 144
196 165 180 216 174 266 298 315 295 260 337 254 201 302 256 306 225 130 177 230
200 204 222 166 137 201 178 165 176 128 278 233 197 222 190 224 175 170 238
LNT-G13B 59
252 341 195 265 183 191 207 187 168 182 155 235 137 249 212 156 127 118 136 148
198 166 173 212 179 263 295 311 301 258 336 259 194 303 258 303 224 140 169 230
198 203 229 165 135 206 175 163 187 123 281 225 198 221 192 221 176 173 193
LNT-G14A 70
192 240 217 182 171 130 115 104 68 109 84 83 111 92 67 91 87 70 62 75
73 123 142 98 79 43 85 32 47 62 66 55 37 109 52 93 69 88 97 83
84 109 150 196 264 161 146 165 102 135 127 77 146 97 115 102 101 68 76 87
120 129 90 67 81 104 161 100 149 73
LNT-G14B 70
199 258 218 247 180 122 122 107 67 109 73 94 99 103 73 93 91 70 64 65
79 127 143 97 79 44 83 32 51 64 69 56 38 107 59 92 80 85 109 84
97 101 151 208 273 159 141 164 109 129 122 78 146 86 113 106 105 71 79 83
112 141 75 76 92 106 163 102 138 81
LNT-G15A 68
283 348 381 367 388 362 307 285 295 299 300 250 213 325 297 262 278 222 280 266
180 271 239 193 252 219 182 211 174 221 184 176 195 220 192 250 210 218 152 156
124 125 148 136 98 147 167 143 118 189 184 170 195 155 149 174 180 190 182 191
187 190 224 208 223 162 133 179
LNT-G15B 68
291 356 354 375 387 359 294 288 286 303 303 281 211 328 284 259 272 217 277 258
163 276 240 188 252 218 178 217 170 223 183 186 196 213 194 251 206 220 158 147
124 124 135 133 109 145 170 134 112 205 185 174 189 154 145 176 152 181 180 190
183 193 216 203 228 152 137 191
LNT-G17A 69
109 164 161 174 136 127 115 100 134 122 117 166 169 167 139 137 183 102 87 71
126 127 122 98 67 104 105 79 76 67 60 86 61 86 139 121 161 146 113 126
99 136 124 101 123 103 104 144 205 154 123 121 137 150 153 116 171 185 191 177
140 210 179 132 160 147 130 153 148
LNT-G17B 69
112 166 158 176 130 124 120 93 128 127 136 158 167 165 137 137 187 106 70 98
108 115 119 84 79 114 121 93 86 63 89 87 60 79 141 103 150 146 128 141
111 143 132 110 102 97 97 136 228 175 113 143 130 150 165 126 167 178 204 175
132 220 188 156 168 177 162 142 168

LNT-G18A 49
188 132 98 221 213 108 193 137 147 159 158 150 164 187 169 166 160 141 136 101
275 196 140 142 142 120 156 140 122 112 140 104 130 69 87 93 91 49 56 35
31 33 50 53 69 66 61 65 81
LNT-G18B 49
176 126 105 217 214 109 198 128 157 150 159 151 161 187 169 166 162 146 144 92
282 196 139 146 140 118 160 140 118 114 143 84 140 77 91 108 100 50 65 40
31 41 51 65 75 70 62 59 83
LNT-G20A 84
516 424 550 370 298 291 377 319 184 220 347 285 332 336 290 280 254 305 275 232
162 158 173 143 149 107 98 79 61 72 63 77 59 64 71 97 58 85 105 104
106 93 106 145 125 102 148 108 116 75 65 117 122 80 118 112 66 60 76 98
89 72 62 79 67 82 103 99 88 69 64 56 73 65 129 190 169 142 182 178
251 189 190 187
LNT-G20B 84
506 427 547 368 308 314 388 318 187 217 354 290 338 343 294 292 246 315 281 241
171 167 178 140 146 112 97 81 69 65 64 83 63 70 73 81 53 92 107 100
106 99 102 142 122 101 141 110 113 79 58 119 120 78 123 106 74 69 87 102
87 62 75 78 64 86 109 104 81 70 56 60 68 77 140 201 179 155 173 185
249 186 185 187
LNT-G21A 68
212 300 233 175 121 154 173 241 190 194 207 244 202 132 223 165 185 165 146 165
150 153 134 135 169 128 130 123 138 204 136 197 145 121 169 170 154 139 189 148
178 145 140 199 121 129 141 96 98 134 88 120 136 102 153 129 185 167 143 109
159 122 139 150 114 104 146 137
LNT-G21B 68
183 298 241 161 131 144 175 243 197 198 215 238 206 131 217 163 184 155 144 180
148 165 129 148 157 132 143 131 143 205 137 197 141 119 170 169 158 154 192 147
176 142 145 200 118 135 147 98 113 127 93 114 133 110 148 129 183 171 144 108
153 132 134 151 106 106 138 136
LNT-G22A 68
208 105 158 150 246 157 168 202 197 203 220 187 144 118 82 60 132 144 161 119
88 142 126 133 138 139 107 78 97 103 91 86 99 85 99 92 57 55 86 117
108 95 97 111 99 81 96 84 136 124 108 81 79 87 107 109 123 129 100 81
100 106 121 60 53 60 68 65
LNT-G22B 68
217 106 157 155 254 137 154 180 205 172 213 204 169 114 74 73 127 146 149 132
87 144 128 139 138 137 107 79 100 89 94 88 103 91 94 88 61 52 86 109
108 97 98 112 100 81 94 88 141 119 109 82 87 78 107 110 121 135 107 72
111 98 125 65 49 61 64 67
LNT-G23A 77
191 195 183 163 252 201 177 229 173 191 124 162 139 154 100 113 128 67 88 78
75 74 86 109 132 156 163 149 152 208 114 97 110 120 118 142 91 105 95 93
92 94 98 117 72 69 76 80 91 75 58 81 77 114 91 101 117 214 132 162
200 197 181 153 71 52 78 83 88 104 84 83 82 77 112 108 106
LNT-G23B 77
210 185 171 169 261 195 191 223 176 184 122 157 158 147 108 109 122 65 90 80
68 75 88 107 134 155 166 146 161 201 107 94 120 108 113 138 83 90 106 89
102 75 128 107 69 77 80 77 87 74 55 81 96 119 101 106 108 192 134 162
200 200 178 161 84 52 79 71 91 101 81 84 83 82 118 105 121
LNT-G24A 65
490 310 336 156 184 242 399 221 195 201 260 271 165 204 122 152 108 135 133 129
87 99 89 112 92 94 101 110 84 98 132 107 135 148 158 113 145 107 86 135

184 164 169 122 130 123 105 90 84 84 137 171 119 82 98 96 150 158 207 172
140 89 146 103 131
LNT-G24B 65
511 308 331 153 190 220 355 197 182 185 236 273 122 212 139 151 99 134 154 130
109 110 83 112 85 89 111 91 95 100 133 113 151 150 154 111 147 119 81 133
199 177 159 108 127 134 110 88 89 81 131 168 129 79 94 98 154 155 208 165
138 89 147 106 116
LNT-G25A 68
502 274 244 301 358 472 595 230 175 110 153 108 78 84 136 186 159 182 160 211
284 271 364 324 357 124 93 111 106 157 122 114 114 84 81 92 120 73 70 41
93 92 67 84 86 57 59 101 125 192 204 271 214 139 184 127 98 120 146 180
156 151 82 82 106 104 96 86
LNT-G25B 68
506 255 241 209 344 500 580 229 197 101 147 113 74 88 134 185 167 181 186 209
263 249 340 420 365 123 96 124 111 158 135 122 135 98 94 99 128 93 67 79
115 118 85 83 95 77 49 95 123 188 203 266 219 131 184 136 105 118 145 172
167 150 82 84 108 103 61 104
LNT-G26A 66
131 183 328 230 287 318 197 140 138 235 242 120 114 373 308 307 179 71 146 211
369 196 119 127 118 236 181 255 127 120 192 108 162 194 132 159 220 199 194 260
140 117 215 201 197 127 89 164 200 142 152 130 160 125 89 83 89 82 62 52
62 53 58 58 64 80
LNT-G26B 66
193 178 321 227 294 314 196 135 147 223 245 118 118 380 300 300 168 87 145 202
374 194 119 123 115 237 187 254 116 122 199 108 176 174 144 156 199 219 202 268
127 127 200 202 189 115 91 184 228 130 163 129 158 120 99 81 92 73 64 40
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LNT-G27A 89
104 96 88 102 112 91 138 84 60 68 63 61 54 76 69 82 75 82 67 60
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166 166 129 152 124 105 138 168 183 194 176 179 171 99 180 179 136 200 190 191
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LNT-G27B 89
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215 180 194 182 167 195 248 160 210 258 328 211 170 105 149 211 157 250 334 252
255 220 328 289 229 237 204 154 126
LNT-G28A 60
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LNT-G28B 60
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110 152 114 143 82 80 121 122 63 63 44 81 102 122 218 160 177 94 121 150
LNT-G29A 52
241 215 310 459 401 398 591 380 374 366 202 162 220 178 363 176 139 337 307 260
224 141 206 170 118 157 137 219 167 161 137 126 116 96 132 141 119 128 130 250
120 191 285 250 203 185 140 117 184 183 255 248
LNT-G29B 52
235 208 317 465 399 389 589 374 376 361 203 164 211 178 354 186 141 344 312 257

232 134 200 169 119 151 135 230 170 156 137 140 105 93 135 137 116 134 127 240
113 179 289 240 223 184 167 131 170 167 247 241
LNT-G31A 61
413 443 366 339 494 570 461 569 444 441 479 313 410 404 313 328 240 183 222 278
311 316 184 227 192 185 168 173 155 195 232 194 200 175 102 108 119 138 106 138
133 133 142 119 123 107 120 107 109 107 83 119 110 149 121 127 91 91 102 113
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LNT-G31B 61
358 442 337 339 407 524 461 509 429 432 518 339 438 414 302 315 239 174 231 275
314 312 178 219 196 177 168 170 158 193 236 202 195 177 95 107 118 134 107 122
143 142 144 107 116 127 124 107 122 91 93 126 102 158 112 130 94 91 104 116
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LNT-G32A 53
509 380 308 261 257 359 468 380 459 420 406 503 386 472 409 307 360 240 164 206
260 314 304 178 224 199 178 147 150 111 166 163 132 155 152 65 94 103 102 88
124 133 138 121 138 142 129 136 113 124 103 116 113
LNT-G32B 53
533 390 312 256 248 360 471 379 456 420 403 508 388 480 407 301 363 229 173 201
257 298 306 176 217 200 171 157 145 128 171 145 141 154 140 81 99 94 95 90
122 135 135 123 135 139 132 130 124 120 104 107 115
LNT-G33A 62
180 157 143 107 156 149 97 148 111 103 101 113 120 97 95 117 69 79 112 93
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163 172 178 134 181 166 173 215 158 193 198 195 160 120 128 112 104 156 127 112
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LNT-G33B 62
193 152 139 110 154 142 99 145 120 103 122 125 119 105 89 119 79 67 119 83
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159 178 165 134 196 154 172 217 156 193 196 198 157 125 123 121 96 161 127 107
85 106
LNT-G35A 54
158 212 122 142 90 59 171 190 163 257 139 223 218 131 139 152 133 118 224 198
217 172 103 83 106 76 100 98 158 203 134 106 121 85 156 155 127 151 134 126
128 166 95 123 157 106 114 74 118 109 217 166 123 155
LNT-G35B 54
152 209 121 135 98 55 174 185 165 265 138 224 216 136 137 145 137 131 226 192
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130 160 101 128 162 122 109 77 118 106 214 171 119 156
LNT-G36A 59
206 188 210 270 212 154 184 183 202 180 120 125 70 112 97 80 116 126 164 123
159 222 190 123 120 239 149 172 211 250 185 158 204 172 164 130 102 125 100 62
114 85 96 88 134 148 129 125 165 108 96 119 99 89 158 84 99 219 154
LNT-G36B 59
213 200 217 272 226 152 187 193 204 161 137 116 73 119 105 88 105 134 153 105
172 214 187 121 128 231 179 193 221 250 168 151 214 178 189 121 112 116 90 69
119 99 104 87 139 142 134 128 164 104 100 117 106 87 161 101 84 225 182
LNT-G37A 89
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LNT-G37B 88

139 147 120 309 202 129 133 70 88 77 94 84 132 171 146 136 137 177 179 95
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153 143 127 130 120 63 74 110 115 130 100 133 117 79 88 104 84 178 207 148
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80 79 128 143 113 152 108 97
LNT-G39A 64
225 152 172 318 302 260 214 182 198 252 230 194 235 180 231 209 135 243 232 252
244 257 239 173 231 144 182 253 328 123 92 161 172 166 175 157 149 145 163 129
139 116 82 89 133 110 115 90 95 97 90 79 83 71 104 106 94 87 70 105
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LNT-G39B 64
223 150 176 320 313 255 198 204 209 236 222 189 238 191 221 208 138 258 200 228
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158 116 82 98 123 119 110 91 91 97 83 88 79 69 108 97 85 90 73 97
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LNT-G40A 80
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LNT-G40B 80
252 267 236 267 141 106 85 92 101 66 107 88 122 173 106 146 124 150 128 133
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96 110 134 126 141 119 164 145 124 86 90 68 132 138 125 106 104 185 162 134
124 191 141 180 270 217 186 115 78 49 56 62 62 103 103 118 120 226 224 185
LNT-G41A 48
336 395 367 367 260 291 311 338 271 266 205 232 157 130 167 166 146 117 110 187
172 176 270 416 249 385 332 450 333 332 230 228 398 204 248 150 159 258 217 255
222 243 170 123 147 194 270 223
LNT-G41B 48
349 403 357 380 264 297 306 309 269 261 212 231 157 132 163 167 137 121 115 190
168 174 266 422 242 380 332 458 346 327 236 228 396 205 244 161 151 241 214 274
226 252 171 128 135 185 267 234
LNT-G42A 90
211 270 253 170 197 187 101 152 174 117 134 139 115 60 72 93 111 71 54 51
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164 137 109 227 204 279 211 104 139 93 88 123 153 161 205 157 123 158 129 194
176 149 202 159 165 124 186 85 132 199
LNT-G42B 90
218 276 263 160 196 191 105 162 173 128 138 152 114 54 60 95 96 67 56 52
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162 167 221 168 121 115 138 80 80 82 63 157 200 189 341 210 296 232 174 144
165 117 105 188 212 279 215 114 135 102 87 118 151 165 207 154 120 169 132 201
178 144 201 155 170 132 175 96 138 203
LNT-G43A 69
189 139 156 209 171 187 179 198 188 211 130 120 167 191 206 162 129 121 164 100
115 100 89 172 134 151 204 134 202 174 159 133 148 122 128 177 139 218 141 102
82 105 83 111 122 144 168 146 111 126 78 156 109 129 130 88 94 90 140 91
146 138 106 112 82 110 107 145 115
LNT-G43B 69
175 128 168 216 172 179 188 187 189 217 130 125 160 189 202 160 128 127 173 104
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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 Buildings* (Laxton and Litton 1998) 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 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

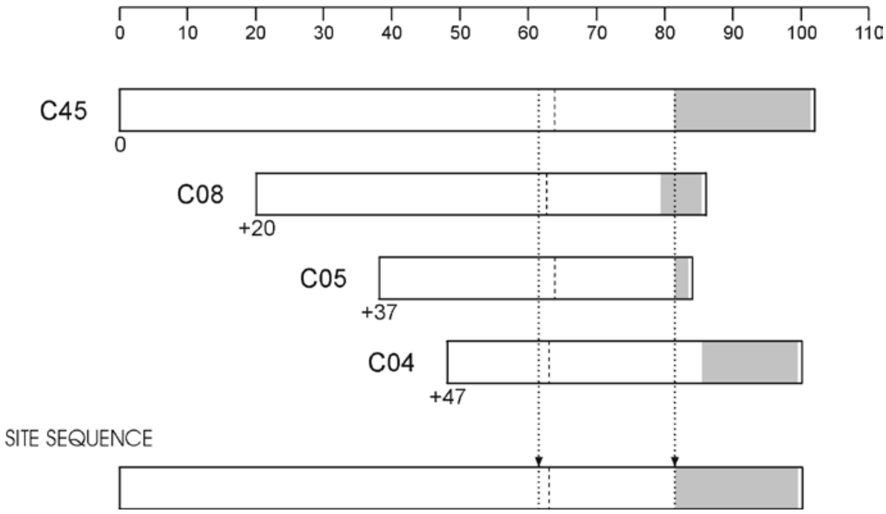

Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

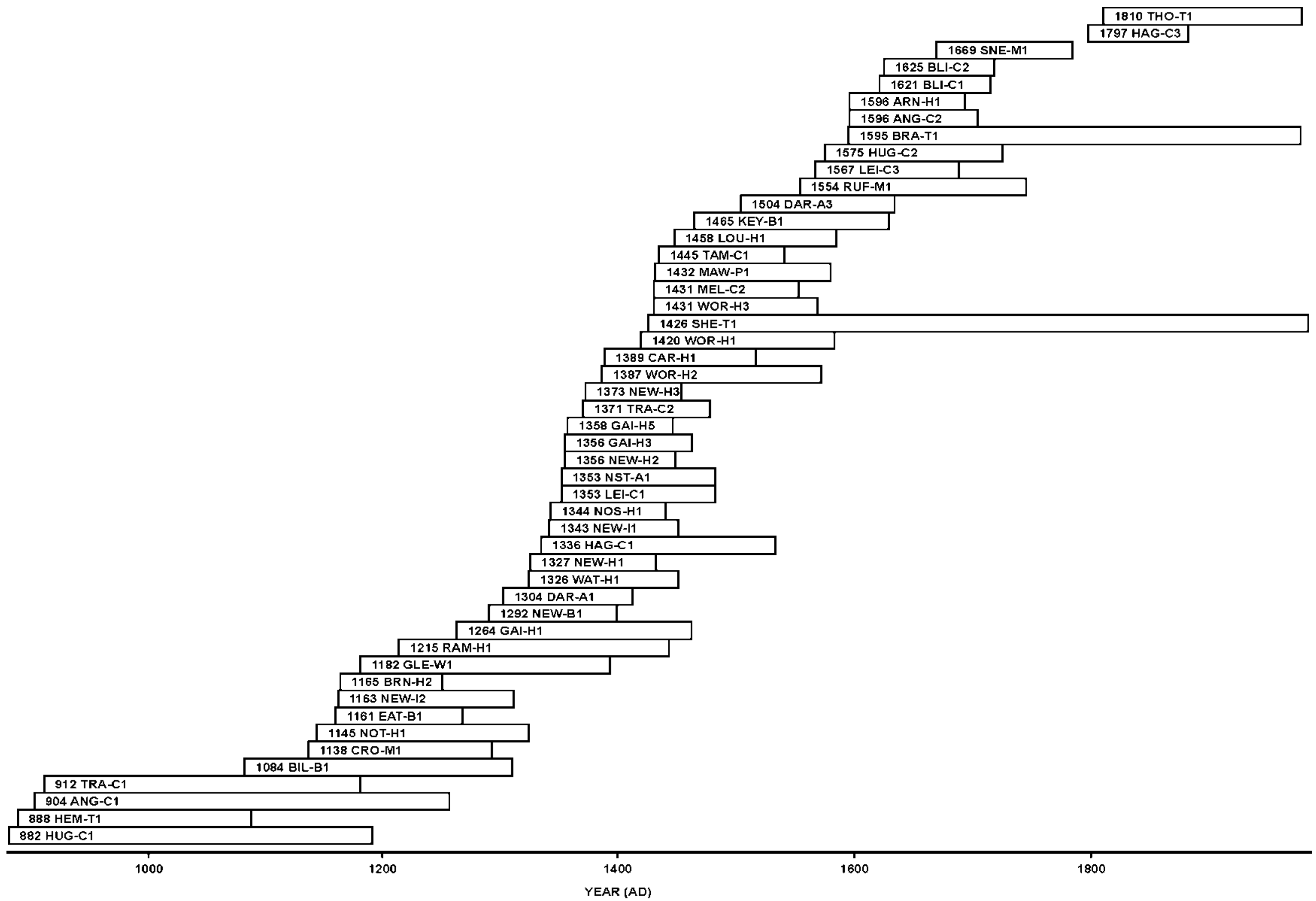

Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

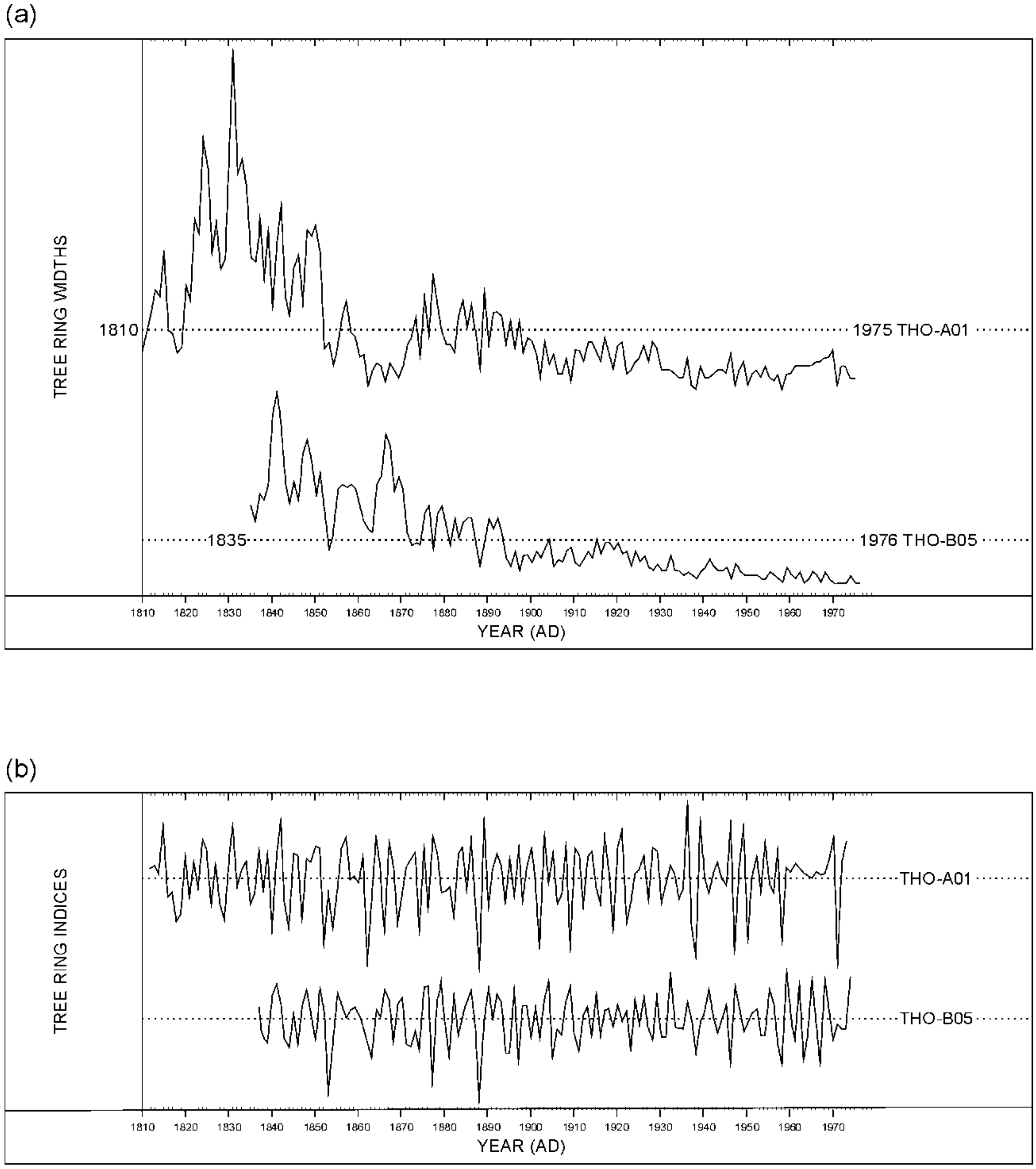

Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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