Scientific Dating

Ruins of Former Manor House, Witchampton, near Wimborne, Dorset

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

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RUINS OF FORMER MANOR HOUSE, WITCHAMPTON, NEAR WIMBORNE, DORSET

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SUMMARY

Dendrochronological analysis was undertaken on six of the seven samples obtained from a series of lintels and wall timbers to the ruins of the former Manor House at Witchampton. This analysis produced a single site chronology comprising three samples and having an overall length of 123 rings. These rings were dated as spanning the years AD 1432–1554. Interpretation of the sapwood on these samples would suggest that the timbers represented were felled in the period AD 1569–94. Three further measured samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank David and Felice Hodges, the owners of Abbey House in whose grounds the ruins are now located, for their support and enthusiasm for this programme of tree-ring analysis. We would also like to thank Meriel O'Dowd (Historic England Heritage at Risk Architect/Surveyor) for requesting the analysis and Keith Miller (Historic England Inspector of Ancient Monuments) for his help in arranging access and for much of the background information on the site used below. Finally, we would like to thank Shahina Farid and Cathy Tyers (Historic England Scientific Dating Team) for commissioning this programme of tree-ring dating and their assistance during the production of this report.

ARCHIVE LOCATION

Dorset Historic Environment Record
Environment and the Economy
Dorset County Council
County Hall
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DATE OF INVESTIGATION

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CONTENTS

INTRODUCTION

The Grade II listed "*ruins of former manor house*" are on the Heritage at Risk register and lie within the area designated as a Scheduled Monument, identified in the National Heritage List for England as "*remains of medieval buildings ('Abbey buildings')*". The structures are the remains of a substantial early medieval domestic building, thought likely to be a manor house. It was evidently of high status as it is of two storeys and built of flint and rubble walls with ashlar dressings. It is believed to have been originally constructed in the thirteenth century but was reduced to use for agricultural activities by the eighteenth/nineteenth century.

The partially standing walls are located in an isolated area in the grounds of Abbey House next to the River Allen (Figs 1–2). Recent removal of ivy has exposed the walls revealing six *in situ* timbers comprising wall beams and lintels, and one *ex situ* timber (Figs 3–5). The now *ex situ* timber is thought to be a lintel shown *in situ* in Figure 4a. Whilst the extant walls had been cleared of much overgrowth, the terrain is uneven and overgrown and the tops of the walls remained unconsolidated with a danger of falling masonry.

SAMPLING

Sampling and analysis by dendrochronology of the timbers to the ruins were requested by Meriel O'Dowd to obtain, if possible, precise independent dating evidence for the timbers, which it was thought might potentially be associated with the primary construction phase, and hence help inform a proposed programme of repair and regeneration. Thus, from the small number of timbers available a total of six samples was obtained by coring, with a seventh sample being sliced from the *ex situ* lintel with a chainsaw. Each sample was given the code WCH-A (for Witchampton, site 'A') and numbered 01–07 (Table 1). Although most of the timbers were believed to be potentially associated with the primary phase of construction, one (represented by sample WCH-A02) was somewhat thinner and, hence, thought more likely to be a later insertion. The locations of these samples were recorded at the time of sampling and annotated on to a rectified photograph, reproduced here in Figure 6.

ANALYSIS AND RESULTS

Each of the seven samples obtained from the lintels and wall beams was prepared by sanding and polishing. It was seen at this time that one sample, WCH-A02, had too few rings for reliable dating, and it was rejected from this programme of analysis. The annual growth ring widths of the remaining six samples were measured, the data of these measurements being given at the end of this report. The data of the six measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

This comparative process indicated that three samples, WCH-A01, WCH-A03, and WCH-A07, cross-matched with each other. Series WCH-A03 and WCH-A07 show a very high level of similarity with each other (t=8.3) whereas WCH-A01, shows a lower level of similarity with both WCH-A03 and WCH-A07 (t=3.8 and t=3.4 respectively). This potential cross-matching was, nevertheless, confirmed by the comparison of sample WCH-A01 with reference chronologies, which confirmed that it was coeval with these other two timbers. Thus, all three samples were combined to form site chronology WCHASQ01, this being 123 rings long (Fig 7). Site chronology WCHASQ01 was then compared to the reference material for oak, this indicating a consistent and repeated match when the date of its first ring is AD 1432 and the date of its last measured ring is AD 1554 (Table 2).

The three remaining measured but ungrouped samples were then compared individually to the reference material for oak, but there was no satisfactory cross-matching. These three samples must, therefore, remain undated.

This analysis may be summarised thus:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
WCHASQ01	3	123	1432–1554
ungrouped	3	---	undated
unmeasured	1	---	------

INTERPRETATION

Analysis by dendrochronology of the timbers of the ruins of the former manor house has produced a single site chronology, WCHASQ01, its 123 rings dated as spanning the years AD 1432–1554. None of the dated samples retains complete sapwood (the last ring produced by the trees before they were felled) and it is, thus, not possible to determine the exact felling date for any of the timbers, although it appears likely that all three are coeval.

Two of the samples (WCH-A01 and WCH-A03) do, however, retain the heartwood/sapwood boundary (Table 1 and Fig 7). This means that although the timbers - both wall beams, have lost all of their sapwood, it is only the sapwood that has been lost and it is, therefore, possible, by allowing for 15–40 sapwood rings (the 95% confidence interval), to estimate their likely felling date range. This boundary is only a year apart on the two samples, with the average date of it being AD 1554. Allowing for the missing sapwood, this would give these two wall beams an estimated felling date in the range AD 1569–94.

The felling date of the timber represented by the third sample, WCH-A07, in site chronology WCHASQ01, cannot be determined because, not only is it missing all of its sapwood rings, but an unknown number of heartwood rings as well. However, given that it cross-matches so well with sample WCH-A03, it is very likely that the source trees for both timbers were growing in the same woodland and are likely to have been felled at a similar time. The inference, therefore, is that the tree from which this lintel was derived was also felled in the period AD 1569–94.

DISCUSSION AND CONCLUSION

It would thus appear that at least three timbers, two wall beams and a lintel, are coeval, these having been felled during the later-sixteenth century. These timbers are, therefore, significantly later than the presumed thirteenth century origins for the building and hence appear likely to relate to an alteration or a repair phase.

As intimated above, the cross-matching between samples WCH-A03 and WCH-A07 would suggest that the timbers were probably derived from a single area of woodland source; the individual trees probably growing quite close to each other. The third timber, represented by sample WCH-A01, may have come from another area of woodland. It is likely, however, that the woodland source for the dated timbers was relatively local for, although site sequence WCHASQ01 was compared with reference data for all parts of England, the highest levels of similarity are generally found with reference chronologies from south-west England.

Three measured samples remain ungrouped and undated, despite all of them having sufficient rings for reliable analysis, and none showing any problems such as distortion or compression, which would make cross-matching difficult. It is, however, a common feature of tree-ring analysis for some samples not to combine or to date individually and it is possible that these timbers represent different phases of construction or alteration.

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TABLES

Table 1: Details of tree-ring samples from the ruins of former Manor House, Witchampton, near Wimborne, Dorset

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
WCH-A01	Wall beam 1	65	h/s	1489	1553	1553
WCH-A02	Wall beam 2	nm	---	------	------	------
WCH-A03	Wall beam 3	123	h/s	1432	1554	1554
WCH-A04	Lintel 1 (ex-situ)	60	h/s	------	------	------
WCH-A05	Lintel 2	68	h/s	------	------	------
WCH-A06	Lintel 3 (outer)	54	no h/s	------	------	------
WCH-A07	Lintel 4 (inner)	89	no h/s	1443	------	1531

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

nm = sample not measured

Table 2: Results of the cross-matching of site sequence WCHASQ01 and relevant reference chronologies when the first-ring date is AD 1432 and the last-ring date is AD 1554

Reference chronology	Span of chronology	*t*-value	Reference
Avebury Manor, Avebury, Wiltshire	AD 1393–1596	7.8	(Arnold and Howard 2011 unpubl)
Pye Corner, Moulsford, Oxfordshire	AD 1340–1558	7.7	(Alcock *et al* 1991)
Fiddleford Manor, Sturminster Newton, Dorset	AD 1433–1553	6.9	(Bridge 2003)
Priest's House, Wimborne Minster, Dorset	AD 1259–1634	6.8	(Miles 1994)
Poltimore House, Poltimore, Devon	AD 1380–1559	6.7	(Arnold *et al* 2005)
Dauntesy House, Dauntsey, Wiltshire	AD 1393–1580	6.4	(Tyers *et al* 2014 unpubl)
The Old Mansion, Clarendon, Wiltshire	AD 1315–1625	6.3	(Tyers 1999)
Holy Cross Church, Crediton, Devon	AD 1317–1536	6.1	(Tyers 2004)

FIGURES

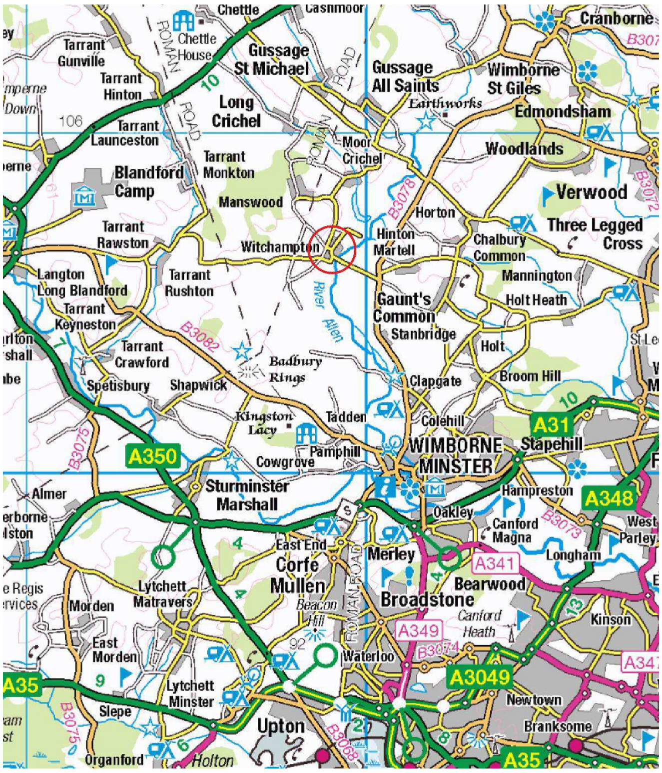


Figure 1a: Map to show the general location of Witchampton, © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

Figure 1b: Map to show the village and the location of the "ruins of former manor house", © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

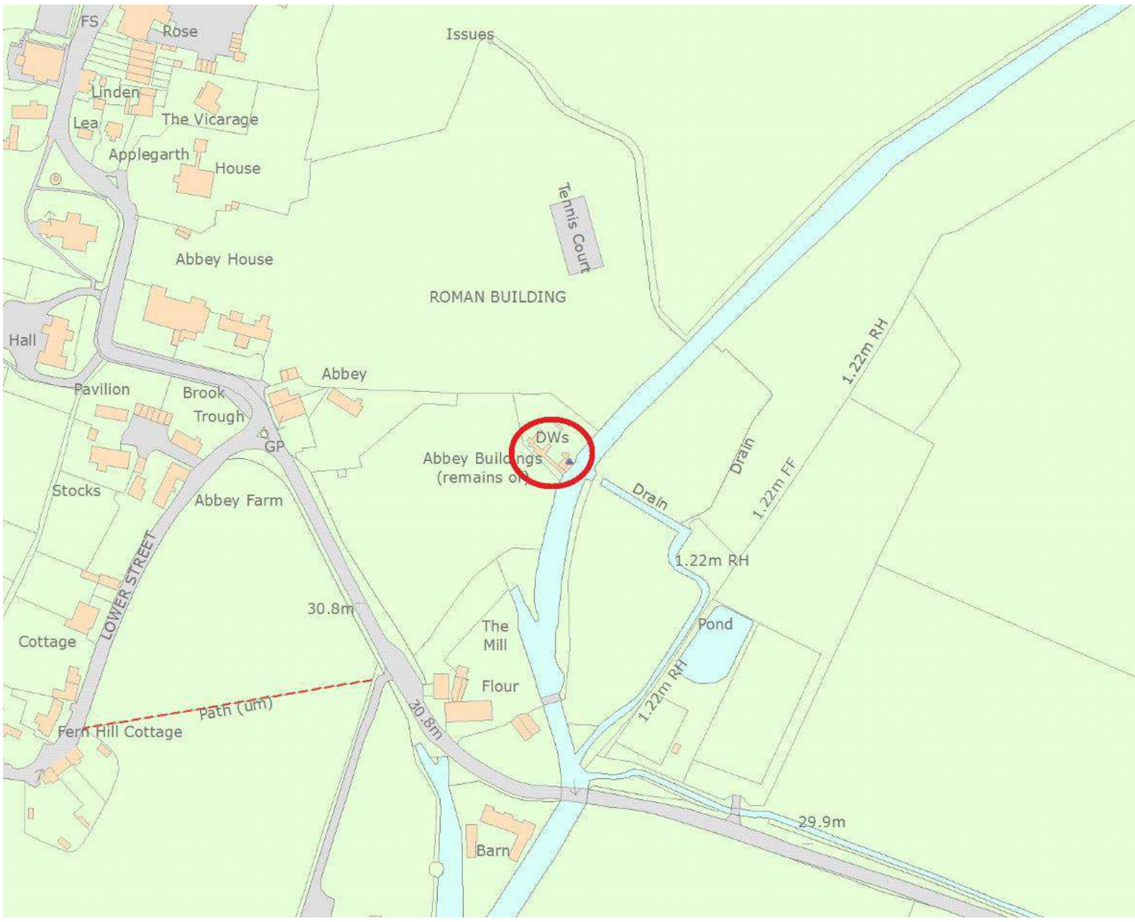


Figure 1c: Map to show the detailed location of the "ruins of former manor house". © Crown Copyright and database right 2016. All rights reserved. Ordnance Survey Licence number 100024900

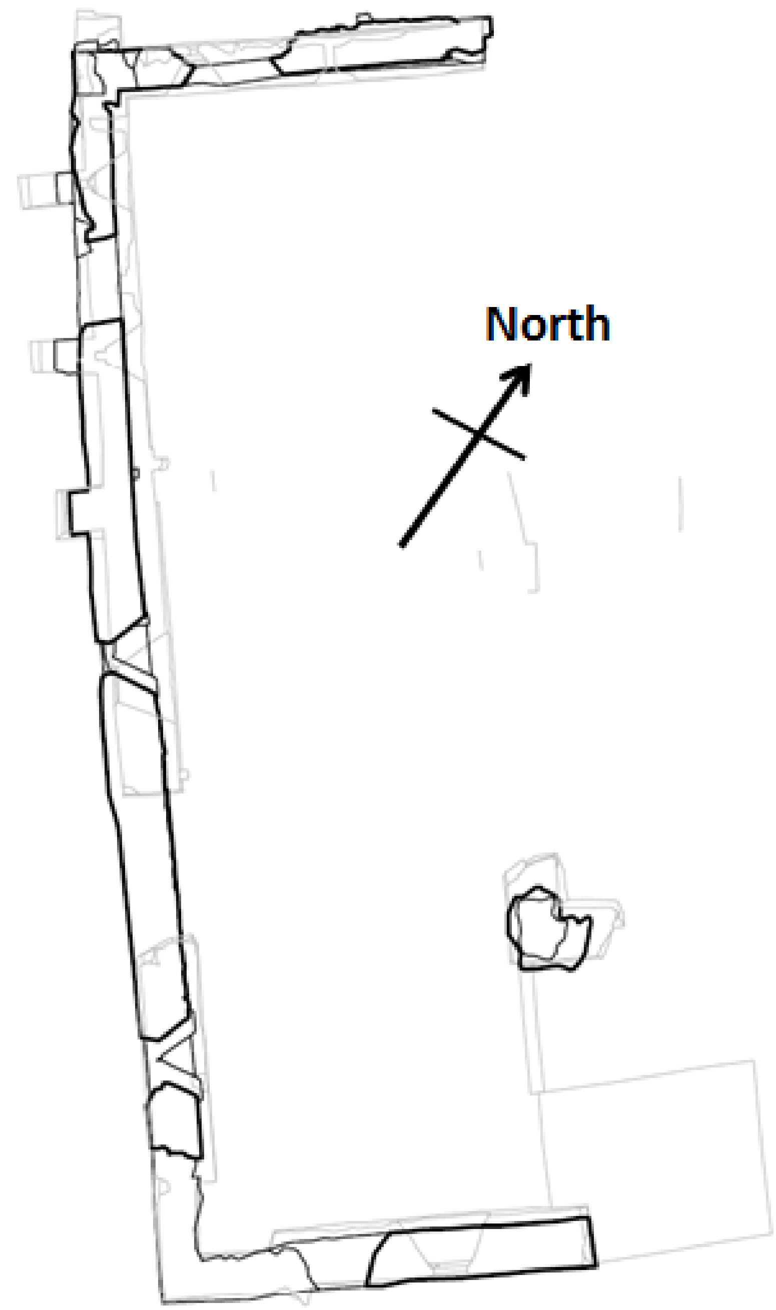


Figure 2: Plan of the ruins at first floor level (after English Heritage Drawn Survey Team)

Figure 3: Photograph of the ruins with the location of some of the surviving timbers indicated (viewed from approximately north-east looking south-west. Photograph Robert Howard)

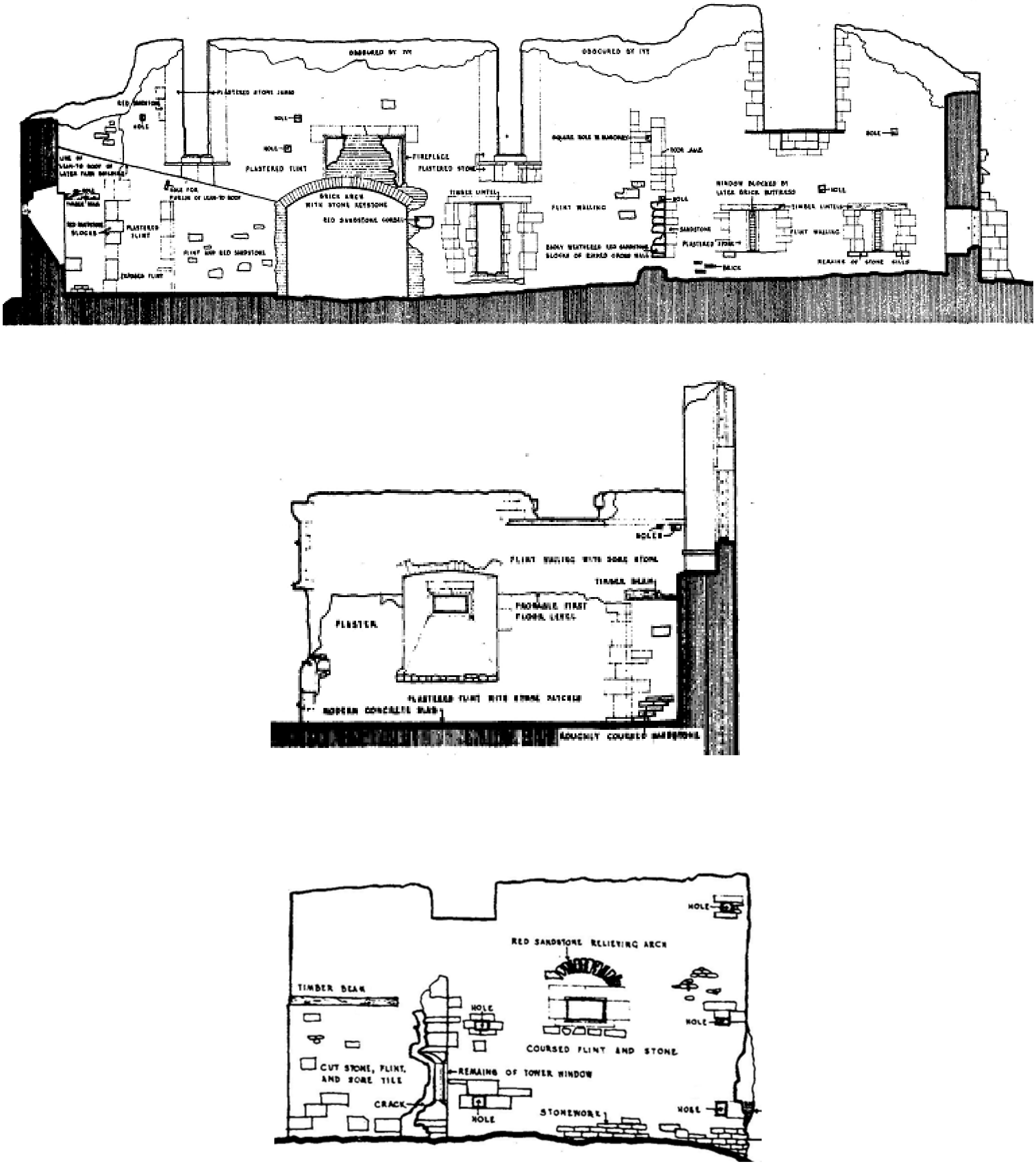


Figure 4a–c: Internal elevation of south-west wall (top) plus internal and external elevations of the south east wall (middle and bottom) (W A V Nutall, July 1961, "medieval field study"*, The School of Architecture, Liverpool College of Building)*

Figure 5: Photograph showing the one of the window lintels (photograph Meriel O'Dowd,)

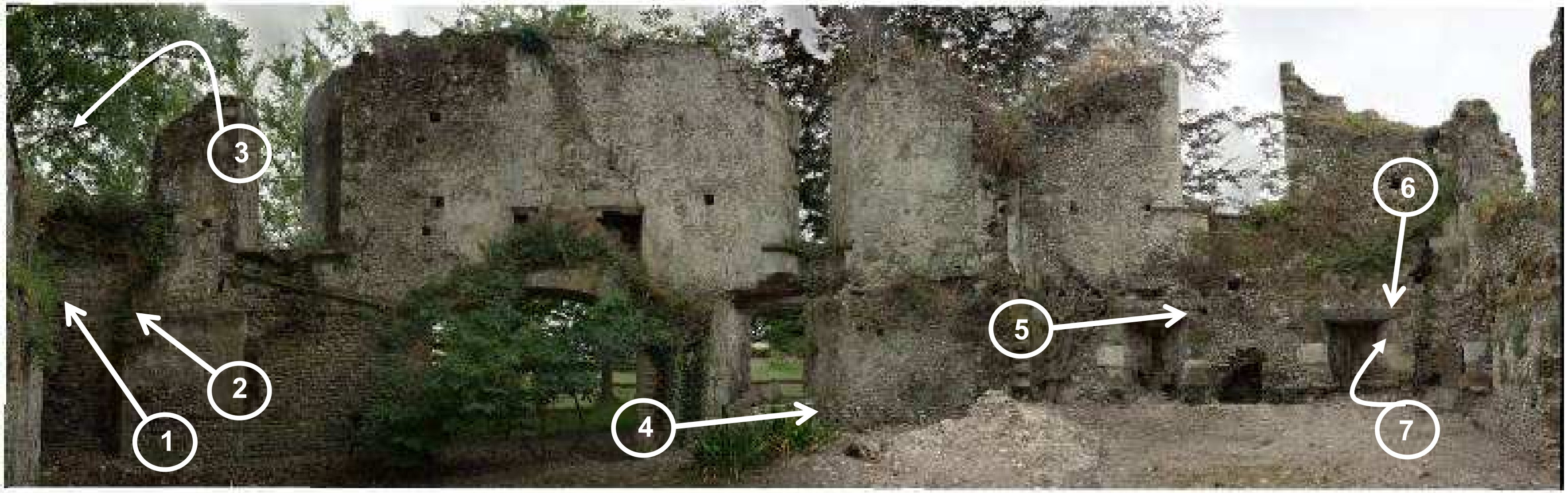
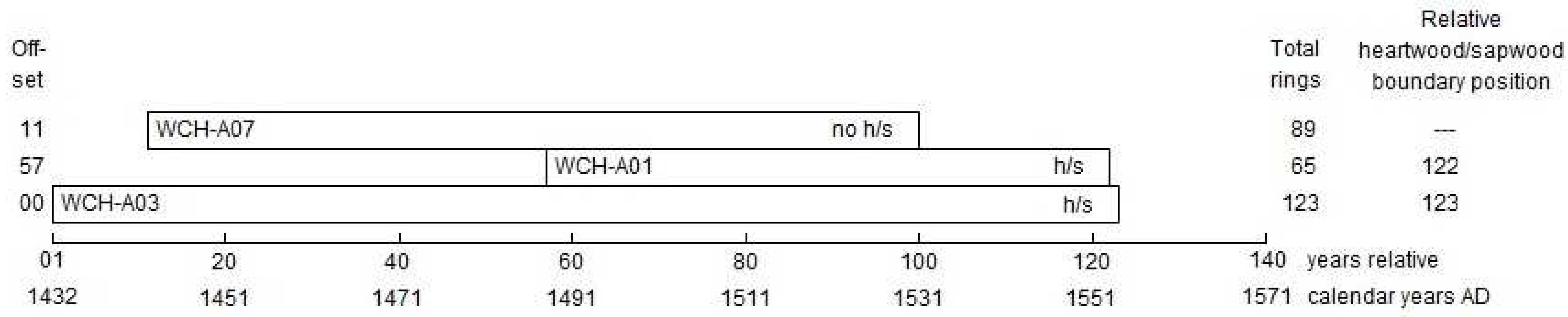


Figure 6: Annotated rectified photograph to locate the sampled timbers (ruins viewed from approximately north-east looking south-west. After English Heritage Drawn Survey Team)



White bars = heartwood rings; h/s = heartwood/sapwood boundary

Figure 7: Bar diagram of the samples in site chronology WCHASQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WCH-A01A 65
64 57 60 42 36 46 60 94 88 66 46 33 39 40 58 58 41 47 41 75
114 73 100 61 71 70 58 56 68 134 150 96 66 126 55 65 46 39 52 61
66 56 82 43 72 72 86 83 117 75 84 105 117 57 53 57 64 60 66 76
73 104 113 80 85
WCH-A01B 65
65 56 61 46 37 41 62 102 90 56 54 18 49 38 62 55 45 43 43 67
117 69 98 66 69 71 55 66 67 136 145 102 71 125 55 46 55 32 63 55
64 57 83 46 60 67 96 81 114 73 83 96 121 60 58 50 57 66 64 75
80 96 112 83 84
WCH-A03A 123
247 171 98 115 113 96 69 83 67 147 117 108 109 147 127 81 103 76 126 160
171 112 137 142 148 126 132 71 74 67 71 129 99 140 151 123 107 85 89 86
92 121 106 100 64 55 51 53 71 84 108 130 162 163 136 190 188 178 155 146
98 76 106 104 223 146 92 87 118 142 190 140 153 96 85 92 129 126 122 146
129 131 164 179 106 112 179 188 133 107 157 112 89 68 51 143 203 118 119 202
161 117 95 137 89 86 73 73 62 68 80 60 109 93 68 56 62 90 36 62
68 68 70
WCH-A03B 123
249 175 106 111 74 100 74 76 75 155 105 108 103 158 125 87 94 73 133 153
171 116 131 134 151 130 126 88 67 57 69 153 97 137 153 107 106 76 96 87
100 117 100 108 60 55 59 60 64 96 107 131 150 171 128 189 196 168 160 137
100 76 101 107 215 148 90 91 117 142 190 119 157 95 78 95 123 148 109 148
133 130 171 173 126 106 179 192 116 126 145 123 85 65 46 151 195 120 134 212
148 129 87 134 85 99 81 69 54 73 86 63 112 78 69 53 69 84 45 61
78 72 81
WCH-A04A 60
488 396 408 393 490 432 293 203 287 275 277 326 350 391 343 302 450 227 269 308
243 221 195 103 73 137 462 556 615 554 341 289 370 357 185 228 160 182 125 128
109 85 68 93 93 112 125 84 134 125 105 93 69 80 92 108 90 175 129 135
WCH-A04B 60
485 405 393 395 484 444 275 200 298 271 274 310 350 400 335 296 443 214 308 314
245 206 195 99 72 137 439 559 640 537 334 292 371 354 210 220 170 170 118 125
123 103 66 92 108 96 117 72 137 125 106 81 90 63 89 85 109 211 103 134
WCH-A05A 68
880 611 330 229 286 494 582 457 360 477 221 368 378 409 343 342 207 175 424 437
251 131 145 117 148 209 231 150 263 201 156 121 156 151 265 145 182 187 223 332
268 351 212 192 136 120 103 157 138 164 232 221 279 221 349 409 246 227 192 255
203 346 460 309 173 165 250 425
WCH-A05B 68
872 631 365 223 286 478 564 438 358 503 237 383 391 421 332 298 214 182 443 426
248 123 136 118 148 228 226 150 237 201 171 121 159 154 266 145 179 179 215 359
270 371 206 179 128 104 112 156 143 165 253 225 253 227 290 401 250 234 192 228
221 333 485 280 179 171 250 415
WCH-A06A 54
169 189 224 197 196 264 92 45 80 98 59 64 64 74 50 93 108 129 103 119
207 214 250 239 261 258 234 168 200 234 201 264 275 343 411 263 265 270 362 241
335 431 265 201 170 291 242 260 178 314 318 271 239 299

WCH-A06B 54
157 184 238 204 188 259 94 50 83 75 68 90 48 68 56 83 112 137 103 121
198 214 257 241 266 255 240 166 195 251 210 267 270 346 407 276 260 257 371 248
326 434 267 214 167 301 240 278 167 315 335 264 253 291
WCH-A07A 89
225 216 213 284 196 127 113 123 156 140 141 201 151 140 152 98 78 74 44 76
162 110 160 178 153 136 91 112 97 135 165 182 196 110 64 71 125 103 176 164
191 207 214 159 194 199 161 202 184 143 117 206 131 209 132 117 125 143 165 301
171 208 166 131 139 190 178 170 201 188 193 215 232 118 139 178 250 135 179 250
215 163 132 118 162 204 176 168 239
WCH-A07B 89
229 229 204 283 172 130 120 118 173 139 146 170 139 151 148 94 83 82 42 80
160 107 171 186 157 127 108 108 108 150 159 168 185 121 57 82 114 101 167 172
197 207 214 168 187 200 159 196 195 139 115 217 146 192 135 120 121 150 157 304
167 185 170 125 132 171 188 170 200 181 201 206 221

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 outside ring, which grew in 1976

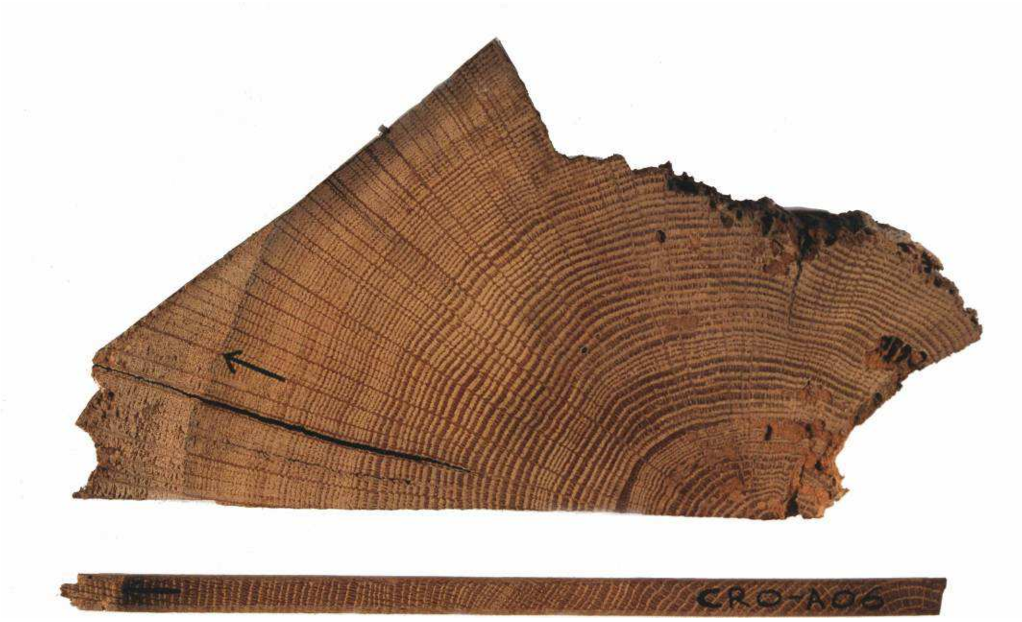


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

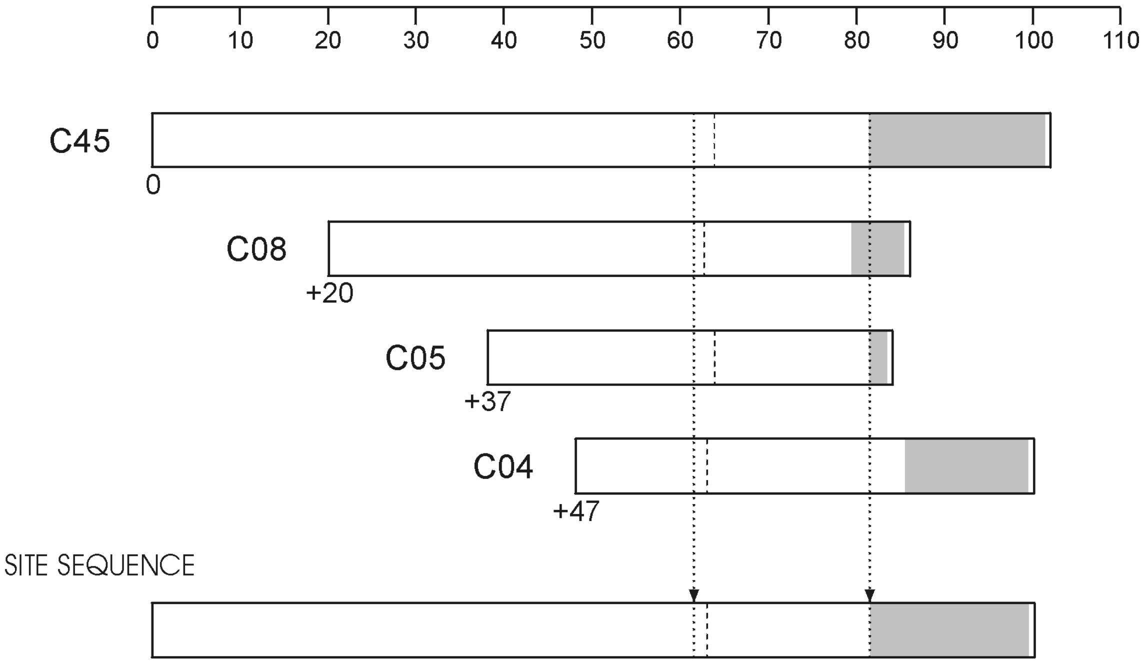


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

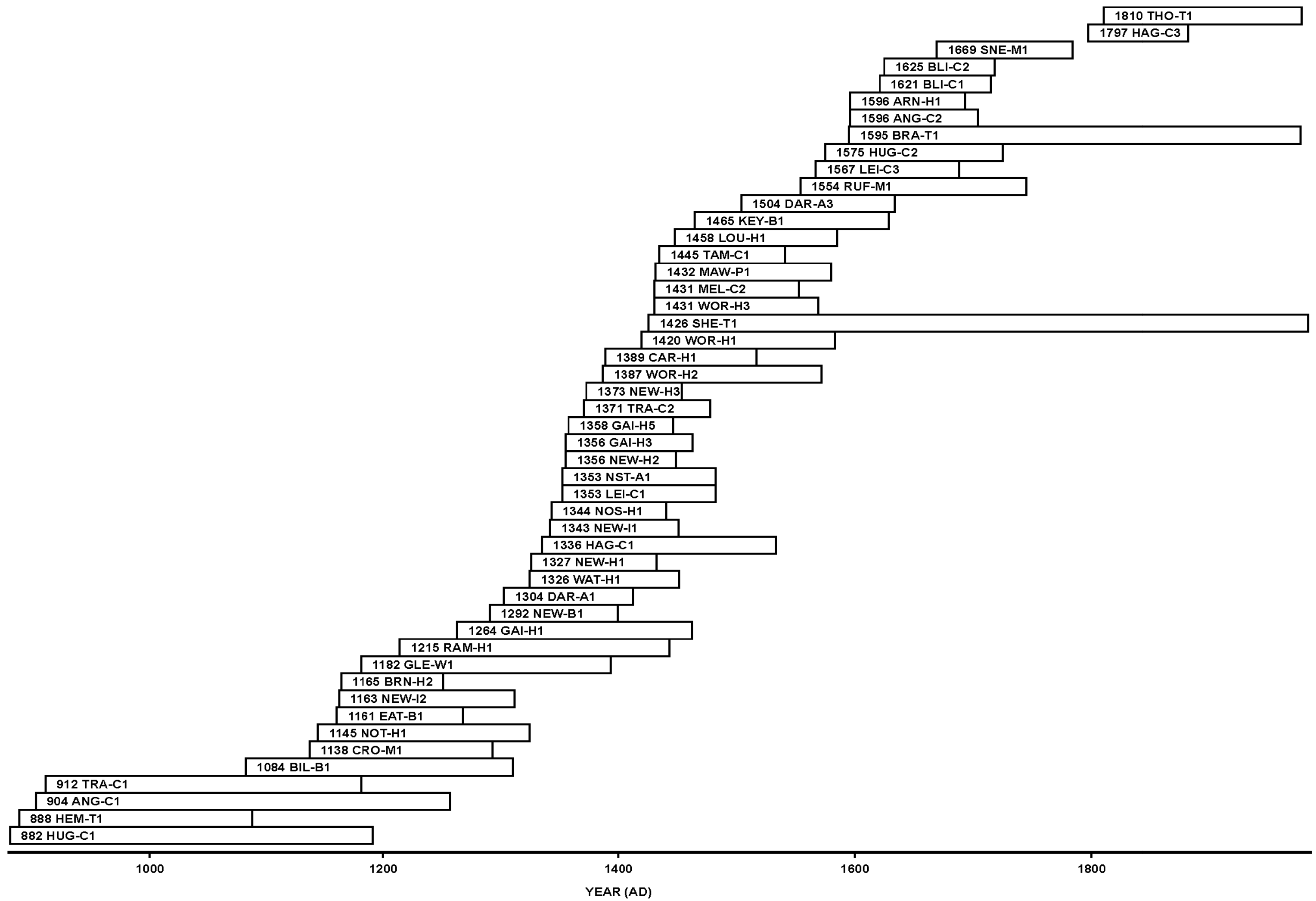
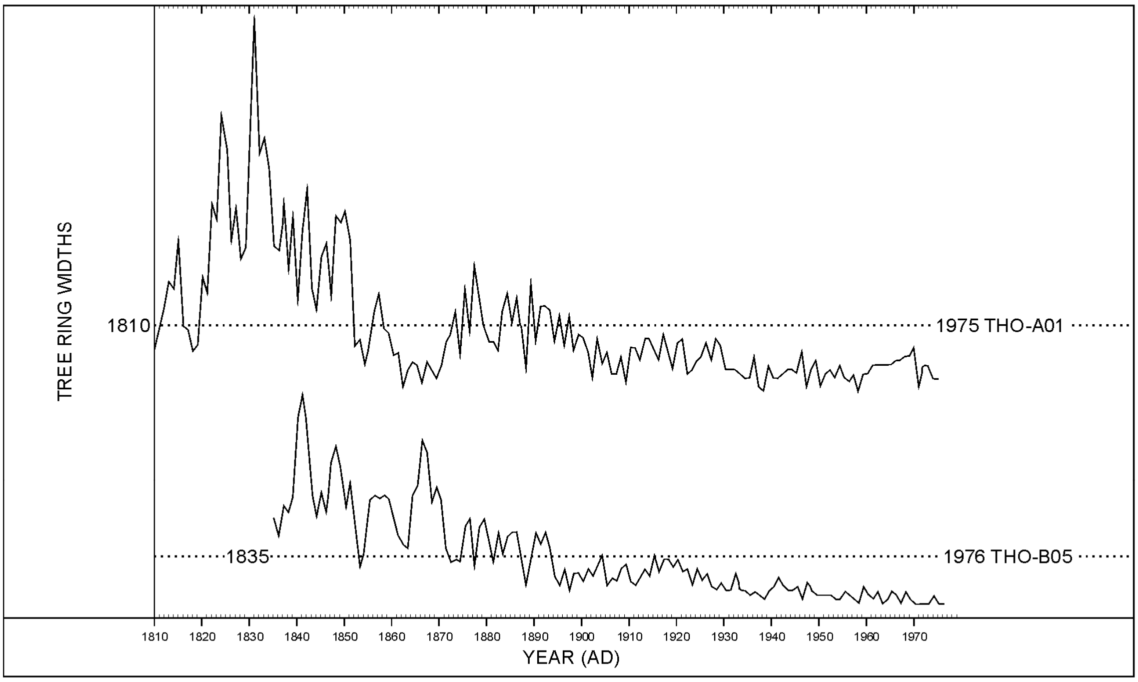


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

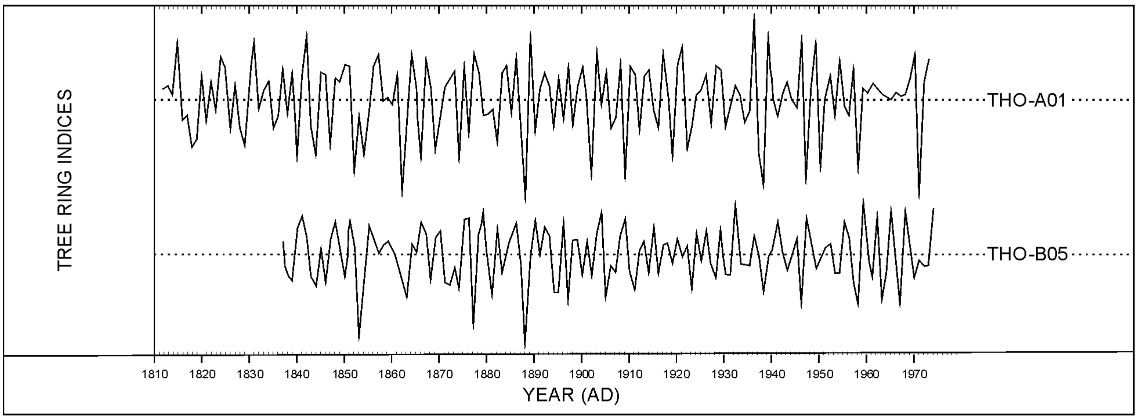


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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