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MANOR HOUSE,
1 EAST GREEN, HEIGHINGTON,
NEAR DARLINGTON, COUNTY DURHAM
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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Alison Arnold and Robert Howard

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SUMMARY

Dendrochronological analysis of 12 samples from the front range and rear stair wing roofs of the Manor House, Heighington, produced a single site chronology, HEIASQ01, comprising 11 samples and having an overall length of 159 rings. These rings were dated as spanning the years AD 1471–1629. Interpretation of the sapwood on the dated samples would indicate that the roof timbers of both the front range and rear stair wing were cut as part of a single programme of felling some time between AD 1630 and AD 1655.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Mrs Elizabeth Banks, the owner of the Manor House, for her enthusiasm and cooperation with this programme of tree-ring analysis and for hospitality and help during sampling. We would also like to thank the North East Vernacular Architecture Group and Martin Roberts, then Historic Building Inspector at English Heritage's Newcastle-upon-Tyne Office, for help and advice during sampling and also for providing the draft NEVAG building survey report and drawings used in this report.

ARCHIVE LOCATION

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DATE OF INVESTIGATION

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CONTENTS

INTRODUCTION

The Manor House stands to the north side of East Green, near the centre of the village of Heighington (NY 2505 2235 Figs 1- 3). The following information has been summarised from the initial draft of the building survey report (NEVAG forthcoming). Together with its neighbouring other half to the south (now Manor Farm) it was once a single, hearth-passage plan, farmhouse or small manor house, believed to date to the late-sixteenth or early-seventeenth century. In the late-seventeenth century the house was enlarged, and half a century later it was given a fine new dining room and staircase. Later still, in the eighteenth century, the building was divided into the two houses seen today (Fig 4) of which Manor House, unlike Manor Farm, is thought to retain the original roofs and first floor-frames.

Currently Manor House comprises a two-storey front range of single room depth orientated on a north-south axis facing west, with a gabled, two-storey, rear stair wing, orientated on an east-west axis, with adjacent offshoot. The roof of the front range (Fig 5) is divided into four bays by three principal rafter with tiebeam and collar trusses, the principal rafters being notched at the apex. The double purlins to each pitch are trenched into the backs of, and face-splayed and pegged together over, the principal rafters. The purlins span between the three trusses and the masonry end gable walls. There has been some replacement or reinforcement of the older timbers, especially of the purlins and the common rafters.

Carpenters' marks survive on two roof trusses in the front range, being numbered II and III on the southern and central trusses, respectively. This implies a possible missing truss at the south gable which was replaced when a possible smoke hood here was taken down and replaced by a chimney in the later seventeenth century. No such marks are to be seen on the northernmost truss of this range.

The roof structure of the rear stair wing comprises a single, central, principal rafter with tiebeam truss, without a collar, but again with double purlins trenched into the backs of the principals. This roof rises to almost the same height as, and is supported off the rear timbers of, the front range roof. The relationship of the two roofs strongly suggests that they were built at the same time, the common rafters of the front range being shortened at the junction of the two roofs and pegged to the purlins.

The first floor frame of the front range is seen as a number of beams in the ceilings to the ground floor rooms. The entrance hall has a single oak ceiling beam, chamfered with a concave stepped stop on its northern side only, while the living room ceiling is formed of two oak beams. The northern beam has deep chamfers and concave step stops, the southern one (also serving as the bresummer to a former open hearth) having a thinner chamfer towards the room and a deep, rougher, chamfer towards the fireplace wall. The dining room ceiling contains a single oak beam, another chamfered and concave stopped timber.

SAMPLING

Tree-ring sampling and analysis of timbers within the Manor House were requested by Martin Roberts, who at the time was the Historic Buildings Inspector based at English Heritage's Newcastle office. It was hoped that tree-ring analysis would establish with greater reliability and accuracy the probable construction date of the Manor, and confirm that both the roof of the front range and the rear stair wing were of one and the same phase of construction. In addition the analysis would add to the growing body of information relating to hearth-passage plan buildings with tiebeam and principal rafter roofs in the north-east region.

To this end, an examination was made of all the visible timbers within the building. It was seen at this time that whilst the majority of roof timbers were of a character suitable for tree-ring analysis (ie, were of oak and were likely to have the minimum number of rings required for reliable analysis), some timbers, principally the few accessible timbers of the first-floor frame, appeared to be derived from slightly faster grown trees. As such these timbers were unlikely to provide core samples with the usual minimum number of 54 rings here deemed necessary for reliable dating and, thus sampling was restricted to the roofs of the front range and rear stair wing.

Thus, from the suitable timbers available, a total of 12 samples was obtained by coring. Each sample was given the code HEI-A (for Heighington, site 'A') and numbered 01–12. As far as was evident, all the sampled timbers appeared to represent the primary construction phase of the present building and showed no evidence of reuse or later insertion and were hence likely to have been acquired specifically for the present building. The positions of the sampled timbers are shown on drawings made and provided by Martin Roberts from the draft building survey report (NEVAG forthcoming), reproduced here as Figures 6a–d. Details of the samples are given in Table 1. In this table the front range trusses have been numbered 1-3 from north to south (this ignoring the fact that at least two of the trusses are numbered from south to north, while a third truss is not numbered at all), that in the rear stair wing as truss 4 (Fig 5), and with timbers being further identified on a north–south, or east–west basis as appropriate.

ANALYSIS

Each of the 12 samples obtained in this programme of tree-ring dating was initially prepared by sanding and polishing, with the annual growth-ring widths of all 12 samples then being measured. The data of these measurements are given at the end of this report.

The data of the 12 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing a single group comprising 11 cross-matching samples to be formed. The samples of this group, cross-matching with each other at offsets as shown in Figure 7, were combined at their indicated offsets positions to form site chronology HEIASQ01, this site chronology having an overall length of 159 rings.

Site chronology HEIASQ01 was then compared with an extensive series of reference chronologies for oak, cross-matching repeatedly and consistently with a number of these when the date of its first ring is AD 1471 and the date of its last measured ring is AD 1629. The evidence for this dating is given in Table 2.

The single remaining ungrouped sample was also compared with a series of reference chronologies for oak, but there was no satisfactory cross-matching at any position, and this sample must, therefore, remain undated.

INTERPRETATION

None of the 11 dated samples of site chronology HEIASQ01 retain complete sapwood, and it is thus not possible to indicate a precise felling date for any of the trees represented. Eight of the samples do, however, retain some sapwood or at least the heartwood/sapwood boundary, meaning that only the sapwood rings and bark is missing.

Initially taking the two roofs separately, the average date of heartwood/sapwood boundary on the six samples from the front range roof which retain it is AD 1614. Using a 95% confidence limit of 15–40 for the number of sapwood rings the trees are likely to have had would give the timbers represented by these six samples an estimated felling date in the range AD 1629–54. The average heartwood/sapwood boundary date of the two samples from the rear stair wing roof is AD 1619. Using the same 95% confidence limit for the number of sapwood rings would give the timbers represented by these two samples an estimated felling date in the range AD 1634–59.

It will be seen, therefore, that although the estimated felling date range of the two sets of timbers have a considerable overlap, from AD 1634 – 54, and are quite probably of a single phase of felling, it is just possible that the timbers of the rear stair wing roof were felled a few years later than those from the front range roof. This variation, however, might be as a result of the bias in the sample set, the front range roof being represented by six samples, the rear stair wing roof represented by only two samples whose heartwood/sapwood boundary dates lie within the overall range of the boundary dates for the front range samples. Taken together, the average date of the heartwood/sapwood boundary on all eight samples from both areas is AD 1615. Using a 95% confidence limit of 15–40 for the number of sapwood rings the trees are likely to have had would give the timbers represented an estimated felling date in the range AD 1630–55.

Although, because that they do not retain even the heartwood/sapwood boundary, the felling date range of the trees represented by the remaining three samples cannot be given, there is no reason, given that the timbers appear be integral to the rest of the structure, and there is no evidence by way of redundant mortices or peg holes etc, of their reuse from an older structure, to suspect that they were not also felled sometime between AD 1630 and AD 1655.

It would appear, therefore, that the roofs of the front range and rear stair wing of Manor House date to the early to mid part of the seventeenth century, and that both the front range and the rear stair wing are, as intimated by NEVAG (forthcoming), of a single phase of construction. Such an interpretation is further supported by the fact that samples from different areas cross-match sufficiently well with each other as to suggest that the trees they represent were growing close to each other in the same copse or stand of woodland. Sample HEI-A08, from the front range roof, and sample HEI-A11, from the rear stair wing, for example, cross-match with a value of t=8.9, while samples HEI-A09 and HEI-A12, also from the front range and stair wing respectively, cross-match with a value of t=10.8, suggesting the possibility that the two timbers represented may in fact be derived from the same tree. Such a phenomenon would be less likely if the trees had been felled at different times. The level of cross-matching between other samples also suggest a single-source woodland.

The location of this source woodland cannot be precisely determined through tree-ring analysis. However, as might be seen from Table 2, which lists some of the reference chronologies used to date site chronology HEIASQ01, the greatest similarity is with material from other sites in County Durham and Northumberland. This would suggest that the timber used in the construction of the Manor House was most likely of relatively local origin.

A single sample, HEI-A06, remains ungrouped and undated. There are no particular problems with this sample, such as compressed or distorted rings, which would make cross-matching and dating difficult. However amongst this number of suitable samples from a site, the inability to date one or more is a common feature of tree-ring analysis.

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TABLES

Table 1: Details of tree-ring samples from Manor House, Heighington

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
HEI-A01	East principal rafter, truss 1	140	h/s	1471	1610	1610
HEI-A02	West principal rafter, truss 1	58	no h/s	1551	------	1608
HEI-A03	Tiebeam, truss 1	81	h/s	1532	1612	1612
HEI-A04	East principal rafter, truss 2	61	no h/s	1526	------	1586
HEI-A05	West principal rafter, truss 2	68	no h/s	1536	------	1603
HEI-A06	Tiebeam, truss 2	58	no h/s	------	------	------
HEI-A07	Collar, truss 2	100	h/s	1511	1610	1610
HEI-A08	West principal rafter, truss 3	72	h/s	1543	1614	1614
HEI-A09	Tiebeam, truss 3	115	8	1515	1621	1629
HEI-A10	Collar truss 3	112	2	1510	1619	1621
HEI-A11	South principal rafter, truss 4	58	h/s	1561	1618	1618
HEI-A12	Tiebeam, truss 4	95	h/s	1525	1619	1619

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

Table 2: Results of the cross-matching of site sequence HEIASQ01 and relevant reference chronologies when first ring date is AD 1471 and last ring date is AD 1629

Reference chronology	Span of chronology	*t*-value	Reference
The Chantry, Morpeth, Northumberland	AD 1336–1651	9.2	(Arnold and Howard 2009a)
Hallgarth Manor Cottages, Hallgarth Pittington, Co Durham	AD 1336–1624	6.5	(Howard *et al* 2001)
Low Harpurley Farmhouse, Wolsingham, Co Durham	AD 1356–1604	6.3	(Arnold *et al* 2006)
Norton Conyers, Wath, West Yorkshire	AD 1448–1609	6.0	(Arnold and Howard 2008 unpubl)
Rock Farm, Wheatley Hill, Co Durham	AD 1397–1569	5.9	(Arnold and Howard 2004)
Fell Close, Healeyfield, Consett, Co Durham	AD 1496–1651	5.5	(Arnold *et al* 2004)
Bull Hole Byre, Bearpark, Durham	AD 1452–1620	5.3	(Arnold *et al* 2002)
Cockle Park Tower, Hebron, Morpeth, Northumberland	AD 1394–1602	5.2	(Arnold and Howard 2009b)

FIGURES

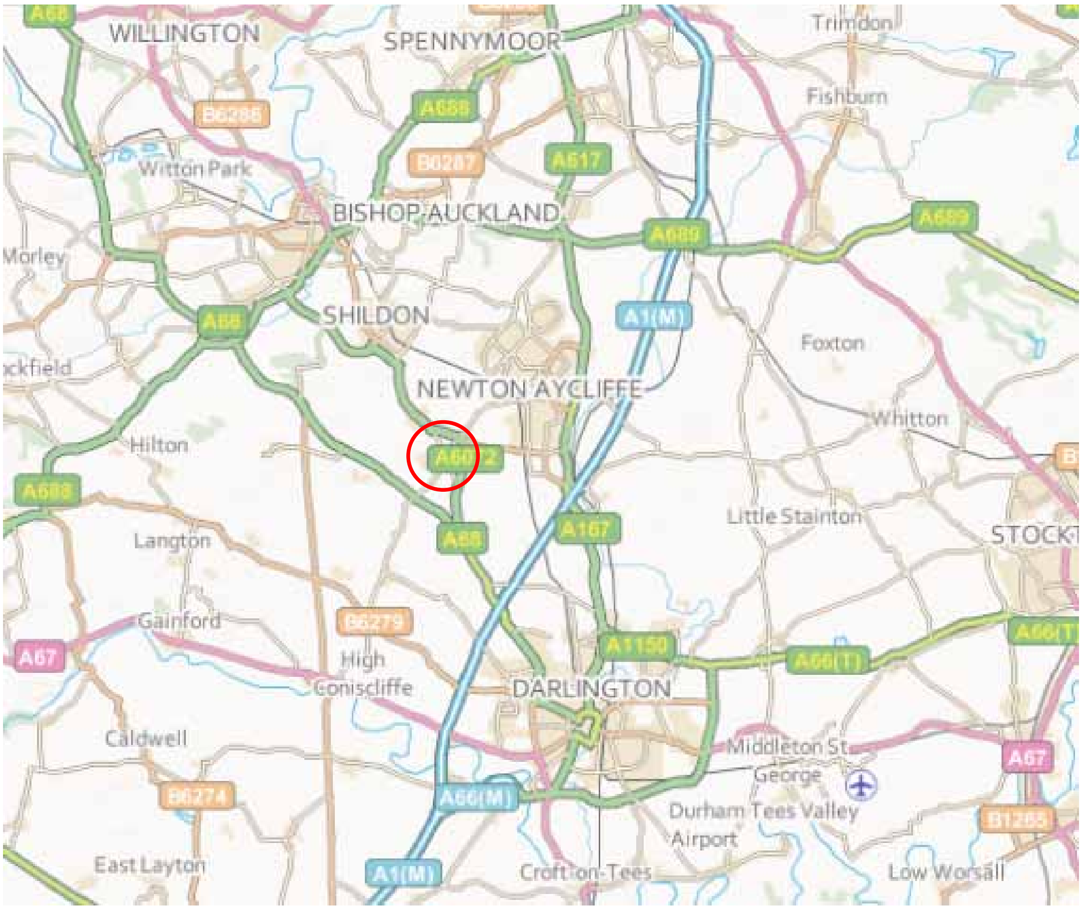


Figure 1: Map to show the general location of Heighington. © Crown Copyright. All rights reserved. English Heritage 100019088. 2012

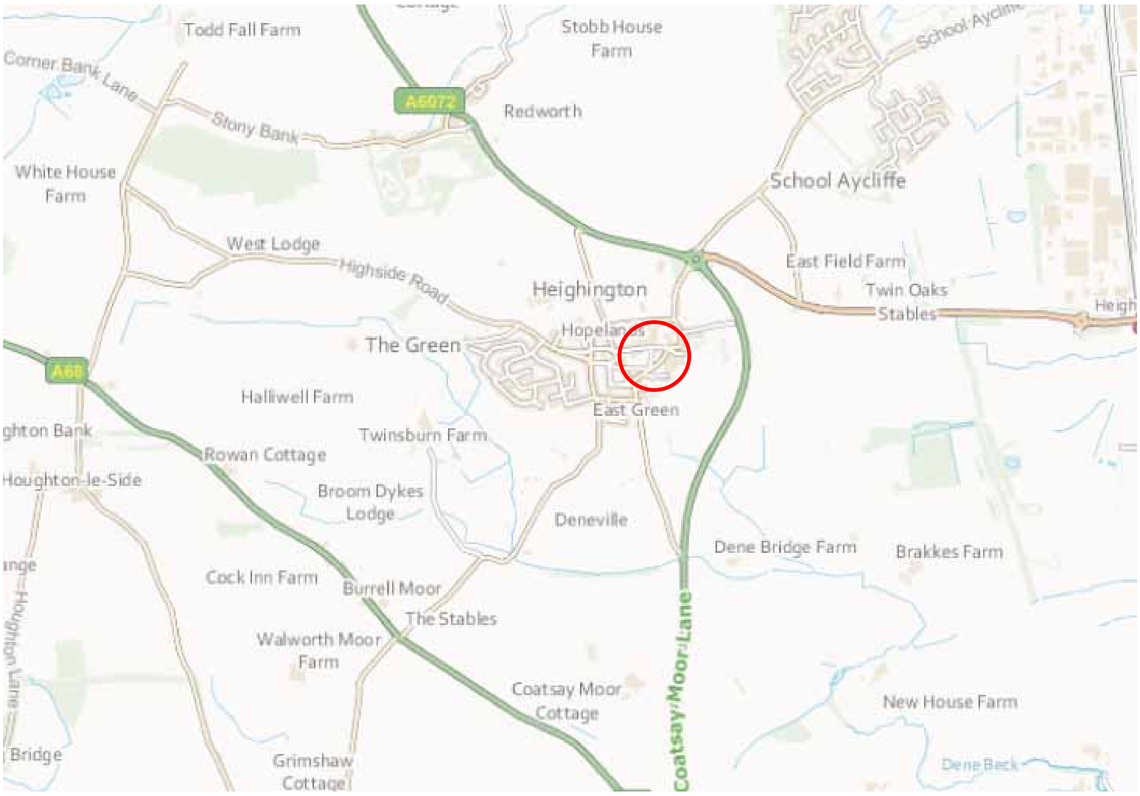


Figure 2: Map to show the general location of Heighington Manor. © Crown Copyright. All rights reserved. English Heritage 100019088.

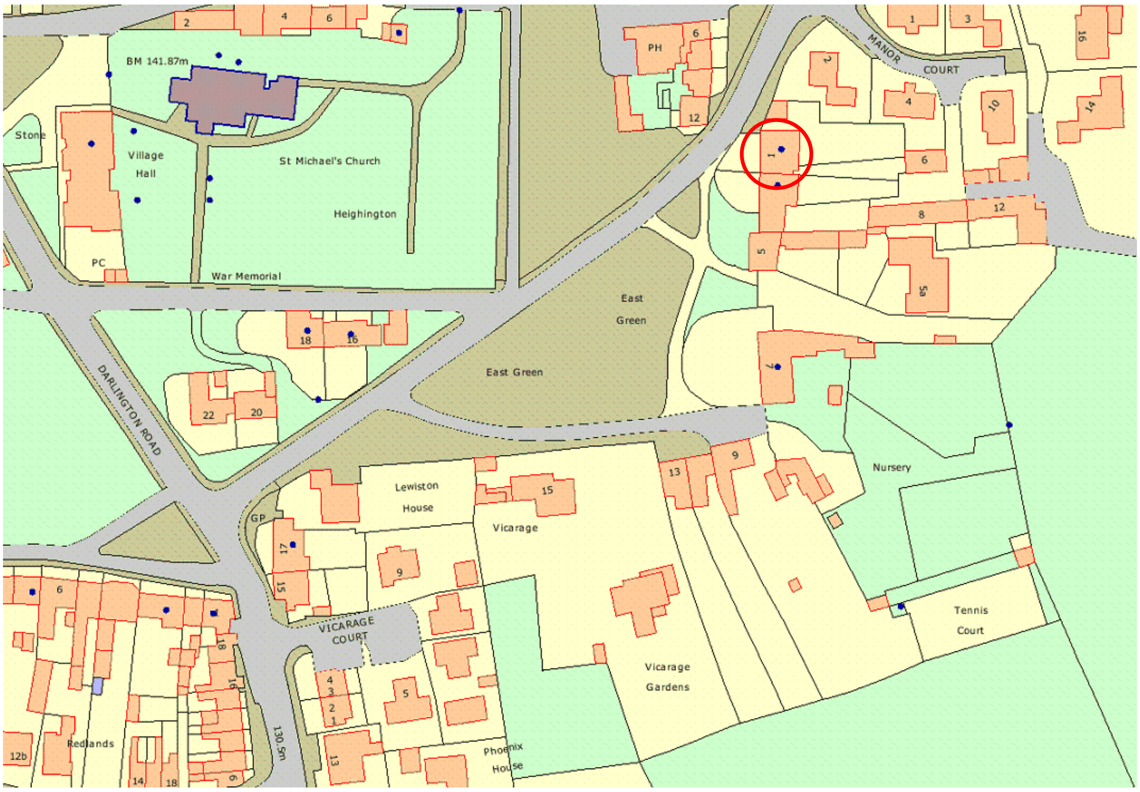


Figure 3: Map to show the location of Heighington Manor. © Crown Copyright. All rights reserved. English Heritage 100019088. 2012

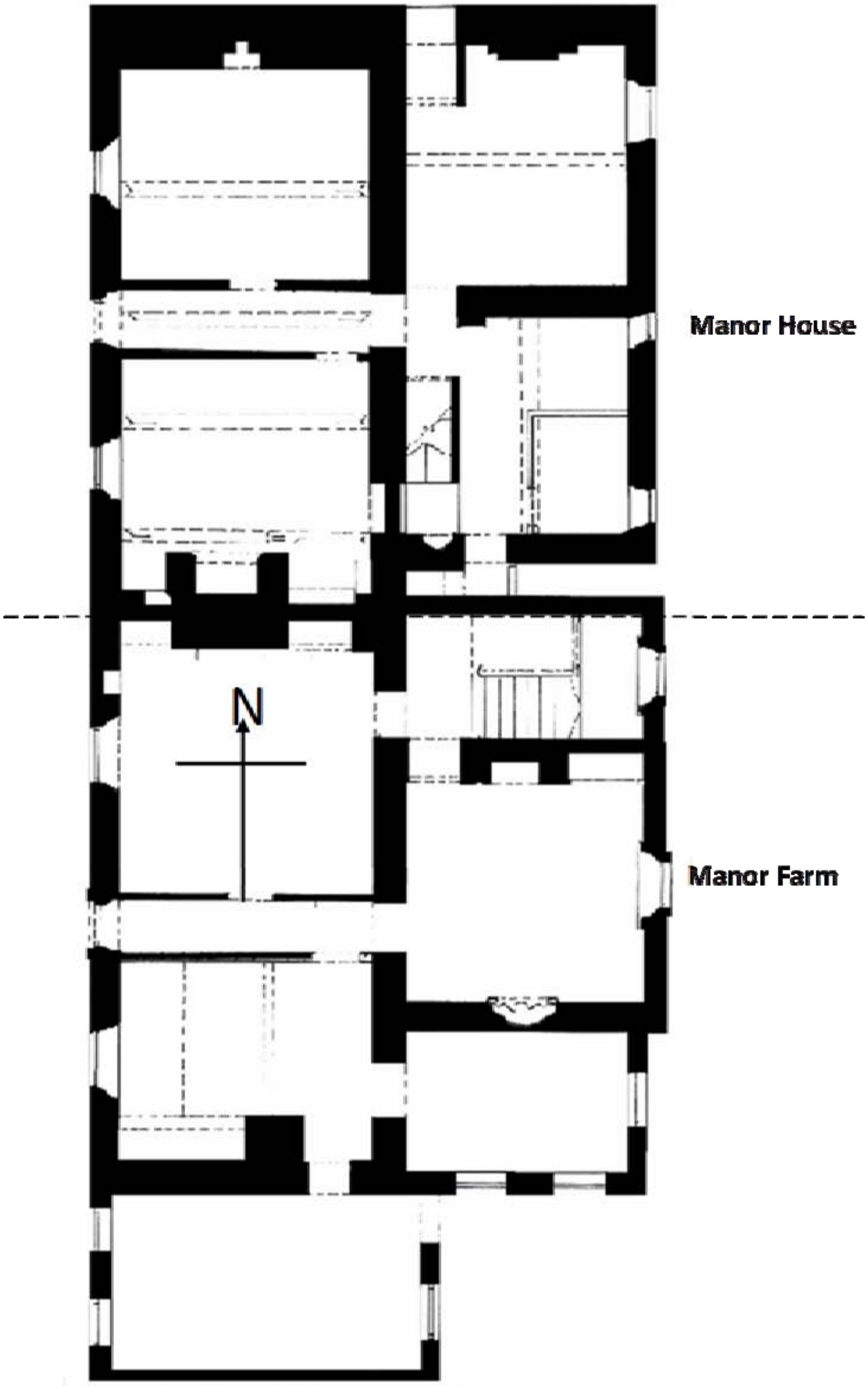


Figure 4: Ground floor plan of Heighington Manor (after NEVAG forthcoming)

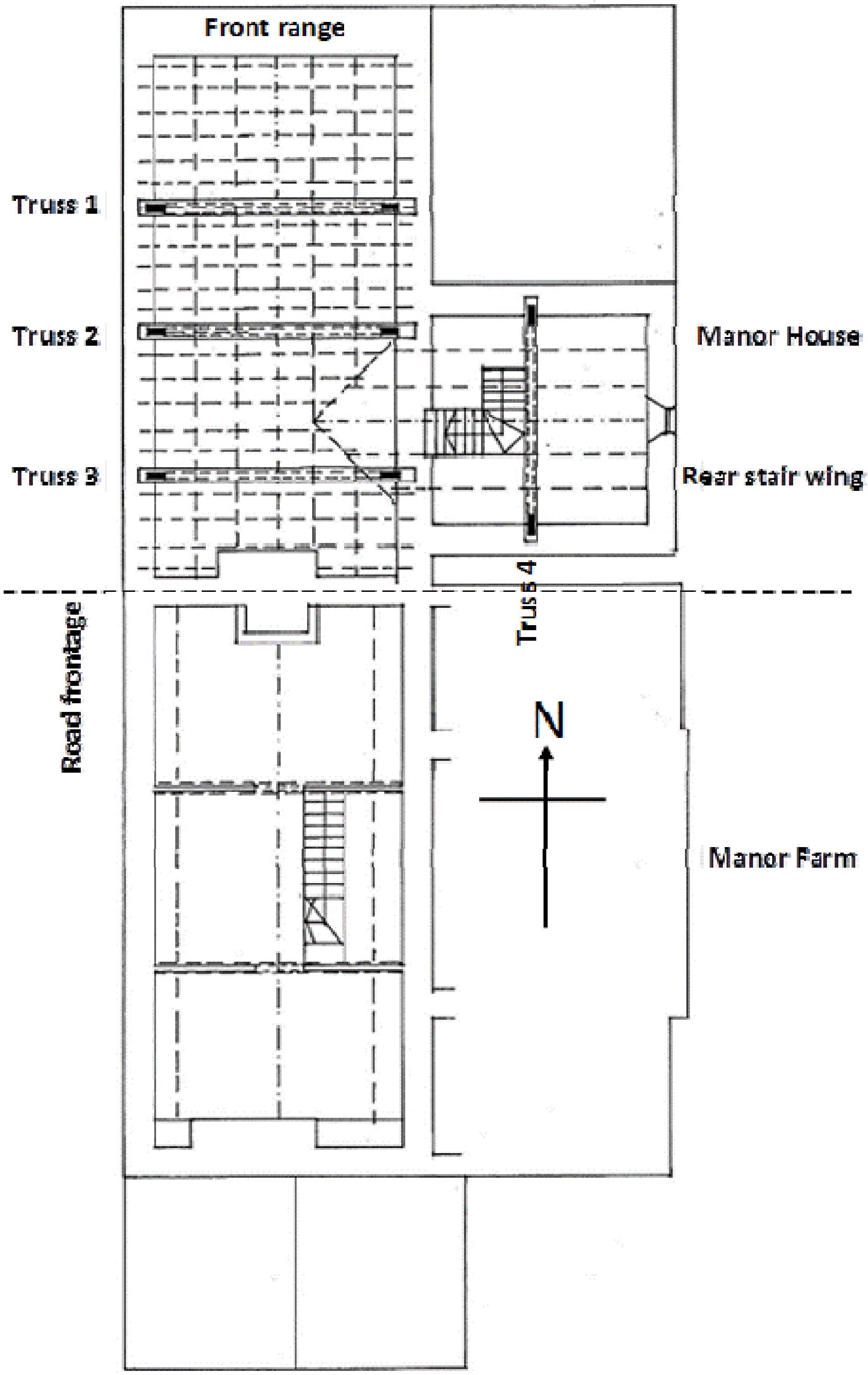


Figure 5: Roof plan of Heighington Manor (after NEVAG forthcoming)

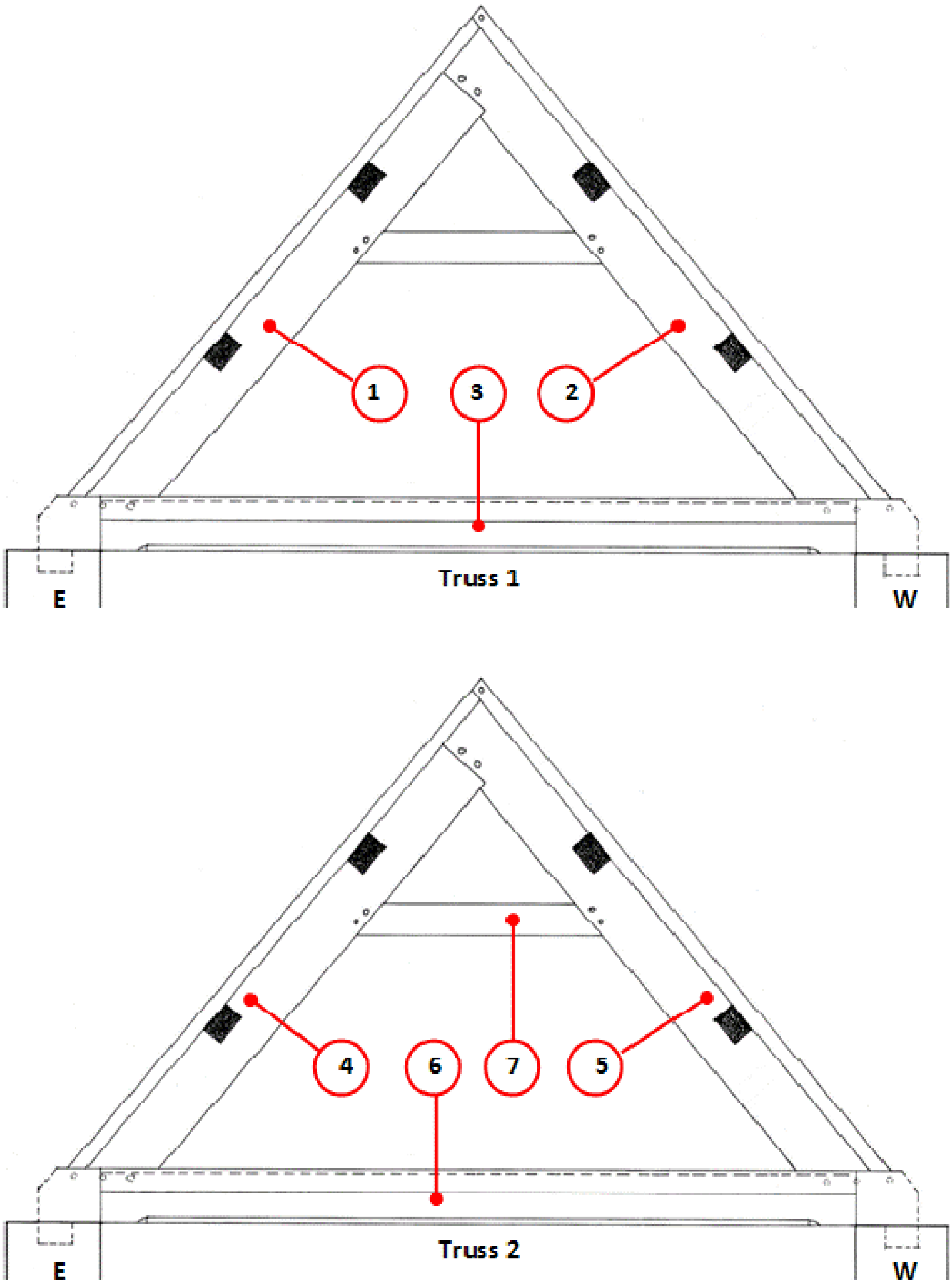
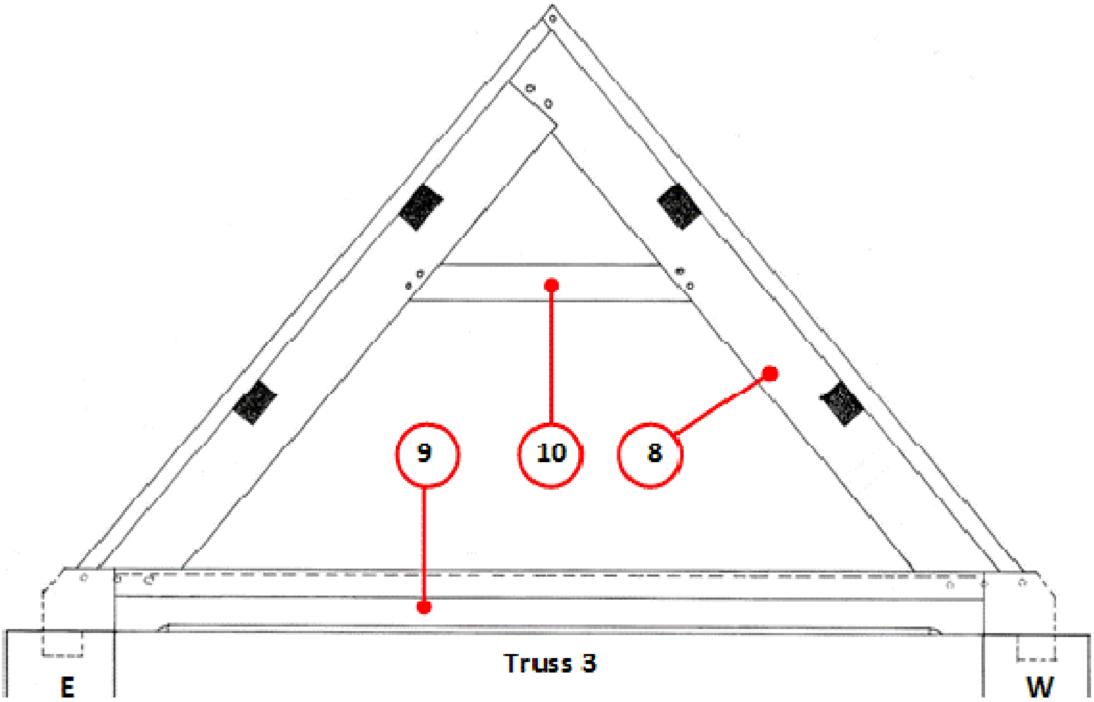


Figure 6a/b: Drawing of the roof trusses to show sampled timbers (after NEVAG forthcoming)



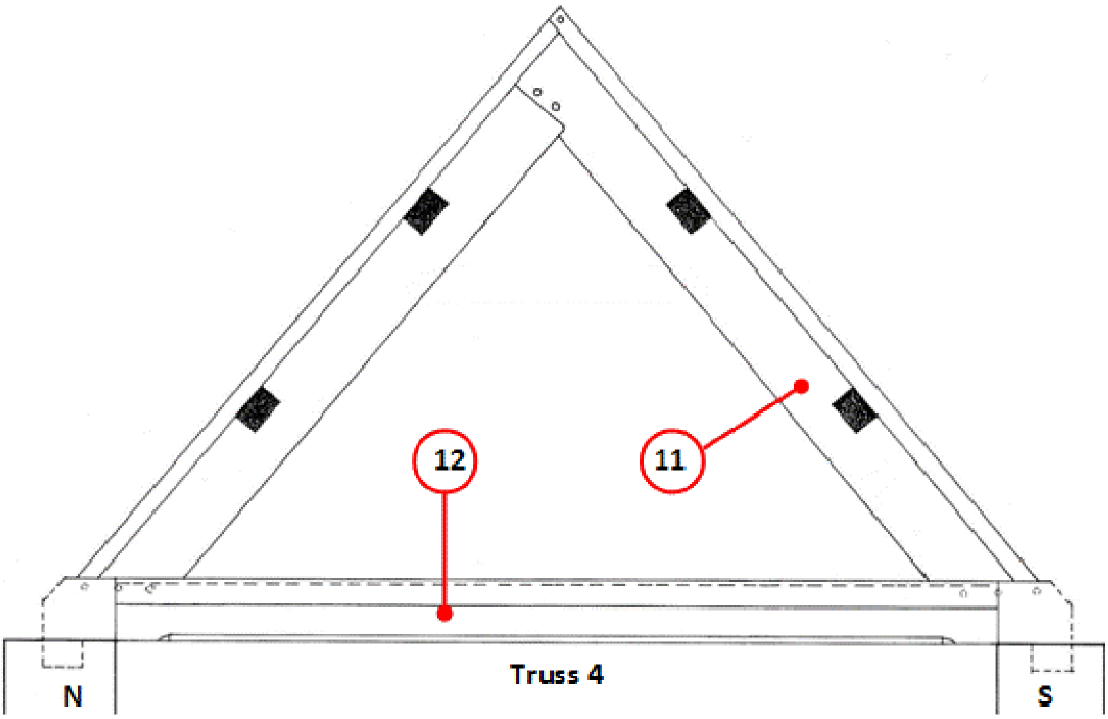
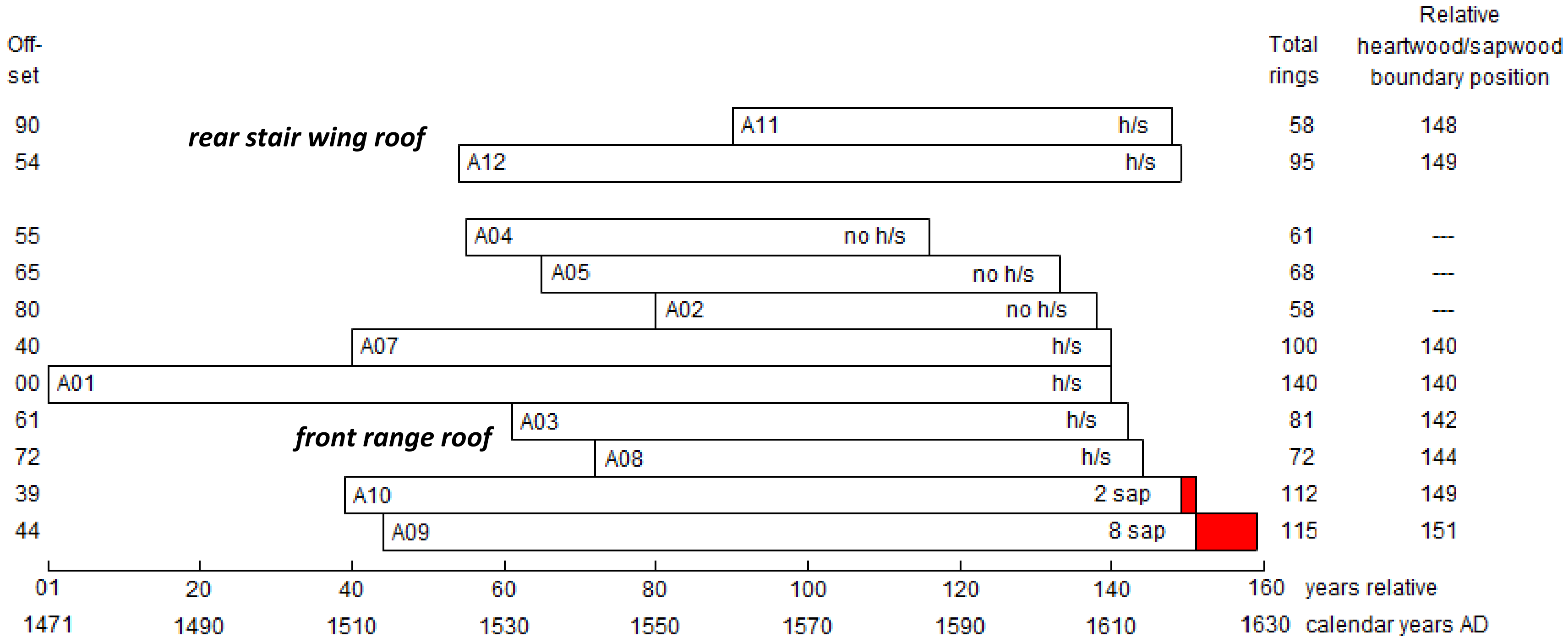


Figure 6c/d: Drawing of the roof trusses to show sampled timbers (after NEVAG forthcoming)



White bars = heartwood rings; Red bar = sapwood rings; h/s = the heartwood/sapwood ring is the last ring on the sample

Figure 7: Bar diagram of the samples in site chronology HEIASQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HEI-A01A 140
204 179 255 237 302 351 288 247 230 169 191 102 195 164 162 156 222 159 168 140
135 118 137 160 161 174 171 130 164 135 140 185 172 174 222 160 98 156 147 181
184 145 92 132 125 144 98 161 178 129 146 153 98 100 110 100 114 110 116 103
112 82 105 159 125 108 91 90 136 129 107 99 125 111 118 88 85 113 79 110
153 98 119 113 138 158 128 175 191 197 159 140 126 137 104 95 67 80 95 139
102 102 96 104 79 75 90 72 112 141 118 98 88 100 112 124 98 44 30 64
49 48 49 57 62 48 49 52 38 61 66 62 74 84 66 79 65 71 62 112
HEI-A01B 140
201 170 255 241 296 350 288 246 257 148 177 107 183 171 158 155 211 167 153 144
128 111 144 166 158 187 168 124 167 131 135 190 173 160 213 157 95 146 164 180
180 146 89 143 127 143 97 152 178 130 146 149 99 102 114 107 104 115 119 114
102 103 91 158 124 105 83 91 139 131 104 89 126 115 110 86 95 89 75 118
163 102 114 111 132 147 131 175 195 197 178 128 131 132 113 94 61 76 98 135
107 103 98 105 85 78 81 80 105 142 108 103 97 104 99 146 114 37 33 59
47 54 50 58 61 48 43 51 44 62 60 66 73 83 73 72 67 81 54 82
HEI-A02A 58
142 162 216 214 266 267 202 206 232 172 241 262 307 255 238 194 142 196 200 270
307 209 270 154 130 159 187 231 177 190 160 116 131 99 123 219 177 119 179 148
104 120 160 188 261 172 170 153 131 66 53 57 89 168 141 189 184 197
HEI-A02B 58
148 167 236 241 269 265 211 207 240 190 264 255 304 257 241 209 145 194 199 295
304 215 284 155 129 169 184 229 184 195 164 126 124 96 131 220 173 113 167 150
105 125 157 181 259 170 174 153 126 77 41 66 85 148 151 198 178 192
HEI-A03A 81
225 271 275 324 352 395 382 509 549 433 319 289 149 105 105 86 108 92 127 243
204 254 328 407 288 165 152 162 149 147 157 152 132 144 130 116 129 184 235 203
202 245 212 217 149 148 163 133 156 105 146 156 148 109 153 119 107 103 69 57
36 43 46 52 51 42 58 48 60 46 40 54 64 65 66 60 62 50 55 52
90
HEI-A03B 81
203 280 271 319 339 386 385 471 570 461 317 289 161 100 105 96 117 81 124 238
224 254 324 417 280 171 139 177 137 153 153 140 128 138 120 115 114 195 206 207
165 284 213 226 141 126 166 144 149 105 139 147 151 115 150 117 101 112 66 52
37 40 45 52 46 52 49 52 64 49 31 56 69 61 66 62 58 52 55 43
84
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308 323 302 358 347 424 327 407 465 470 439 361 347 374 314 216 258 331 331 307
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320 324 323 363 355 426 353 410 446 477 420 382 340 354 315 235 243 343 297 308
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151
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220 73 57 56 90 103 88 101 118 196 223 205 208 278 243 168 261 225 267 271
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143 140 154 145 114 113 56 56 67 50 73 59 78 73 62
HEI-A12B 95
294 319 300 298 332 402 343 277 226 190 212 275 321 401 386 310 310 310 307 315
335 247 226 190 122 146 199 204 196 100 92 81 63 80 118 148 121 120 158 127
119 92 88 128 123 146 114 100 158 159 120 99 165 171 170 230 120 129 121 111
96 144 101 125 139 83 36 72 100 118 132 110 111 121 105 85 72 90 188 137
139 133 155 137 126 90 52 64 62 44 56 64 79 67 59

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

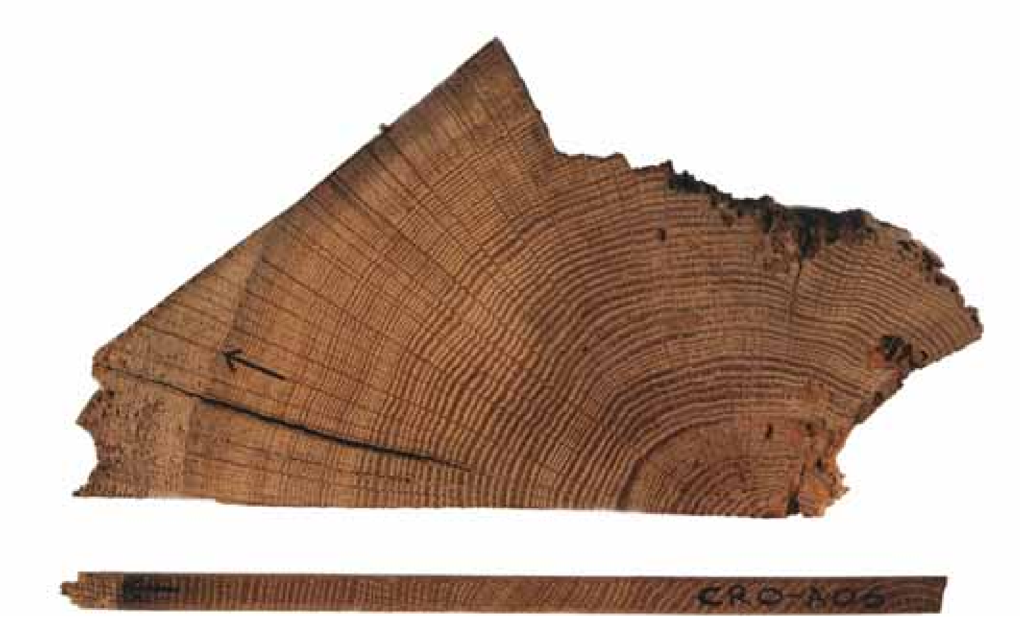


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

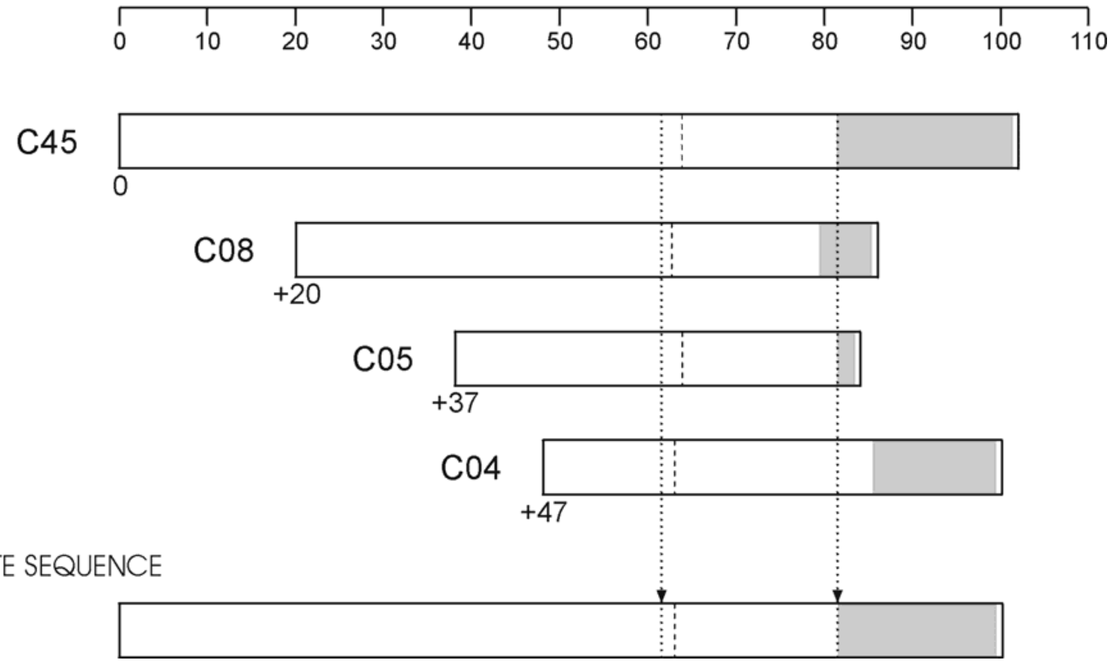


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

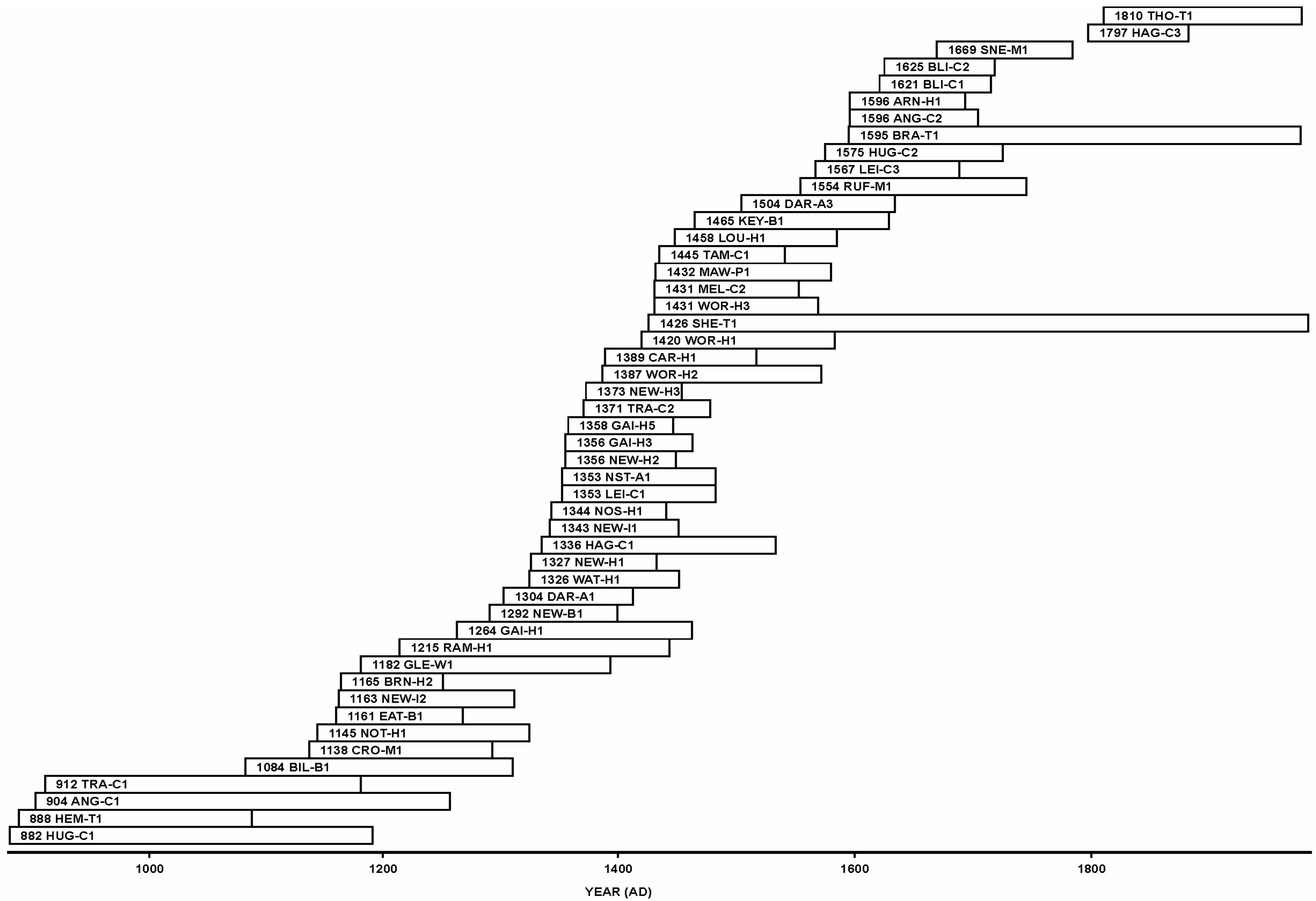
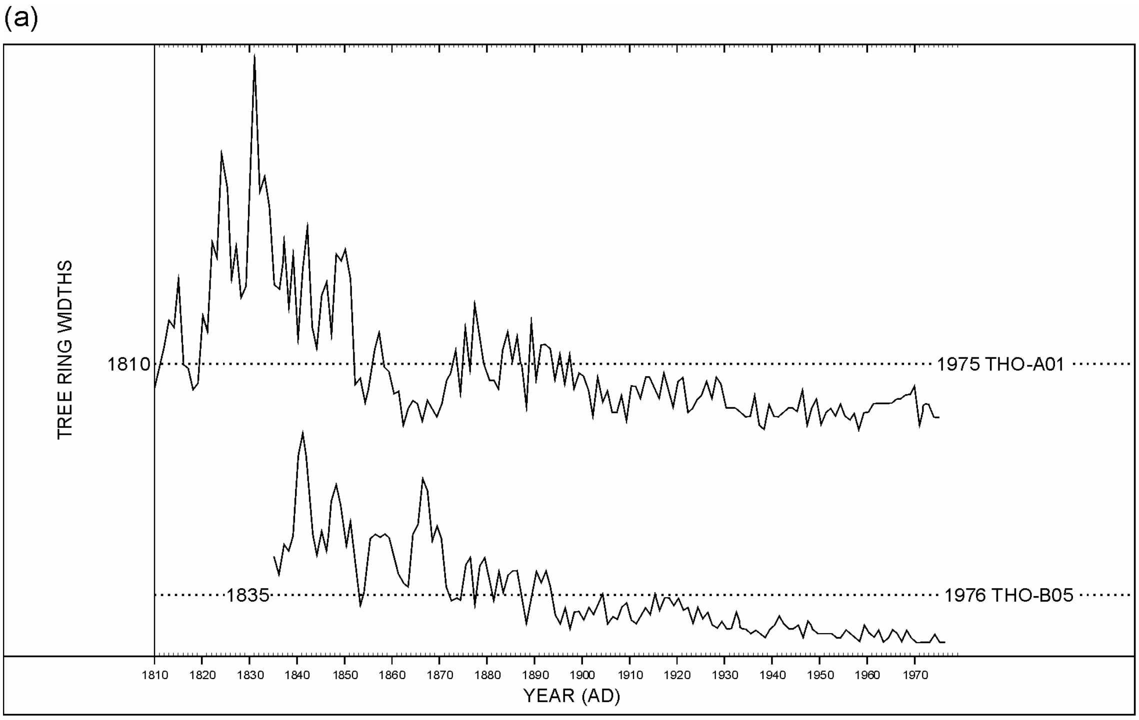


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



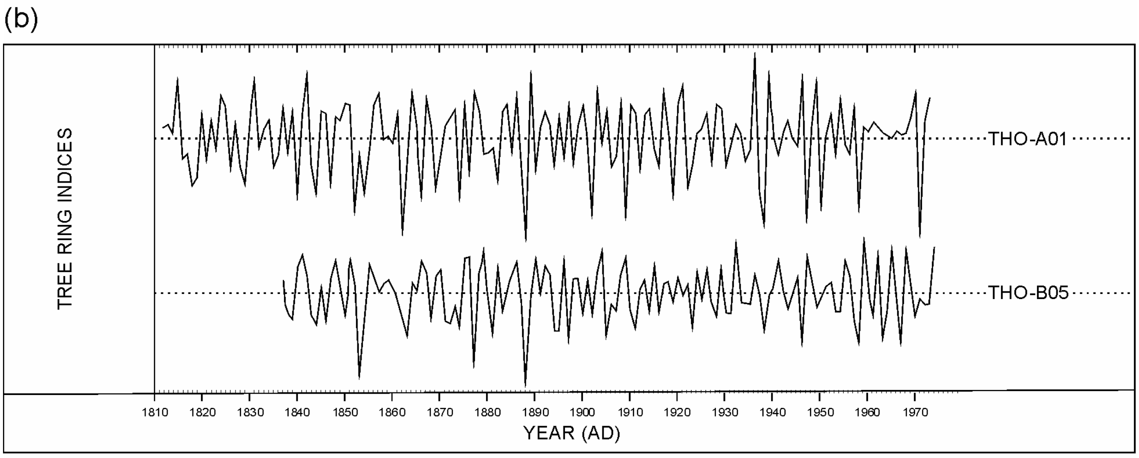


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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 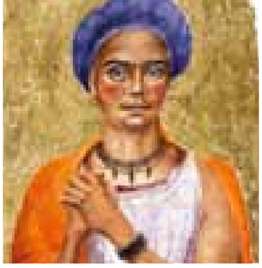   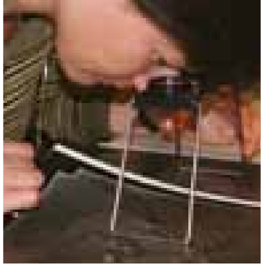 

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