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Tree-ring Analysis of *Ex Situ* Timbers

Alison Arnold, Robert Howard, Cathy Tyers, and Ian Tyers

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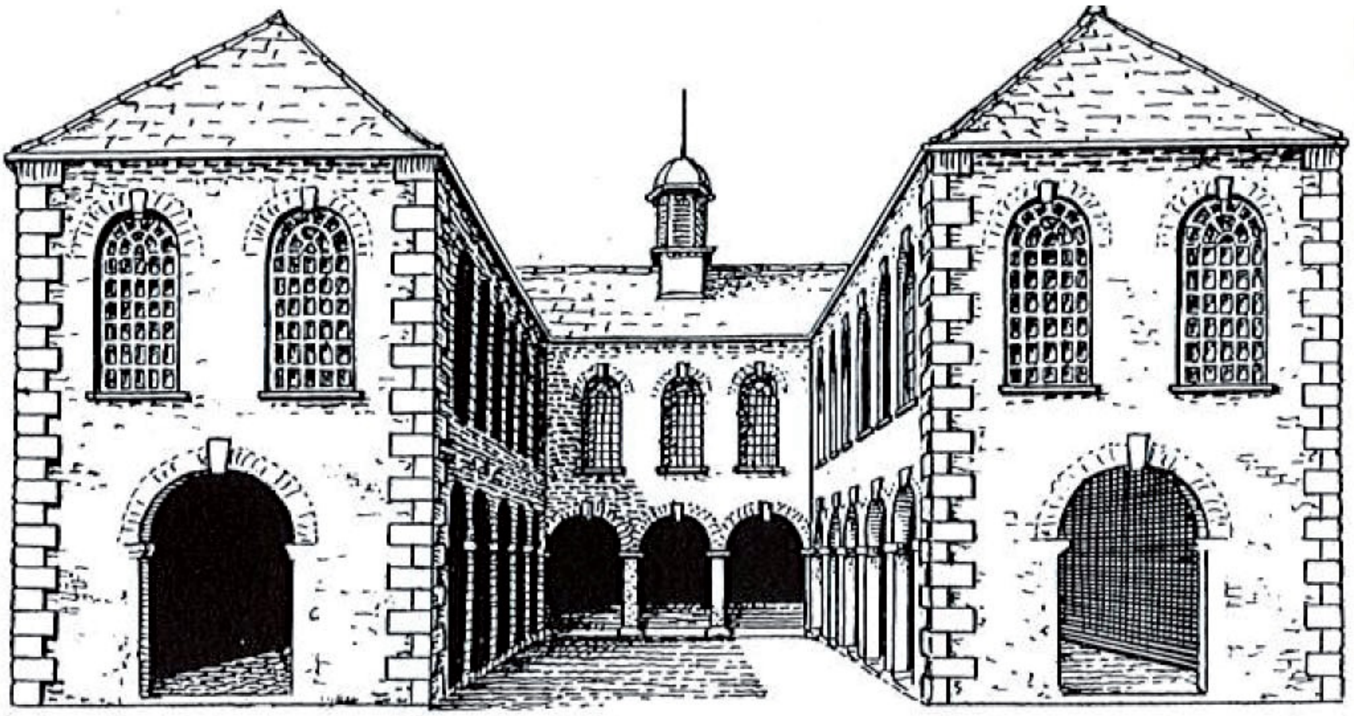

Research Report Series no. 52-2019

Front Cover: Reconstruction of the First White Cloth Hall viewed from the north by Peter Brears (from Burt and Grady 2002)

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NGR: SE 30447 33422

ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)

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SUMMARY
Dendrochronological analysis was undertaken on samples from 19 oak timbers and one conifer timber, all *ex situ*, from the former west range of First White Cloth Hall. This analysis produced a single site chronology, comprising samples from 12 of the oak timbers, with an overall length of 111 rings. These rings dated as spanning the years AD 1366–1476. Interpretation of the sapwood on these dated samples indicates that at least three timbers were derived from trees felled in the summer of AD 1476, with it being highly likely that the remaining nine dated timbers were derived from trees felled at, or about, the same time as part of a single programme of felling and construction. As such, this date is somewhat earlier than had been expected based on the documented opening of First White Cloth Hall in the early eighteenth century. The samples from the other oak timbers, some from floor beams, and the conifer timber could not be dated.

CONTRIBUTORS
Alison Arnold, Robert Howard, Cathy Tyers, and Ian Tyers

ACKNOWLEDGEMENTS
We would like to thank CFA Archaeology Ltd and Paul Nathan-Geary of Geary & Associates for enabling access to the storage facility for sampling the *ex situ* timbers on three separate occasions. We are grateful to Kate Newell and Phil Ward of Leeds City Council, as well as both Mike Cressey and Shelly Warner of CFA Archaeology Ltd for their assistance and the provision of information. Shahina Farid, Historic England Scientific Dating Team, is also thanked for commissioning and facilitating this programme of dendrochronology.

ARCHIVE LOCATION
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DATE OF INVESTIGATION
2016–18

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CONTENTS

INTRODUCTION

First White Cloth Hall (also known as First Leeds Cloth Hall) is located on the south-west side of Kirkgate in the heart of Leeds (Figs 1a–c). This Grade II* listed building has become increasingly derelict over the past few decades and remains on the Heritage at Risk register. It has been the subject of a number of building and archaeological surveys and the following information is summarised from the listing entry (LEN 1375042), Cressey (2013), and Gwilliam and Richardson (2015). The Lancaster University Archaeology Unit report (1997) was unavailable to the authors at the time of the production of this report.

First White Cloth Hall, which opened in May AD 1711, appears to have been constructed in response to the opening of a dedicated cloth hall in nearby Wakefield in AD 1710, this all relating to the rivalry between Halifax, Huddersfield, Wakefield, and Leeds with respect to the cloth trade in the early eighteenth century. First White Cloth Hall provided both secure storage and a building for the trade in undyed cloth, which had previously been carried out in the general open-air cloth market in nearby Briggate. The original building comprised a range (the south range) running north-west to south-east that was parallel with, but set back from, Kirkgate, with a range on either side (the east and west ranges), running north-east to south-west, projecting to the street frontage on Kirkgate, thus forming a U-plan building with a rectangular courtyard opening onto Kirkgate (Fig 2). However, it is suggested that the principal facade of First White Cloth Hall was the south-west facing (site south) based on Cossins map, which is thought to have been produced in the late 1720s. The south range of First White Cloth Hall was turned into an Assembly Room when the building became redundant following the construction and opening of a larger hall in the late AD 1750s. However, both these buildings were superseded by the Third White Cloth Hall in the latter part of the AD 1770s, a building which included the provision of assembly rooms. First White Cloth Hall is believed to have been subsequently converted to an alehouse and shops and housing, with the front of the courtyard being in-filled in the early nineteenth century (Fig 3). The late-twentieth century saw First White Cloth Hall in a state of steady decline resulting in the emergency demolition of the west range in AD 2010.

The three ranges of First White Cloth Hall were constructed of brick with stone dressings, two-storeys in height, although an attic floor was certainly present in the east range, and both the east and west ranges had basement areas. The roof of the now demolished west range comprised five trusses (Figs 3 and 4) and is described in detail in Cressey (2013). Four of the trusses were king-post trusses with principal rafters (Figs 5 and 6), although it was noted that the fourth of these had slightly curved principal rafters, which may have been reused. The fifth truss, which formed the hipped section of the roof where it joined the south range, comprised principal rafters and a collar (Fig 7). A single row of purlins, trenched into the principal rafters, and a ridge piece supported the common rafters between the five trusses. The ridge was square-set into the jowled king-posts. A significant amount of timber was salvaged from the west range during demolition and placed in storage. Trusses 2, 3, and 5 remain articulated but other individual timbers were noted at the time as also being salvaged including the principal rafters from truss 4, some purlins and common rafters, and other unidentified timbers, these being held in storage for possible future reuse.

SAMPLING

Dendrochronological analysis of the extant *ex situ* timbers from the west range was requested by Zoe Kemp, Historic England Architect/Surveyor, in order to provide independent dating evidence. It was hoped that this would enhance understanding of the west range, and thereby First White Cloth Hall as a whole, in relation to the provision of advice on future management and development of this and adjacent listed buildings on Kirkgate. An assessment of dendrochronological potential was duly undertaken during which it was noted that core samples had previously been removed from some of the *ex situ* timbers. It was subsequently determined that dendrochronological assessment and limited sampling of these timbers had been undertaken as part of the emergency building recording carried out by CFA Archaeology in 2010 (Tyers 2011; Cressey 2013), but that analysis had not been subsequently commissioned as part of these works. These cores were therefore incorporated into this programme of dendrochronological analysis, along with more extensive sampling of the extant assemblage in order to address appropriately, the presence of primary and possibly reused timbers, as well as extending the analysis to timber elements other than those associated with the roof.

Access for coring to the timbers of the articulated trusses was relatively straight forward but the loose timbers, some of which were very substantial, were piled together hampering both assessment and actual sampling (Figs 8–11). Thus, from the timbers considered potentially suitable for analysis a total of 23 samples were obtained by coring from 20 timbers. Each sample taken in 2011 had been given the code flch and numbered 1–6, whilst those taken in the more recent sampling programme were given the code LWC-H and numbered 01–17, with all being from oak (*Quercus* spp) timbers with the exception of LWC-H17, which was from a conifer timber (Table 1). Trusses are numbered as per Figures 3 and 4 with Truss 1 at the site-north end of the west range, and Truss 5 where the west range met the south range. Timbers have been numbered according to the scheme imposed during demolition and the labels attached to individual timbers where they still existed (Table 1; Figs 5, 7, 8, and 10). The approximate location of cores from the articulated trusses are indicated in Figures 12–14, whilst Figures 15–19 illustrate some of the loose timbers that have been sampled.

ANALYSIS AND RESULTS

Two of the 22 oak samples were rejected prior to measurement as they had too few rings for reliable dating purposes. The ring series from the duplicate samples from three timbers were combined to produce individual timber series in advance of full analysis, the duplicates cross-matching with *t*-values of 12.0 (LWC-H04/flch2), 10.7 (LWC-H01/flch3), and 17.7 (LWC-H02/flch5). In each case the number of sapwood rings assigned to the combined individual timber series is calculated using the average date of the heartwood/sapwood boundary ring, rounded up or down as appropriate, to the nearest whole number.

The 17-ring series representing individual oak timbers were then compared with each other using a combination of software written by Tyers (2004) and the Litton/Zainodin grouping programme (see Appendix). Tyers (2004) facilitates cross-matching and dating through a process of qualified statistical comparison and visual comparison. It uses a variant of the Belfast CROS programme (Baillie and Pilcher 1973). This comparative process, using both the Litton/Zainodin grouping procedure (minimum *t*-value of 6.3) and the Baillie and Pilcher 1973 approach (Table 2), showed that 12 of the oak ring series cross-matched (Fig 20). These 12 ring series were combined at the relative offset positions to form LWCHSQ01, a site chronology with an overall length of 111 rings. This site chronology was then compared to an extensive series of reference chronologies for oak, this indicating consistent and repeated matching when the date of its first ring is AD 1366 and the date of its last ring is AD 1476 (Table 3). Each of the ungrouped individual oak ring series was compared to site chronology LWCHSQ01 and the reference chronologies but there was no satisfactory cross-matching and thus, these five ring series remain undated, although it is considered likely that they are associated with the eighteenth-century or later phases of modification within the building.

The single ring series representing a conifer timber was compared to an extensive series of relevant reference chronologies from sites with imported conifer timbers across the British Isles, as well as reference chronologies from elsewhere in Europe and known source areas in North America. However, no conclusive cross-matching was identified and it, therefore, also remains undated.

INTERPRETATION

The 12 dated oak timbers (Fig 20) appear to be coeval and samples from three of these retained complete sapwood, this meaning that they each have the last ring produced by the trees represented before they were felled. In each case this last sapwood ring is only partially formed, the spring-wood being present and apparently complete, indicating that the felling of the tree in each instance occurred in the summer of AD 1476.

All of the other dated samples either retain some sapwood or, at least, the heartwood/sapwood boundary ring. The relative position and date of this heartwood/sapwood boundary ring on these other samples is clearly similar to that on the three timbers of known felling date and all have felling date ranges, based on the 95% confidence range of 10–46 (English Heritage 1998), that encompass the precise felling date of AD 1476 identified. The date of the heartwood/sapwood boundary ring within this entire group of dated samples varies by 21 rings from AD 1442 (T3/3) to AD 1463 (P1). Whilst such a variation might not suggest an identical year of felling for all timbers, it would indicate that they were felled over a relatively short period of time as part of a single felling programme. This, combined with the overall level of intra-site cross-matching (Table 2), suggests that all of the dated timbers were derived from trees felled in, or around, AD 1476.

DISCUSSION AND CONCLUSION

The analysis undertaken indicates that the dated timbers from the west range of First White Cloth Hall were felled over a short period of time in, or around, AD 1476. The overall cross-matching produced between the dated ring series suggests that the timbers are likely to have been derived from a single woodland source and, although the site chronology (LWCHSQ01), was compared with reference chronologies from across the British Isles, the highest levels of similarity were found with other sites in West Yorkshire and the surrounding counties to the west and south, examples of which are found in Table 3, suggesting that the source woodland is relatively local.

Eight of the dated timbers are from the three trusses that remain articulated, whereas the remaining four timbers are loose timbers, two of them labelled and numbered purlins but two unlabelled timbers (timbers U2 and U4), one thought, potentially, to be a tiebeam showing evidence of possible reuse and the other of unknown function. Thus, with two possible exceptions (timbers U2 and U4), all of the dated timbers are associated with the roof of the west range, as none of the potential floor beams have been successfully dated. The possible tiebeam (timber U2) flagged up as potentially reused is clearly coeval with all of the other dated timbers and thus, the evidence for reuse needs to be reassessed and the possibility of it having been reset needs to be considered. Cressey (2013) had also flagged up the presence of redundant mortises on the principal rafters from truss 4, suggesting reuse. Unfortunately, these principal rafters were not clearly identified amongst the pile of loose timbers, although they are noted as salvaged (Cressey 2013), and hence, the dating of truss 4 remains enigmatic, as does that of truss 1 from which it was noted that no timbers had been salvaged during demolition.

Regardless of the potential reuse of a number of timbers, it is clear that the bulk of the salvaged roof timbers date to the late-fifteenth century and thus, they predate considerably the early eighteenth-century date for the apparent construction and the opening of First White Cloth Hall. This seems to suggest that First White Cloth Hall incorporated a significantly older building present on the site as its west range, or alternatively, reused a roof in its entirety with only minimal evidence (eg the truss 4 tiebeam) showing any signs of having been reused or reset.

The east and south ranges also have king-post roofs (Gwilliam and Richardson 2015) and, whilst the available photographic evidence suggests that there may be some potential differences in timber characteristics, the main form seems to be identical to that in the west range, although the south-range trusses have a wider span, thus, raising questions as to the date of these two extant roofs. It is therefore strongly recommended that dendrochronological analysis be undertaken in both of these extant ranges in order to enhance the understanding of the late fifteenth-century date produced for the west range and further elucidate the construction and development of the east and south ranges of First White Cloth Hall.

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TABLES

Table 1: Details of the tree-ring samples from the west range of First White Cloth Hall, 100 Kirkgate, Leeds

Timber	Sample	Timber location/function	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
		Intact trusses					
T2/1	lwc-h05	Truss 2, principal rafter, T2/1	78	7	1376	1446	1453
T2/2*		Truss 2, king post, T2/2	104	23 bs	1373	1453	1476
	lwc-h04	*ditto*	*101*	*19*	*1373*	*1454*	*1473*
	flch2	*ditto*	*76*	*24 bs*	*1401*	*1452*	*1476*
T2/3*		Truss 2, principal rafter, T2/3	73	30 bs	1404	1446	1476
	lwc-h01	*ditto*	*70*	*27*	*1404*	*1446*	*1473*
	flch3	*ditto*	*72*	*31 bs*	*1405*	*1445*	*1476*
T2/5	flch4	Truss 2, tiebeam, T2/5	76	16	1393	1452	1468
T3/1	lwc-h07	Truss 3, principal rafter, T3/1	nm	---	------	------	------
T3/2	lwc-h06	Truss 3, king post, T3/2	95	h/s	1366	1460	1460
T3/3	flch1	Truss 3, principal rafter, T3/3	84	34 bs	1393	1442	1476
T5/1	lwc-h08	Truss 5, principal rafter, T5/1	94	13	1380	1460	1473
T5/2		Truss 5, principal rafter T5/2	87	h/s	1376	1462	1462
	lwc-h02	*ditto*	*87*	*h/s*	*1376*	*1462*	*1462*
	flch5	*ditto*	*86*	*h/s*	*1376*	*1461*	*1461*
T5/3*	lwc-h03	Truss 5, collar, T5/3	55	h/s	------	------	------
		Loose timbers					
P1	lwc-h11	Purlin, P1	64	h/s	1400	1463	1463
P2	lwc-h13	Purlin, P2	73	4	1393	1461	1465
P3	flch6	Purlin, P3	nm	---	------	------	------
R4	lwc-h12	Common rafter, R4	67	no h/s	------	------	------
U1	lwc-h09	Unlabelled 1, ?floor beam?	67	21	------	------	------
U2	lwc-h10	Unlabelled 2,?tiebeam?, ?reused?	79	16	1395	1457	1473
U3	lwc-h14	Unlabelled 3, ?floor beam?	42	h/s	------	------	------

Table 1: (continued)

U4	lwc-h15	Unlabelled 4, unknown	73	15+3mm	1398	1455	1470
U5	lwc-h16	Unlabelled 5, ?floor beam?	65	13	------	------	------
U6	lwc-h17	Unlabelled 6, unknown, conifer	115	h/s?	------	------	------

Key:
nm = not measured
h/s = the heartwood/sapwood boundary ring is the last ring on the sample
bs = complete sapwood retained on the sample, the last measured ring date is the felling of the tree represented and it is partially formed indicating felling in the summer
* = mean timber sequence (component samples are listed in small type)

*Table 2: Matrix of the t-values produced between all of the cross-matching ring series in site chronology LWCHSQ01. \ = overlap less than 30 years; - = t-values less than 3.00; * = empty triangle*

Timbers	T2-1	T2-2	T2-3	T2-5	T3-2	T3-3	T5-1	T5-2	P1	P2	U2	U4
T2-1	*	6.55	9.08	3.99	5.69	5.66	3.73	5.73	4.50	3.04	3.83	6.53
T2-2	*	*	3.27	4.89	10.77	4.32	3.73	4.41	-	-	3.65	4.31
T2-3	*	*	*	4.38	-	5.33	3.48	4.36	3.98	3.72	3.45	5.02
T2-5	*	*	*	*	4.60	3.83	3.19	4.89	-	3.79	-	6.62
T3-2	*	*	*	*	*	4.72	3.66	4.09	-	-	-	4.61
T3-3	*	*	*	*	*	*	5.08	5.24	3.86	3.97	-	6.35
T5-1	*	*	*	*	*	*	*	10.56	6.67	4.50	-	3.99
T5-2	*	*	*	*	*	*	*	*	7.08	6.13	-	5.63
P1	*	*	*	*	*	*	*	*	*	6.29	4.63	4.23
P2	*	*	*	*	*	*	*	*	*	*	-	5.74
U2	*	*	*	*	*	*	*	*	*	*	*	4.14
U4	*	*	*	*	*	*	*	*	*	*	*	*

Table 3: Results of the cross-dating of 111-year site chronology LWCHSQ01 and some relevant reference chronologies when the first-ring date is AD 1366 and the last-ring date is AD 1476

Reference chronology	Span of chronology	t-value	Reference
All Hallows Church, Kirkburton, West Yorkshire	AD 1306–1633	9.6	Arnold and Howard 2007a
Horbury Hall, Wakefield, West Yorkshire	AD 1368–1473	9.4	Howard *et al* 1992
Bramall Hall, Stockport, Cheshire	AD 1359–1590	8.8	Arnold and Howard 2013 unpubl
Netherhall Barn, Rawthorpe/Dalton, West Yorkshire	AD 1376–1453	8.7	Arnold and Howard 2007b
Elland Old Hall, Calderdale, West Yorkshire	AD 1372–1574	8.6	Hillam 1984
St Mary's Abbey, Halesowen, West Midlands	AD 1310–1535	8.6	Arnold and Howard 2008
Black Ladies, Brewood, Staffordshire	AD 1372–1671	8.6	Tyers 1999
Bullace Trees Farm barn, Liversedge, West Yorkshire	AD 1292–1740	8.1	Arnold and Howard 2012 unpubl
Ordsall Hall, Salford, Greater Manchester	AD 1366–1534	8.1	Arnold *et al* 2004
Lea Road Foundry site, Church Street, Dronfield, Derbyshire	AD 1344–1526	7.9	Tyers 2003

FIGURES

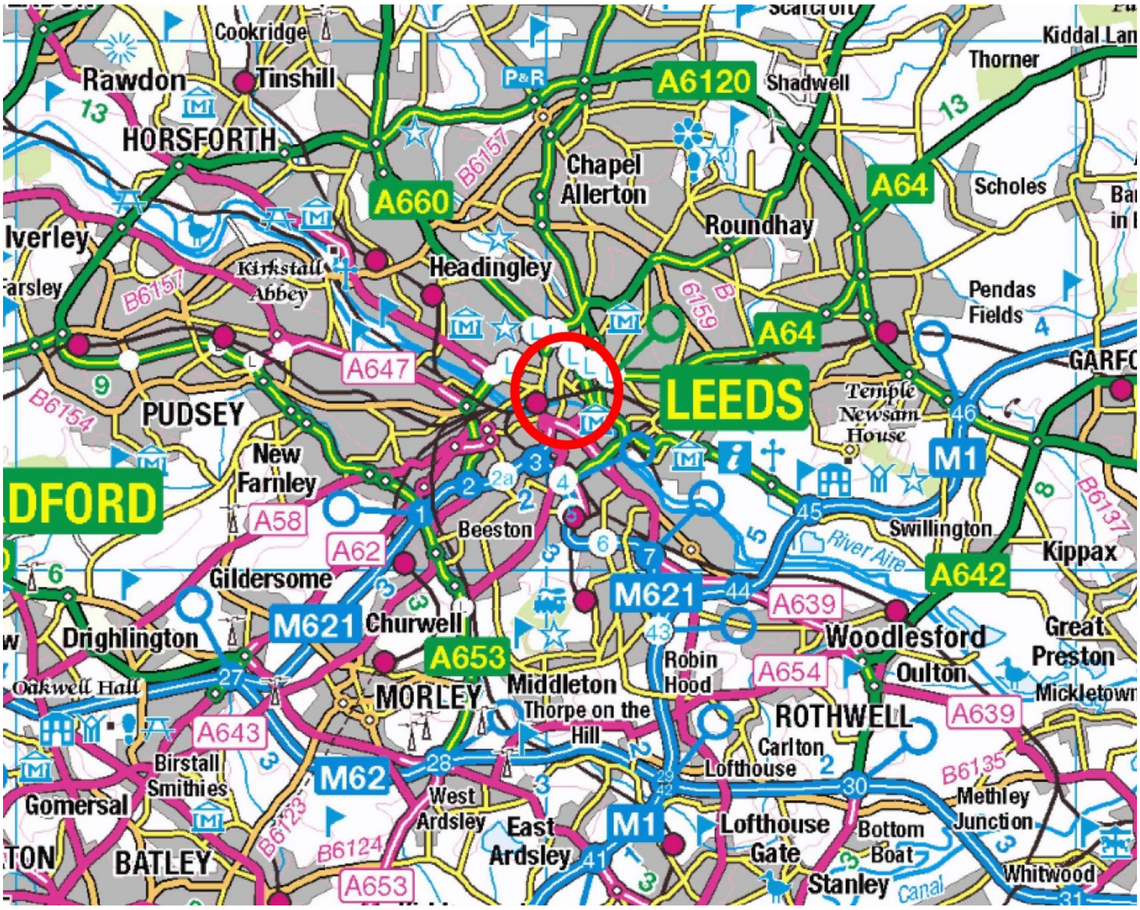

Figure 1a: Map to show the general location of First White Cloth Hall in Leeds. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

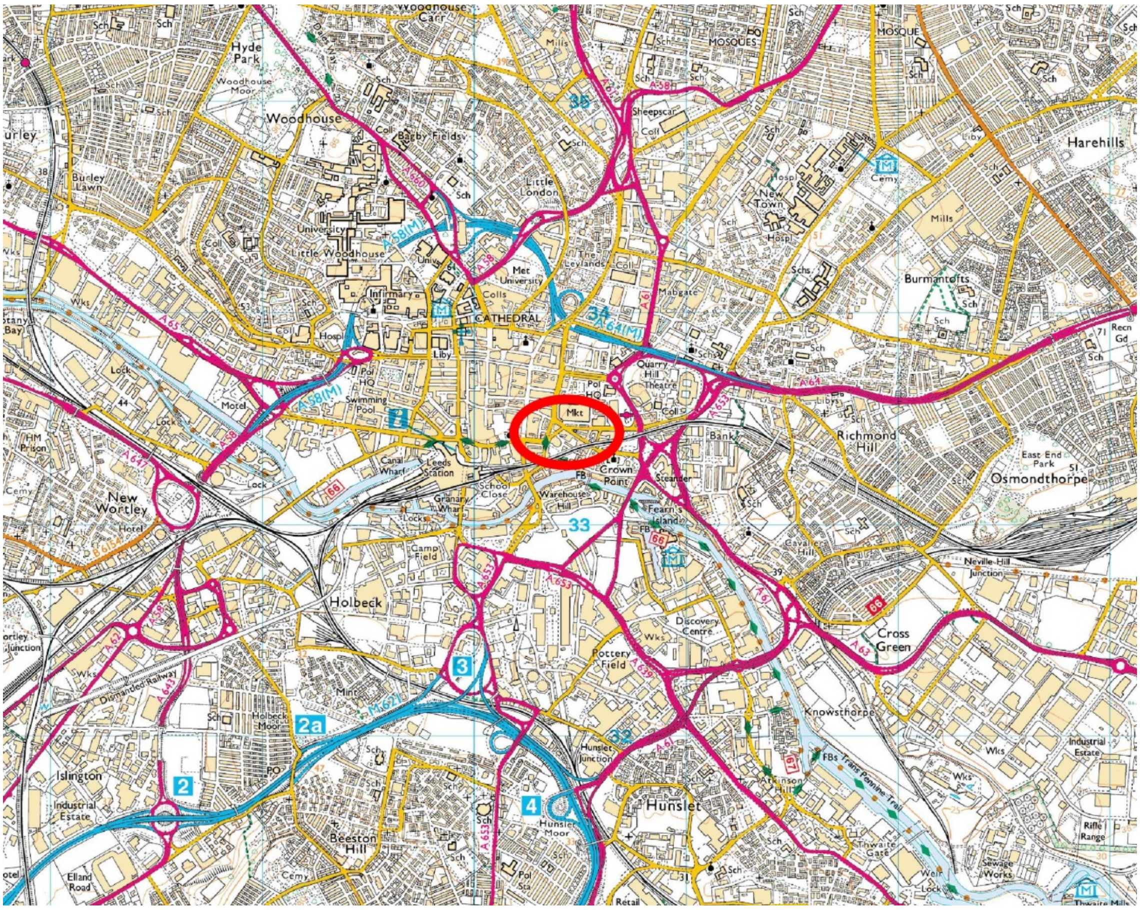

Figure 1b: Map to show a more detailed location of First White Cloth Hall in Leeds. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

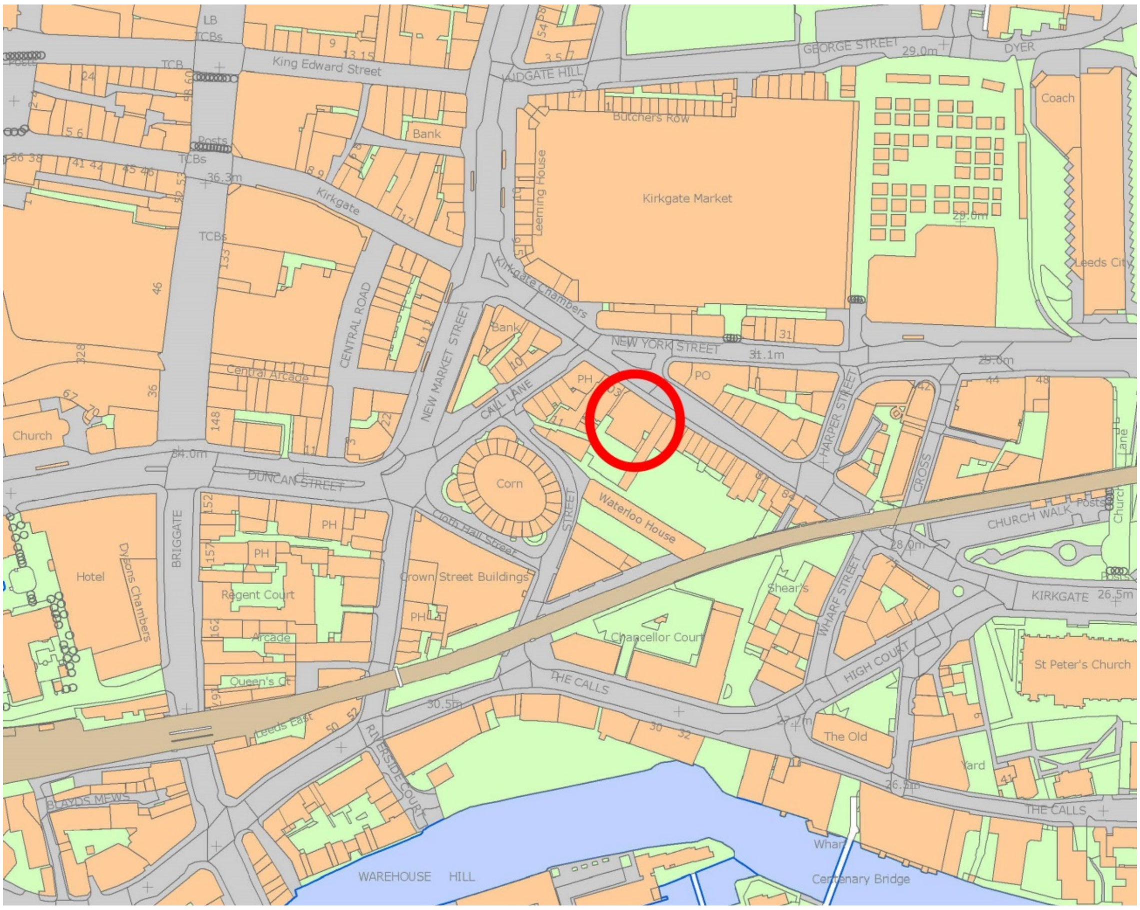

Figure 1c: Map to show the precise location of First White Cloth Hall in Leeds. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

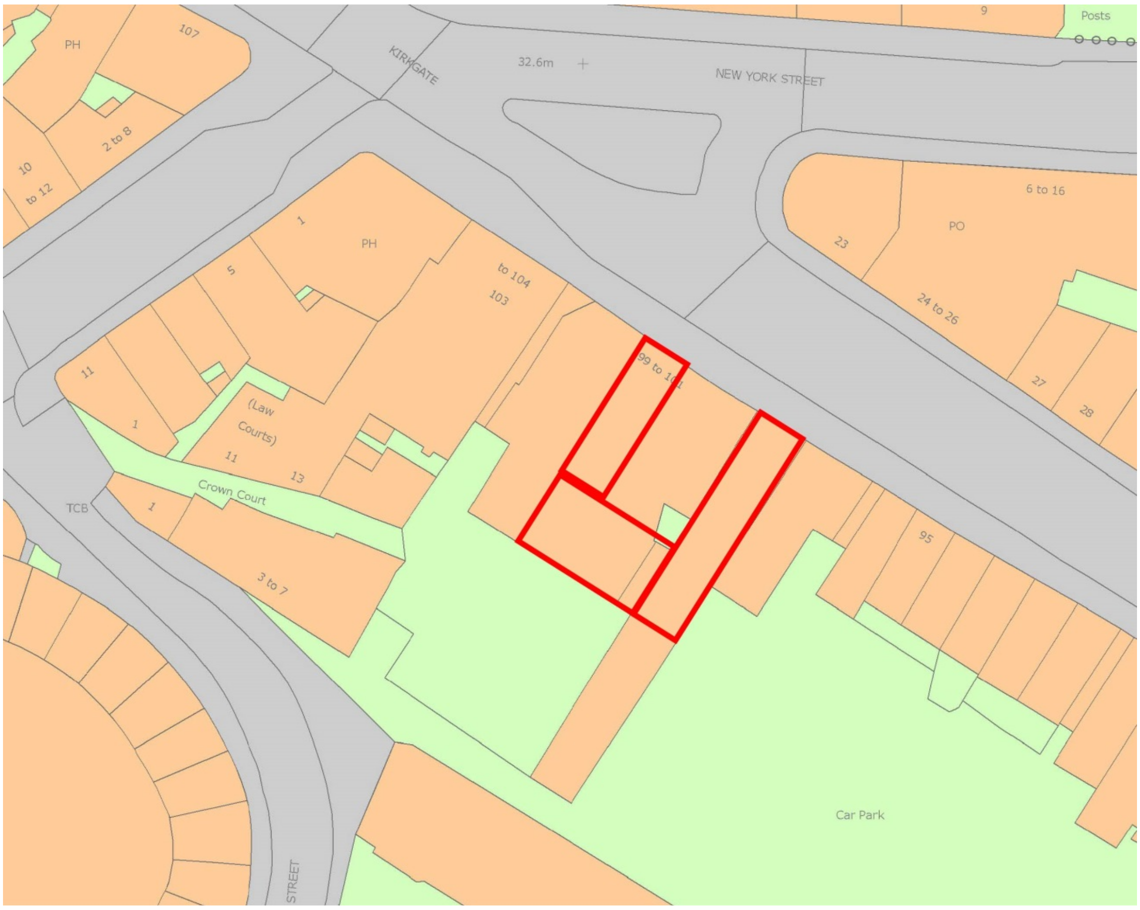

Figure 2: Map with sketch illustrating the U-plan footprint of First White Cloth Hall. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

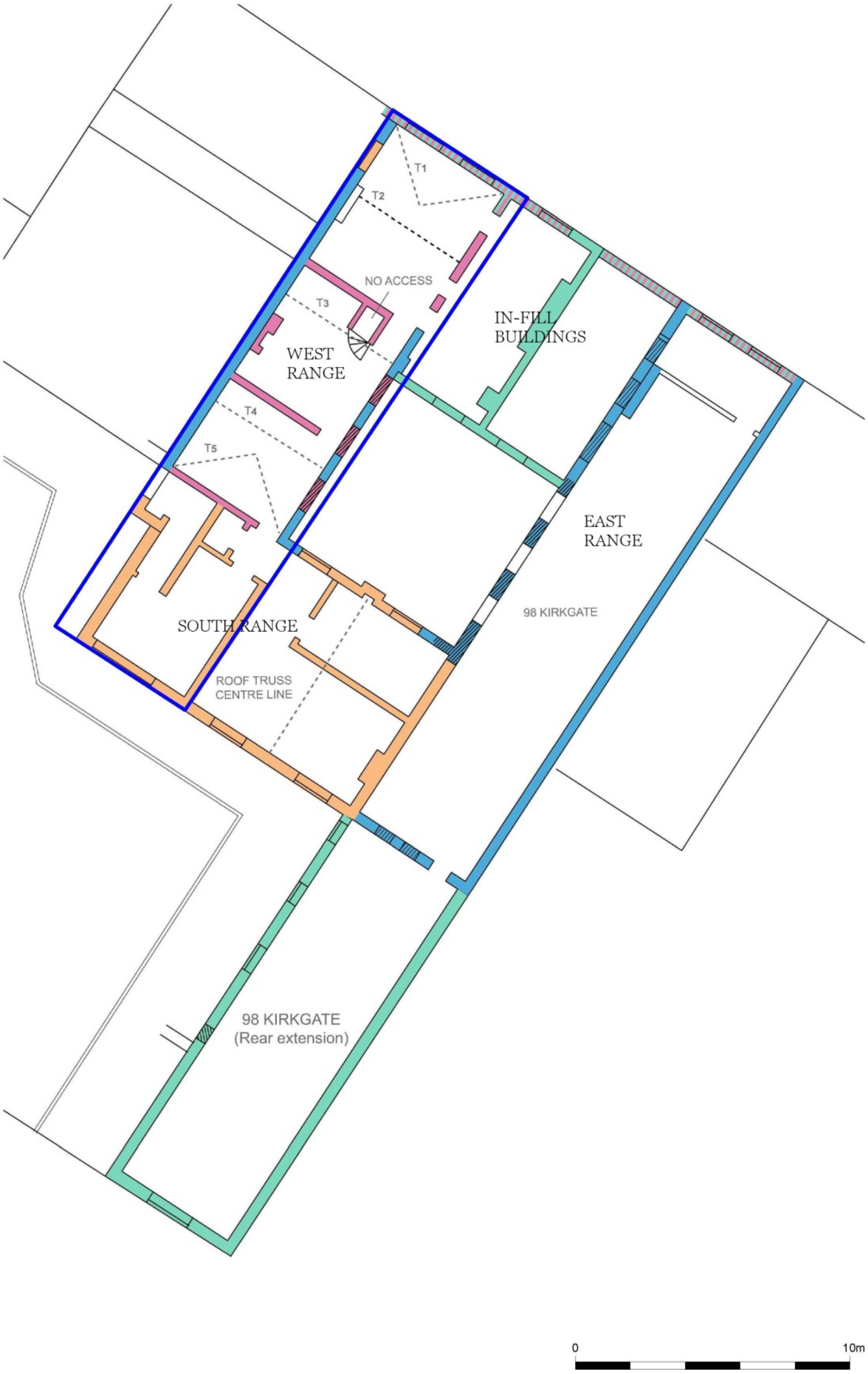

Figure 3: First-floor plan showing the relationship of the west, south, and east ranges of First White Cloth Hall and the infill buildings at the northern end of the courtyard. The location of the trusses in the west range is indicated (after Cressey 2013, Fig 2b)

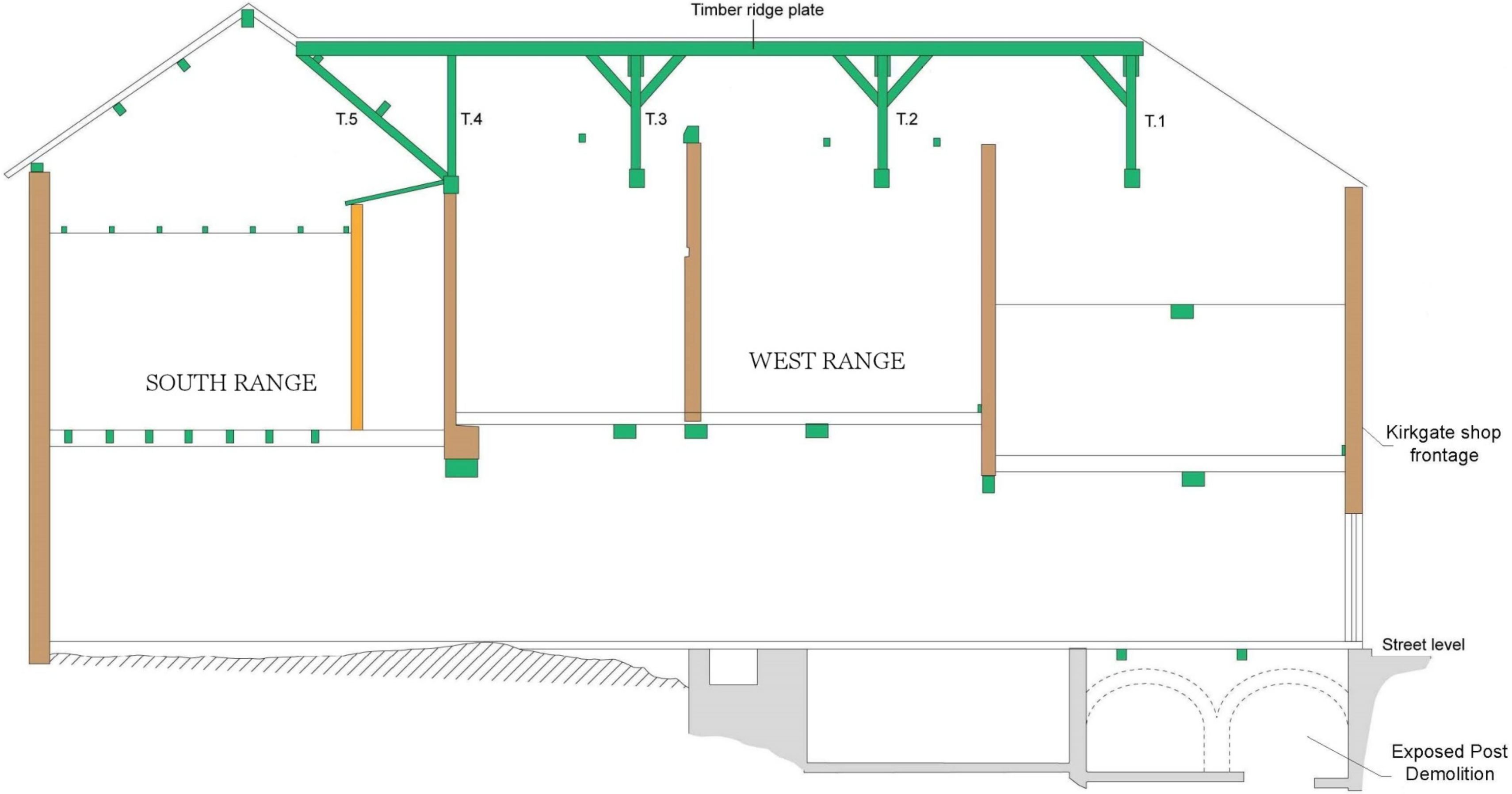

Figure 4: Section, looking west, showing the location of the trusses in the west range (after Cressey 2013, Fig 8)

Figure 5: Truss 2 following salvage during demolition (photograph CFA Archeaeology Ltd)

Figure 6: Truss 3 following salvage during demolition (photograph CFA Archaeology Ltd)

Figure 7: Truss 5 following salvage during demolition (photograph CFA Archaeology Ltd)

Figure 8: Trusses 2, 3, and 5 in storage with truss number labels still attached, truss 2 at the front, truss 5 against the wall at the back (photograph Cathy Tyers, Historic England)

Figure 9: Loose timbers (group 2) in storage (photograph Cathy Tyers, Historic England)

Figure 10: Loose timbers (group 2) in storage, showing some of the extant timber labels (photograph Cathy Tyers, Historic England)

Figure 11: Loose timbers (group 1) in storage (photograph Cathy Tyers, Historic England)

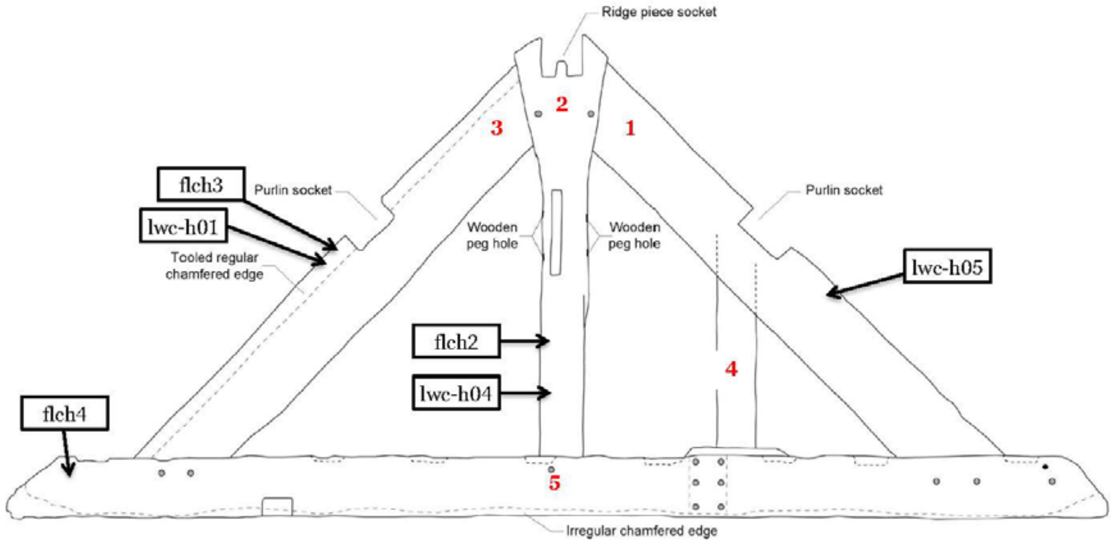

Figure 12: Truss 2 showing the timber numbering scheme, the sampled timbers and the approximate location of the samples (after Cressey 2013, Fig 9a)

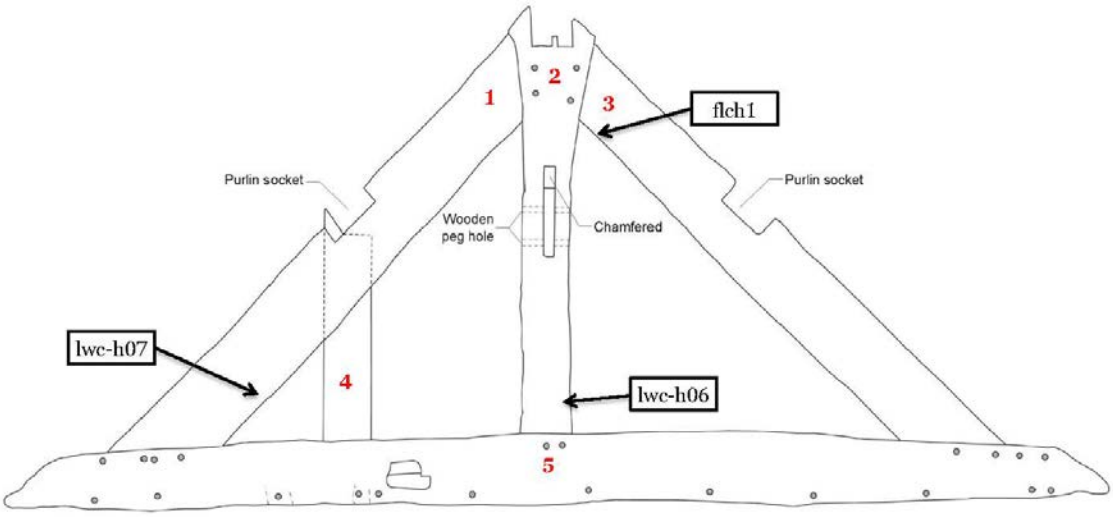

Figure 13: Truss 3 showing the timber numbering scheme, the sampled timbers and the approximate location of the samples (after Cressey 2013, Fig 9b)

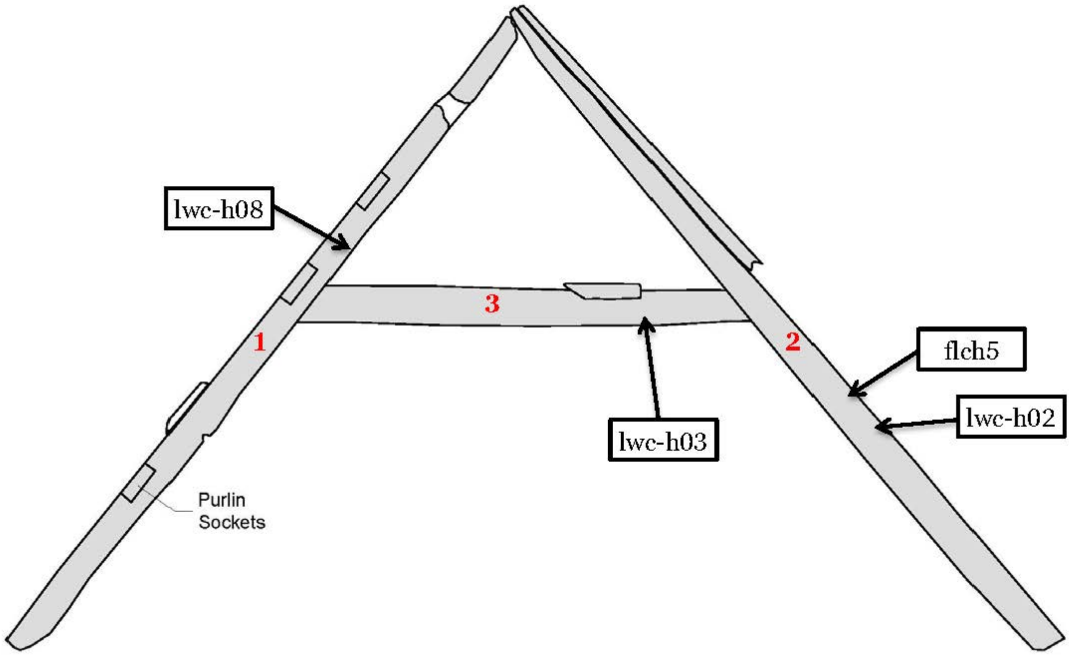

Figure 14: Truss 5 showing the timber numbering scheme, the sampled timbers and the approximate location of the samples (after Cressey 2013, Fig 10)

Figure 15: Annotated photograph showing some of the sampled loose timbers (photograph Robert Howard)

Figure 16: Timber P1 (group 1), centre (photograph Cathy Tyers, Historic England)

Figure 17: Timber P2 (group 1), and timber R4 (photograph Cathy Tyers, Historic England)

Figure 18: Timber P3 (group 2), centre (photograph Cathy Tyers, Historic England)

Figure 19: Timber R4 (group 1), centre (photograph Cathy Tyers, Historic England)

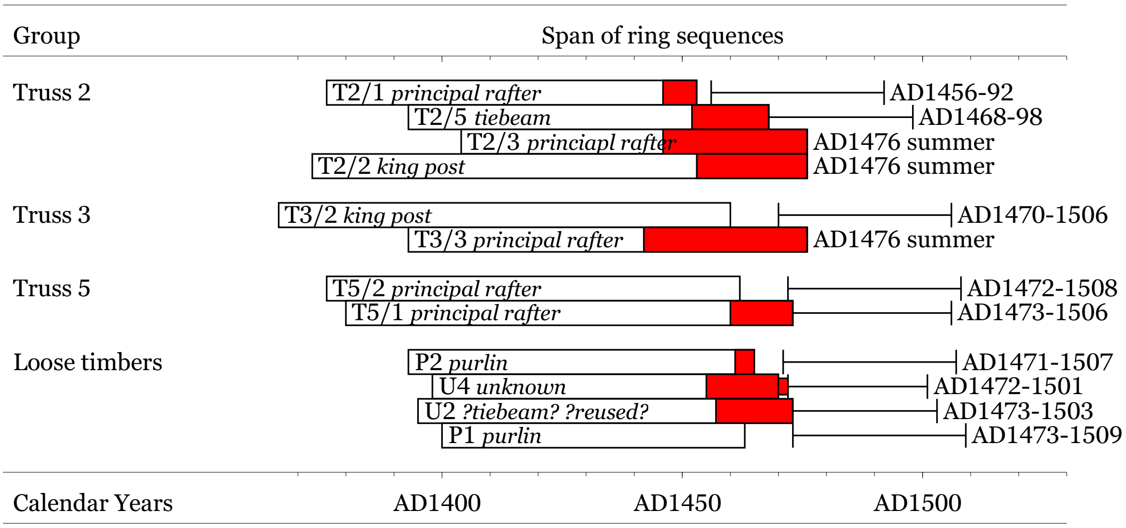

Figure 20: Bar diagram of the cross-matching ring series in site chronology LWCHSQ01 with individual felling dates / felling date ranges. White bars = measured heartwood rings; red bars = measured sapwood rings; narrow red bars = unmeasured sapwood rings

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

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LWC-H01A   70
 300 307 317 301 308 281 298 241 243 212 201 200 180 186 214 135 203 161 149 170
 157 175 145 144 136 153 142 132 157 108 164 147 171 131 134 103 103  85  95  96
 123 123  77  92 106 104  68 103 103  98 125 107  98  96  75  84  85  64  78  95
  78 117 107  92 130 114  99 101 105 146
LWC-H01B   70
 297 327 312 311 341 291 295 246 232 221 201 206 168 193 219 135 193 167 149 170
 160 166 158 127 156 164 139 132 155 107 155 148 173 125 135 106 107  89  89  93
 120 121  76 100  97 103  71 104 101  98 116 105  95  89  82  73  82  71  82  83
  79 117 110  96 128 113 101 103 105 144
LWC-H02A   87
 611 507 582 678 571 447 589 559 494 376 387 386 377 287 254 348 196 229 250 220
 242 175 231 246 309 248 195 182 173 195 221 141 179 195 187 165 200 144 150 160
 119 128 160 115 156 156 120 190 131 166 102 100 162 118 128 133 180 125 149 134
 144 146 161 123 146 181 134 204 246 193 101 103 126 164 174 209 143 146 161 157
 175 179 155 154 153 165 206
LWC-H02B   87
 623 520 576 694 574 445 571 568 497 377 368 395 377 287 259 340 190 237 240 237
 236 175 235 242 314 242 185 182 187 181 226 150 171 201 196 159 182 137 153 160
 125 132 172 114 153 155 120 181 131 168 106 103 153 128 128 125 171 140 155 125
 135 151 166 121 150 174 144 202 243 194 102 101 134 163 170 208 138 146 168 150
 181 171 162 159 146 174 196
LWC-H03A   55
 276 269 172 104 110 135 208 141 280 209 130  85 100 132 142 182 159 132 150 134
 141 159 163 161 133 165 160 169 240 134 176 193 210 178 175 160 150 140 146 151
 123 117 107 139  87  97 118  82  82  71  59  71  59  71  96
LWC-H03B   55
 281 280 172 102 105 132 206 128 279 201 130  91  92 134 142 182 161 132 150 136
 142 157 156 167 129 164 171 182 226 137 178 194 208 178 175 159 163 134 139 154
 110 118 107 146 101 104  98  87  87  75  62  70  54  74  98
LWC-H04A  101
 278 295 215 254 229 308 241 239 172 234 184 205 115 305 552 415 327 289 382 342
 380 294 246 275 217 224 250 389 321 150 167 175 239 232 146 229 246 190 141 171
 117 114  81 110 109 115  62 115 108  91  83  91  83 104 101 113  89  69  43  87
  65  96 100 108  86  51  43  40  47  50  44  46  42  33  40  48  43  40  62  40
  59  58  46  59  45  63  59  52  43  48  52  52  62  46  63  95  59  78  87  62
  93
LWC-H04B  101
 273 300 209 260 225 313 242 238 180 246 196 207 116 298 550 423 341 294 376 318
 378 287 257 284 228 223 251 368 294 152 154 193 229 240 157 223 245 189 143 175
 120 110  81 109 115 115  65 106 115  87  84 101  81 101 100 114  82  75  50  88
  57  98  91 107  82  54  50  40  49  43  50  41  44  34  37  44  43  46  51  53
  50  50  44  67  44  70  54  55  43  46  51  49  63  50  62  93  62  68  96  60
  98
LWC-H05A   78
 401 361 259 276 212 203 305 262 277 193 349 396 344 277 328 301 292 257 303 259
 276 180 238 250 320 257 209 225 237 281 275 221 226 237 281 248 240 203 190 195
 182 210 217 151 230 150 154 159 173 176 156 129 167 143 121 132 152 101 142 150
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115 115 113 99 103 96 96 97 133 118 84 121 101 103 95 110 134 114
LWC-H05B 78
395 361 263 276 210 208 250 270 287 191 368 394 352 293 327 293 296 253 296 264
283 193 240 250 314 257 207 217 243 282 284 221 218 250 267 244 237 201 191 190
173 233 216 159 223 170 150 157 165 179 146 128 160 151 130 131 155 100 147 141
120 113 121 90 103 87 96 109 135 115 84 108 106 100 102 103 127 115
LWC-H06A 95
269 150 86 164 171 173 176 207 283 173 288 193 250 190 167 134 151 153 208 107
324 550 418 414 349 304 246 319 351 303 287 226 281 268 373 307 165 190 239 249
267 163 212 220 179 204 233 144 158 159 137 128 142 98 148 143 110 121 153 172
142 156 121 133 139 80 125 87 119 124 121 103 59 42 37 41 36 37 38 34
35 29 41 49 37 59 38 42 40 33 40 40 45 50 62
LWC-H06B 95
279 154 91 145 166 173 190 175 263 166 303 185 246 194 169 137 155 145 217 104
319 543 437 410 333 312 256 312 341 314 289 233 282 264 386 328 165 200 238 251
246 162 208 225 187 206 231 146 161 157 128 134 132 90 159 138 125 115 155 171
147 143 129 129 140 81 125 88 120 115 125 101 53 43 35 39 40 33 37 37
33 34 33 51 40 53 43 40 39 42 37 39 38 40 62
LWC-H08A 94
259 211 242 332 346 294 333 423 318 210 235 396 317 372 310 272 332 275 369 290
377 289 214 259 223 209 235 160 254 217 223 175 207 143 189 179 125 123 150 123
159 171 134 174 137 140 98 98 181 162 152 150 226 156 150 134 125 130 146 110
111 141 106 128 157 135 109 75 102 143 137 137 147 140 187 146 168 162 165 134
140 153 121 143 100 129 156 150 212 231 213 221 221 228
LWC-H08B 94
262 212 246 360 337 296 307 374 307 210 246 383 324 360 307 257 295 268 385 296
383 296 213 254 229 189 240 160 234 210 221 170 193 170 171 171 135 103 155 127
167 169 135 173 140 136 107 96 178 148 152 148 237 153 148 135 123 134 145 108
109 140 106 127 153 140 109 72 100 157 125 137 141 148 184 150 168 160 165 133
150 140 131 132 101 128 165 146 221 203 254 176 217 226
LWC-H09A 67
183 212 214 208 153 168 166 155 152 115 125 350 335 353 280 246 190 194 246 417
464 464 392 260 201 268 305 296 330 240 390 285 196 160 218 236 323 248 235 245
149 131 129 276 345 259 215 235 171 170 167 146 155 179 170 155 151 137 158 93
73 69 82 78 124 176 96
LWC-H09B 67
182 205 215 198 137 160 141 169 174 127 116 328 285 368 275 254 200 193 278 460
478 437 384 265 207 264 292 317 323 234 382 284 198 162 218 237 307 248 239 228
140 128 134 278 354 265 260 212 181 143 171 145 168 181 171 163 124 135 150 104
75 56 93 77 146 168 100
LWC-H10A 79
265 371 280 217 147 241 297 230 285 273 230 203 203 297 268 258 159 210 170 184
167 161 163 200 94 145 154 153 146 142 106 95 103 210 167 98 98 146 79 117
152 118 103 100 82 90 106 90 85 89 73 67 93 84 78 68 59 96 82 121
171 200 170 116 120 184 145 142 103 153 165 171 150 110 99 100 193 160 162
LWC-H10B 79
265 370 281 222 150 239 292 228 275 275 235 192 212 296 261 255 165 210 174 185
174 157 175 209 98 135 149 136 146 138 123 110 110 161 176 103 101 151 89 131
154 118 104 97 82 94 106 85 89 84 70 71 90 82 79 70 64 93 84 123
179 219 156 135 117 171 150 143 95 153 156 162 151 106 98 101 180 163 163
LWC-H11A 64
462 512 381 396 364 242 250 176 201 245 241 236 302 225 167 203 146 138 150 130
160 157 138 230 157 159 133 94 162 172 160 118 226 126 165 179 128 159 150 150

175 189 99 142 195 176 123 104 111 134 129 130 172 154 164 205 314 253 246 194
205 190 206 256
LWC-H11B 64
457 493 377 402 293 237 255 179 212 230 235 242 300 212 176 214 152 138 162 125
166 161 139 228 153 161 132 91 168 171 165 118 234 118 177 167 129 152 156 156
176 187 130 121 193 167 110 104 115 133 142 121 179 162 168 184 332 271 234 193
231 187 207 252
LWC-H12A 67
231 172 158 161 202 241 183 184 197 169 160 157 114 201 173 125 146 123 126 125
142 153 142 125 149 151 125 124 125 135 114 102 119 109 95 84 99 85 101 83
96 78 95 75 100 93 100 78 75 92 93 98 87 107 62 70 72 67 75 85
81 75 68 85 90 104 116
LWC-H12B 67
234 175 160 158 209 234 184 188 194 160 151 157 113 192 171 119 148 135 147 128
139 152 146 125 150 157 128 122 120 135 119 105 109 103 93 89 99 83 101 89
90 94 98 72 99 95 107 100 68 93 101 95 90 109 62 68 71 64 77 84
79 73 75 82 90 105 112
LWC-H13A 73
334 351 383 304 317 334 269 318 298 219 219 261 202 238 203 167 189 145 158 189
184 175 183 117 114 110 109 108 146 120 146 137 112 110 90 123 160 123 112 151
116 169 141 104 145 132 144 158 146 95 125 131 156 95 108 113 123 104 151 131
100 137 105 149 125 119 168 118 128 140 143 94 159
LWC-H13B 73
333 353 392 305 302 341 280 312 296 209 233 253 200 235 196 188 196 151 141 192
169 188 183 128 107 128 102 103 156 124 132 138 115 107 75 137 156 143 121 182
126 170 132 111 146 133 144 153 160 92 121 147 152 105 105 123 112 104 143 135
107 123 114 142 129 121 162 131 121 137 142 103 156
LWC-H14A 42
323 234 308 291 324 364 337 406 385 415 505 500 513 536 514 473 359 333 440 423
512 520 431 518 400 278 364 417 386 477 568 485 465 384 262 266 332 334 312 328
331 300
LWC-H14B 42
332 223 304 294 331 372 352 402 388 409 514 495 525 557 522 465 376 328 426 409
517 524 439 491 389 277 396 442 395 489 568 480 468 371 257 275 326 340 315 321
334 299
LWC-H15A 73
420 379 577 618 418 482 426 377 447 304 360 318 362 308 385 276 364 366 307 354
339 197 369 301 201 276 292 263 234 257 260 364 221 180 280 207 292 292 203 212
226 160 165 158 115 175 168 181 110 129 195 161 153 204 201 156 249 150 171 159
125 137 115 143 126 98 128 132 123 175 171 129 168
LWC-H15B 73
415 372 575 609 415 500 412 378 435 309 358 317 358 322 389 297 362 368 306 354
323 185 367 295 208 271 294 278 226 248 248 360 226 185 275 215 306 289 209 212
228 146 166 162 115 168 168 168 111 143 194 165 156 211 195 162 238 146 168 156
126 140 112 140 127 98 125 133 112 187 165 125 170
LWC-H16A 65
335 306 282 296 350 386 364 368 352 464 434 428 461 529 442 421 332 281 359 392
400 356 398 373 317 300 278 283 310 281 267 163 114 72 106 125 194 148 190 150
95 82 151 215 234 200 175 250 181 131 98 122 190 198 220 193 162 84 62 93
100 121 156 153 156
LWC-H16B 65
332 282 280 303 351 406 393 418 376 455 434 429 475 525 410 439 325 290 385 392
414 366 380 382 320 295 292 306 315 287 260 170 108 73 101 128 200 150 190 153

101 87 163 232 219 196 175 246 177 128 90 124 183 195 223 194 149 79 63 107
100 103 137 151 155
LWC-H17A 115
507 523 496 446 470 336 323 328 289 317 195 206 184 177 138 193 195 159 129 151
102 145 117 135 152 123 142 142 140 90 108 102 147 112 109 126 114 173 160 118
107 98 98 80 92 88 134 142 115 106 93 108 107 87 87 91 70 81 67 57
68 60 65 87 112 67 72 59 71 76 88 62 65 75 60 92 103 125 190 165
110 93 132 118 109 122 106 99 115 121 124 140 142 118 151 139 155 115 100 92
95 96 146 124 80 109 143 84 118 99 64 80 77 100 109
LWC-H17B 115
498 517 504 440 464 350 319 320 280 319 198 203 175 177 140 189 205 153 132 146
111 138 112 139 144 132 142 138 151 89 107 98 129 115 107 135 136 154 143 120
98 110 94 80 84 96 126 134 115 104 100 110 109 85 91 90 71 82 70 56
67 60 70 88 112 65 73 62 71 78 87 62 65 78 62 89 107 129 187 163
107 101 120 117 107 129 98 112 106 116 130 137 150 115 142 140 156 117 109 96
100 96 141 130 79 108 146 90 119 99 67 75 81 103 109
FLCH1 84
312 308 250 288 197 322 248 304 307 232 253 258 258 324 245 313 339 340 284 297
257 237 206 179 176 209 151 218 168 170 158 154 143 122 109 110 137 113 99 110
94 109 103 106 88 99 78 63 73 65 84 85 81 69 82 81 94 80 103 103
91 94 72 86 81 80 77 74 72 75 85 67 80 81 85 103 70 98 82 105
91 68 108 82
FLCH2 76
273 148 173 204 281 289 202 246 275 175 155 163 118 111 79 109 120 128 76 125
136 97 121 112 101 127 127 143 109 86 60 108 77 100 112 120 107 69 54 44
62 47 61 62 42 40 58 44 52 56 65 60 65 59 58 60 52 61 57 58
59 59 60 51 73 65 66 110 64 87 83 60 91 76 85 82
FLCH3 72
307 346 286 317 283 303 243 244 243 231 212 181 181 218 160 218 164 158 158 184
176 155 139 164 163 152 138 169 106 153 170 166 116 132 93 112 79 85 96 128
125 70 111 100 104 84 98 92 105 107 118 114 95 71 81 86 85 81 80 77
121 98 98 133 130 113 101 110 94 75 89 65
FLCH4 76
333 315 302 312 263 380 292 350 302 276 353 252 286 321 189 248 273 250 282 396
238 251 258 228 223 221 108 193 250 180 212 196 192 179 225 185 174 180 139 219
128 164 164 190 166 170 130 150 135 99 127 146 166 103 151 166 153 159 228 169
113 193 189 161 156 188 166 162 147 165 114 117 135 142 180 258
FLCH5 86
489 488 603 671 576 440 589 555 481 386 325 352 354 264 269 342 209 265 257 232
247 194 258 230 314 257 211 206 221 211 257 164 186 212 184 165 180 170 139 155
122 98 149 120 126 142 121 169 140 139 107 90 147 114 124 109 169 99 130 123
118 140 139 117 131 164 121 177 193 182 109 97 130 159 173 173 144 135 157 144
174 177 170 158 145 148

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled

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

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

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

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

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

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

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

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

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

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

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

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

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

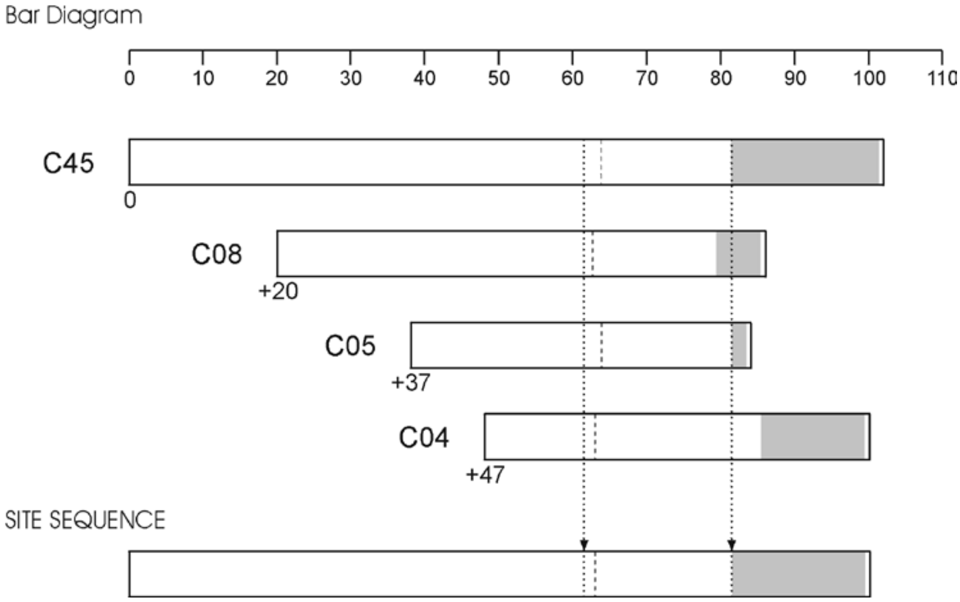


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

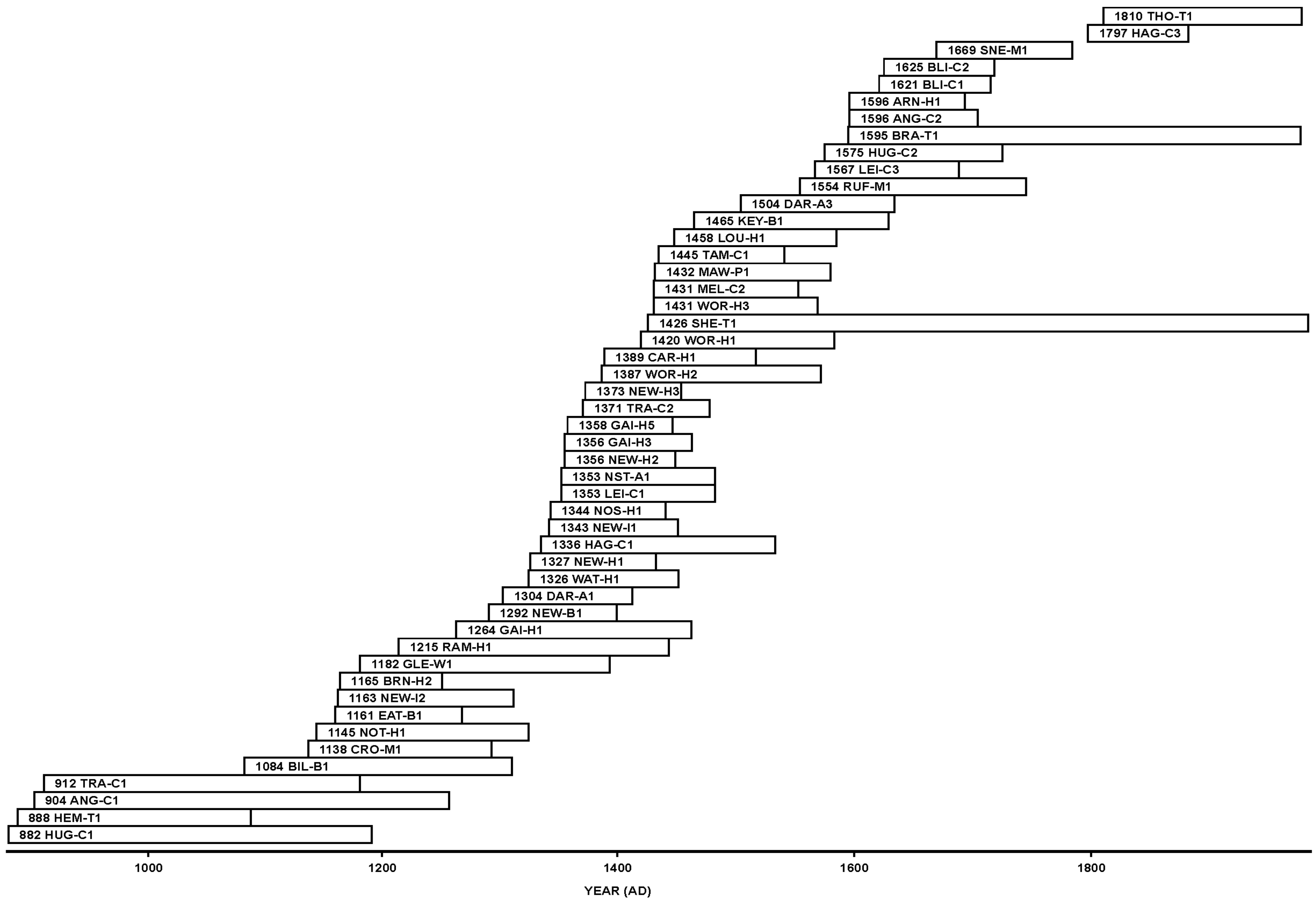
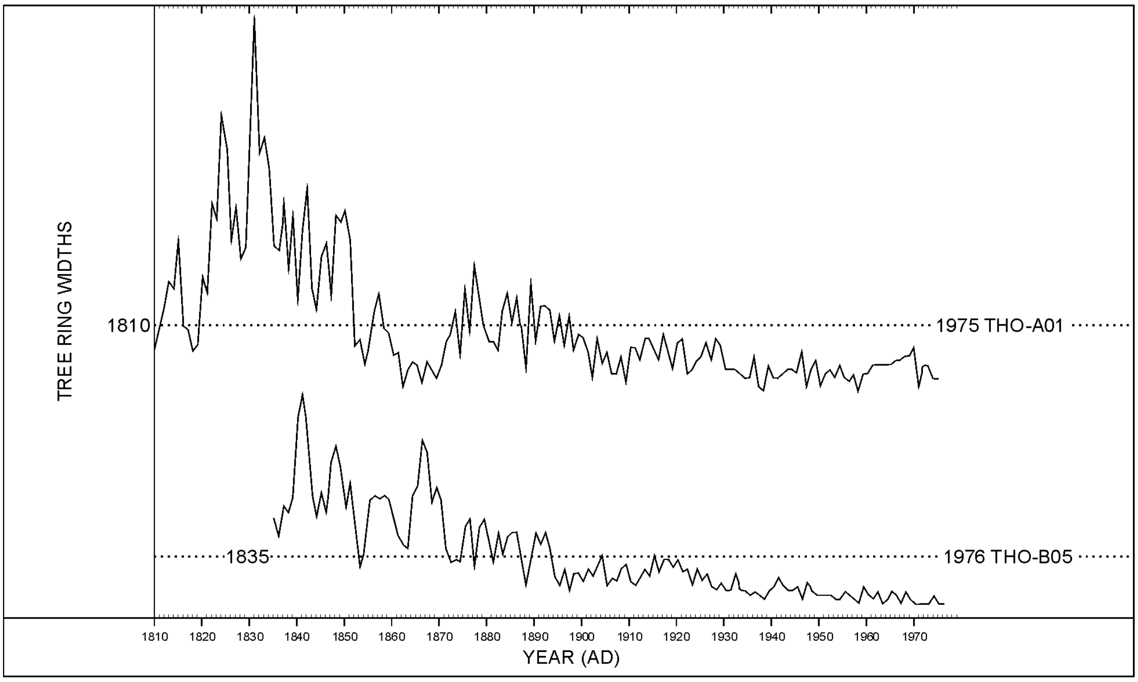


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

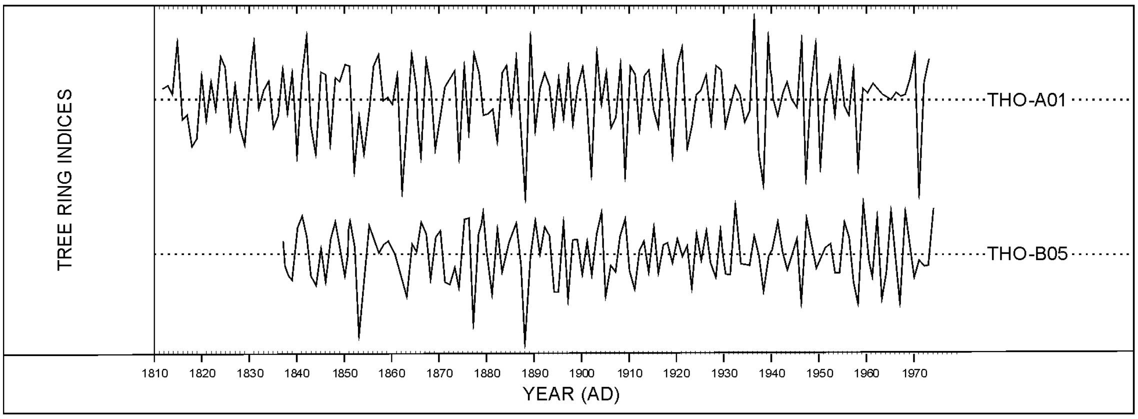


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known
Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young 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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ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)