



The Former White Lion Public House, Holker Road, Buxton, Derbyshire

Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers

Alison Arnold, Robert Howard, Cathy Tyers, Bisserka Gaydarska and Michael Dee



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Summary

Dendrochronological analysis was undertaken on 10 of the 11 samples (one sample having too few rings for reliable analysis) obtained from different timbers throughout the body of this building. This analysis produced a single site chronology comprising six cross-matching samples, this site chronology being 65 rings long. A number of matches were found for the series composed of six timbers with a tentative end date of AD 1780 but these were not very strong, and were matched only with local chronologies, so were not accepted as an independent secure dendrochronological date.

Radiocarbon dating was undertaken on four single-ring samples from one of the timbers represented in the tentatively dated site master chronology. Wiggle-matching of these results suggests that the final ring of this sequence formed in *cal AD 1750–1789 (69% probability)* or *cal AD 1928–1983 (26% probability)*, or in *cal AD 1770–1787 (59% probability)* or *1956–1968 (9% probability)*.

The tentative matching identified for the site master chronology by ring-width dendrochronology is thus supported independently by the radiocarbon wiggle-matching, giving a felling date of AD 1780_{DR}.

Contributors

Alison Arnold, Robert Howard, Cathy Tyers, Bisserka Gaydarska and Michael Dee

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Front cover image

The former White Lion Public House, Buxton under repair in 2022 (photograph Robert Howard)

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Contents

Introduction.....	1
Sampling	3
Analysis and Results	9
Radiocarbon dating.....	12
Wiggle-matching.....	14
Discussion and Conclusion.....	17
References	18
Data of Measured Samples	21
Appendix: Tree-Ring Dating.....	23
The Principles of Tree-Ring Dating.....	23
The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory.....	23
1. Inspecting the Building and Sampling the Timbers.....	23
2. Measuring Ring Widths.	27
3. Cross-Matching and Dating the Samples.	27
4. Estimating the Felling Date.....	28
5. Estimating the Date of Construction.	30
6. Master Chronological Sequences.....	30
7. Ring-Width Indices.	31
References	35

Illustrations

Figure 1: Maps to show the location of the former White Lion Public House and attached stable block, in red. Scale: top right 1:13,000; bottom 1:1,600. © Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900. ...2

Figure 2: Plan at 3rd-floor level to help locate sampled timbers (after Bench Architects)5

Figure 3: Plan at 2nd-floor level to help locate sampled timbers (after Bench Architects) ...6

Figure 4: 3rd floor, north-west room, annotated photograph (looking south-west) to help identify sampled timbers (photograph Robert Howard).....6

Figure 5: 3rd floor, south-west room, annotated photograph (looking south-east) to help identify sampled timbers (photograph Robert Howard).....7

Figure 6: 2nd floor, south-west room, annotated photograph (looking south) to help identify sampled timbers (photograph Robert Howard)7

Figure 7: 2nd floor, north-west room, annotated photograph (looking west) to help identify sampled timbers (photograph Robert Howard)8

Figure 8: 2nd floor, south-east room, annotated photograph (looking north-west) to help identify sampled timbers (photograph Robert Howard).....8

Figure 9: Bar diagram of the six samples of site chronology BUXTSQ01 11

Figure 10: Schematic illustration of BUX-T08 to locate the single ring sub-samples submitted for radiocarbon dating (C = complete sapwood)..... 13

Figure 11: Probability distributions of dates from sample BUX-T08. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly 15

Figure 12: Probability distributions of dates from BUX-T08, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1780. The format is identical to that of Fig 11 The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly 15

Tables

Table 1: Details of tree-ring samples from the former White Lion Public House, Holker Road, Buxton, Derbyshire	4
Table 2: Results of the cross-matching of site sequence BUXTSQ01 and relevant reference chronologies when the first-ring date is AD 1716 and the last-ring date is AD 1780	10
Table 3: Radiocarbon measurements from oak sample BUX-T08	12

Introduction

In 2019 Buxton Spa Town (HSM02) was selected as a High Street Heritage Action Zone (HSHAZ); a programme, largely funded by central government, devised to unlock the potential of high streets across England, fuelling economic, social and cultural recovery.

Buxton historic town, near the River Wye, has been renowned for the healing properties of its spa waters since The Romans settled it in c. AD 78 when it was named *Aquae Arnemetiae*, meaning the Spa of the Goddess of the Grove. Today, the old part of the town is believed to be concentrated around the marketplace, which was probably a focal point for trade, being right next to the boundary with three counties and drawing in trade from a wide area of upland Derbyshire and Staffordshire. This old hub continued to have an important role whilst the town grew in size and influence in the late 18th century under the development of the 5th Duke of Devonshire as a resort spa in the style of Bath. In the 20th century, the commercial focus of the town moved from Higher Buxton down to Spring Gardens. Today the town is still famous for its bottled Buxton Mineral Water.

Scientific dating was requested as one of the supporting elements to the HSHAZ programme at the Grade II listed (<https://historicengland.org.uk/listing/the-list/list-entry/1259203>) White Lion, which is suggested to have been used as a carriers' inn from around AD 1798 during Buxton's flourishing as a spa town. By the mid-19th century it was known as the White Lion Inn and had stables and a coach house. The building(s), however, may have initially been much smaller than appears today, with some suggestion that it may have formed part of a 17th-century small holding. As such, it is the only currently identified building that possibly pre-dates the large-scale 18th-century development of the town.

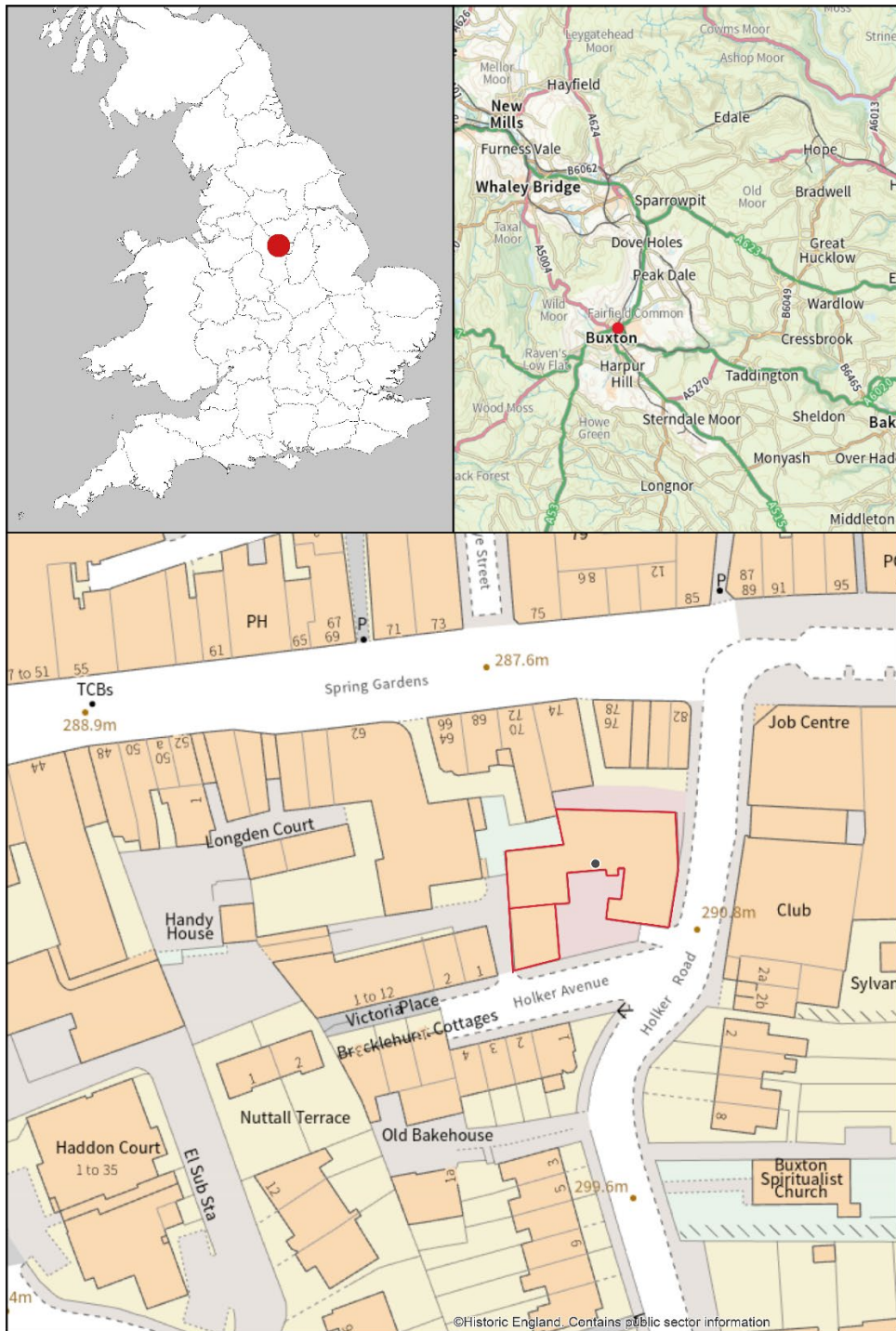


Figure 1: Maps to show the location of the former White Lion Public House and attached stable block, in red. Scale: top right 1:13,000; bottom 1:1,600. © Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900.

Sampling

Current opening-up works, undertaken as part of an extensive programme of repair, alteration and conservation, had exposed timber phasing of possibly 16th- or 17th-century date. With such an assemblage of timbers available, sampling and analysis by dendrochronology at the former White Lion was requested by Tim Allen, Historic England Development Advice Team Leader (North), Midlands Region, as one of the supporting elements to the HSHAZ programme in the town. In particular, the request was to sample both any primary phase timbers, and any timbers which might relate to the subsequent development of the building. It was hoped that this analysis would help deliver towards the overall objectives of the HSHAZ programme by improving understanding of the town centre area to deliver a good evidence base for future planning and improvement decisions.

An initial survey of the timbers visible showed that the potential for dendrochronology was somewhat limited by the fact that, while most of the timbers were not particularly small, they did appear to be derived from fairly fast-grown timbers with relatively low numbers of annual growth rings. It was, however, felt advisable to take advantage of the currently available access and sample those timbers which appeared to offer the best chances of success. Although there might have been timbers to parts of other buildings at this site, they were not undergoing building works and were not accessible at this time.

Thus, from the various timbers which were accessible at this time, a total of 11 timbers were sampled by coring. Each sample was given the code BUX-T (for 'Buxton') and numbered 01–11. Of this number, six samples (BUX-T01–BUX-T06) were obtained from rooms on the 3rd floor, with a further five samples (BUX-T07–BUX-T11) being taken from 2nd-floor rooms. Details of the samples are given in Table 1, with the sampled timbers being located on plans, Figures 2–3, and further identified in a series of annotated photographs shown here as Figures 4–8.

Table 1: Details of tree-ring samples from the former White Lion Public House, Holker Road, Buxton, Derbyshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD _{DR}	Last heartwood ring date AD _{DR}	Last measured ring date AD _{DR}
	3rd floor, north-west room					
BUX-T01	North purlin	nm (10)	--	-----	-----	-----
BUX-T02	South purlin	40	11C	-----	-----	-----
BUX-T03	South common rafter 7 (from east)	52	12C	-----	-----	-----
	3rd floor, south-west room					
BUX-T04	North purlin	49	13C	1732	1767	1780
BUX-T05	South purlin	44	11c	1736	1768	1779
BUX-T06	South common rafter 2 (from east)	53	h/s	-----	-----	-----
	2nd floor, south-west room					
BUX-T07	West ceiling beam	58	15c	1721	1763	1778
BUX-T08	East ceiling beam	65	19C	1716	1761	1780
	2nd floor, north-west room					
BUX-T09	West ceiling beam	47	12C	1734	1768	1780
BUX-T10	East ceiling beam	50	11C	1731	1769	1780
	2nd floor, south-east room					
BUX-T11	Cut-off north principal rafter to west truss	33	h/s	-----	-----	-----

C = Complete sapwood is retained on the sample

c = complete sapwood exists on the sampled timber, but all or part lost from sample during coring

h/s = the heartwood/sapwood ring is the last ring on the sample

nm = sample not measured

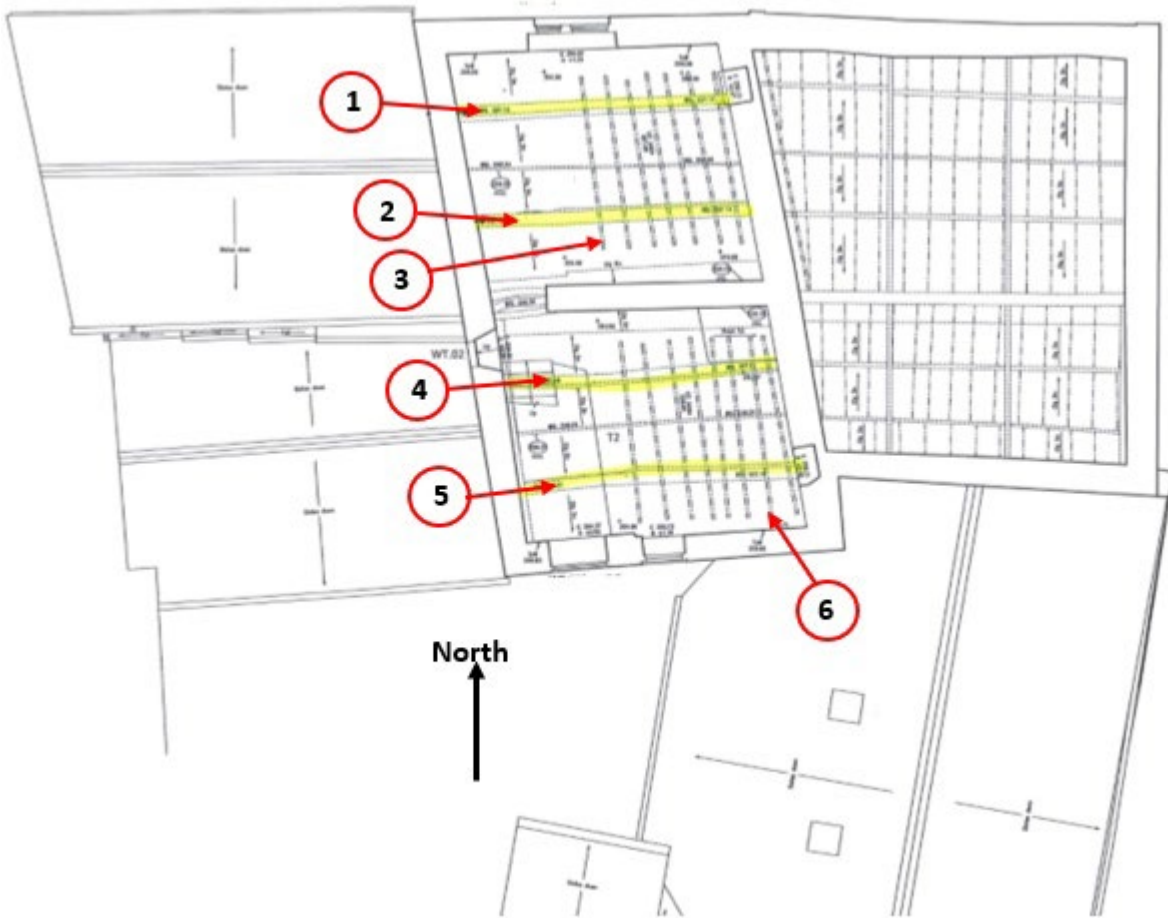


Figure 2: Plan at 3rd-floor level to help locate sampled timbers (after Bench Architects)

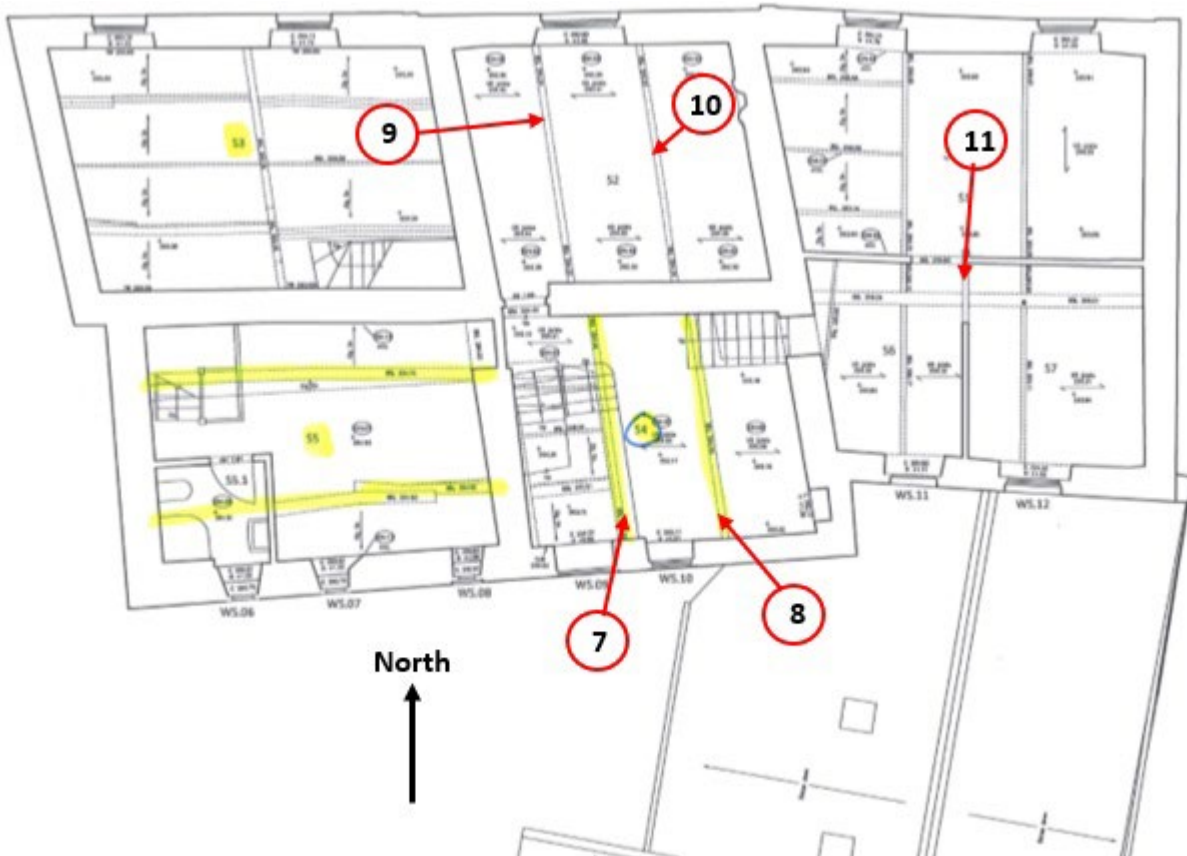


Figure 3: Plan at 2nd-floor level to help locate sampled timbers (after Bench Architects)

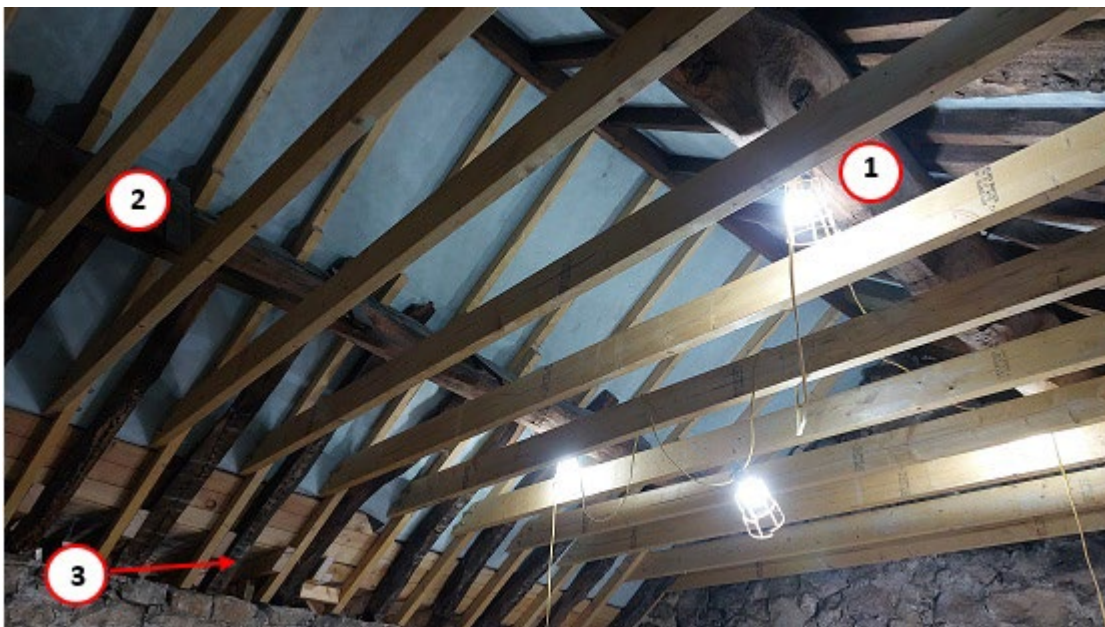


Figure 4: 3rd floor, north-west room, annotated photograph (looking south-west) to help identify sampled timbers (photograph Robert Howard)



Figure 5: 3rd floor, south-west room, annotated photograph (looking south-east) to help identify sampled timbers (photograph Robert Howard)



Figure 6: 2nd floor, south-west room, annotated photograph (looking south) to help identify sampled timbers (photograph Robert Howard)



Figure 7: 2nd floor, north-west room, annotated photograph (looking west) to help identify sampled timbers (photograph Robert Howard)

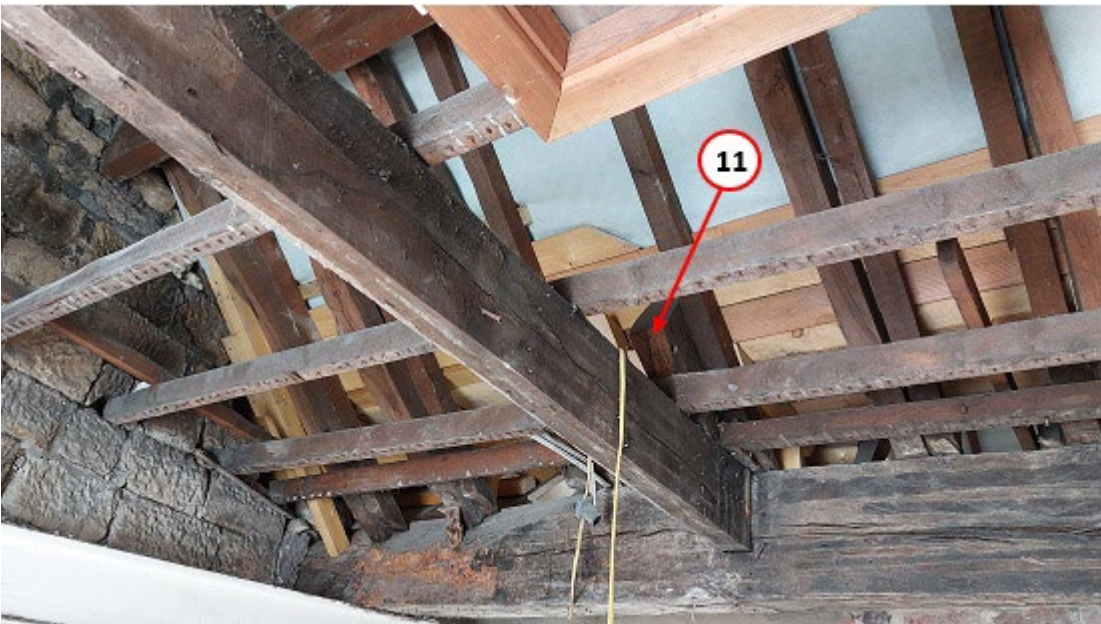


Figure 8: 2nd floor, south-east room, annotated photograph (looking north-west) to help identify sampled timbers (photograph Robert Howard)

Analysis and Results

Each of the 11 samples obtained from the timbers spread throughout this building was prepared by sanding and polishing. It was seen at this time that one sample, BUX-T01, had very low numbers of annual growth rings and it was rejected from analysis.

The annual growth rings widths of the remaining 10 samples were, however, measured, these measured data being given at the end of this report. The 10 measured series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of a single group comprising six measured samples, these combining at a minimum value of $t=5.1$, and cross-matching with each other at the positions illustrated in Figure 9. It was noted, however, that there were no same-tree matches between any of these samples.

These six samples were combined at their indicated offset positions to form BUXTSQ01, a site chronology with an overall length of 65 rings. This site chronology was then compared with an extensive range of oak reference chronologies, but no conclusive cross-dating position was identified thus these six cross-matched timbers remain undated by ring-width dendrochronology. However, some low but consistent cross-matching was noted against a number of reference chronologies when the site chronology spans AD 1716–1780 (Table 2).

Site chronology BUXTSQ01 was then compared with the four remaining measured but ungrouped samples, but there was no satisfactory cross-matching. These four measured but ungrouped samples were, therefore, compared individually with the full corpus of reference material for oak, but again there was no satisfactory cross-matching and these four samples must also remain undated by ring-width dendrochronology for the moment.

Table 2: Results of the cross-matching of site sequence BUXTSQ01 and relevant reference chronologies when the first-ring date is AD 1716 and the last-ring date is AD 1780

Reference chronology	Span of chronology	<i>t</i> -value	Reference
The Firs, 2 Church Lane, Lyddington, Rutland	AD 1625–1772	6.0	Arnold and Howard 2016 unpubl
Kirby Hall, Northamptonshire	AD 1509–1795	5.5	Arnold <i>et al</i> forthcoming
Great Bidlake, Bridstowe, Devon	AD 1681–1772	5.3	Arnold and Howard 2011
East Midlands Master Chronology	AD 882–1981	4.9	Laxton and Litton 1988
Sarehole Mill, Birmingham	AD 1677–1767	4.6	Howard <i>et al</i> 1988 unpubl
Post Mill, Kibworth Harcourt, Leicestershire	AD 1582–1773	4.5	Arnold <i>et al</i> 2004
158 Watling Street, Towcester, Northamptonshire	AD 1702–1805	4.5	Bridge and Tyers 2022
St Firmin Church, Thurlby, Lincolnshire	AD 1599–1792	4.3	Arnold and Howard 2010
Old Manor Farm, Tugby, Leicestershire	AD 1662–1784	4.3	Arnold and Howard 2015 unpubl
Worcester Cathedral Composite Chronology	AD 1484–1772	3.7	Arnold <i>et al</i> 2003 unpubl

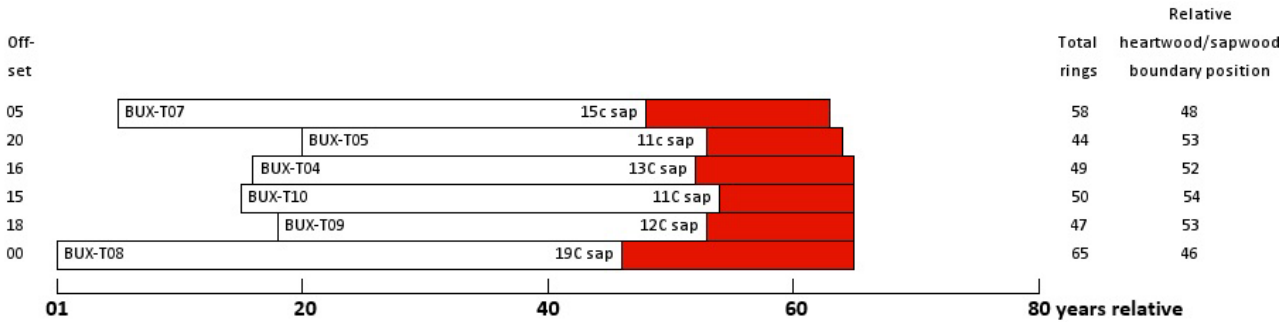


Figure 9: Bar diagram of the six samples of site chronology BUXTSQ01

Radiocarbon dating

Following the failure of the ring-width dendrochronology to provide secure calendar dating for site master chronology, BUXTSQ01, sample BUX-T08 was selected for radiocarbon dating and wiggle-matching. This core has 65 growth rings that span relative rings 1–65 of this tree-ring chronology (Fig 9).

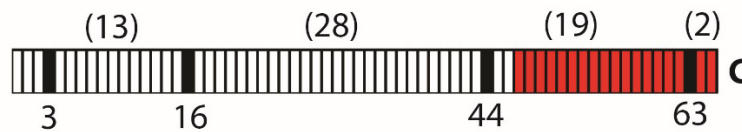
Radiocarbon dating is based on the radioactive decay of ^{14}C , which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 3, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Table 3: Radiocarbon measurements from oak sample BUX-T08

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}\text{C}$
GrM-32411	BUX-T08, ring 3 (<i>Quercus</i> sp., heartwood)	105±20	-23.92±0.15
GrM-32412	BUX-T08, ring 16 (<i>Quercus</i> sp., heartwood)	152±22	-23.40±0.15
GrM-32415	BUX-T08, ring 44 (<i>Quercus</i> sp., heartwood)	156±20	-24.82±0.15
GrM-32416	BUX-T08, ring 63 (<i>Quercus</i> sp., sapwood)	169±22	-24.81±0.15

Four radiocarbon measurements have been obtained from single annual tree-rings from timber BUX-T08 (Table 3; Fig 10). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Number of years between rings sampled for radiocarbon dating



Relative year of ring sampled for radiocarbon dating

Figure 10: Schematic illustration of BUX-T08 to locate the single ring sub-samples submitted for radiocarbon dating (C = complete sapwood)

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen (GrM-), the Netherlands in 2023. Each ring was converted to α -cellulose using an intensified aqueous pretreatment (Dee et al. 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma et al. 1996; Aerts-Bijma et al. 1997). The graphite was then pressed into aluminium cathodes and dated by Accelerator Mass Spectrometry (AMS) (Synal et al. 2007; Salehpour et al. 2016).

Data reduction was undertaken as described by Wacker et al. (2010), and the facility maintains a continual programme of quality assurance procedures (Aerts-Bijma et al. 2021), in addition to participation in international inter-comparison exercises (Scott et al. 2017; Wacker et al. 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}\text{C}$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table 3). The quoted $\delta^{13}\text{C}$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Wiggle-matching

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer et al. 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from BUX-T08, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 11 and 12.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti et al. (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (<http://c14.arch.ox.ac.uk/oxcal.html>; Bronk Ramsey et al. 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 11 and 12 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than A_n (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 11 illustrates the chronological model for BUX-T08. This model incorporates the gaps between each dated annual ring known from tree-ring counting (e.g. that the carbon in ring 3 of the measured tree-ring series (GrM-32411) was laid down 13 years before the carbon in ring 16 of the series (GrM-32412); Fig 10), with the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer et al. 2020).

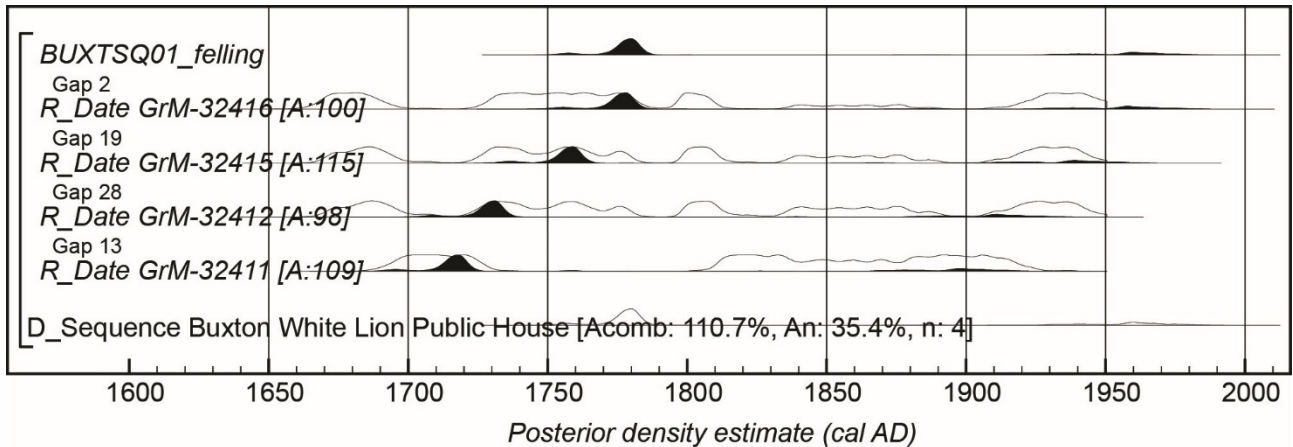


Figure 11: Probability distributions of dates from sample BUX-T08. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggles-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

The model has good overall agreement (Acomb: 110.7, An: 35.4, n: 4; Fig 11), with all radiocarbon dates having good individual agreement (A > 60). It suggests that the final ring of BUX-T08, and thus the final ring of the site master sequence, BUXTSQ01, formed in cal AD 1750–1789 (69% probability; BUXTSQ01_felling; Fig 11) or cal AD 1928–1983 (26% probability), or in cal AD 1770–1787 (59% probability) or 1956–1968 (9% probability).

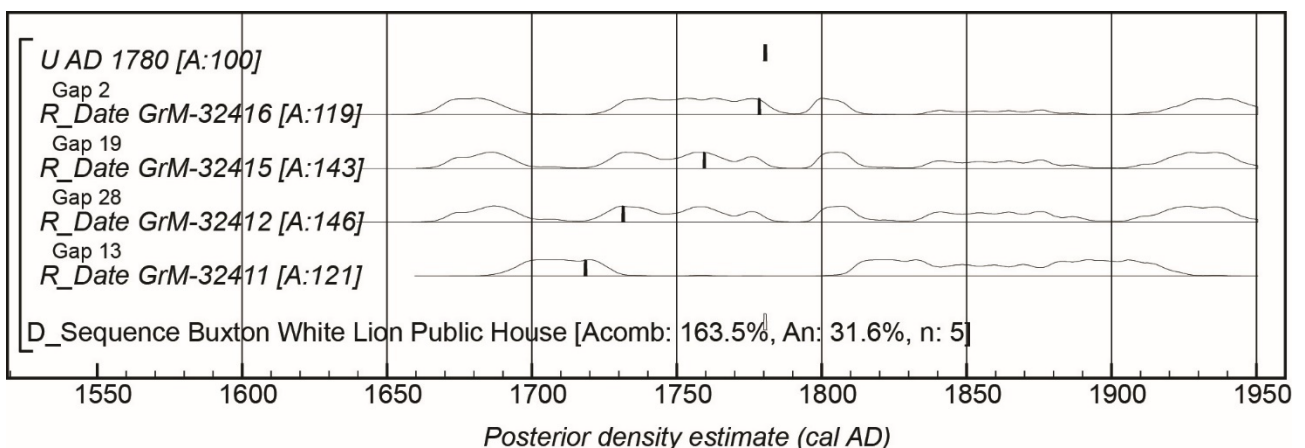


Figure 12: Probability distributions of dates from BUX-T08, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1780. The format is identical to that of Fig 11. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

When the last surviving ring of this timber is constrained to have formed in AD 1780, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 163.5, An: 31.6, n: 5; Fig 12), with all the radiocarbon dates again having good individual agreement ($A > 60$).

Discussion and Conclusion

Most of the timbers in the White Lion contained numbers of growth rings towards, or below, the lower limit for reliable dating by ring-width dendrochronology. The site master chronology formed by this method, BUXTSQ01, only provides tentative cross-matching with the existing corpus of reference chronologies (Table 2). The radiocarbon wiggle-matching, however, includes the end date for the site master chronology tentatively identified by ring-width dendrochronology (Fig 11). When the last ring of the wiggle-match sequence is constrained to be AD 1780, the model has good overall agreement (Acomb: 163.1; An: 31.6; n: 5; Fig 12), and all the individual dates have good individual agreement ($A > 60$). This allows the tentative dating provided by the ring-width dendrochronology to be considered as a radiocarbon supported dendrochronological date, with the trees represented felled in summer/autumn AD 1780_{DR}. The subscript _{DR} indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, BUXTSQ01, should not be utilised as a ring-width master sequence for dating other sites.

The building was thought to have a long history, possibly originating in the 17th century with subsequent extensions and repairs. As BUXTSQ01 contains both timbers from the roof and from the 2nd-floor ceilings, this analysis shows that much of the building seems to have been constructed of timber felled in AD 1780_{DR}. Evidence suggests that, with the exception of reused timbers, in most historical periods construction took place within a very few years of felling (Miles 2006). For this building, the samples match very well with each other suggesting they are all from the same patch of woodland. The dates thus suggest that the construction of the building was most likely in AD 1780_{DR}, or within a few years after this date. This might suggest that it was constructed for use as a carrier's inn at the end of the 18th century.

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Data of Measured Samples

Measurement in 0.01 mm unit

BUX-T02A 40

259 322 410 290 199 235 223 355 346 366 304 377 349 340 387 337 327 243 257 373
253 356 247 374 270 240 362 290 367 312 267 316 171 107 109 159 171 134 137 170

BUX-T02B 40

264 323 399 296 193 246 234 350 355 364 319 374 339 337 389 300 332 251 250 368
251 364 267 378 259 251 364 282 364 321 260 315 165 109 103 162 175 156 114 166

BUX-T03A 52

192 150 128 147 150 276 201 208 205 214 227 278 375 231 216 283 318 300 231 242
232 222 163 188 196 153 242 240 195 296 170 142 154 125 121 118 120 94 118 128
75 120 121 121 117 96 106 96 104 90 78 95

BUX-T03B 52

195 152 123 146 157 271 204 212 201 199 232 278 373 230 223 276 310 287 232 257
233 214 159 196 200 152 238 235 196 308 168 139 154 126 123 117 114 102 110 143
73 110 119 116 131 92 110 103 110 73 95 104

BUX-T04A 49

310 272 158 108 141 160 311 324 257 175 180 146 102 131 192 257 271 246 264 299
291 236 314 307 314 279 440 440 343 312 173 426 339 283 442 368 423 340 320 295
314 248 304 167 216 162 226 176 154

BUX-T04B 49

296 278 160 122 150 155 303 327 237 171 185 151 103 126 187 265 271 247 268 296
300 239 307 321 306 297 430 446 342 296 201 410 354 279 443 403 390 320 343 276
328 242 290 180 211 144 239 166 153

BUX-T05A 44

240 227 383 401 308 232 207 276 228 282 400 524 510 362 381 415 424 417 532 478
432 431 598 619 474 529 342 595 506 403 514 465 515 291 312 280 368 231 318 223
284 214 243 228

BUX-T05B 44

261 237 371 401 321 235 213 268 232 282 402 532 514 375 378 410 433 413 496 465
442 426 614 606 450 535 342 594 494 394 491 465 553 306 312 268 371 218 312 239
278 221 256 231

BUX-T06A 53

145 127 151 126 184 108 185 184 211 162 123 76 119 132 112 100 95 95 81 64
50 57 83 58 94 63 57 87 98 103 91 93 159 112 165 139 170 134 238 238
182 89 92 113 100 64 77 47 60 78 114 186 202

BUX-T06B 53

156 131 142 133 179 106 184 189 211 166 110 94 101 128 117 105 110 105 100 68
53 67 78 72 79 56 64 85 100 85 83 96 121 124 182 142 164 149 250 238
178 103 112 114 105 60 73 60 56 75 128 151 208

BUX-T07A 58

109 103 94 179 238 207 198 283 345 285 355 326 291 325 279 238 160 257 274 233
157 181 149 165 166 171 171 209 218 215 260 357 268 198 223 212 203 237 201 209
210 173 253 193 131 160 196 183 134 162 140 162 133 143 139 132 137 148

BUX-T07B 58

106 116 96 212 286 167 201 259 353 289 357 323 293 312 257 249 182 280 275 220
 146 167 144 162 147 172 192 207 202 224 300 342 271 203 198 209 211 232 215 181
 226 175 248 176 154 159 182 184 147 152 127 167 128 143 126 140 131 157

BUX-T08A 65

143 110 117 236 239 259 279 232 389 350 318 437 366 389 361 331 303 301 300 296
 274 196 258 333 208 175 173 151 167 148 139 118 137 153 121 163 162 164 128 164
 159 202 181 143 118 125 115 218 117 100 112 167 137 90 110 121 151 93 109 78
 98 101 148 66 148

BUX-T08B 65

148 108 108 213 246 282 276 228 394 350 312 451 396 414 380 305 296 303 283 291
 282 186 258 337 209 175 173 142 171 125 140 104 148 167 129 154 157 182 131 151
 147 206 177 145 115 134 109 212 114 104 125 159 139 90 117 121 143 95 110 85
 98 96 145 86 150

BUX-T09A 47

365 363 425 370 479 499 427 391 400 391 401 385 457 440 488 515 354 387 356 368
 297 259 335 234 393 314 307 364 281 410 298 231 229 268 271 261 242 187 253 259
 217 184 216 186 244 266 232

BUX-T09B 47

351 372 424 360 483 503 434 380 368 407 374 400 487 441 481 479 340 396 417 338
 295 281 330 231 407 328 295 365 275 417 296 220 215 271 276 277 257 199 257 238
 247 159 224 182 243 236 266

BUX-T10A 50

307 399 367 327 216 260 262 405 412 325 358 343 309 330 328 373 352 399 328 339
 320 304 293 321 271 278 282 375 347 307 323 278 412 242 231 278 354 315 250 262
 301 376 396 352 232 286 259 243 238 265

BUX-T10B 50

303 385 366 343 232 272 262 394 417 318 343 349 303 314 329 360 342 429 339 328
 340 305 300 314 287 281 281 387 359 301 328 265 393 248 223 289 371 331 259 234
 296 381 399 347 244 284 246 251 235 259

BUX-T11A 33

200 350 330 322 199 241 120 74 69 108 101 119 121 262 268 220 202 277 228 234
 268 176 195 196 220 282 179 160 181 143 303 297 264

BUX-T11B 33

207 375 325 318 229 249 125 68 73 117 79 120 132 254 251 217 217 271 225 226
 260 191 194 201 218 284 197 161 180 159 320 289 259

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 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



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 (i.e. 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).

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; e.g. 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 (e.g. 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 AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two-corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

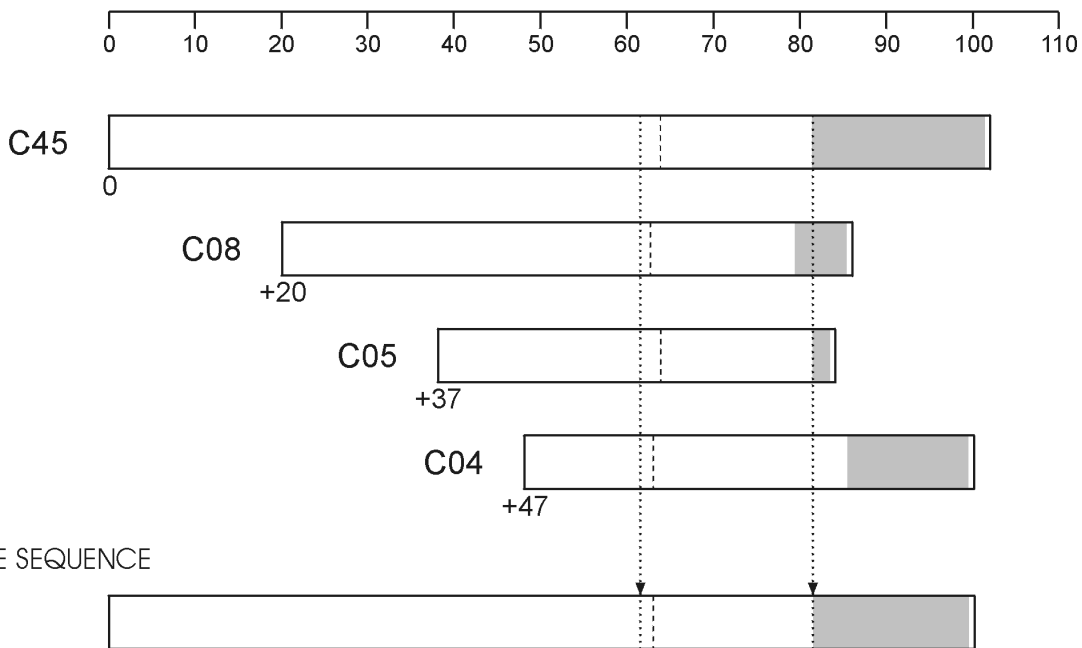


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them. The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

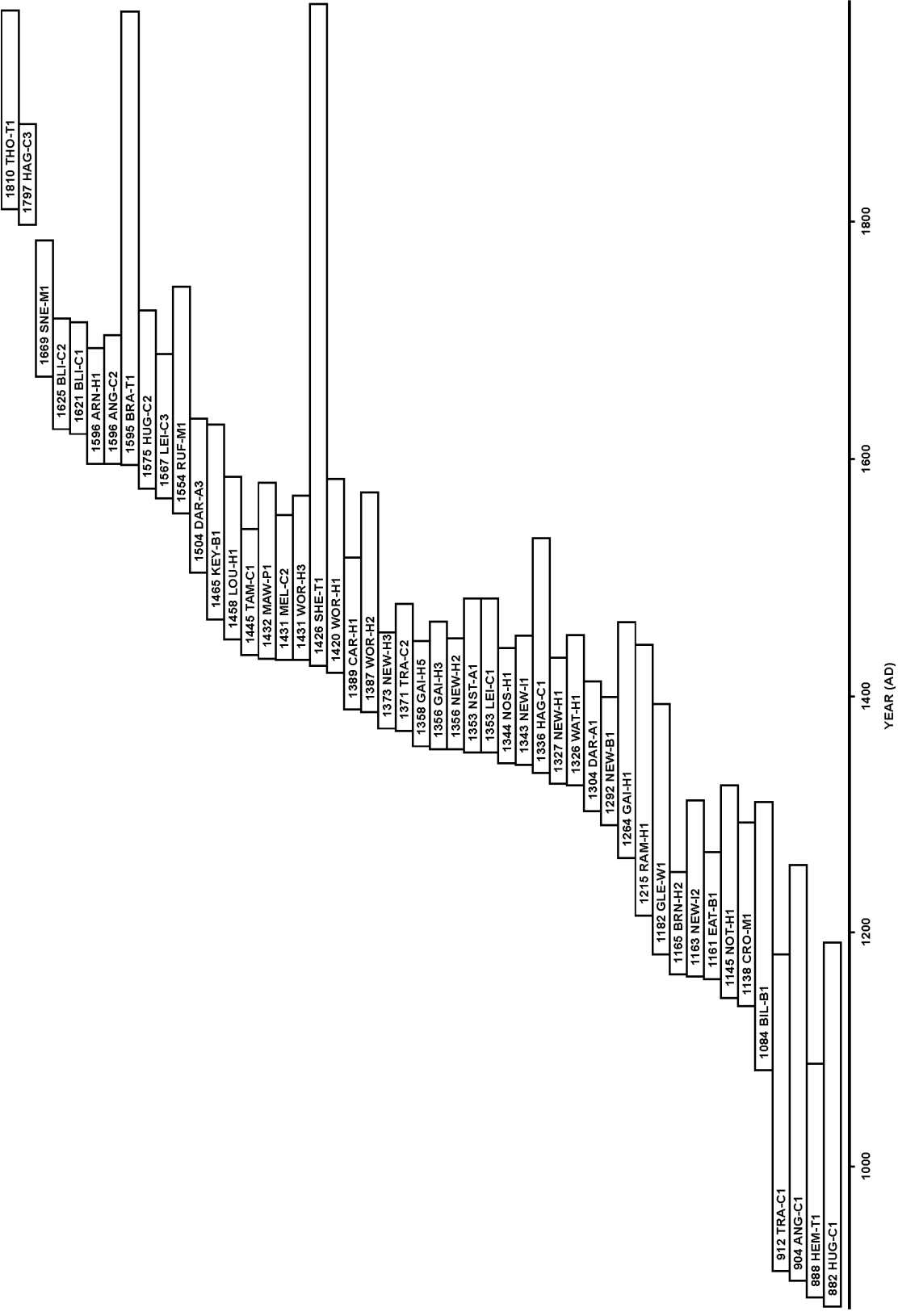
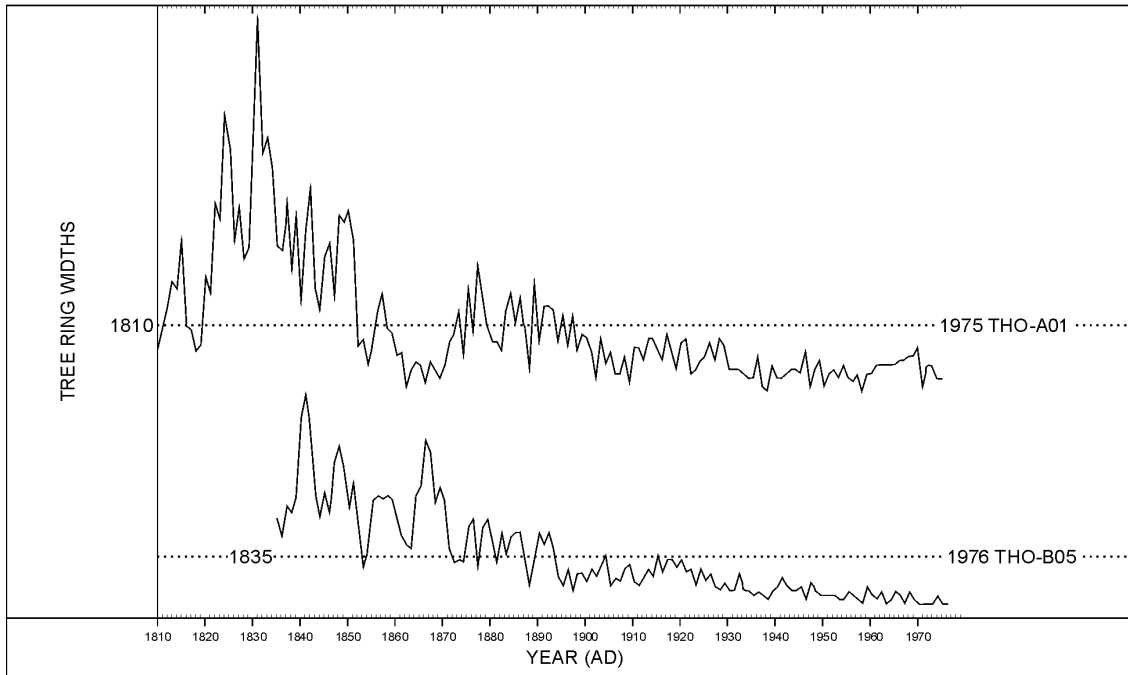


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

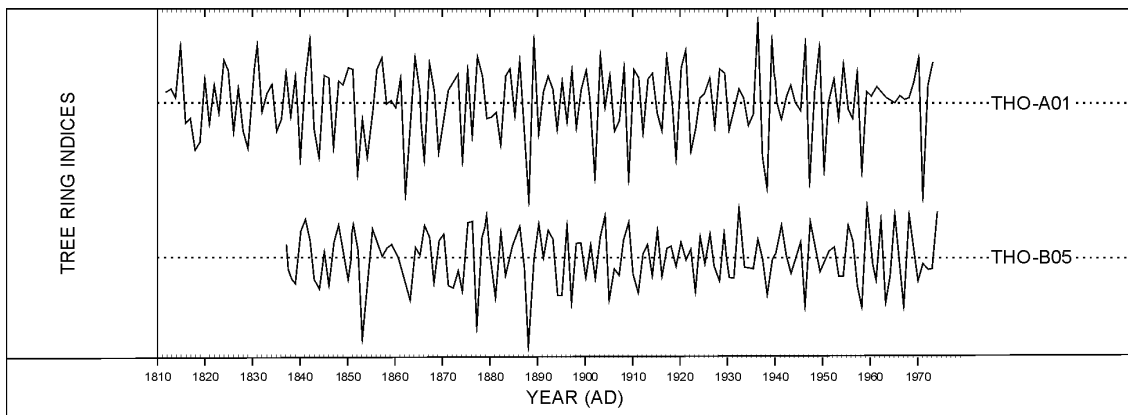


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely

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