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DRONFIELD HALL BARN, 19 HIGH STREET, DRONFIELD, DERBYSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY
Dendrochronological analysis was undertaken on 17 of the 19 core samples obtained from the main range and short, south wing of Dronfield Hall barn. This analysis produced a single dated site chronology comprising 13 samples, all of them from the main range. This site chronology has an overall length of 89 rings dated as spanning the years AD 1341–1429. Interpretation of the sapwood on the dated samples would suggest the likelihood that all the timbers used for the construction of the main range were cut as part of a single episode of felling in, or very shortly after, AD 1429.

One further measured sample from the lintel to the south door of the main range, plus three measured samples from the south wing, remain ungrouped and undated

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Nottingham Tree-ring Dating Laboratory would like to thank Professor David Hey, and other members of the local history group for the considerable help and assistance in arranging access for the assessment and sampling of the timbers, and for much of the background information given in this report's introduction. We would also like to thank Stanley Jones for further information on the history and development of the site and for the use of his plans and drawings. Finally we would like to thank Shahina Farid and Cathy Tyers (English Heritage Scientific Dating Team) for commissioning this programme of tree-ring dating.

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Derbyshire Historic Environment Record
Environmental Services Department
Shand House
Dale Road South
Matlock
Derbyshire
DE4 3RY

DATE OF INVESTIGATION
2013

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CONTENTS

INTRODUCTION

Dronfield Hall barn, a Grade II* listed building, stands to the north side of Dronfield High Street, being set back some 100 metres from the road in its own enclosed grounds (Figs 1a/b). A survey, undertaken in 1970 by historic buildings archaeologist Stanley Jones, showed that the original timber-framed building had been a four-bay, two-storey structure aligned east-west. There were two equal-sized chambers at first-floor level, each chamber open to the ridge and spanned centrally by an arch-braced tiebeam truss. It was postulated, on the basis of the characteristics of the remaining framing, that this building might date to the first half of the fifteenth century. This main range may once have had a coeval range attached centrally, to its south wall (Fig 2).

The 1970 survey also showed that the timber-framed building had a south-facing elevation that differed markedly from that to the north: the north elevation presenting a sparsely timbered face of vertical studs, while the south elevation was distinguished by its use of deep curved braces. The framing to the south side, however, appears to have been interrupted which could imply that a masking structure was intended; one possibility being an external staircase. This staircase would have given access to the two first-floor chambers which appear to have been divided from each other by an internal partition.

Internally the building now retains four king-post roof trusses, there being curved braces between the king-posts and the ridge plate as well as between the single remaining south-wall post of truss 1 and the tiebeam, and from this wall post to the wall plate. The trusses carry a single purlin to each pitch of the roof (Figs 3a/b).

At some point the building was converted from domestic to agricultural use when the possible external stair tower may have been removed, and a further bay added to its west end. The timber-framed walls were mostly removed and replaced by coursed, squared, rubble walling and the requisite opposed large-wagon doors installed. It is believed that as part of these alterations a short wing was added to the east end of the south-side: this being built to accommodate stables with storage for fodder overhead. Particularly interesting in this wing is a tiebeam which may once have topped a coved canopy above the dais of an open hall, which is suggested by evidence for the curved ribs of the canopy in the form of sloping mortises.

Since the 1970 survey, Professor David Hey, Emeritus Professor of Local and Family History at the University of Sheffield and a patron of The Dronfield Heritage Trust, has unearthed considerable documentary evidence for the history of Dronfield and how this barn may relate to its remaining historic buildings, of which there are a number (Tyers 2003, Arnold and Howard forthcoming). One such document allows speculation that what is now Dronfield Hall barn may have been originally built by one Alice Deincourt.

SAMPLING

A programme of dendrochronology sampling and analysis of the timbers to the main range and short south wing of Dronfield Hall barn was requested by Bob Hawkins, English Heritage Designation Advisor, to provide more accurate and reliable independent dating evidence for the original structure of the building and the date of any reused timbers, or any timbers subsequently inserted. It was hoped that this information would inform plans to repair and conserve the building as part of the locally established Dronfield Heritage Project.

Thus from the timbers available a total of 19 samples was obtained by coring. Each sample was given the code DRN-D (for Dronfield, site 'D') and numbered 01–19 (Table 1). Thirteen samples, DRN-D01–D13, were obtained from the roof and single remaining apparently primary wall timbers of the main range, with a further five samples, DRN-D14–D18, being obtained from the roof and two ground-floor ceiling beams of the south cross-wing; these timbers believed to represent a later alteration phase. A final sample, DRN-D19, was obtained from the lintel to the south cart door to the barn, this timber also being part of the later alterations

Where possible, the locations of these samples were recorded at the time of sampling, either on a drawing made by Stanley Jones, or on photographs or simple schematic sketch plans, these being shown as Figures 4a-d. Details of the samples are given in Table 1. In this table, as in the drawings, the trusses of the barn have been numbered from east to west, with individual timbers then being further identified on a north-south basis as appropriate.

ANALYSIS AND RESULTS

Each of the 19 samples obtained from the two parts of the barn was prepared by sanding and polishing. It was at this stage that two samples were rejected, both from the south wing, as having too few rings for reliable dating. The annual growth ring-widths of the remaining 17 samples were measured, the data of these measurements being given at the end of this report. The data of the 17 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing a single group comprising 13 cross-matching samples to be formed into site chronology DRNDSQ01. The 13 samples combined at their indicated offset positions are shown in Figure 5, producing a sequence with an overall length of 89 rings.

Site chronology DRNDSQ01 was then compared to an extensive corpus of reference material for oak, indicating a consistent and repeated match with a number of these when the date of its first ring is AD 1341 and the date of its last measured ring is AD 1429. The evidence for this dating is given in Table 2.

Site chronology DRNDSQ01 was also compared to the four remaining measured but ungrouped samples, but there was no further satisfactory cross-matching. These four ungrouped samples were then compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and these samples must, therefore, remain undated.

INTERPRETATION AND CONCLUSION

Analysis by dendrochronology of the timbers of Dronfield Hall barn has produced a single dated site chronology comprising 13 of the 17 samples measured. The 89 rings dated span the years AD 1341–1429 and all dated samples are from the main range.

Main range

As may be seen from Table 1 and Figure 5, four of the dated samples retain complete sapwood, the last ring produced by the tree before it was cut down. In each case this last growth ring, and thus the felling date of the trees from which the timbers derive, is identical at AD 1429. The other nine dated samples in the site chronology retain some sapwood or at least the heartwood/sapwood boundary. The relative position and date of this boundary, and the amount of sapwood the samples retain, is such that it is likely that all these other samples also represent timbers which were felled in, or around, AD 1429. All dated samples, therefore, appear to represent timbers cut as part of a single episode of felling specifically for the construction of the main range of the barn which would have taken place shortly thereafter.

The overall cross-matching between the 13 samples in the dated site chronology suggests that each timber was probably derived from a single, albeit potentially extensive, woodland source. Furthermore, although compared with reference data for all parts of England, the highest levels of similarity between the site chronology and the reference chronologies are found predominantly with sites in Derbyshire and the surrounding counties suggesting that the timbers used in the construction of the main range of Dronfield Hall barn are from relatively local woodland.

Of further note in respect of this programme of analysis are the relatively low numbers of sapwood rings found on some of the samples from the main range. As will be seen from Table 1, sample DRN-D05 has 15 sapwood rings (the lower limit of the usual 95% confidence interval of 15–40 sapwood rings), while samples DRN-D09 and D04 have fewer at 14 and 13 sapwood rings respectively. Given that it has a heartwood/sapwood boundary date of AD 1417, and working on the assumption it was also felled in AD 1429, the timber represented by sample DRN-D10 would have had only 12 sapwood rings. The highest number of sapwood rings, 28, would be found on sample DRN-D02, this figure also based on the belief that the timber was felled in AD 1429. As such, these numbers of sapwood rings might be considered a little low, and, without the presence of complete sapwood on some of the samples, would have given an estimated felling date range of 1429–54, a range which just includes the actual felling date, but which could have been taken to suggest a potentially later felling date.

South wing

None of the five samples from the timbers of the south wing have dated. Two of these samples, from the king post and a principal rafter, although relatively large timbers, had too few rings for reliable dating, while a third sample, from the dias beam, had a very low number of rings. All such timbers are from the roof. Two other south-wing timbers, both ground-floor ceiling beams, did have higher numbers of rings, but still remain undated. There is some structural indication that these two timbers may have been inserted later, either together as a pair or at different times, thus possibly making them 'singletons'. While such timbers can occasionally be dated, it is usually much more difficult than with well replicated groups of samples. It is possible that these timbers are from trees grown in locations, and/or at times, for which there is, as yet, insufficient local reference material available for cross-matching and dating.

Door lintel

Likewise, the lintel to the south doorway of the main range is believed to be a later insertion, and this too may represent an isolated timber of a different date and from a different source. It too, at least for the moment, is undated.

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TABLES

Table 1: Details of tree-ring samples from the Dronfield Hall Barn, Dronfield, Derbyshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Main range					
DRN-D01	North principal rafter 1, truss 1	54	h/s	1367	1420	1420
DRN-D02	South main wall post, truss 1	60	25	1367	1401	1426
DRN-D03	Brace, south main wall post to tiebeam, truss 1	55	17C	1375	1412	1429
DRN-D04	South wall plate, truss 1-2	76	13C	1354	1416	1429
DRN-D05	Tiebeam, truss 2	79	15C	1351	1414	1429
DRN-D06	North principal rafter, truss 2	68	h/s	1346	1413	1413
DRN-D07	South principal rafter, truss 2	65	h/s	1354	1418	1418
DRN-D08	Tiebeam, truss 3	60	h/s	1364	1423	1423
DRN-D09	Tiebeam, truss 4	67	14C	1363	1415	1429
DRN-D10	King post truss 4	60	10	1368	1417	1427
DRN-D11	South principal rafter, truss 4	73	h/s	1348	1420	1420
DRN-D12	South common rafter 1, bay 4	66	h/s	1341	1406	1406
DRN-D13	South common rafter 2, bay 4	64	h/s	1243	1406	1406
	South wing					
DRN-D14	Dias beam, truss 5	44	h/s	------	------	------
DRN-D15	King post, truss 5	nm	---	------	------	------
DRN-D16	West principal rafter, truss 5	nm	---	------	------	------
DRN-D17	Ground-floor ceiling beam 1 (north beam)	125	22C	------	------	------
DRN-D18	Ground-floor ceiling beam 2 (south beam)	101	14	------	------	------
	Main range					
DRN-D19	South doorway lintel	60	2	------	------	------

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

Table 2: Results of the cross-matching of site sequence DRNDSQ01 and relevant reference chronologies when the first-ring date is AD 1341 and the last-ring date is AD 1429

Reference chronology	Span of chronology	*t*-value	Reference
7–12 Church Street, Dronfield, Derbyshire	AD 1313–1526	10.5	(Arnold and Howard forthcoming)
Manor House, West Bromwich, West Midlands	AD 1318–1590	10.2	(Arnold and Howard 2009)
Sinai Park, Burton upon Trent, Staffordshire	AD 1227–1750	10.2	(Tyers 1997)
Lea Road Foundry Site, Church Street, Dronfield, Derbyshire	AD 1344–1526	10.2	(Tyers 2003)
Primrose Hill, Kings Norton, Birmingham	AD 1354–1593	10.0	(Arnold and Howard 2008)
All Hallows Church, Kirkburton, West Yorkshire	AD 1306–1633	8.5	(Arnold and Howard 2007)
East Midlands Master Chronology	AD 882–1981	8.2	(Laxton and Litton 1988)
Anne Hathaway's Cottage, Stratford upon Avon, Warwickshire	AD 1319–1462	8.0	(Alcock *et al* 1991)

FIGURES

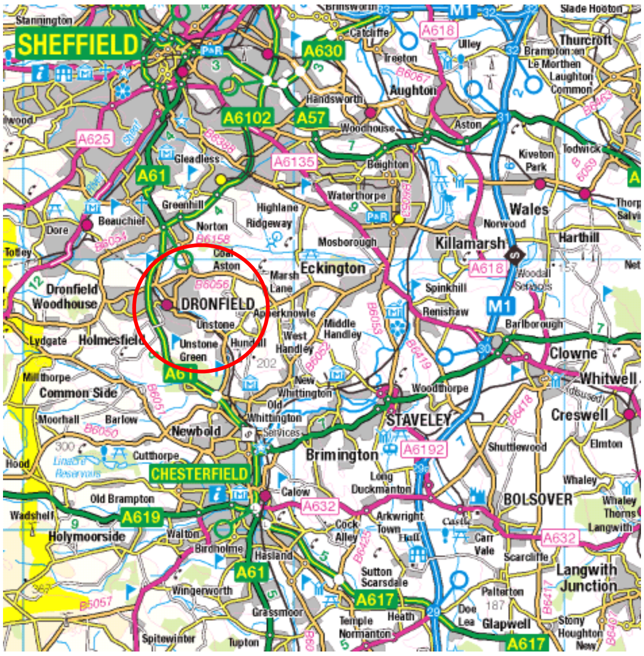


Figure 1a: Map to show the location of Dronfield (circled). © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 1b: Map to show the location of Dronfield Hall barn (circled). © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

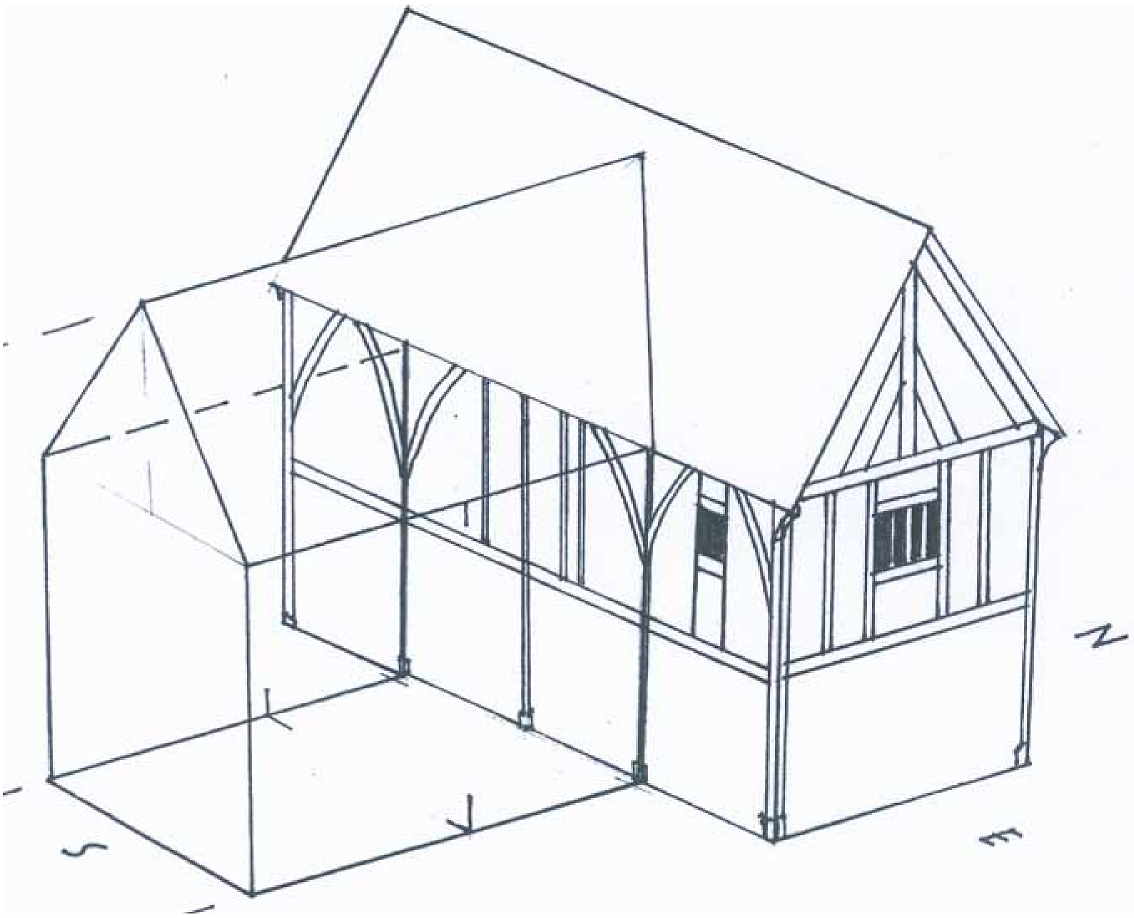


Figure 2: Suggested arrangement of the main range and the probably coeval range set centrally to the south (after Stanley Jones)

Figure 3a/b: Views of the barn looking east to west (top) and from truss 1 into present short south wing (bottom) (Robert Howard)

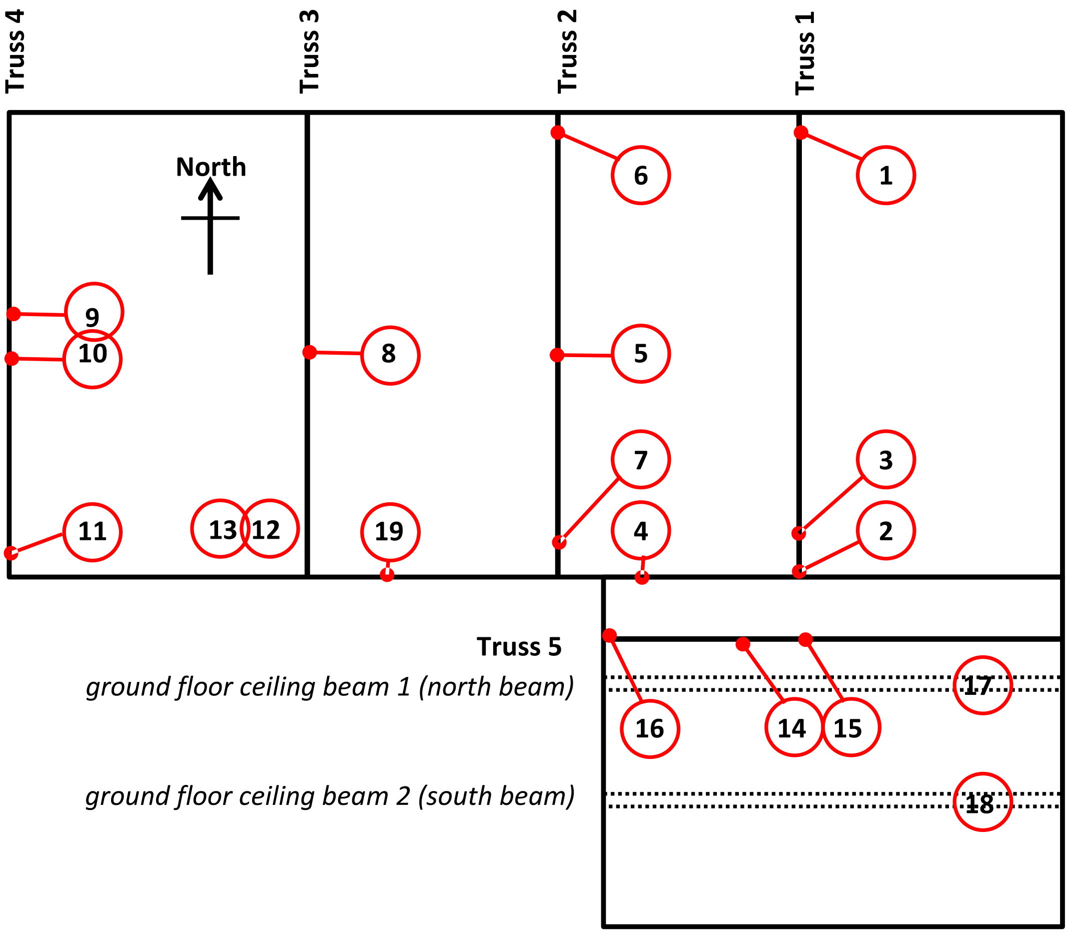


Figure 4a: Simple schematic sketch plan to locate sampled timbers

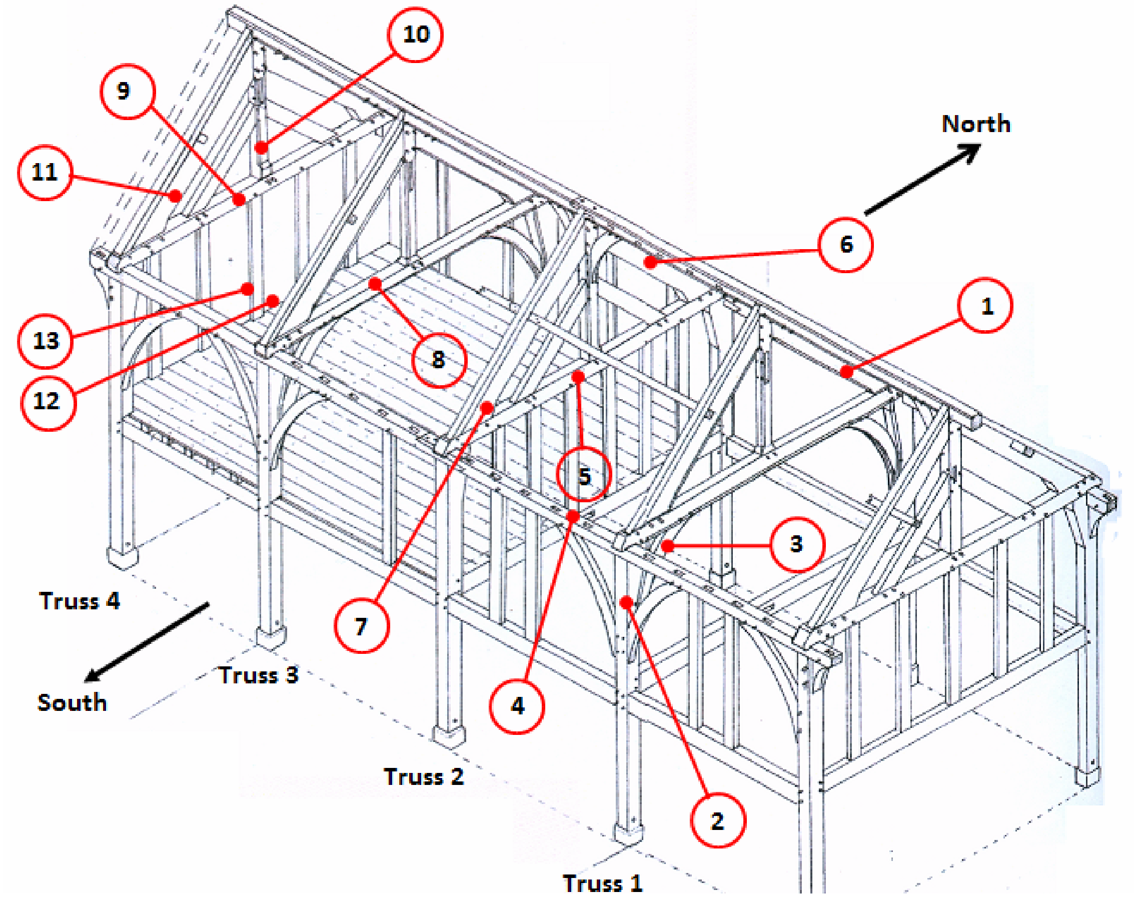


Figure 4b: Drawing of the main range of the barn to locate the sampled timbers (based on a part reconstruction by Stanley Jones)

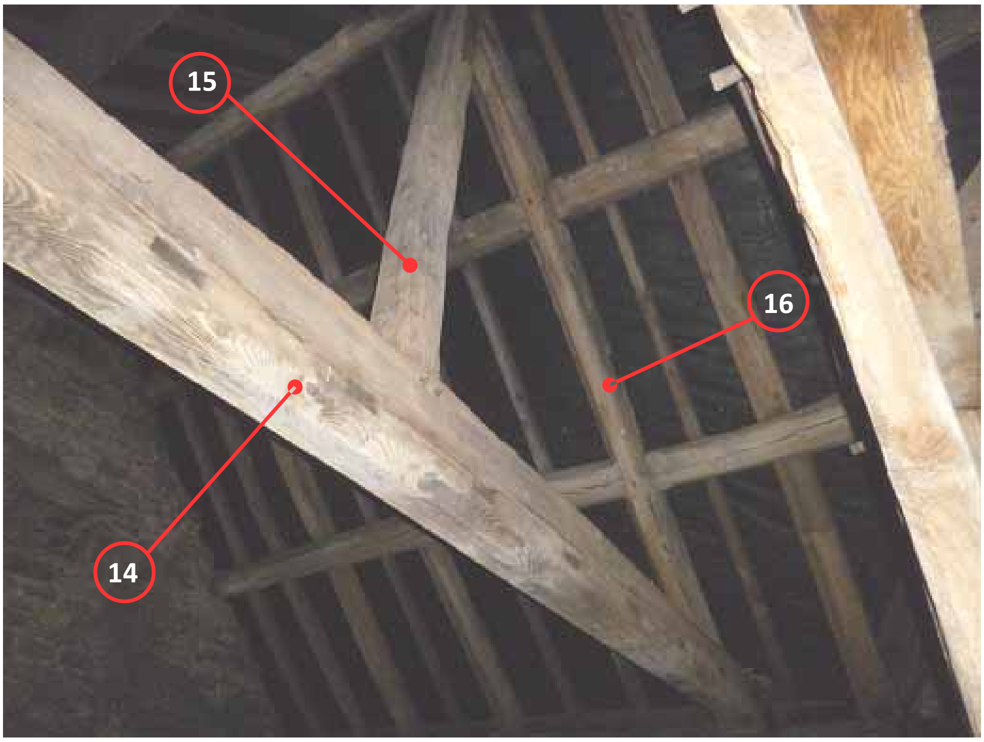
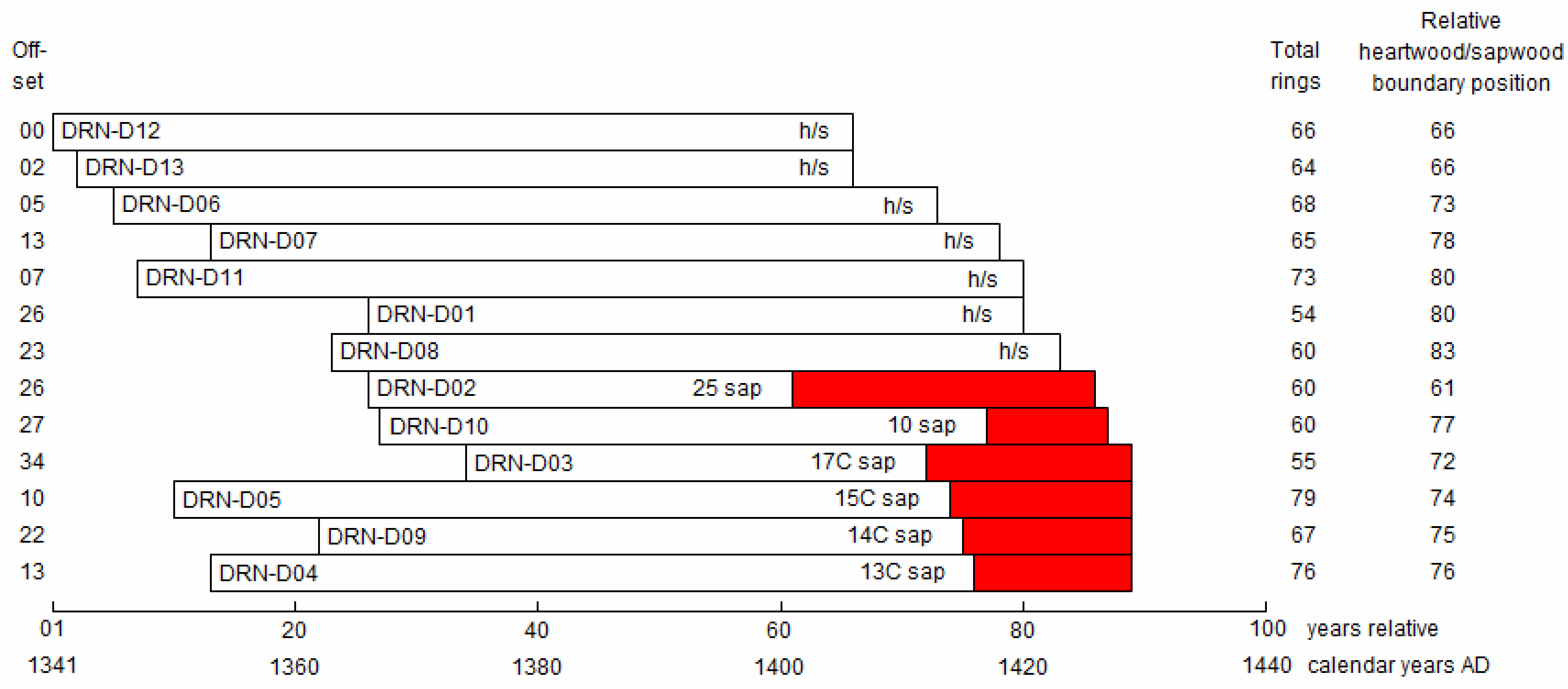


Figure 4c/d: Views of truss 5 (top) and the exterior of the barn (bottom) to locate sampled timbers (Robert Howard)



White bars = heartwood rings, red bars = sapwood rings; h/s = heartwood/sapwood boundary; C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree represented

Figure 5: Bar diagram of the samples in site chronology DRNDSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

DRN-D01A 54
168 167 426 394 184 334 284 223 147 173 209 310 250 147 142 205 112 159 111 192
171 148 247 139 254 189 275 199 289 322 306 362 235 292 315 210 235 178 161 211
154 168 184 150 148 193 160 151 156 140 167 190 129 218
DRN-D01B 54
195 171 430 384 191 352 277 225 150 176 215 280 252 155 145 200 110 161 120 178
170 170 247 164 258 185 257 196 288 315 317 350 245 315 257 229 233 178 160 202
145 171 201 145 146 203 161 150 143 132 179 204 117 180
DRN-D02A 60
340 368 391 375 305 409 301 403 295 339 451 300 306 276 239 276 278 258 300 269
302 196 209 196 231 162 213 258 236 163 150 159 250 275 200 168 231 175 190 186
196 188 281 171 228 221 225 181 246 218 185 127 162 264 260 182 203 153 143 209
DRN-D02B 60
337 348 414 379 302 414 302 403 290 351 457 300 312 285 245 290 278 251 290 297
313 197 212 196 228 165 210 256 237 181 142 160 246 262 202 168 238 184 190 187
143 228 261 156 243 235 218 178 256 218 168 111 153 265 287 205 208 171 121 199
DRN-D03A 55
136 119 136 149 179 188 193 230 240 229 239 341 450 363 290 289 496 291 396 268
306 414 283 250 214 303 227 225 303 255 220 181 125 208 262 181 208 258 232 167
171 147 158 151 134 278 212 173 207 132 181 137 92 130 145
DRN-D03B 55
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294 422 282 240 221 293 226 228 305 259 212 187 146 217 228 202 206 239 207 178
196 132 160 154 134 295 215 168 215 131 182 125 104 118 142
DRN-D04A 76
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351 323 326 337 264 266 269 264 250 246 267 264 325 345 267 214 207 192 200 268
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122 134 179 170 196 122 203 170 185 236 140 140 104 167 143 149
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356 323 325 292 260 278 277 278 259 251 264 243 323 325 268 215 187 187 200 266
194 218 256 259 231 217 250 224 198 225 196 173 142 137 200 223 184 140 192 113
121 137 181 178 191 128 209 179 184 230 160 141 105 128 131 137
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286 301 300 337 221 259 307 320 286 199 206 214 201 306 246 297 340 235 256 206
254 223 235 195 214 229 189 198 193 256 185 182 175 162 165 171 141 170 172 152
118 113 103 84 95 81 109 103 77 90 121 102 100 112 127 100 113 112 126
DRN-D05B 79
204 152 203 299 302 351 283 431 468 280 294 453 349 357 314 368 286 250 344 305
299 304 306 335 228 267 325 308 273 217 193 229 200 306 257 289 335 243 250 206
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113 121 108 79 90 92 104 103 71 96 109 107 98 111 125 109 113 118 121
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268 227 319 359 310 262 320 330 250 153 171 189 266 232 162 242 252 222 239 192
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360 356 276 231 156 190 153 189 210 155 220 164 131 156 251 177 229 217 328 220
243 176 270 298 204 163 189 197
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395 423 354 336 477 425 276 273 301 296 346 301 318 283 382 378 260 306 346 337
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469 413 365 359 480 421 273 271 306 309 330 307 310 282 377 377 242 297 348 352
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91 149 81 58 87
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301 308 337 331 398 443 439 326 346 357 386 210 279 368 368 323 275 273 254 192
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303 294 336 333 403 453 444 325 353 359 412 200 289 360 368 329 262 272 263 182
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259 280 328 322 268 316 312 158 118 187 262 238 121 87 201 241 200 209 158 155
164
DRN-D18B 101

129 210 216 316 493 433 312 321 348 345 370 409 343 389 236 298 305 270 257 235
175 135 211 181 162 185 145 141 142 113 140 95 93 87 140 209 89 81 76 50
53 90 70 60 67 67 73 66 61 90 84 93 160 215 170 173 149 95 115 143
123 157 162 150 84 117 107 156 190 268 286 264 251 237 294 324 272 259 264 274
256 269 337 325 268 309 321 155 121 188 264 284 85 92 189 240 202 173 173 165
205
DRN-D19A 60
281 263 316 349 233 284 396 263 286 341 367 313 303 232 221 292 210 185 178 196
215 205 214 182 211 192 190 225 279 373 360 240 211 204 207 265 202 237 234 157
204 329 358 473 368 342 321 317 228 271 195 240 275 299 228 331 275 283 326 245
DRN-D19B 60
377 234 310 368 217 295 319 328 291 353 384 293 300 228 228 280 180 196 167 187
213 199 211 166 201 198 192 229 287 372 337 237 218 178 203 244 178 243 203 175
214 332 368 459 353 303 267 323 244 278 193 262 289 266 242 310 275 233 319 318

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 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

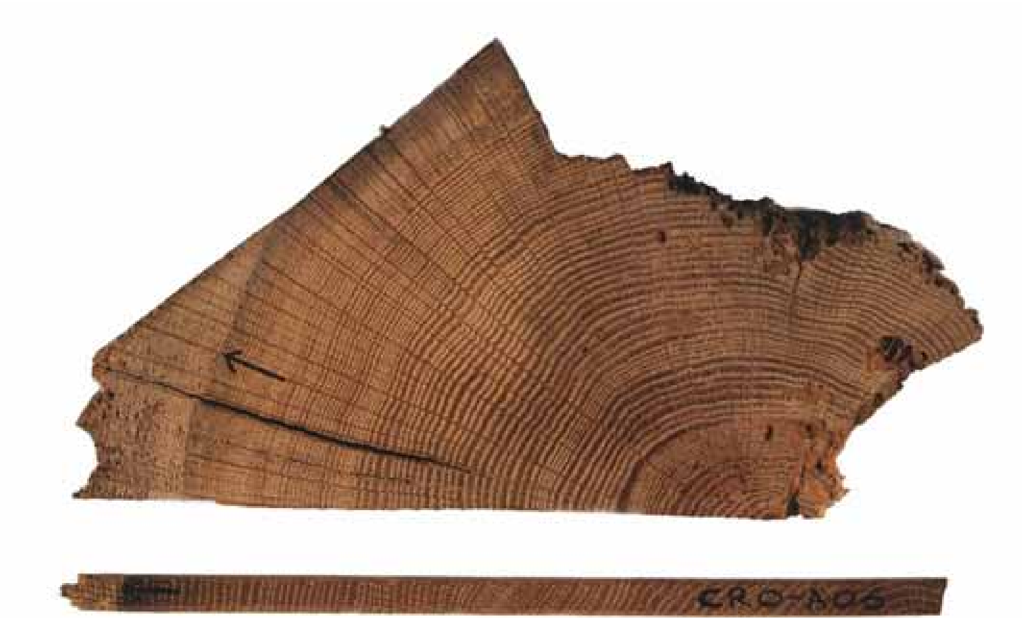


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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. As m There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

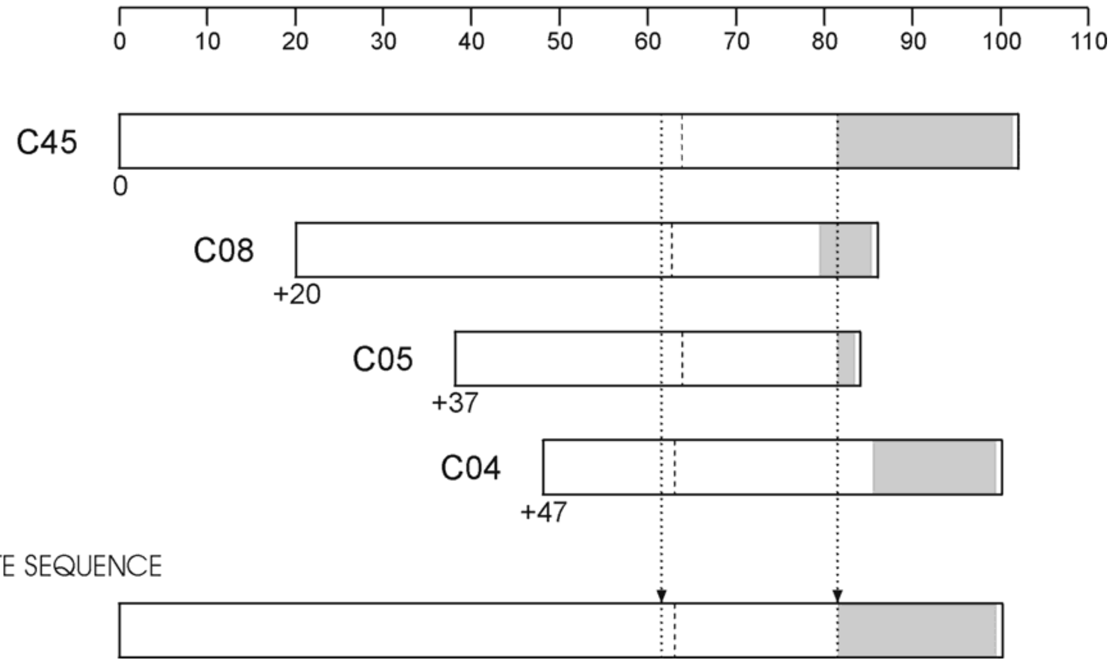


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

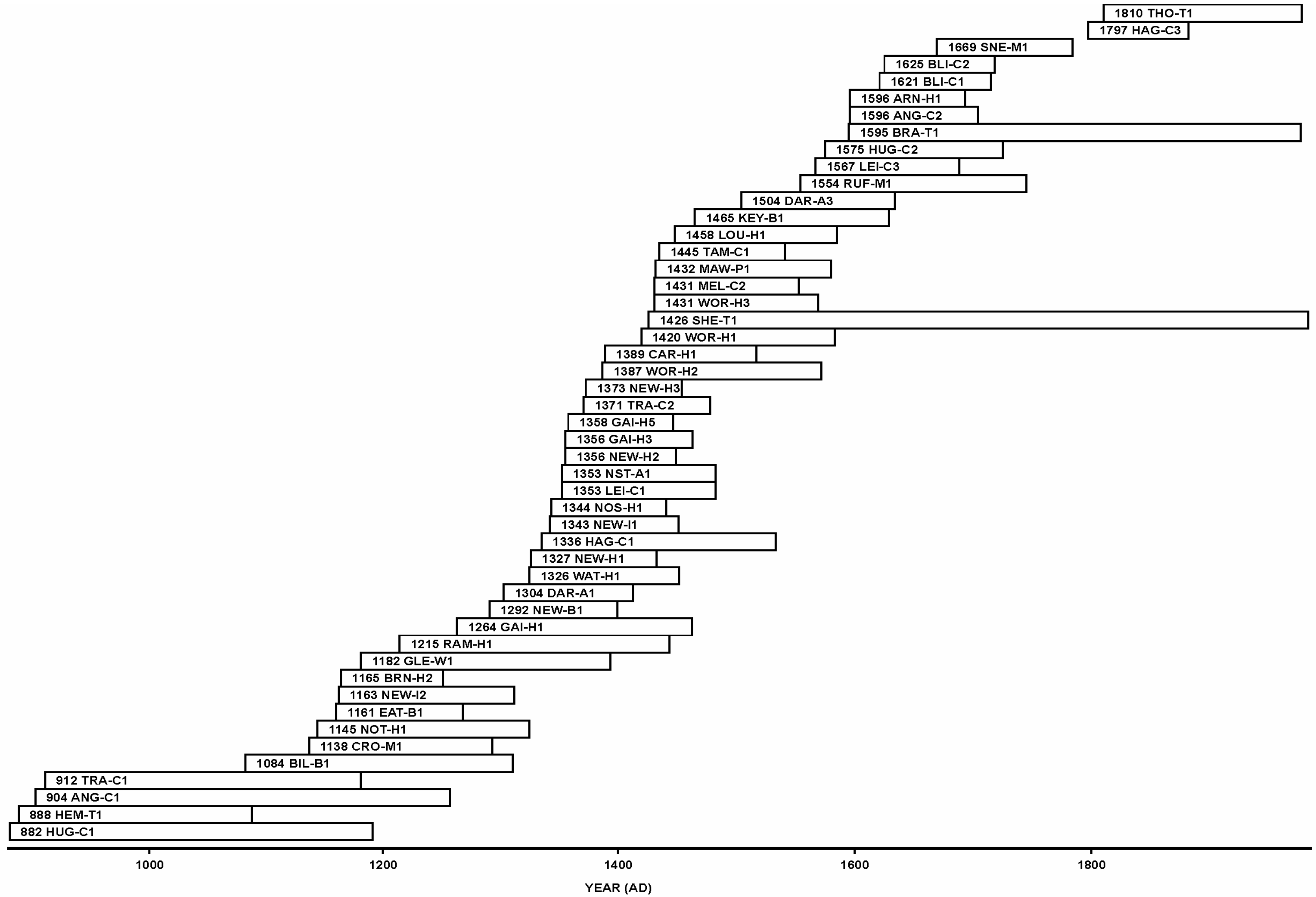
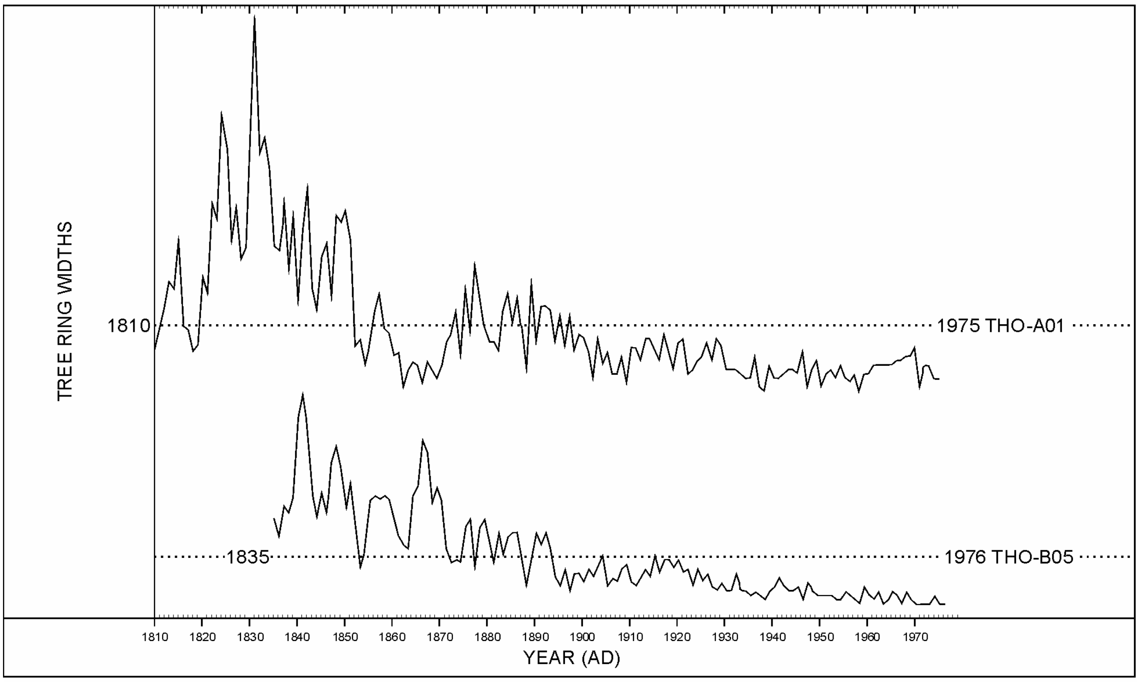


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

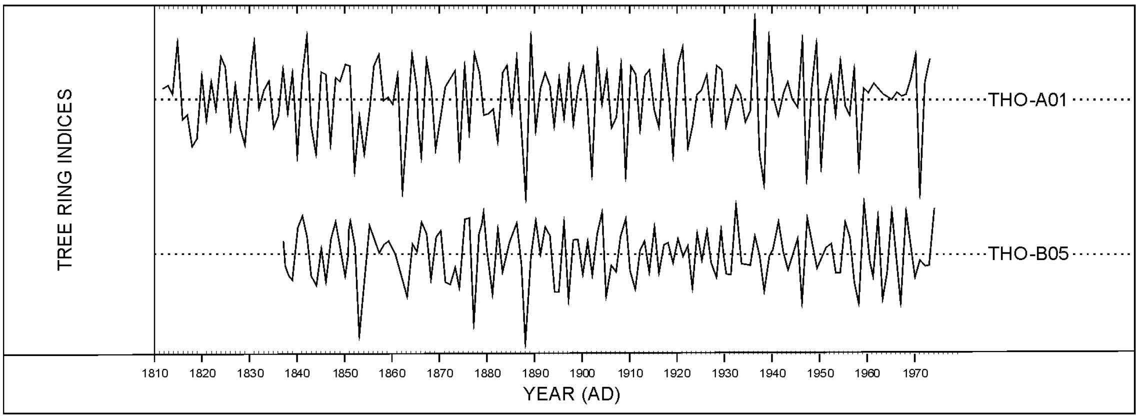


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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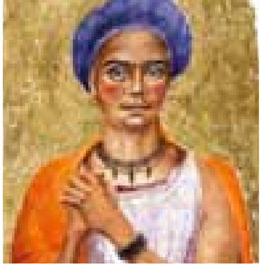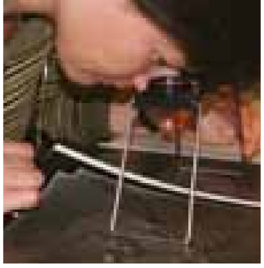

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