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CASTLE COTTAGE, LOCKERIDGE, WILTSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Matt Hurford, Robert Howard and Cathy Tyers

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SUMMARY

Dendrochronological analysis was undertaken on four of the 10 samples taken from Castle Cottage. The ring sequences from these samples failed to match each other and they could not be dated individually against the reference data. The timbers therefore remain undated and hence no independent dating evidence was provided for the initial construction of this building.

CONTRIBUTORS

Matt Hurford, Robert Howard and Cathy Tyers

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ARCHIVE LOCATION

Wiltshire Archaeological Service
The Wiltshire and Swindon History Centre
Cocklebury Road
Chippenham
SN15 3QN

DATE OF INVESTIGATION

2009–10

CONTACT DETAILS

Matt Hurford and Cathy Tyers
Dendrochronology Laboratory
Graduate School of Archaeology
University of Sheffield
West Court, 2 Mappin Street
Sheffield S1 4DT
Tel: 0114 276 3146
Email: m.hurford@sheffield.ac.uk, c.m.tyers@sheffield.ac.uk

Robert Howard
Nottingham Tree-Ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
Tel: 0115 9603833
Email: roberthoward@tree-ringdating.co.uk

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INTRODUCTION

In 2009 the Wiltshire Buildings Record successfully obtained support through the English Heritage Historic Environment Enabling Programme for their project 'Wiltshire cruck buildings and other archaic roof types'. The detailed aims and objectives of the project are set out in the Project Design (Lloyd 2009). The overall aim is to establish a typological chronology of archaic roof types and hence elucidate the development of carpentry techniques in the county. This will then facilitate detailed comparison with other counties, allowing Wiltshire to be placed in a regional context. Investigation of these late medieval buildings (*c* AD 1200 – *c* AD 1550) will combine building survey, historical research, and dendrochronological analysis.

A series of buildings identified by the Wiltshire Buildings Record as having the potential to contribute to the aims and objectives of the project was assessed for dendrochronological suitability during 2009. In order to maximise the potential, these detailed dendrochronological assessments and the WBR's assessments of the significance of the buildings within the project informed the selection of the buildings subsequently subjected to detailed study.

A single final report produced by the Wiltshire Building Record (forthcoming a) will summarise the overall results from the project. However, each building included in the project will have an associated individual report produced by the WBR (forthcoming b), whilst the primary archive of the dendrochronological analysis is the English Heritage Research Department Report Series.

A brief introduction to dendrochronology can be found in the Appendix. Further details can be found in the guidelines published by English Heritage (1998) which are also available on the English Heritage website (http://www.english-heritage.org.uk/publications/dendrochronology-guidelines/).

Castle Cottage

Castle Cottage is a Grade II listed building located at the east end of the village of Lockeridge, Wiltshire (SU14846799; Figs 1–3). The earliest phase of the building, comprising a timber-framed open hall and parlour (Fig 4), is thought to date to the late-fifteenth century. During the seventeenth century the outer timber-framed walls were converted to sarsen stone. Possibly at the same time the building was extended to the south by the addition of the north-south range and the chimney stack inserted in the east end of the open hall. The open hall may also have been floored at this time. Further modifications occurred during the nineteenth and twentieth centuries including, in the late twentieth century, a kitchen being added to the south-east of the north-south range (Fig 4).

The focus of this investigation is on the remaining elements of the late medieval open-hall house, basic details of which are given below, based on notes made during the dendrochronological sampling and on information derived from the Wiltshire Buildings Record report (forthcoming b) on Castle Cottage.

Truss B, originally with the small open hall to the east and the parlour to the west, comprises two cruck blades and a collar (Fig 5) which, unusually for Wiltshire, protrudes beyond the cruck blades to support the roof structure above. The south cruck blade has an empty mortice hole, perhaps for a through purlin, that is absent in the north blade, indicating that at least one cruck blade is either a reused or replacement timber. Both cruck blades have been truncated shortly above the floor of the attic. The collar has ten pegs in the soffit and a single empty mortice at the centre of the soffit, indicating that the truss was formerly closed. Purlins are present to the west and east of Truss B, those to the east having plain chamfers. The only visible wall plates were the north wall plate in the open hall bay and the south wall plate in parlour bay. The roof timbers visible in the attic over both bays comprise a ridge piece, supported by a yoke, carried on a pair of larger than normal common rafters to the west of truss B, and numerous common rafters and laths, all of which are smoke-blackened (Fig 6).

Embedded in the east gable wall is Truss A. It is of principal-rafter type, the southern principal clearly being a later replacement. The tiebeam and collar are both cranked, though only the tiebeam appears original. This truss is believed to be later in date than the timbers associated with the late-medieval open-hall house, but it remains a possibility that it incorporates remnants of an original truss, hence its inclusion in the investigation.

SAMPLING

Sampling and analysis by tree-ring dating of the timbers associated with the remains of the late medieval core of Castle Cottage was commissioned by English Heritage. It was hoped to provide independent dating evidence for the construction of the original medieval hall house and hence inform the overall objectives of the *Wiltshire Cruck Buildings and other archaic roof types* project. The dendrochronological study also formed part of the English-Heritage-funded training programme for the first author.

In order to address these objectives, a total of 10 timbers was sampled by coring from the extant remains of the medieval open-hall house. Each sample was given the code LRC-C (for Lockeridge, Castle Cottage) and numbered 01–10. In one instance a duplicate core was obtained from the same timber; LRC-C08A and LRC-C08B were taken in order to maximise the length of the derived ring sequence. The location of samples was noted at the time of coring and marked on the drawings provided by the Wiltshire Buildings Record, these being reproduced here as Figures 7–10. Further details relating to the samples can be found in Table 1. In this table the timbers have been located and numbered following the scheme on the drawings provided.

The sampling encompassed as wide a range of elements as possible, whilst focusing on those timbers with the best dendrochronological potential. Samples were not taken from the south principal rafter or collar of Truss A, as they were thought to be later replacements, or from the tiebeam, as it was clear that it contained too few rings for reliable analysis. The north wall plate in Bay 1 was not sampled due to access issues, whilst the south wall plate in Bay 2 was rejected as it was clearly derived from a fast-grown tree and contained too few rings for reliable analysis. The south purlin in Bay 2, and the ridge and the yoke of Truss A were excluded as they were clearly elm (*Ulmus* spp.) and hence outside the remit of this particular project, though some of the sampled timbers were also subsequently identified as elm rather than oak (*Quercus* spp).

ANALYSIS AND RESULTS

Each of the 11 samples, representing 10 timbers, obtained was prepared by sanding and polishing. It was seen at this point that the samples from two oak timbers, LRC-C06, C08A and C08B, had an insufficient number of rings for reliable dating, and so were rejected from this programme of analysis. Four other samples, LRC-C01, C03, C07 and C09, were identified as elm and hence were also rejected. The annual growth rings of the remaining four oak samples were measured, the data of these measurements being given at the end of this report. The data of these four samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix) but no groups were formed. Each individual sample was then compared to an extensive range of reference chronologies for oak but there was no satisfactory matching and thus the timbers remain undated. This analytical process was aided by the use of software written by Tyers (2004).

This analysis can be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span(where dated)
	4	---	ungrouped and undated
	6	---	unmeasured

DISCUSSION AND CONCLUSION

Unfortunately the tree-ring analysis of the timbers at Castle Cottage has been unable to establish the date of the earliest phase of the building.

Two of the four measured samples, LRC-C02 and C05, show clear disturbances to their growth patterns where growth is suddenly retarded. This, combined with the overall short length of the measured sequences, will have reduced the chances of successful cross-matching and dating. The dating of individual samples is markedly more difficult than that of longer well-replicated site chronologies, in which the general climatic signal is enhanced relative to the background 'noise' resulting from the local growth conditions of individual trees.

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Wiltshire Buildings Record forthcoming b *Castle Cottage, Lockeridge*, WBR report

TABLES

Table 1: Details of tree-ring samples from Castle Cottage, Lockeridge, Wiltshire

Sample number	Sample location	Species	Total rings	Sapwood rings	Average ring width (mm)	Cross-section dimensions (mm)	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
LRC-C01	Truss B north cruck blade	elm	nm	--	--	210x270	--	--	--
LRC-C02	Bay 1 north purlin	oak	70	24C winter	1.72	220x180+	--	--	--
LRC-C03	Truss B collar	elm	nm	--	--	130x160	--	--	--
LRC-C04	Bay 2 north purlin	oak	67	no h/s	2.07	140x240	--	--	--
LRC-C05	Truss B south cruck blade	oak	62	no h/s	1.67	100x230	--	--	--
LRC-C06	Bay 1 south purlin	oak	nm	--	--	105x220	--	--	--
LRC-C07	Bay 2 south common rafter 01	elm	nm	--	--	100x100	--	--	--
LRC-C08	Bay 2 north common rafter 01	oak	nm	--	--	150x170	--	--	--
LRC-C09	Bay 2 south common rafter 02	elm	nm	--	--	80x80	--	--	--
LRC-C10	Truss A north principal	oak	48	no h/s	2.17	???x???	--	--	--

nm = not measured

no h/s = the heartwood/sapwood ring is not present on the sample

C=complete sapwood is present on the sample; the outermost ring of LRC-C02 appears to be complete, indicating a winter felling

+=the timber was partially embedded in the wall so the complete dimension could not be measured

???=the timber was almost entirely encased and so its dimensions could not be measured

FIGURES

Figure 1: Map to show the location of the village of Lockeridge, Wiltshire (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

Figure 2: Map to show the location Castle Cottage within the village of Lockeridge (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

Figure 3: Castle Cottage, west elevation

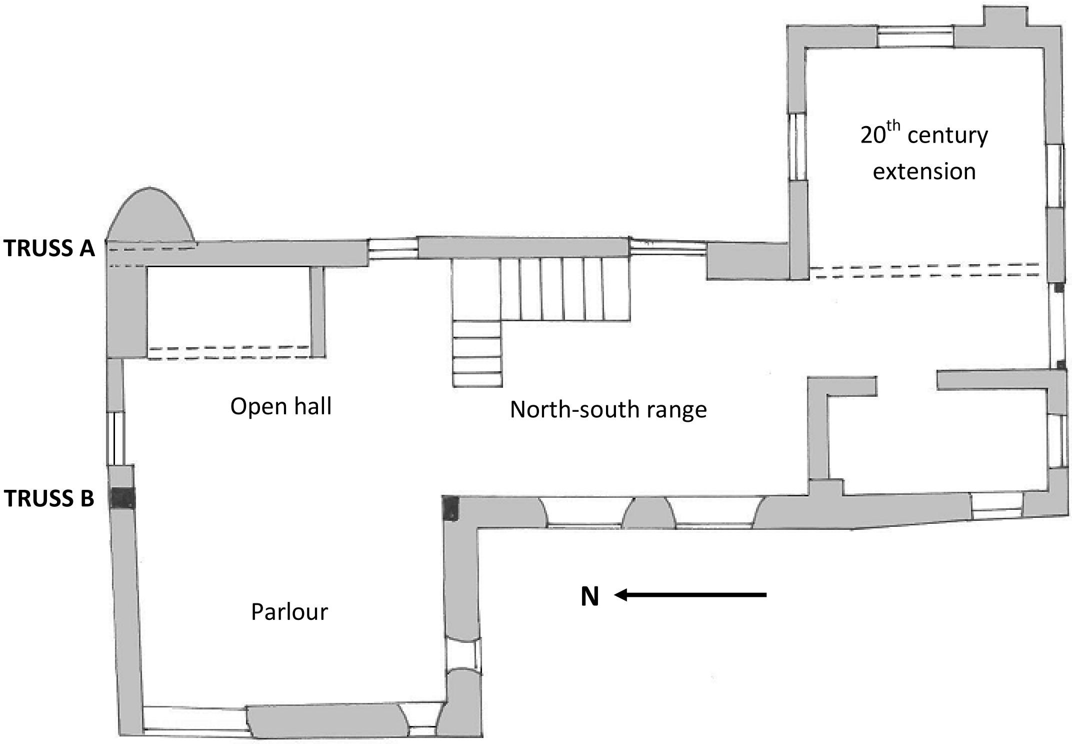

Figure 4: Ground floor plan of Castle Cottage (based on a plan from the Wiltshire Buildings Record archive)

Figure 5: The east face of truss B viewed on the first floor

Figure 6: General view of the roof viewed looking west

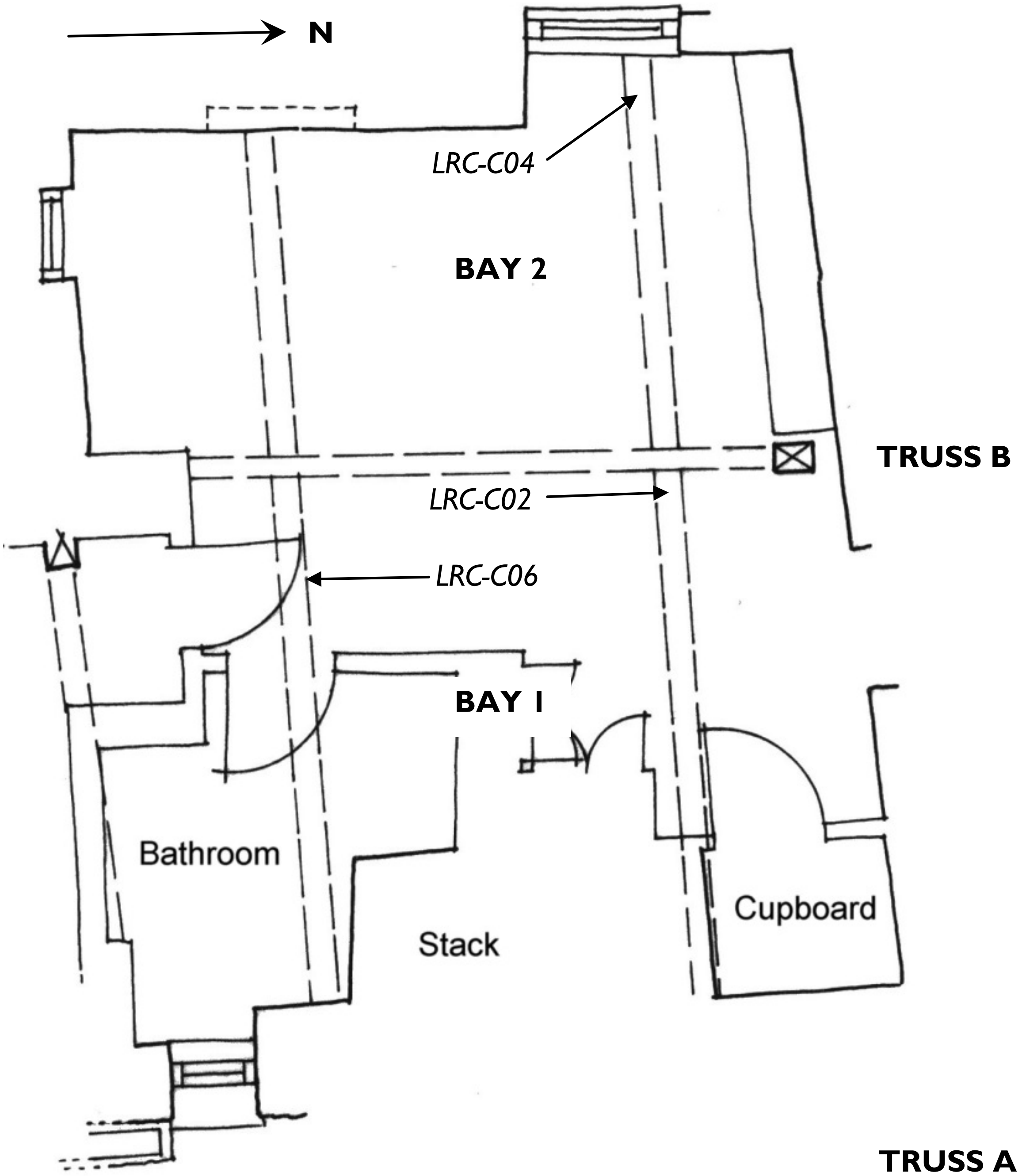

Figure 7: First-floor plan showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)

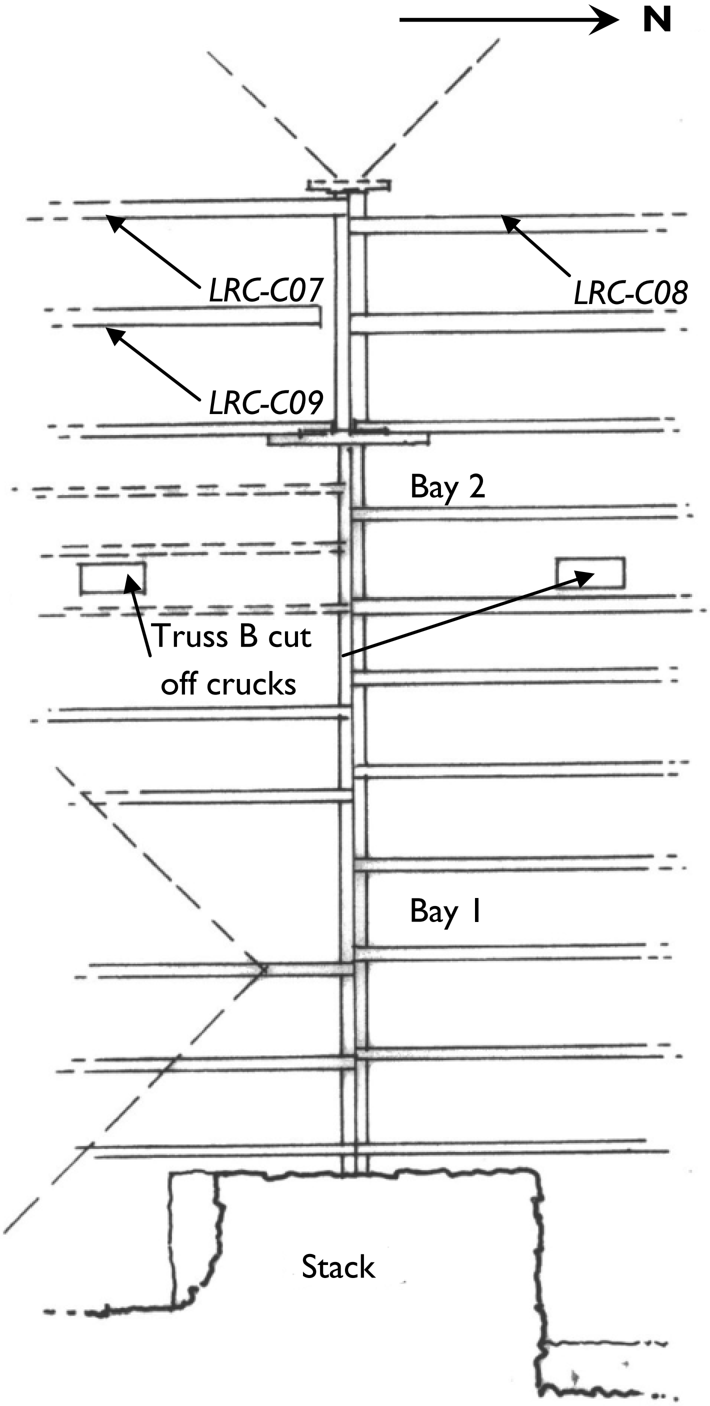

Figure 8: Roof plan showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)

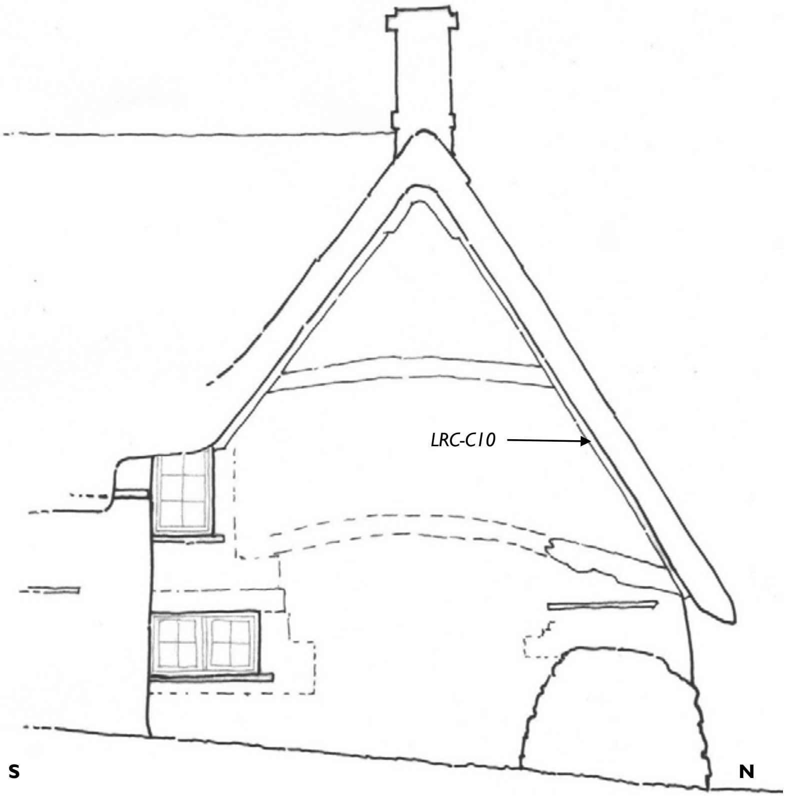

Figure 9: The east face of Truss A showing the sample location (based on a drawing by Clive Carter of the Wiltshire Buildings Record)

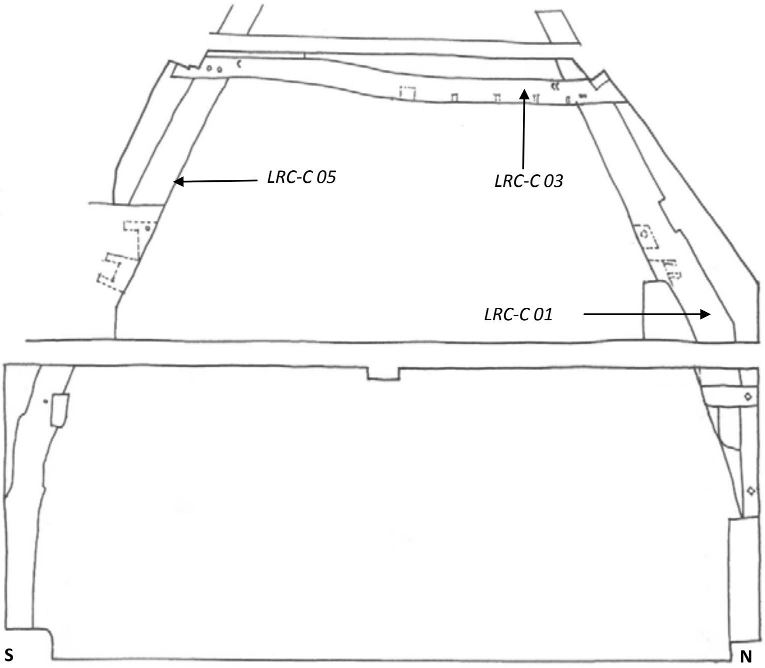

Figure 10: The east face of Truss B showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

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LRCC02A  70
 189 202 239 248 291 296 289 268 308 306 287 282 351 273 331 238 277 318 160 232
 205 248 325 308 318 129 294 103  55  80  65  64  79  66  72  65  87  80  70 180
 151  98 160 208 222 241 219 248 220 213 119 150 120 155 161 146 154  68  36  33
  35  53  51  56  53  81  64  73  86  88
LRCC02B  70
 190 197 245 248 293 319 278 267 298 304 281 283 355 271 328 230 286 305 160 246
 207 248 320 304 321 134 290 106  54  85  61  65  81  64  75  61  87  80  73 180
 150  97 163 200 233 243 221 236 213 204 118 149 122 149 165 147 154  62  38  36
  35  50  47  58  50  81  65  72  89  90
LRCC04A  67
 225 306 301 293 363 373 393 434 410 328 376 403 307 309 281 284 363 283 214 187
 217 146 176 252 216 249 141 158 159 193 224 256 299 277 147 142 205 204 225 213
 160 150 115 125 176 119 141 135  93 101  82  77  85 128 132 107 127 107 133 122
 142 124 102 122 124 140 181
LRCC04B  67
 230 305 297 295 357 377 396 433 416 322 373 408 303 309 288 275 374 277 213 189
 222 142 174 247 218 250 137 147 162 187 222 266 294 272 152 141 198 204 226 211
 162 142 122 129 171 123 137 133  99  96  86  72  88 128 130 118 131 111 137 118
 137 115 104 117 120 140 184
LRCC05A  62
 282 395 399 357 278 332 397 284 387 306 274 138 101 173 232 165 262 279 250 226
 240 274 245 101  67  78  93 127 130 133 147 154 168 168 171 172 106 118  99  89
 129 132 170 146 111  47  24  47  44  51  58  78  76  78  79  71  89  80 118  87
 117 137
LRCC05B  62
 268 383 402 355 269 335 396 272 400 312 270 137  95 181 222 179 263 291 259 222
 240 258 256  99  71  69  96 116 135 131 149 161 172 179 160 176 102 119 102  85
 130 132 162 142 118  43  23  46  51  47  57  79  77  78  76  71  88  76 118  94
 111 128
LRCC10A  48
 467 370 316 327 368 255 315 367 383 243 215 228 281 261 253 235 250 199 218 296
 253 204 252 240 185 147 128 193 216 166 161 126 143 186 156 158 269 146 166 181
 147 108 124 138 109 101 109  96
LRCC10B  48
 472 364 314 329 371 255 305 367 383 235 213 229 282 264 246 242 245 199 215 293
 252 206 256 236 188 140 131 193 211 166 168 133 146 170 158 158 274 149 166 185
 146 113 121 140 113  93 109  93
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

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

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

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

t-value/offset Matrix

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

Bar Diagram

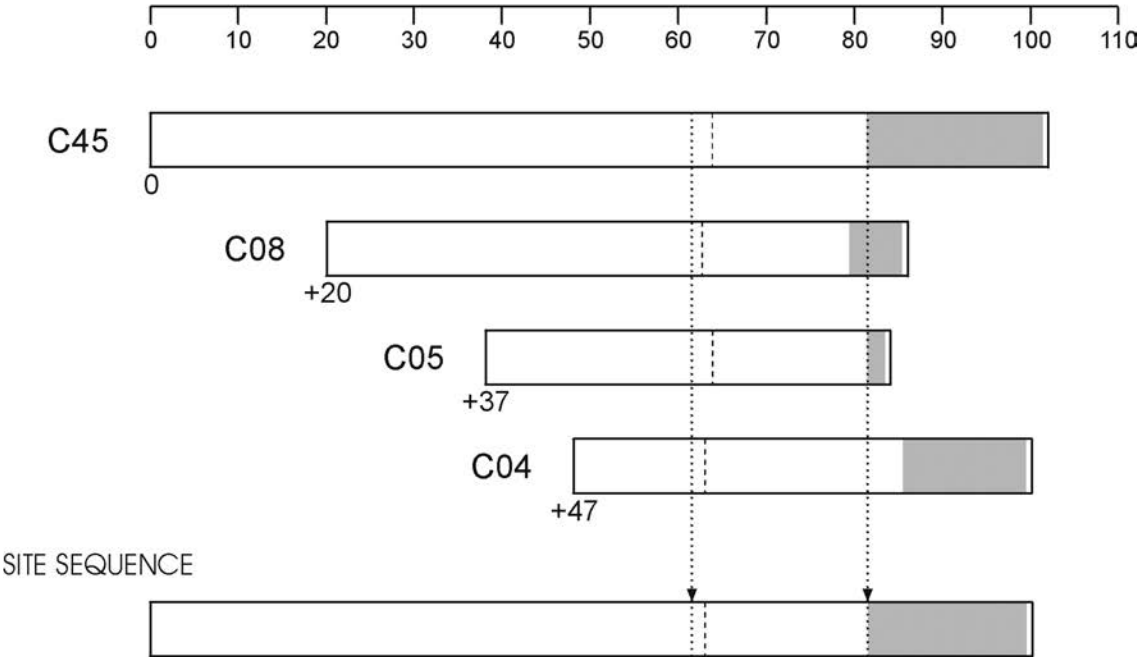


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

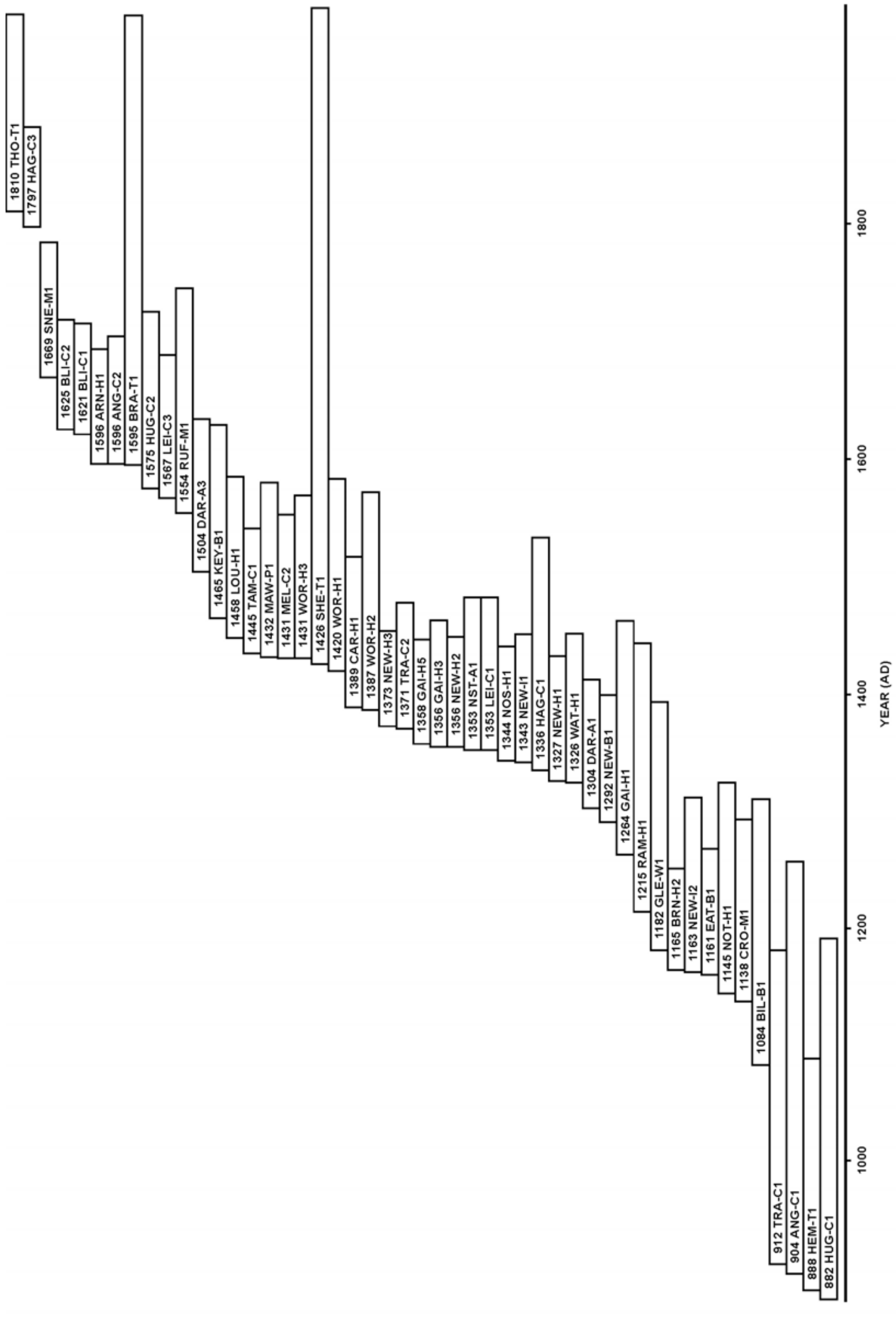
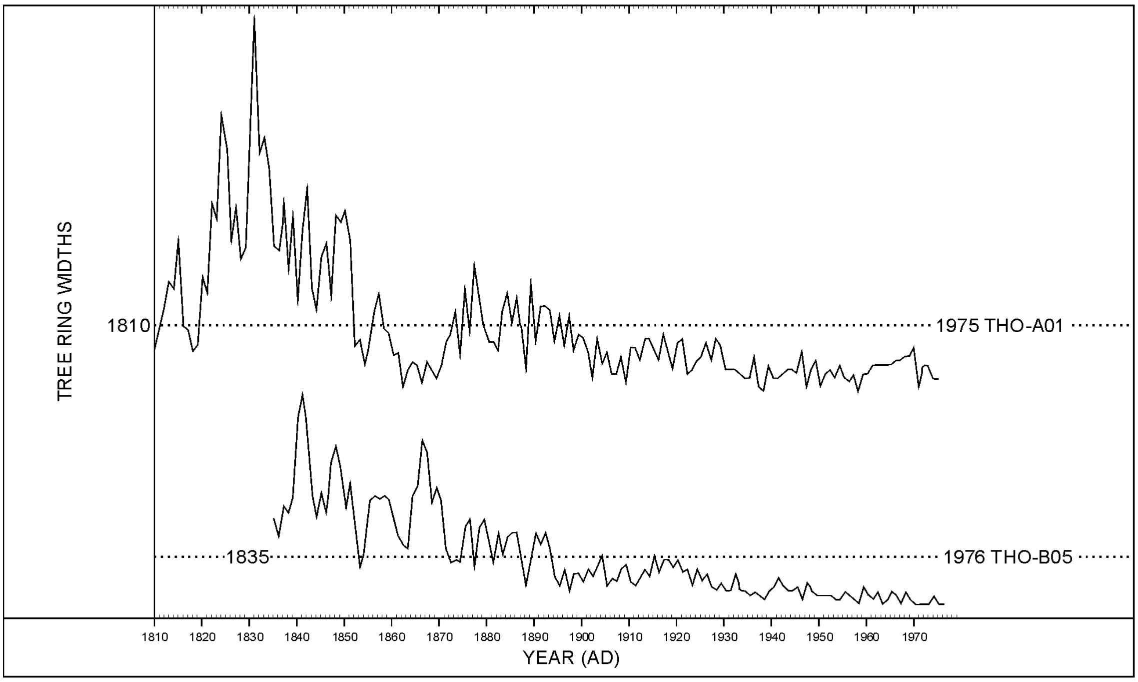


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

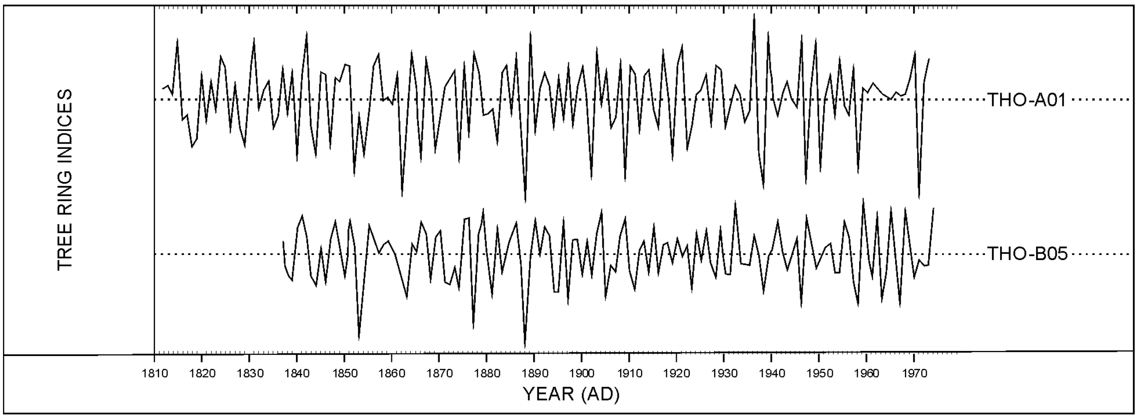


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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