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# Former Hills Furnishing Stores
# 104 Kirkgate
# Leeds
# West Yorkshire

## Tree-ring Analysis of *ex situ* Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: Hitherto unknown timber framing and panelling revealed during post-fire clearance. 104 Kirkgate, Leeds. Photograph: Kate Newell

# FORMER HILLS FURNISHING STORES LTD
# 104 KIRKGATE
# LEEDS
# WEST YORKSHIRE

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SUMMARY
Analysis by dendrochronology of samples from 30 different *ex situ* oak timbers resulted in the production of a single site chronology accounting for samples from 25 timbers. This site chronology is 304 rings long spanning the years AD 1329–1632. A second site chronology accounting for two further samples was also created. This second site chronology is 123 rings long, but could not be dated. A further single sample was dated individually, spanning AD 1390–1466. Interpretation of the sapwood on all the dated samples shows that at least two timbers were felled in AD 1632, with others probably also being felled in the early AD 1630s. One timber (showing evidence for reuse) has an estimated felling date in the range AD 1462–78 and it is possible that one other timber was also felled earlier than the majority of the dated timbers. Two samples remain both ungrouped and undated.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would firstly like to thank the owner and Geary & Associates, for their help and assistance with visiting and accessing this site and the *ex situ* timbers for the purpose of tree-ring sampling. We would also like to thank Kate Newell, Senior Conservation Officer Leeds City Council, for her assistance in accessing the timbers, and for her help in understanding and interpreting the function and possible original general positions of the timber remains. Finally, we would like to thank Zoe Ke mp, Historic England Heritage At Risk Surveyor for requesting the work to be undertaken, and Shahina Farid (Historic England Scientific Dating Team) for commissioning and facilitating this programme of tree-ring analysis and for compiling the maps reproduced as Figure 1.

ARCHIVE LOCATION
West Yorkshire Archaeology Advisory Service Historic Environment Record
Gildersome Spur Industrial Estate
Nepshaw Lane South
Morley
Leeds LS27 7JQ

DATE OF SURVEY
2016

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# CONTENTS

## INTRODUCTION

The building at 104 Kirkgate (Fig 1) is described in the 2009 Condition Survey for the Kirkgate Township Heritage Initiative as a mid-terrace, three-storey frontage with a two-storey rear house dating to AD 1820–50, which was converted to a ground floor retail outlet in the late-nineteenth century. It is unlisted but it neighbours the Grade II* First White Cloth Hall (LEN 1375042) thought to date to the early eighteenth century, which is described by Thoresby as 'a stately hall, built on pillars on arches in the form of an exchange, with a quadrangular court within'. It is also shown on Cossins' map of 1725. A recent programme of dendrochronology, however, has identified substantial construction fabric using timbers felled in AD 1476 surviving in the former west range of this building (Arnold *et al* 2019a).

In November 2015 a catastrophic fire raged through 104 Kirkgate, most recently a large furniture store, and severely damaged a number of adjacent properties. Post conflagration, the furniture store was demolished to make it safe, with the adjacent properties having to be vacated. This demolition work, however, revealed hitherto unknown timber framing within the ruins and exposed timber panelling in some of the other close-by buildings (front cover).

As many structural and framing timbers as possible were retrieved from the charred remains and set aside beneath adjacent railway arches (Fig 2a/b), while a number of the charred and dislodged panelling pieces were stored inside adjacent damaged buildings (Fig 2c/d). Although, given the severity of the fire and the conditions of the demolition process, the exact original location of individual timbers was confused, it was generally possible, thanks to the work of Kate Newell, to identify the likely function of some timbers such as wall posts, plates, studs, main floor beams, or joists etc.

## SAMPLING

Dendrochronological analysis of both the salvaged *ex situ* structural timbers and the panel pieces was requested by Zoe Kemp, Heritage at Risk Surveyor for Historic England. This work was undertaken in order to provide independent dating evidence for the previously unknown timber-frame structure. It was hoped that this would help understand the development of similar buildings along this terrace and that of Kirkgate itself, as well as help evaluate their potential for listing and future management.

An initial assessment of the dendrochronological potential of both the structural timbers and the panel pieces showed that many of them had high numbers of growth rings, and were clearly suitable for tree-ring analysis.

Thirty samples were taken from the timbers available. The majority of samples were taken by the removal of cross-sectional slices from the structural and framing timbers with a chainsaw, or by taking smaller sections from the most badly burnt panel pieces, these being beyond conservation and restoration. A few structural and framing timbers, which were potentially suitable for salvage and subsequent reuse, were sampled by coring. Each sample was given the code LKG-A (for Leeds, Kirkgate, site 'A'), and numbered 01–30. The designation assigned and likely function of each sampled timber was recorded at this time (Table 1).

## ANALYSIS AND RESULTS

Each of the samples obtained from the timber elements of 104 Kirkgate was prepared by sanding and polishing and its annual growth ring widths were measured (these data are given at the end of this report). The 30 measured series, details of which can be found in Table 1, were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process resulting in the production of two site chronologies, one of which was very well replicated.

The first cross-matching group comprises 25 samples, these grouping at a minimum value of $t$=5.1. These 25 cross-matching samples were combined at their indicated offset positions to form LKGASQ01, a site chronology with an overall length of 304 rings (Fig 3). Site chronology LKGASQ01 was then compared to an extensive corpus of reference chronologies for oak, this indicating a consistent and repeated strong cross-dating with a number of these when the date of its first ring is AD 1329 and the date of its last measured ring is AD 1632 (Table 2).

The second cross-matching group comprises only two samples, these cross-matching at a value of $t$=5.6. These two samples were also combined at their indicated offset positions to form LKGASQ02, a site chronology with an overall length of 123 rings (Fig 4). Site chronology LKGASQ02 was then also compared to the full corpus of reference chronologies for oak, but there was no satisfactory cross-dating, and the sequence must therefore remain undated.

Site chronologies LKGASQ01 and LKGASQ02 were then compared with the three remaining ungrouped samples, but there was no further satisfactory cross-matching. Each of these three remaining ungrouped samples was, therefore, compared individually to the full corpus of reference chronologies. This indicated consistent and repeated strong cross-dating only for sample LKG-A10, its 77 rings dated as spanning the years AD 1390 to AD 1466 (Fig 3; Table 3).

## INTERPRETATION AND DISCUSSION

It is clear that, with only two exceptions (LKG-A10 and LKG-A22), the vast majority of dated samples represent a coherent single phase group of timbers. Of the main coeval group of 24 dated samples, two (LKG-A16 and LKG-A20) from floor frame timbers, retain complete sapwood (Fig 3; Table 1). This means that they both have the last ring produced by the trees represented before felling. In both cases this outermost sapwood ring, and thus the felling of the trees, is dated to AD 1632.

Within this group of coeval samples, eight others from floor-frame timbers, structural timbers, and panelling elements, retain some sapwood, or at least the heartwood/sapwood boundary (Fig 3; Table 1). The relative position and date of the boundary on these samples ranges from AD 1595 (LKG-A21) to AD 1612 (LKG-A18) which, with a mean date of AD 1605 and using the usual sapwood estimate of 15–40 (95% confidence interval), produces an estimated felling date range of AD 1620–45. As such it is highly likely that these other samples represent timbers which were also felled in the early AD 1630s. The remaining 14 samples within this group have no trace of sapwood but with the outermost heartwood rings ranging in date from AD 1570 (LKG-A17) to AD 1618 (LKG-A04), it is likely that these form part of the same felling event and were also felled in the early AD 1630s.

There are, however, two exceptions to this uniform dating. Sample LKG-A10 represents a stud post and, in the absence of any trace of sapwood, has a *terminus post quem* for felling of AD 1481. This may indicate that the timber was felled somewhat earlier and has been subsequently reused but, in the absence of any physical traces of reuse, it remains possible that it represents the inner part of a long-lived tree that was heavily trimmed and was coeval with the early seventeenth-century felling episode identified. This latter seems relatively unlikely though as the only other samples from the early AD 1630s felling group representing very long-lived trees are both panels rather than major structural elements. The second exception is represented by sample LKG-A22 from a floor-frame timber. This sample has a heartwood/sapwood boundary ring dated to AD 1447. Using the usual 95% confidence interval of 15–40 for the number of sapwood rings the tree might have had would give this timber an estimated felling date in the range AD 1462–87. An earlier date for this timber is, however, not unexpected, there being clear structural evidence that it was a reused beam. It is clearly possible that LKG-A10 could be coeval with LKG-A22 but the absence of sapwood and lack of cross-matching between these two series means that this can neither be supported, nor refuted.

That the majority of dated samples represent a single episode of felling is further supported by the strength of cross-matching between many of them producing values of in excess of $t$=6.0, and in some cases indicating the possibility that timbers were derived from the same tree (eg LKG-A13/LKG-A15/LKG-A16/LKG-A20, $t$-values ranging from 9.9 to 18.5; LKG-A14/LKG-A18, $t$-value of 15.1; LKG-A17/LKG-A19, $t$-value of 9.2). This strong cross-matching is particularly noticeable between the ring-width series from the structural and floor-frame timbers. The level of cross-matching suggests that the majority of samples, but not all, represent trees originally growing in the same woodland. As such, they are more likely than not to have been felled at a similar, if not identical, time. However, although likely to have been felled at a similar time, the level of cross-matching between the samples from the panelling elements is lower, suggesting perhaps that the timber for these was obtained from more diverse sources.

## CONCLUSIONS

Analysis by dendrochronology has thus resulted in the production of a single dated site chronology accounting for samples from a total of 25 timbers, and dated a further single sample individually. Interpretation of the sapwood and the heartwood/sapwood boundary rings on the dated samples indicates that, although at least one later fifteenth-century beam was reused at 104 Kirkgate, and possibly a second, the majority of timbers represent work undertaken in the early AD 1630s.

Although compared with reference material from all over Britain, there is a strong trend for site chronology LKGASQ01 to show the highest levels of similarity with reference chronologies composed of data from other buildings in northern and eastern England, with sites in West Yorkshire being particularly well represented along with sites in Northumberland and County Durham (Table 2). This suggests that the trees are likely to have been derived from relatively local woodland sources with the possibility that the panelling elements were derived from slightly more diverse, but nevertheless relatively local, woodland sources to the floor frame and structural timbers. The individually dated LKG-A10 generally shows the highest levels of similarity with reference chronologies in northern England, again with sites in West Yorkshire being particularly well represented, along with sites in Durham, Greater Manchester, Lancashire, North Yorkshire and north Derbyshire (Table 3). This, again, suggests that this tree was likely to have been derived from a relatively local woodland source but probably different from the main AD 1630s group of timbers.

A second site chronology of two cross-matching samples remains undated. In addition, two samples, LKG-A01 and A11 remain both ungrouped with any other samples and undated individually. This lack of grouping and dating is despite both samples having quite sufficient numbers of rings for reliable dating, and neither sample showing any problems such as compression or distortion of rings which might cause problems. It is possible that these timbers are from places, or grew during times, for which there is currently insufficient reference data available to provide a cross-match, although this latter seems relatively unlikely. It is, however, a common feature of tree-ring analysis to find that some samples will not date and it should be noted that the lack of secure dating for these two individual samples and the pair of samples comprising LKGASQ02 does not necessarily indicate that they are of a different date to the timbers that have been securely dated.

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# TABLES

*Table 1: Details of the tree-ring samples from former Hills Furnishing Stores, 104 Kirkgate, Leeds, West Yorkshire*

| Sample number | Timber function | Total rings | Sapwood rings | First measured ring date AD | Last heartwood ring date AD | Last measured ring date AD |
|---|---|---|---|---|---|---|
| | Structural timbers | | | | | |
| LKG-A01 | Timber 1 – location uncertain | 76 | no h/s | ------ | ------ | ------ |
| LKG-A02 | Timber 2 – wall plate | 88 | no h/s | 1508 | ------ | 1595 |
| LKG-A03 | Timber 4 – wall post (core sample) | 117 | h/s | 1490 | 1606 | 1606 |
| LKG-A04 | Timber 5 – wall plate | 109 | no h/s | 1510 | ------ | 1618 |
| LKG-A05 | Timber 6 – wall post | 91 | no h/s | 1502 | ------ | 1592 |
| LKG-A06 | Timber 8 – location uncertain | 129 | 26 | 1501 | 1603 | 1629 |
| LKG-A07 | Timber 9 – wall post (core sample) | 80 | no h/s | 1513 | ------ | 1592 |
| LKG-A08 | Timber 10 – brace | 90+15nm | 8+15nm | ------ | ------ | ------ |
| LKG-A09 | Timber 11 – corner post | 92 | no h/s | ------ | ------ | ------ |
| LKG-A10 | Timber 17 – stud post | 77 | no h/s | 1390 | ------ | 1466 |
| LKG-A11 | Timber 18 – location uncertain | 73 | 13 | ------ | ------ | ------ |
| | Floor frame | | | | | |
| LKG-A12 | Timber 3 – main floor beam (core sample) | 111 | 19 | 1516 | 1607 | 1626 |
| LKG-A13 | Timber 13 – joist A | 80 | no h/s | 1519 | ------ | 1598 |
| LKG-A14 | Timber 13 – joist B | 88 | 19 | 1536 | 1604 | 1623 |
| LKG-A15 | Timber 13 – joist C | 93 | h/s | 1519 | 1611 | 1611 |
| LKG-A16 | Timber 13 – joist D | 122 | 28C | 1511 | 1604 | 1632 |
| LKG-A17 | Timber 13 – joist E | 61 | no h/s | 1510 | ------ | 1570 |
| LKG-A18 | Timber 13 – joist F | 72 | h/s | 1541 | 1612 | 1612 |
| LKG-A19 | Timber 13 – joist G | 62 | no h/s | 1516 | ------ | 1577 |

*Table 1: (continued)*

| Sample number | Sample location | Total rings | Sapwood rings | First measured ring date AD | Last heartwood ring date AD | Last measured ring date AD |
|---|---|---|---|---|---|---|
| | Floor-frame | | | | | |
| LKG-A20 | Timber 13 – joist H | 104 | 28C | 1529 | 1604 | 1632 |
| LKG-A21 | Timber 13 – joist I | 100 | 28+5nm | 1524 | 1595 | 1623 |
| LKG-A22 | Timber 7 – reused | 57 | h/s | 1391 | 1447 | 1447 |
| | Panelling | | | | | |
| LKG-A23 | Panel 1 | 254 | 13 | 1363 | 1603 | 1616 |
| LKG-A24 | Panel 2 | 242 | no h/s | 1329 | ------ | 1570 |
| LKG-A25 | Rail 1 | 97 | no h/s | 1481 | ------ | 1577 |
| LKG-A26 | Rail 2 | 58 | no h/s | 1545 | ------ | 1602 |
| LKG-A27 | Stud 1 | 46 | no h/s | 1536 | ------ | 1581 |
| LKG-A28 | Stud 2 | 51 | no h/s | 1560 | ------ | 1610 |
| LKG-A29 | Stud 3 | 92 | no h/s | 1496 | ------ | 1587 |
| LKG-A30 | Stud 4 | 90 | no h/s | 1510 | ------ | 1599 |

h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree represented
nm = not measured

*Table 2: Results of the cross-matching of site chronology LKGASQ01 and relevant reference chronologies when the first-ring date is AD 1329 and the last-ring is dated AD 1632*

| Reference chronology | Span of chronology | *t*-value | Reference |
|---|---|---|---|
| | | | |
| Auckland Castle, Bishop Auckland, County Durham | AD 1425 – 1698 | 10.8 | Arnold and Howard 2013a |
| Girlington Hall, Ovington, Northumberland | AD 1412 – 1579 | 9.5 | Arnold *et al* 2019b |
| Calverley Old Hall, Calverley, West Yorkshire | AD 1261 – 1585 | 9.1 | Arnold *et al* forthcoming |
| Howley Hall Farm, Morley, West Yorkshire | AD 1415 – 1632 | 9.1 | Arnold and Howard 2013 unpubl |
| Ledston Hall, Hall Lane, Ledston, Leeds, West Yorkshire | AD 1424 – 1668 | 8.7 | Arnold *et al* 2015 |
| Fell Close, Healeyfield, County Durham | AD 1496 – 1632 | 8.7 | Arnold *et al* 2004 |
| Hallgarth Manor Cottages, Pittington, County Durham, | AD 1336 – 1624 | 8.6 | Howard *et al* 2001 |
| Bull Hole Byre, Bearpark, Durham | AD 1452 – 1620 | 8.4 | Arnold *et al* 2002 |
| Westgate End House, Kemps Bridge, Wakefield, West Yorkshire | AD 1377 – 1567 | 8.3 | Arnold and Howard 2015a |
| Crag House Farm Barn, Cookridge, West Yorkshire | AD 1416 – 1602 | 8.3 | Arnold and Howard 2012a unpubl |

*Table 3: Results of the cross-matching of sample LKG-A10 and relevant reference chronologies when the first-ring date is AD 1390 and the last-ring date is AD 1466*

| Reference chronology | Span of chronology | *t*-value | Reference |
|---|---|---|---|
| | | | |
| Headlands Hall, Liversedge, West Yorkshire | AD 1388 – 1487 | 7.3 | Tyers 2001a |
| 35 Church Street, Eckington, Derbyshire | AD 1365 – 1480 | 7.1 | Howard *et al* 1992a |
| North Transept, Durham Cathedral, Durham | AD 1320 – 1457 | 6.8 | Howard *et al* 1992b |
| Whalley Abbey, Whalley, Lancashire | AD 1362 – 1559 | 6.7 | Arnold and Howard 2015b |
| Bramall Hall, Stockport, Greater Manchester | AD 1359 – 1590 | 6.6 | Arnold and Howard 2013b unpubl |
| Stank Hall Barn, near Leeds, West Yorkshire | AD 1384 – 1444 | 6.5 | Hillam and Groves 1991 |
| Nappa Hall, Askrigg, North Yorkshire | AD 1300 – 1476 | 6.4 | Arnold and Howard 2013b |
| Headley Hall Barns, Upper Headley, West Yorkshire | AD 1381 – 1604 | 6.3 | Tyers 2001b |
| Bullace Trees Farm, Liversedge, West Yorkshire | AD 1371 – 1447 | 6.2 | Arnold and Howard 2012b unpubl |
| First White Cloth Hall, 100 Kirkgate, Leeds, West Yorkshire | AD 1366 – 1476 | 6.0 | Arnold *et al* 2019a |

## FIGURES

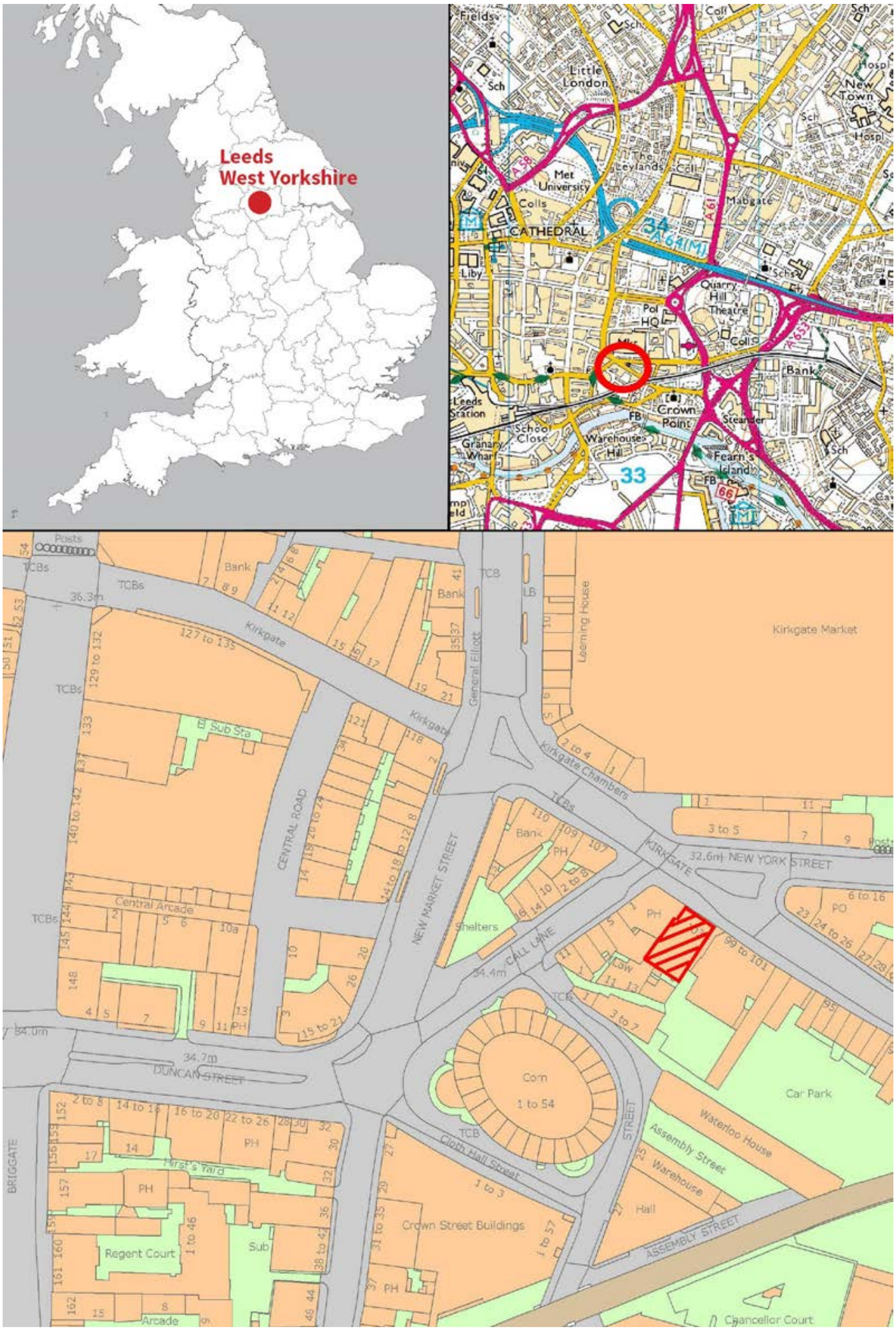



*Figure 1: Maps to show the location of 104 Kirkgate in Leeds, marked in red. Scale: top right 1:20000; bottom 1:1500.* 

*Figure 2a/b: Views of probable structural timbers (top) and floor-frame timbers (bottom; photographs Robert Howard)*

*Figure 2c/d: Views of sections of the wall panelling (photographs Kate Newell)*

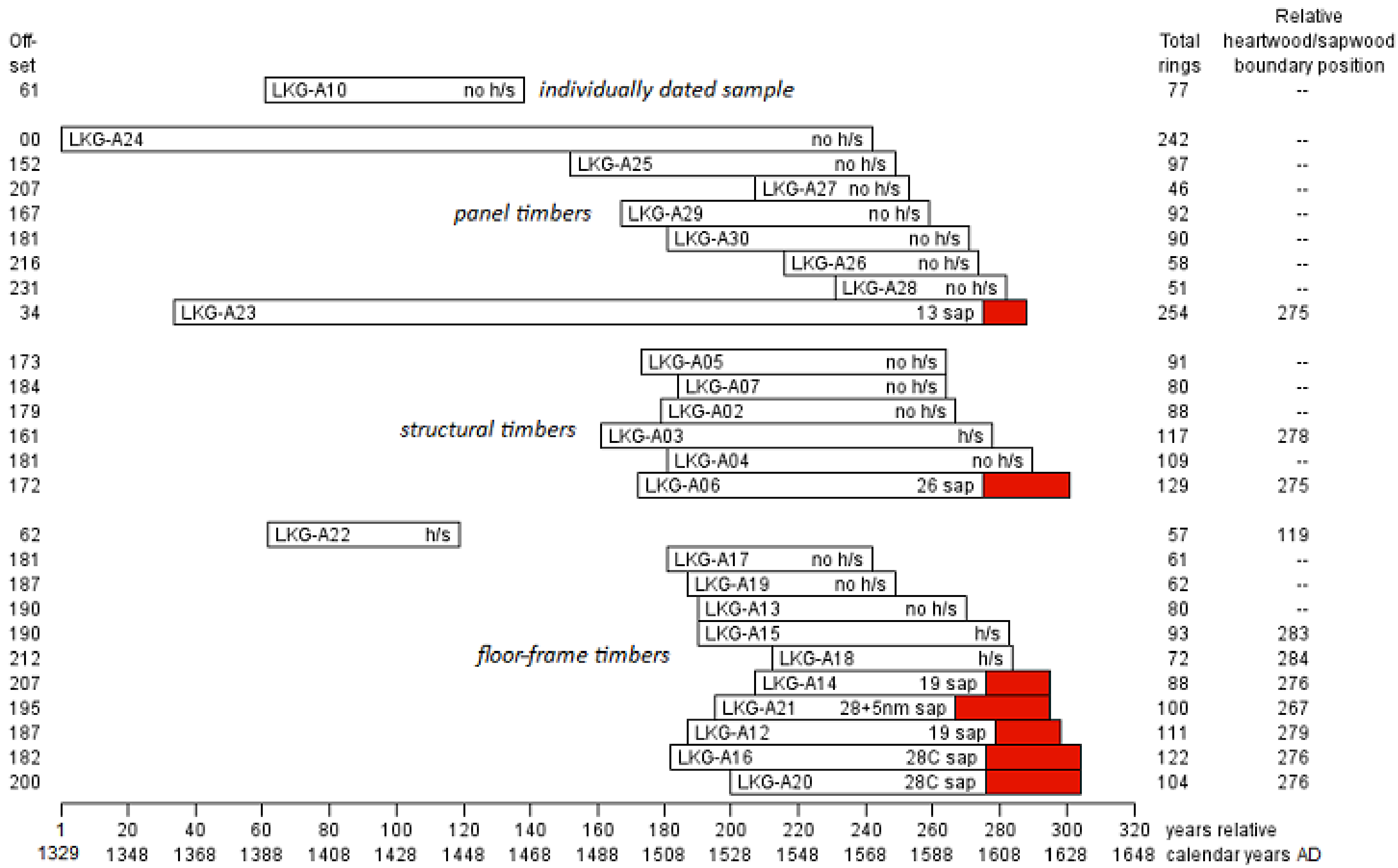



*Figure 3: Bar diagram of the samples dated either individually or as constituents of site chronology LKGASQ01*

White bars = measured heartwood rings; Red bars = measured sapwood rings
h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on the sample, the last measured ring is the felling date of the timber represented
nm = not measured

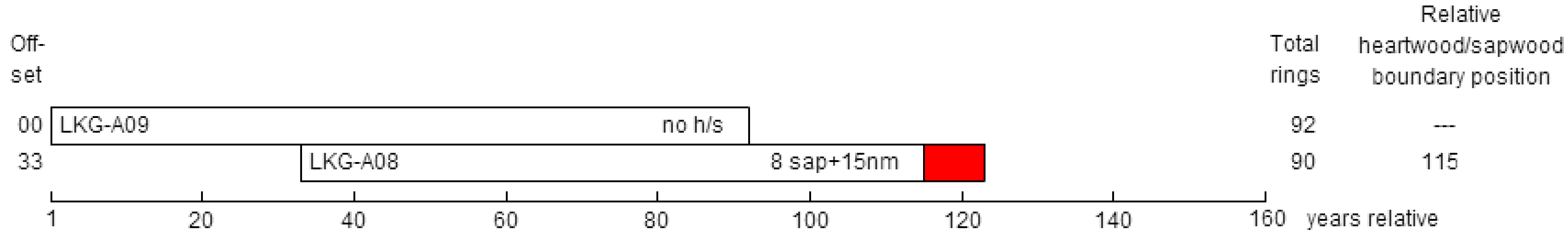



*Figure 4: Bar diagram of the undated samples of site chronology LKGASQ02*

White bars = measured heartwood rings
Solid red bars = measured sapwood rings
nm = not measured

## DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LKG-A01A 76
200 199 108 234 373 450 551 414 464 285 350 252 296 271 328 236 190 212 310 233
272 232 211 161 104 96 103 128 115 164 131 95 71 129 198 243 232 211 160 189
159 126 168 168 193 145 153 153 165 168 162 107 107 97 154 134 117 103 110 121
148 157 162 164 106 98 71 71 75 97 112 90 87 85 124 122

LKG-A01B 76
199 197 106 241 355 455 557 378 476 293 314 288 382 310 352 245 204 191 257 195
248 232 210 167 123 81 87 125 126 164 142 100 79 132 201 265 240 215 155 183
142 100 131 228 181 150 131 159 176 171 158 104 103 103 139 119 110 100 101 121
123 143 145 167 116 109 80 74 70 104 116 109 90 87 121 122

LKG-A02A 88
141 258 250 325 318 413 316 449 289 375 384 455 425 359 364 312 314 359 369 275
340 265 268 215 182 189 179 216 278 340 186 209 195 142 120 154 267 317 229 334
432 275 357 521 328 311 373 375 281 143 130 172 162 246 275 324 281 146 103 59
48 80 203 252 176 178 165 181 76 41 68 118 128 115 121 134 103 40 113 111
75 96 63 25 37 83 100 177

LKG-A02B 88
139 250 280 354 309 387 308 430 312 357 362 444 403 375 357 271 373 383 358 273
337 262 267 206 179 207 193 213 276 343 175 214 189 140 112 159 262 323 227 326
442 264 356 500 359 324 377 379 271 153 128 183 159 248 261 329 293 143 96 58
53 78 206 240 200 178 156 184 65 43 67 118 125 116 127 137 87 48 118 113
70 99 62 32 34 83 93 169

LKG-A03A 117
139 223 172 150 147 194 255 259 160 123 114 112 207 661 516 503 424 303 275 242
137 235 362 409 453 457 416 381 446 427 400 480 509 431 219 465 381 377 393 398
272 400 316 181 209 240 337 388 109 221 274 179 117 137 228 262 181 180 225 132
218 178 168 172 129 183 192 178 117 138 147 203 179 166 90 130 168 121 86 150
134 170 156 208 177 88 82 49 71 159 171 126 53 112 93 103 185 152 102 103
100 57 44 109 119 171 140 150 96 62 78 68 105 147 158 105 200

LKG-A03B 117
135 263 157 175 171 188 250 250 151 127 118 103 210 550 534 496 411 270 261 235
145 333 381 370 445 464 437 389 448 424 407 483 500 419 234 445 396 354 375 398
275 396 340 139 229 220 365 393 129 234 261 169 127 145 230 246 180 181 219 150
204 198 162 153 128 192 193 176 128 137 153 193 168 126 161 115 156 115 96 161
131 168 162 188 174 101 93 43 71 165 178 137 53 112 87 101 182 152 102 98
96 62 45 105 121 164 147 139 100 71 87 46 112 153 144 104 193

LKG-A04A 109
160 299 173 268 200 225 156 199 201 192 153 201 180 162 157 155 157 153 167 187
155 151 113 143 146 152 271 235 107 176 153 96 75 100 153 211 219 220 235 241
310 350 270 312 295 262 223 234 173 218 253 335 282 270 253 202 229 142 209 204
328 282 260 265 259 193 108 164 204 281 259 193 131 189 156 169 258 240 134 168
168 71 84 273 234 249 144 149 102 116 140 145 96 210 200 141 178 123 106 142

200 150 288 200 203 274 175 133 198

LKG-A04B 109
166 291 182 252 204 217 155 200 184 217 164 226 165 181 169 141 174 178 151 194
160 146 118 145 146 157 269 240 109 175 153 92 75 92 152 207 225 232 233 244
311 343 250 317 285 262 226 229 178 214 287 329 297 267 257 212 198 146 212 200
310 306 258 268 272 190 118 173 201 296 240 186 126 193 165 165 254 244 126 168
162 66 87 264 243 256 141 162 100 107 145 151 101 226 213 151 181 112 125 150
206 177 284 212 205 278 190 137 209

LKG-A05A 91
240 201 88 141 162 134 160 161 265 341 337 351 376 305 260 369 488 500 457 378
431 438 414 476 570 593 609 639 762 542 485 336 114 85 82 110 137 229 232 132
138 162 193 263 170 280 278 201 184 317 270 256 278 265 309 254 131 170 277 347
290 349 350 218 191 203 165 168 183 239 175 214 193 216 123 93 119 193 284 199
144 141 133 143 173 181 128 145 136 99 123

LKG-A05B 91
236 208 89 136 162 145 156 173 250 337 335 354 375 296 275 362 465 513 448 370
428 439 401 473 576 607 607 631 768 545 484 337 114 84 76 115 134 217 234 139
140 154 199 260 173 294 287 187 174 322 284 255 263 243 323 231 131 184 278 354
283 321 342 213 192 196 177 184 191 245 181 209 209 221 118 72 115 200 261 195
141 157 121 143 171 182 124 153 138 98 124

LKG-A06A 129
130 229 123 58 50 71 71 72 130 97 92 119 252 356 314 244 285 337 299 282
278 210 200 125 158 203 165 155 214 273 250 288 241 163 85 101 98 90 117 131
90 39 48 74 73 104 204 234 171 182 202 161 165 134 121 187 159 73 93 175
348 199 173 135 89 106 108 160 196 189 120 86 88 111 101 93 68 98 140 160
123 99 96 65 93 128 112 68 93 76 56 56 93 82 96 65 62 81 35 59
62 53 78 77 71 72 59 58 75 93 54 92 70 62 87 72 41 40 41 90
80 93 96 73 56 37 53 58 63

LKG-A06B 129
131 233 117 50 49 71 67 76 122 83 98 134 248 355 301 232 293 322 294 275
271 216 204 142 167 212 181 156 253 328 245 233 214 146 68 121 75 85 117 122
76 42 49 67 78 89 178 246 180 175 198 142 170 131 136 180 155 85 92 152
314 243 196 163 87 110 101 137 196 187 132 84 106 104 105 78 67 93 146 181
110 100 100 65 89 117 125 66 90 89 50 60 92 75 100 73 59 76 37 73
59 55 71 68 90 66 64 57 68 90 62 83 66 59 99 63 52 40 43 87
78 91 101 75 53 40 53 46 65

LKG-A07A 80
377 336 476 454 350 427 351 346 394 332 287 273 251 263 167 202 216 165 229 266
308 301 231 250 308 315 293 264 129 39 162 228 289 201 212 279 218 160 137 142
231 170 289 287 187 128 173 273 304 245 111 129 76 53 42 66 71 97 106 90
118 103 93 68 62 71 106 88 107 79 59 87 74 87 78 53 74 49 56 75

LKG-A07B 80
370 342 474 456 364 330 353 335 423 337 281 272 262 269 160 195 221 160 225 255
318 290 231 238 309 315 268 275 112 48 157 239 311 208 216 272 244 157 153 141
237 154 287 276 201 126 184 243 331 260 118 115 84 59 56 56 65 106 120 106
116 99 90 65 65 70 117 87 108 75 71 78 87 74 84 53 71 48 50 74

LKG-A08A 90
128 88 134 140 150 144 104 108 130 133 120 101 93 111 97 73 98 103 119 259
225 134 173 107 163 228 235 245 297 166 182 228 146 153 168 96 120 144 144 110
98 87 94 125 104 111 90 93 65 62 91 68 51 60 64 46 20 26 46 41
61 51 35 33 38 29 43 47 35 41 32 33 33 44 37 38 40 22 27 25
30 35 53 50 57 25 40 29 37 48

LKG-A08B 90
129 90 132 154 159 138 112 101 131 131 112 117 88 76 100 95 101 80 126 276
223 144 157 118 148 216 226 257 300 174 170 258 146 158 194 106 97 99 125 98
103 92 100 113 110 118 87 95 70 54 98 71 53 57 67 45 18 23 46 42
62 54 32 35 38 25 46 46 32 41 33 30 35 41 40 37 39 25 23 23
35 27 58 56 37 29 40 25 36 48

LKG-A09A 92
184 372 233 157 192 195 180 139 178 104 173 144 193 294 101 165 150 103 226 228
278 285 248 171 134 242 232 246 265 265 243 241 205 140 198 226 177 178 184 168
145 168 165 162 171 121 146 146 111 143 114 189 384 370 239 190 178 171 215 229
207 260 141 161 221 115 135 174 106 103 109 142 103 103 88 107 146 145 149 146
131 109 97 59 77 65 100 103 93 100 96 90

LKG-A09B 92
188 365 238 139 197 184 187 143 169 127 165 160 166 244 104 163 144 101 216 217
264 267 261 166 131 243 229 250 259 255 242 234 218 140 209 187 153 215 184 154
147 175 156 168 176 115 154 143 107 134 118 190 395 371 228 206 174 171 214 220
217 257 142 165 225 110 158 160 101 113 109 130 109 87 79 119 147 138 163 145
121 106 96 49 84 52 119 107 83 89 101 100

LKG-A10A 77
276 209 239 261 248 185 215 201 250 209 339 282 237 301 311 335 314 224 200 246
211 149 214 217 152 198 128 158 148 157 217 200 182 177 150 139 134 142 152 156
115 128 184 135 143 145 160 139 104 100 106 107 93 145 150 150 115 156 156 166
142 151 187 170 167 153 195 156 154 118 114 109 84 95 62 89 115

LKG-A10B 77
289 220 250 254 274 176 220 203 234 207 323 310 263 298 296 328 320 253 257 264
203 157 202 192 156 162 118 118 151 145 207 212 168 184 153 129 157 131 150 153
116 123 184 162 137 128 164 135 96 103 112 115 95 140 137 146 114 165 162 154
145 145 198 170 184 159 179 150 142 115 123 104 90 84 74 84 109

LKG-A11A 73
137 56 242 377 351 338 243 333 266 236 210 237 216 233 182 191 175 192 100 170
160 136 139 127 95 130 100 96 102 67 78 100 97 121 113 93 96 83 102 86
110 103 93 157 131 81 90 70 76 84 67 60 73 87 70 93 90 78 64 91
93 92 71 79 85 76 90 87 48 98 101 67 116

LKG-A11B 73
139 43 249 368 360 341 242 328 262 237 208 244 209 238 189 194 166 189 104 166
164 132 132 128 100 150 91 83 105 82 75 92 93 125 121 103 82 78 93 93
122 96 87 160 107 94 101 87 71 87 68 65 64 76 75 90 89 83 71 84
101 73 83 80 83 82 93 79 61 85 109 70 115

LKG-A12A 111

231 219 286 303 302 333 289 173 213 250 212 181 193 157 160 207 193 180 217 260
290 285 322 275 343 303 210 209 324 328 215 278 282 353 278 321 153 162 234 276
190 226 190 231 298 277 298 295 221 154 187 143 111 149 200 206 164 160 200 229
160 114 98 140 135 135 137 128 178 137 178 153 103 118 78 50 53 98 153 191
171 159 187 84 56 48 50 87 136 131 157 218 136 125 149 165 170 199 152 187
211 100 61 99 89 132 215 187 104 104 137

LKG-A12B 111
243 214 273 322 281 321 289 182 207 251 209 165 205 166 167 200 183 205 214 276
267 286 328 294 328 305 211 210 329 345 212 282 296 345 304 331 164 167 239 271
190 233 182 243 276 279 278 278 235 161 177 139 129 146 203 206 146 162 180 239
160 106 96 128 131 150 147 130 165 138 154 153 100 103 93 57 48 78 165 181
140 150 178 90 51 42 51 96 143 138 146 215 123 117 179 139 186 187 161 181
201 82 60 90 125 129 196 187 115 105 134

LKG-A13A 80
200 254 333 295 185 259 265 264 226 250 232 245 184 128 178 157 170 283 189 155
221 228 197 196 210 357 496 368 371 337 205 204 325 191 228 298 268 209 215 182
264 237 262 207 157 128 89 80 64 85 82 143 163 135 123 131 153 90 93 85
117 120 108 63 61 88 65 146 152 84 87 84 76 79 159 194 153 87 131 136

LKG-A13B 80
216 251 348 291 174 267 268 259 216 241 223 237 180 124 178 166 175 259 207 150
237 213 166 161 253 378 485 335 384 379 270 272 382 233 244 291 248 195 216 183
289 238 275 196 185 118 100 104 79 92 114 157 167 131 115 145 151 92 79 81
116 131 109 63 81 103 60 154 152 71 101 121 67 79 167 181 144 90 129 140

LKG-A14A 88
405 292 216 283 405 250 209 299 366 343 215 272 313 271 246 268 176 198 162 178
184 169 131 138 129 153 154 139 170 131 125 81 90 103 130 139 113 130 131 116
69 52 52 89 106 101 78 90 85 65 95 101 67 92 92 59 59 94 124 158
148 156 139 107 104 93 101 178 257 157 119 158 154 111 149 164 163 153 130 187
164 71 63 98 122 119 171 197

LKG-A14B 88
397 322 243 291 385 256 209 303 380 382 212 289 303 275 241 258 185 188 167 193
177 171 129 127 135 147 150 137 164 137 110 87 81 114 127 153 114 132 128 110
75 50 62 95 101 98 91 101 67 66 92 107 60 109 85 57 63 102 120 146
150 166 139 96 87 114 107 190 248 156 114 144 148 112 148 164 157 153 134 181
150 78 62 108 128 113 171 187

LKG-A15A 93
381 469 569 460 615 571 408 419 348 299 246 253 209 146 167 157 171 198 169 102
126 109 96 76 129 201 257 206 212 251 188 237 371 229 290 307 297 253 210 137
217 174 176 123 154 109 90 109 87 96 101 110 95 92 96 103 118 55 53 87
109 93 84 55 57 66 42 103 107 65 65 72 58 68 137 153 142 78 85 106
71 157 84 75 133 193 118 132 177 103 97 99 171

LKG-A15B 93
383 461 585 484 626 543 413 396 331 278 264 255 212 135 160 164 175 196 157 102
148 107 96 79 128 204 250 210 216 242 187 229 371 226 276 301 298 254 220 139
211 181 176 122 156 128 82 109 79 100 73 131 101 95 103 106 117 62 59 72
112 100 93 51 60 62 54 91 100 71 65 68 71 67 122 171 137 89 62 112

75 140 90 70 111 193 113 128 191 96 103 154 175

LKG-A16A 122
167 124 247 179 249 179 164 246 210 286 372 334 330 404 309 325 283 325 296 304
322 203 254 239 270 429 251 185 256 230 127 129 167 243 284 212 214 229 144 152
259 148 140 151 163 145 190 110 144 138 203 171 172 111 98 115 75 93 105 144
127 132 159 137 153 100 84 97 128 137 106 95 90 70 62 78 93 93 80 97
62 54 70 100 90 57 53 77 54 68 48 40 60 96 65 68 87 31 43 71
66 78 61 71 81 50 40 41 43 62 68 90 62 43 43 43 39 34 50 56
33 69

LKG-A16B 122
164 121 229 169 228 165 191 180 136 242 387 387 339 396 355 342 286 325 320 335
314 210 239 247 276 428 257 168 256 232 123 129 168 239 292 210 208 223 134 157
253 154 143 162 173 146 184 115 146 135 206 177 175 129 92 98 75 98 110 154
133 138 153 127 144 96 90 105 127 131 112 84 87 81 58 78 105 70 84 93
66 52 74 95 96 50 55 78 53 73 40 40 50 91 57 72 78 38 49 68
65 67 59 63 92 50 37 43 44 60 61 90 65 49 43 42 42 38 46 50
35 70

LKG-A17A 61
309 341 250 308 286 339 355 337 260 186 175 305 294 144 266 200 165 163 165 163
224 187 120 140 145 220 260 301 314 289 220 157 130 192 318 371 242 310 303 206
143 218 171 204 212 156 140 140 129 172 184 220 179 196 101 87 76 60 87 110
167

LKG-A17B 61
318 336 261 291 282 325 350 350 258 200 169 279 273 135 249 195 161 161 157 156
214 203 150 127 148 228 277 295 320 326 263 186 139 204 339 345 225 290 245 171
154 217 178 209 206 156 132 153 117 185 185 226 185 175 118 79 74 62 93 104
171

LKG-A18A 72
198 122 198 262 280 149 284 255 264 225 322 192 219 209 217 176 175 104 119 123
146 195 182 182 142 105 65 58 93 121 107 98 103 97 85 49 36 42 74 78
107 71 78 87 70 90 93 53 92 75 56 39 77 107 148 128 151 138 89 98
109 120 196 237 178 135 149 126 118 139 182 189

LKG-A18B 72
202 120 203 248 262 189 275 252 276 219 305 198 198 223 224 171 161 96 107 105
135 194 166 164 119 92 74 58 92 115 112 88 103 93 81 53 34 41 74 85
96 75 76 75 66 100 92 65 95 85 50 57 74 115 146 117 139 142 100 104
110 106 209 225 181 134 157 129 118 143 173 200

LKG-A19A 62
398 383 448 325 223 328 330 242 300 317 328 356 292 268 307 272 171 181 157 214
364 264 286 300 260 162 140 196 290 353 199 228 228 177 145 189 137 154 164 157
126 121 125 134 123 162 139 146 120 92 81 63 105 100 152 154 142 162 184 162
109 145

LKG-A19B 62
402 370 428 338 228 328 354 240 302 323 348 350 296 246 298 269 170 178 165 234
347 263 275 284 254 162 137 197 275 371 194 240 228 170 139 207 126 168 163 146

135 128 123 123 141 160 137 154 123 82 81 72 97 99 156 139 154 156 185 183
81 147

LKG-A20A 104
360 339 272 202 233 205 241 319 241 166 259 227 125 132 185 250 353 238 208 260
183 215 307 210 175 192 217 148 181 125 158 141 190 170 173 125 114 103 82 106
121 201 139 128 173 146 153 98 90 97 146 159 117 87 81 89 53 84 98 89
94 92 63 48 64 88 98 62 57 65 41 62 45 39 59 85 53 59 65 50
40 63 58 52 50 64 75 58 33 42 51 58 62 97 60 43 37 40 50 31
42 37 38 56

LKG-A20B 104
360 351 287 191 228 203 217 332 230 174 241 216 132 143 175 252 364 231 207 267
171 207 317 203 188 189 192 141 185 114 160 137 190 182 178 137 96 112 92 103
123 186 149 139 180 139 157 90 106 101 143 142 96 90 88 83 59 82 100 81
90 89 60 43 70 86 82 73 43 80 40 66 51 37 57 78 55 60 57 51
39 63 50 57 52 65 71 46 36 44 42 64 66 82 67 47 35 37 50 29
50 35 41 57

LKG-A21A 100
319 261 197 220 210 205 250 216 197 195 225 227 494 345 319 321 328 196 86 189
252 287 207 244 204 202 169 176 167 164 145 196 228 122 118 142 154 210 167 214
159 110 104 61 126 128 171 98 100 122 121 137 71 87 81 107 224 128 92 68
50 57 96 100 87 79 83 60 48 106 103 117 76 75 93 65 78 76 71 104
85 59 94 95 61 48 59 52 65 62 54 70 45 32 37 31 62 40 45 51

LKG-A21B 100
324 255 198 212 208 213 261 198 204 203 217 225 488 345 321 331 321 197 89 188
257 283 213 250 196 184 140 170 156 159 142 195 219 125 104 144 159 198 173 201
145 104 118 62 143 131 167 110 109 109 133 126 95 68 84 91 200 116 85 83
48 56 100 103 70 75 75 54 50 122 111 117 64 76 82 64 95 66 80 100
89 67 93 91 84 56 65 53 84 58 53 66 49 34 38 34 60 40 43 49

LKG-A22A 57
275 492 143 200 192 252 239 238 227 307 257 210 360 309 282 211 210 188 175 186
160 209 201 192 208 180 140 153 115 185 160 153 231 168 132 100 98 142 164 178
167 235 139 187 251 178 126 109 121 146 228 147 188 217 163 118 164

LKG-A22B 57
270 491 160 190 182 250 245 244 214 307 269 209 361 303 283 221 195 186 171 174
174 210 196 200 195 188 147 164 123 171 143 171 230 179 120 98 104 144 154 168
175 215 178 166 263 184 120 115 131 143 219 149 192 213 158 116 160

LKG-A23A 254
239 274 260 214 237 247 275 312 346 338 216 230 157 89 146 289 361 281 199 260
253 167 150 72 123 169 175 207 185 128 131 128 118 201 155 176 176 172 157 148
180 180 217 190 111 110 73 170 159 159 124 100 122 46 55 102 114 241 128 104
173 104 57 46 67 140 189 187 206 213 162 165 204 136 146 142 147 174 203 115
172 151 116 103 104 110 118 106 121 247 156 143 93 103 106 106 115 147 109 131
91 67 98 112 154 96 128 104 133 81 113 108 192 148 110 107 66 44 78 48
108 153 151 120 148 112 99 100 76 96 109 102 101 154 112 86 71 72 85 96
98 141 160 160 150 143 241 185 162 131 171 126 96 96 100 106 78 64 82 102
84 65 65 62 75 71 83 59 60 78 74 89 71 82 86 71 89 106 126 81

109 95 95 93 82 82 78 71 92 82 95 95 82 98 71 81 81 81 84 57
71 58 64 49 38 49 56 97 120 95 84 100 103 60 58 70 103 112 96 98
77 97 84 101 96 72 103 107 97 85 98 119 114 93 90 108 115 95 50 79
75 138 62 79 73 90 112 96 97 137 142 84 115 93

LKG-A23B 254
231 278 263 224 234 226 299 287 340 352 235 203 161 105 159 269 381 277 207 271
264 158 151 77 125 167 183 196 175 131 135 115 117 203 160 167 194 169 148 142
178 192 215 196 106 101 75 176 160 167 114 99 106 53 54 113 114 229 142 106
162 115 55 43 73 137 181 182 210 225 153 162 204 145 148 146 140 174 210 103
176 157 121 96 103 112 112 109 122 254 147 150 83 106 117 103 103 152 118 127
100 72 88 116 152 108 119 106 139 83 107 96 196 141 117 107 67 43 75 65
102 150 137 117 159 110 98 87 80 89 108 102 114 136 125 87 75 69 78 80
89 152 145 153 160 157 246 182 185 115 170 144 84 96 115 99 82 68 87 100
92 71 56 65 64 83 82 70 64 59 75 96 78 82 85 73 89 114 126 71
107 100 95 90 82 89 79 62 75 78 85 92 100 100 67 78 92 71 96 56
64 53 68 45 37 51 65 96 120 95 115 98 92 65 58 68 110 101 102 96
78 98 86 93 95 82 103 114 96 90 94 118 111 87 105 79 130 96 62 59
97 137 74 84 77 90 106 106 100 136 141 80 155 90

LKG-A24A 242
117 105 129 89 85 96 84 152 132 125 75 135 144 200 150 153 98 130 118 155
220 130 179 158 134 131 65 83 143 142 87 105 82 89 182 101 78 85 92 98
125 146 91 91 101 137 133 117 129 112 117 78 77 86 75 53 105 92 97 89
73 64 114 85 114 81 82 97 72 89 75 99 70 53 96 73 44 55 69 82
64 66 61 99 81 73 73 58 56 57 75 85 89 79 100 95 72 44 56 62
67 89 71 100 58 70 95 68 110 123 92 99 122 104 155 167 146 100 101 156
134 121 160 132 122 125 162 190 146 193 168 204 154 137 101 101 141 133 182 161
164 154 193 90 144 114 214 181 212 142 184 267 253 295 273 201 167 211 303 177
221 210 150 187 258 191 171 292 220 182 260 180 194 151 154 146 150 178 192 172
150 227 202 172 148 108 152 143 83 156 187 120 156 175 185 212 113 250 190 260
203 199 206 168 189 164 336 257 189 196 216 157 199 139 181 198 187 137 101 142
165 156 142 85 82 140 135 92 79 90 71 95 76 103 95 71 106 95 84 71
96 129

LKG-A24B 242
120 119 119 78 96 96 97 161 133 123 81 148 159 172 132 157 96 130 96 165
177 152 184 156 142 120 65 84 150 142 92 101 76 89 187 134 82 83 89 112
119 130 105 110 69 130 135 114 133 119 118 64 82 85 82 57 96 99 92 97
66 60 111 86 121 81 88 82 98 63 75 102 60 61 98 69 50 55 73 78
63 65 61 115 70 80 72 65 48 57 71 86 90 73 98 98 59 52 55 71
67 78 79 98 67 68 98 65 107 121 92 96 117 103 151 170 152 101 104 156
125 116 158 126 128 112 137 210 162 200 153 229 142 141 114 95 129 128 182 167
172 156 209 95 148 106 193 180 234 151 176 262 256 306 276 210 163 208 301 173
225 225 146 187 264 200 177 275 221 189 248 190 190 167 132 160 155 174 196 151
162 221 209 159 153 119 139 153 81 165 200 118 157 184 154 218 123 206 201 216
203 203 194 172 184 160 333 246 188 194 214 166 175 155 165 203 185 129 104 147
165 161 131 92 89 129 166 84 69 89 83 84 87 91 101 81 112 103 71 71
98 131

LKG-A25A 97
162 106 100 86 45 69 99 77 54 62 37 54 55 52 64 80 72 81 64 50
58 53 43 75 71 82 81 57 92 76 67 48 58 46 44 39 46 38 34 47

30 28 30 39 51 71 60 68 69 80 87 79 78 71 114 163 173 113 135 150
87 90 102 128 168 92 75 139 78 74 135 147 134 97 157 191 125 67 98 112
134 133 198 179 136 115 64 51 85 82 89 82 82 87 66 79 78

LKG-A25B 97
162 110 101 81 37 69 96 70 63 55 34 53 50 51 67 79 68 86 71 55
44 48 50 91 66 80 80 76 89 83 55 48 60 50 42 41 37 46 34 32
33 35 30 50 46 68 67 73 67 75 76 75 89 74 113 165 157 119 143 152
82 92 108 130 171 90 74 135 82 71 138 139 143 92 160 191 118 72 98 109
131 132 211 195 132 109 56 60 84 89 92 71 95 98 59 83 86

LKG-A26A 58
300 209 196 250 233 230 295 229 207 142 214 203 148 115 186 201 192 189 200 220
152 164 132 132 121 175 172 150 172 158 156 175 119 144 159 151 182 125 114 120
170 248 195 148 148 96 70 110 204 251 230 160 167 209 129 149 137 217

LKG-A26B 58
292 215 210 244 225 229 301 224 219 144 210 201 148 112 201 190 206 191 187 235
146 193 138 111 141 175 161 164 164 153 160 167 135 132 161 146 186 105 134 139
153 217 209 132 125 114 76 99 204 229 250 160 174 221 125 137 137 194

LKG-A27A 46
210 188 243 375 351 254 239 237 287 302 176 189 264 171 194 250 168 179 137 202
196 128 99 185 189 243 207 225 257 152 188 173 182 228 259 251 226 237 218 253
289 171 191 246 269 245

LKG-A27B 46
198 186 252 352 367 275 241 221 292 301 188 179 262 187 200 240 185 175 125 203
203 118 96 183 189 246 208 228 258 154 193 179 168 222 243 240 246 234 231 262
270 195 177 267 274 250

LKG-A28A 51
143 161 111 119 173 198 175 134 170 203 227 381 254 245 184 162 126 110 106 146
171 175 112 105 125 153 203 150 100 125 117 110 85 117 175 278 158 201 177 225
146 168 115 171 250 176 151 131 182 150 121

LKG-A28B 51
141 174 119 125 163 196 186 143 145 219 225 355 282 237 187 164 121 117 99 153
161 176 109 126 115 155 196 161 100 116 107 111 88 114 183 271 176 214 161 240
167 181 101 182 243 184 155 146 179 147 124

LKG-A29A 92
138 108 95 118 141 104 96 101 115 99 110 85 69 109 109 107 83 105 130 85
80 72 112 125 94 116 100 107 126 75 109 110 121 130 108 189 156 107 103 114
132 92 129 114 89 122 90 127 133 103 88 60 97 132 122 99 75 79 128 135
114 74 70 72 110 107 131 98 96 107 76 73 96 75 90 103 98 82 97 127
85 89 85 117 101 100 84 90 84 93 87 112

LKG-A29B 92
143 102 92 134 132 100 108 72 125 97 108 103 64 106 120 101 95 100 123 87
86 72 109 131 92 119 105 108 119 71 113 106 121 133 102 194 142 107 99 117
135 102 125 117 88 115 91 125 128 102 107 71 92 134 115 107 78 78 127 135
107 67 59 74 109 112 124 107 95 107 68 68 89 89 89 114 87 90 89 132

100 103 93 114 100 90 82 92 85 79 94 119

LKG-A30A 90
86 108 118 108 128 175 232 197 163 215 166 149 180 146 157 114 159 87 174 142
162 166 114 118 121 157 127 125 126 114 93 104 100 157 146 173 82 71 86 65
71 64 46 64 64 83 78 52 51 63 55 85 81 75 94 78 56 73 89 78
82 85 48 84 78 87 71 54 53 90 82 81 64 59 78 87 95 90 70 84
82 57 57 48 71 87 87 90 78 121

LKG-A30B 90
85 110 121 101 135 176 236 192 172 207 163 148 171 134 178 117 160 100 163 145
185 175 121 124 124 152 140 128 120 114 97 110 100 158 147 168 86 72 84 62
62 66 53 66 67 78 71 53 54 63 56 71 86 78 92 75 60 62 87 75
84 88 55 96 64 94 60 61 62 73 93 73 59 59 70 104 103 79 72 90
84 66 62 60 63 83 93 79 85 125

# 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 | |

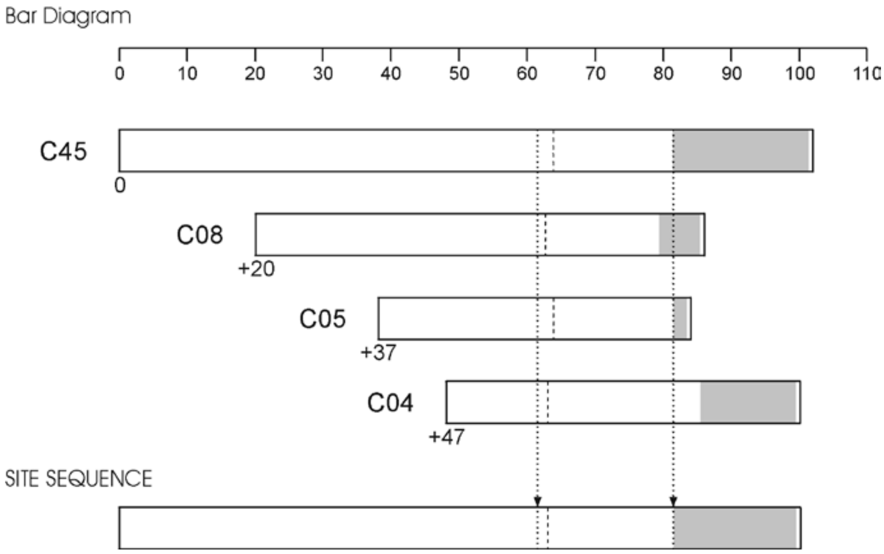



*Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

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.

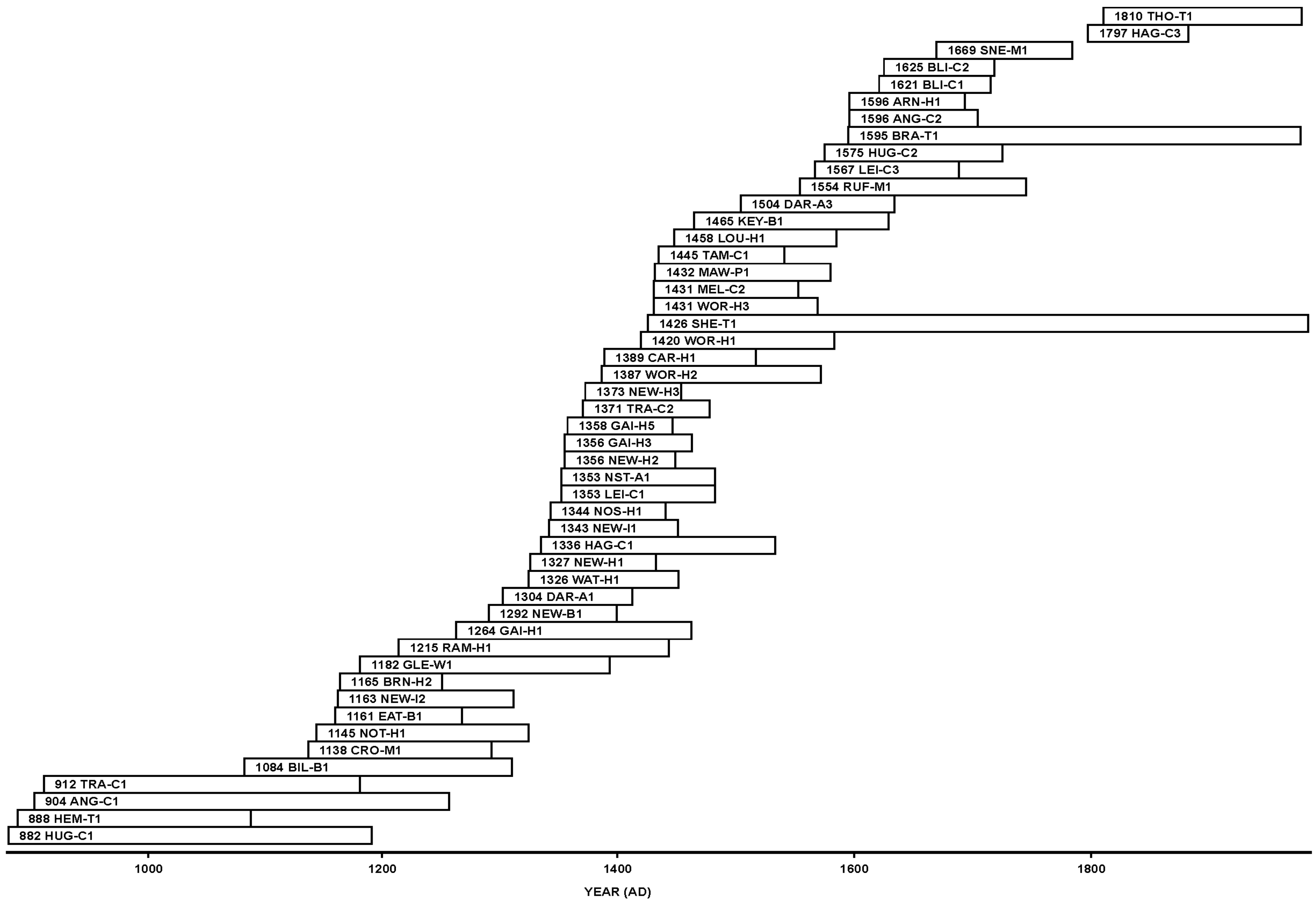
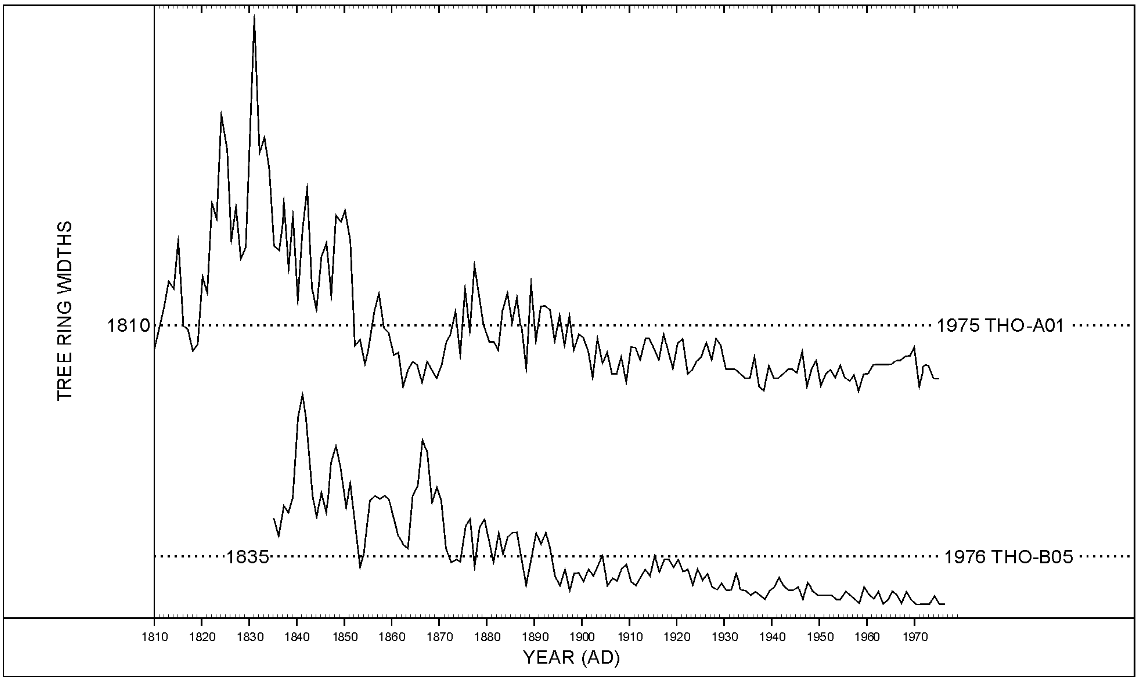



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

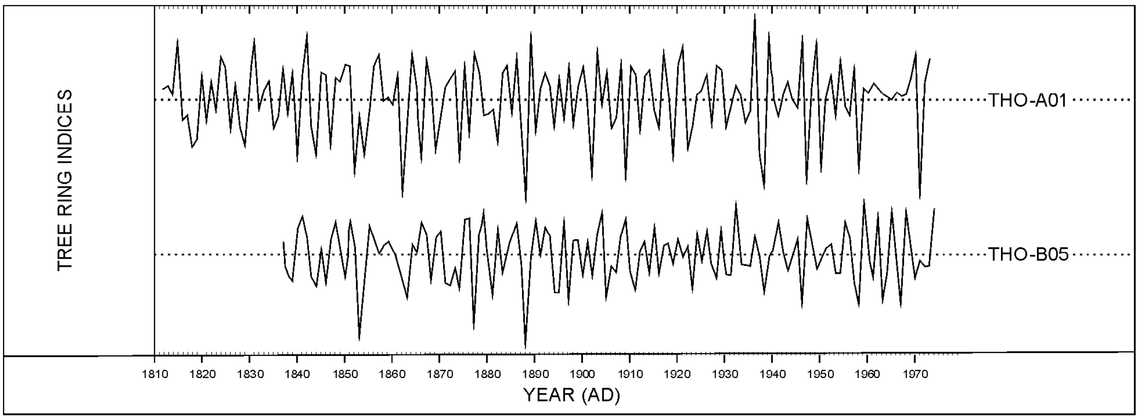



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

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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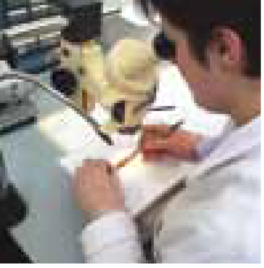
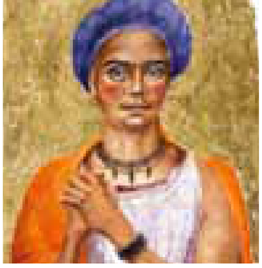


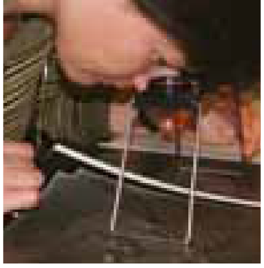


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