RESEARCH DEPARTMENT REPORT SERIES no. 84-2007 ISSN 1749-8775

THE STONEHOUSE, MOORHOUSE, NEAR CARLISLE, CUMBRIA

TREE-RING ANALYSIS OF TIMBERS FROM THE BARN

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard and Cliff Litton

ARCHAEOLOGICAL
SCIENCE

ENGLISH HERITAGE

Research Department Report Series 84/2007

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ISSN 1749-8775

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Research Department Report Series 84/2007

The Stonehouse, Moorhouse, Near Carlisle, Cumbria
Tree-Ring Analysis of Timbers from the Barn

Alison Arnold[1], Robert Howard[1] and Cliff Litton[2]

Summary

A total of eleven samples was obtained from the timbers within two elements of this barn at Moorhouse, near Carlisle; the two cruck trusses to the east end and the principal-rafter truss to the west end. Of the eleven samples obtained, nine were measured. From this data a single site chronology comprising two samples with a combined overall length of 88 rings could be formed. Despite being compared to an extensive collection of reference chronologies neither this site chronology, nor the seven remaining measured but ungrouped samples, could be dated.

Keywords

Dendrochronology
Standing Building

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Introduction

The Stonehouse at Moorhouse (NGR NY3309956808, Figs 1 and 2), near Carlisle, is believed to have originally been built around AD 1600, possibly entirely of clay. The outbuildings include two clay barns, one of which has crucks. This cruck barn is joined to the farmhouse by a two-storey stone building with an ashlar front and a handsome Renaissance doorway containing the cross-passage. The stone building has domestic-style windows both upstairs and downstairs and appears from the road to be a two-bay service end. Internal inspection, however, shows that the upper floor can only be reached by steps from the clay, cruck, barn, and that it is almost certainly a later insertion between the two.

The cruck barn is a long low building, running parallel to the main street through the village of Moorhouse. A substantial stone wall divides the building into two portions, with two cruck trusses (trusses 'A' and 'B') in the east portion and one principal-rafter truss (truss 'C') in the west portion (Fig 3). It is believed that there is a difference in the date of these two portions of this building, and, indeed, that the two cruck trusses to the eastern end might also be of different dates to each other, there being some slight variation in the form of the crucks, and some evidence for reuse amongst some of the timbers here.

Sampling and analysis by tree-ring dating of timbers from this cruck barn were commissioned by English Heritage. This analysis was undertaken as a part of a pilot research project on the clay buildings of the Solway Plain in Cumbria, which aims to develop a firm evidence base for this nationally important and threatened building type. The project ultimately aims to understand the significance of these historic structures and to inform their conservation, by raising awareness of their historical significance and extent, and promoting a programme of training in the specific craft skills necessary to repair and maintain these buildings.

Sampling

From the suitable timbers available a total of 11 core samples was obtained. This total, which comprised all of the suitable timbers, might have been considered insufficient to date each of the phases represented, but these timbers were sampled on the basis that they were part of the pilot project. Each sample obtained was given the code MRH-E (for Moorhouse, site 'E') and numbered 01–11. Seven samples, MRH-E01–E07, were obtained from the two cruck trusses, A-A1, B-B1, in the east half of the building, with a further four samples, MRH-E08–E11, being obtained from the truss C-C1 in the west half. The positions of these samples are marked on Figures 3 and 4a–c. Details of the samples are given in Table 1. In this Table, all frames or trusses, and individual timbers, are identified and numbered following the format given on the drawings provided.

The Laboratory would like to take this opportunity to particularly thank the former owners of Stonehouse, Mr and Mrs McDonagh, for their great help and hospitality during sampling, and for being so enthusiastic about this project, and the current owners, the Scringeour family, for allowing a further site visit in 2007. We would also like to thank Nina Jennings for her tireless work in instituting this project, for arranging access to the site, and for providing the details in the introduction above. The Laboratory would also like to thank Peter Messenger for his helpful discussions on the possible phasing and interpretation of the building.

Analysis

Each of the 11 samples obtained was prepared by sanding and polishing. It was seen at this time that two samples, MRH-E03 and E05 from the eastern crucks, had less than the minimum of 54 rings required for reliable tree-ring dating, and these samples were rejected from the programme of analysis. The annual growth-ring widths of the remaining nine samples were, however, measured, the data of these measurements being given at the end of the report.

The growth-ring widths of all nine measured samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a minimum value of t=4.5, a single group comprising two cross-matching samples could be formed, these two samples being combined at their indicated positions to form site chronology MRHESQ01 (Fig 5). This has an overall length of 88 rings.

Site chronology MRHESQ01, plus the remaining seven measured but ungrouped samples, were then compared to an extensive collection of reference chronologies for oak. There was, however, no satisfactory cross-matching at any position. Site chronology MRHESQ01 and the seven measured but ungrouped samples must, therefore, remain undated for the moment.

Interpretation and conclusion

Although there is no dating for site chronology MRHESQ01 or any of the individual samples, it would appear very likely that the grouped samples, MRH-E01 and E07, represent timbers felled at the same time. These two samples, from cruck blade A and collar B–B1, respectively, in the eastern half of the barn, have almost identical relative heartwood/sapwood boundary positions. Such similarity is indicative of timbers being felled at the same time. As such, and assuming there is no evidence for reuse, this suggests that the trusses in the eastern half are of the same date.

The lack of cross-matching and dating amongst the other samples is unfortunate, but perhaps not unexpected in a pilot programme on a building such as Stonehouse barn where, as indicated in the introduction above, it is possible that each truss represents a different phase of felling and, with only nine samples measured, each phase is possibly represented by relatively few suitable samples. Furthermore, as a consequence of this possible difference in date, it is also possible that the timbers found in the Stonehouse barn are from different woodland sources and thus less likely to cross-match with each other anyway. In any case, as will be seen from Table 1, whilst all the measured samples do have sufficient rings, some of them are towards the lower limit for reliable dating. To compound this problem, it is noticeable that the growth-ring pattern of some of the samples is slightly erratic, suggesting that they have been affected by some non-climatic feature.

This is not an uncommon phenomenon in dendrochronology, where it is often more difficult to cross-match and date small groups of samples than well-replicated groups of timbers which provide samples with high numbers of rings. This is particularly the case with ‘singletons’. However, despite the present situation, it is quite possible that these samples may in due course be dated when further samples, providing a greater range of data, are obtained from the same locality.

Table 1: Details of samples from Stonehouse barn, Moorhouse, near Carlisle, Cumbria

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
MRH-E01	Blade A	71	h/s	------	------	------
MRH-E02	Collar A–A1	89	h/s	------	------	------
MRH-E03	Backing rafter A1	nm	---	------	------	------
MRH-E04	Blade A1	64	2	------	------	------
MRH-E05	Blade B1	nm	---	------	------	------
MRH-E06	Blade B	54	h/s	------	------	------
MRH-E07	Collar B–B1	88	h/s	------	------	------
MRH-E08	Principal rafter C	72	h/s	------	------	------
MRH-E09	Principal rafter C1	54	10	------	------	------
MRH-E10	Collar C–C1	62	12	------	------	------
MRH-E11	Purlin C1	72	16C	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on the sample

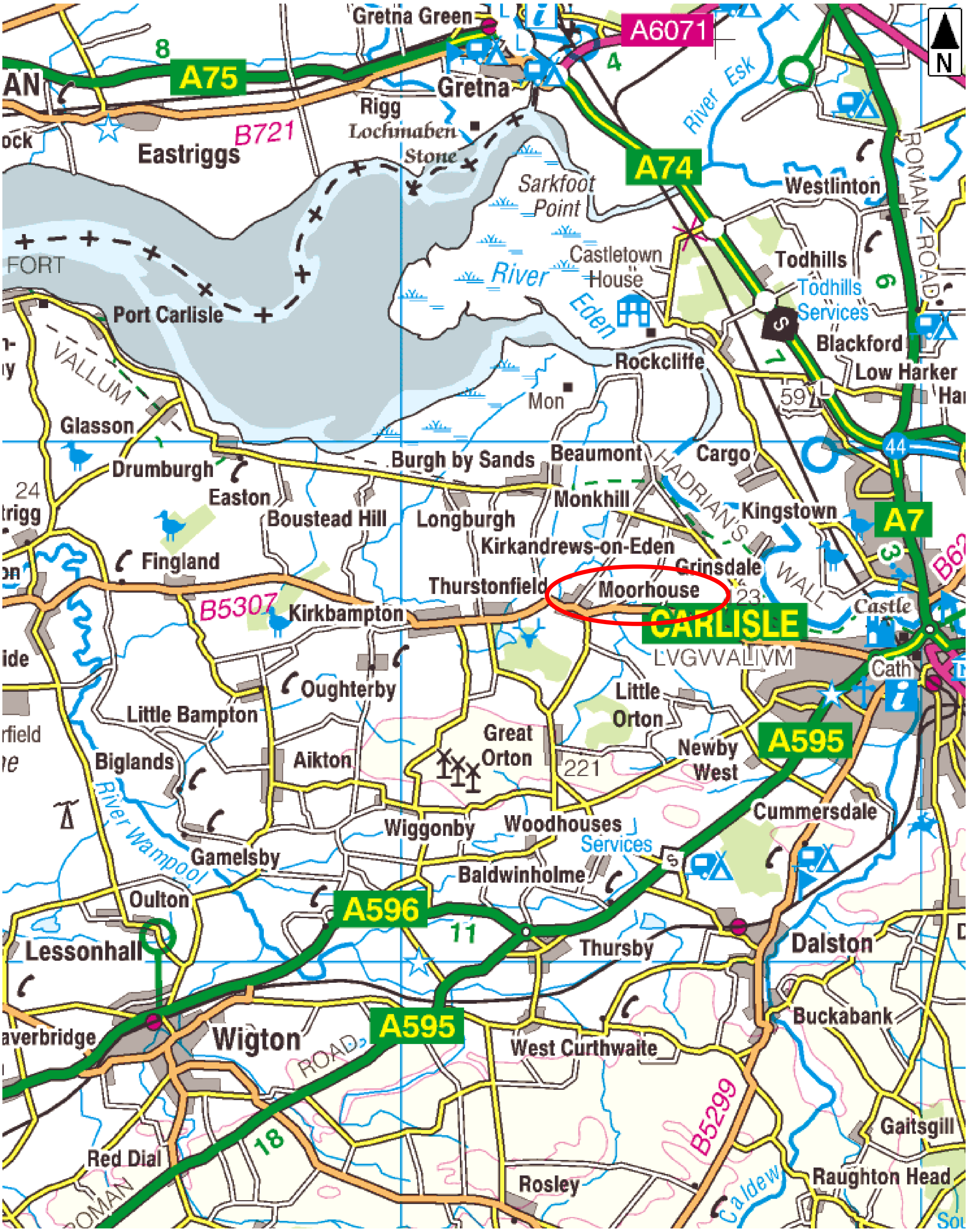

Figure 1: map showing the location of Moorhouse, Cumbria.

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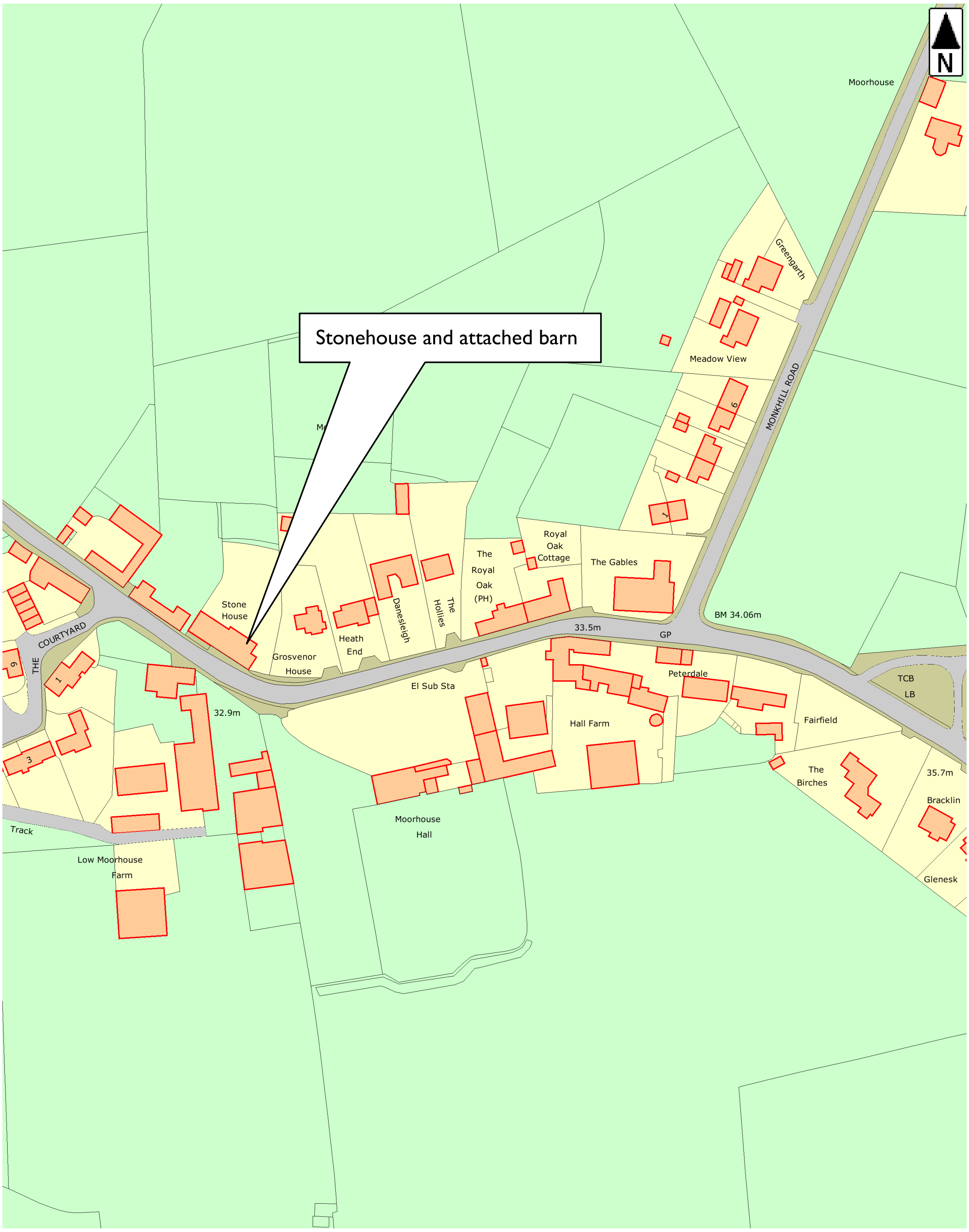

Figure 2: map showing the location of Moorhouse, Cumbria.

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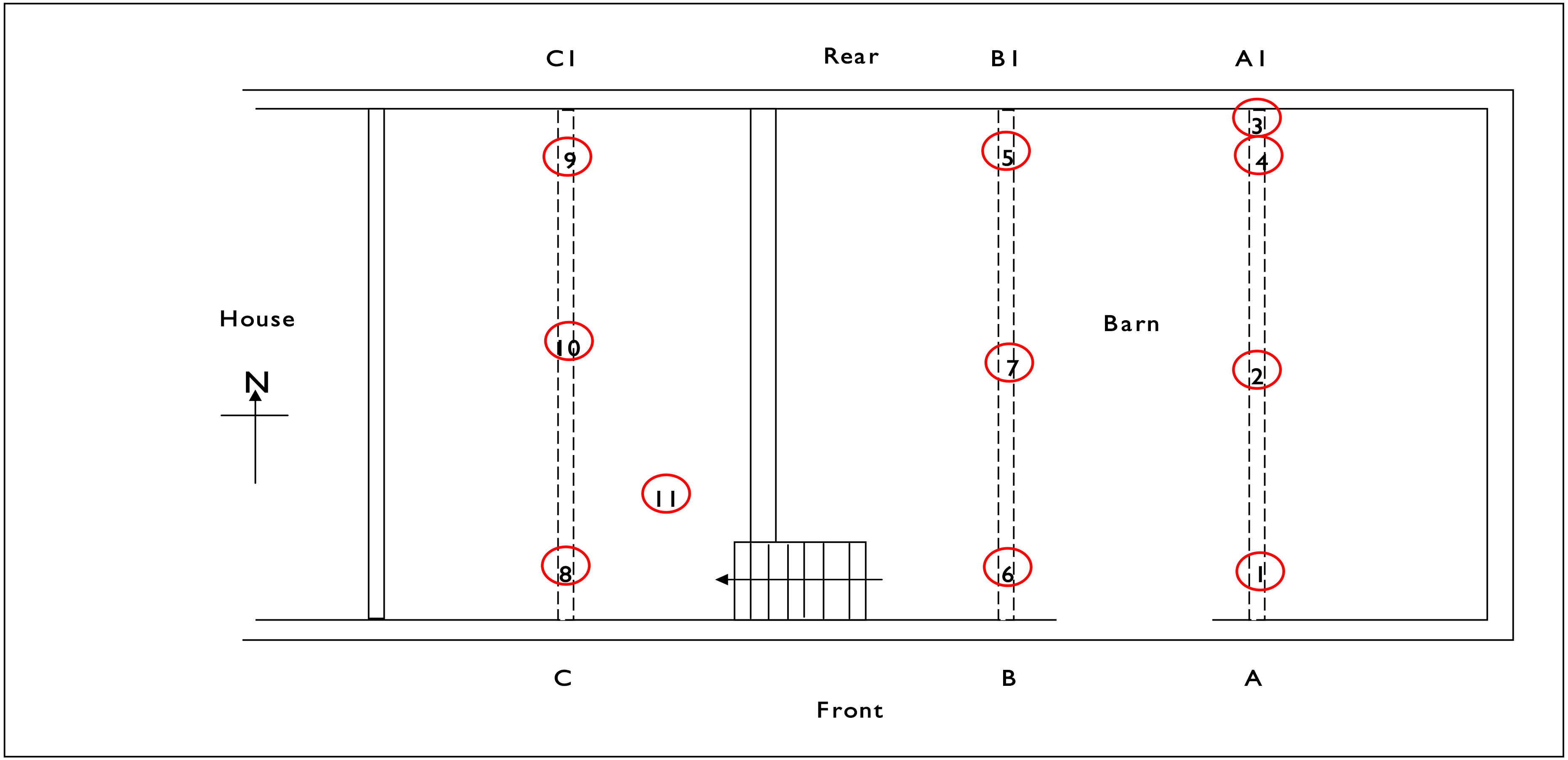
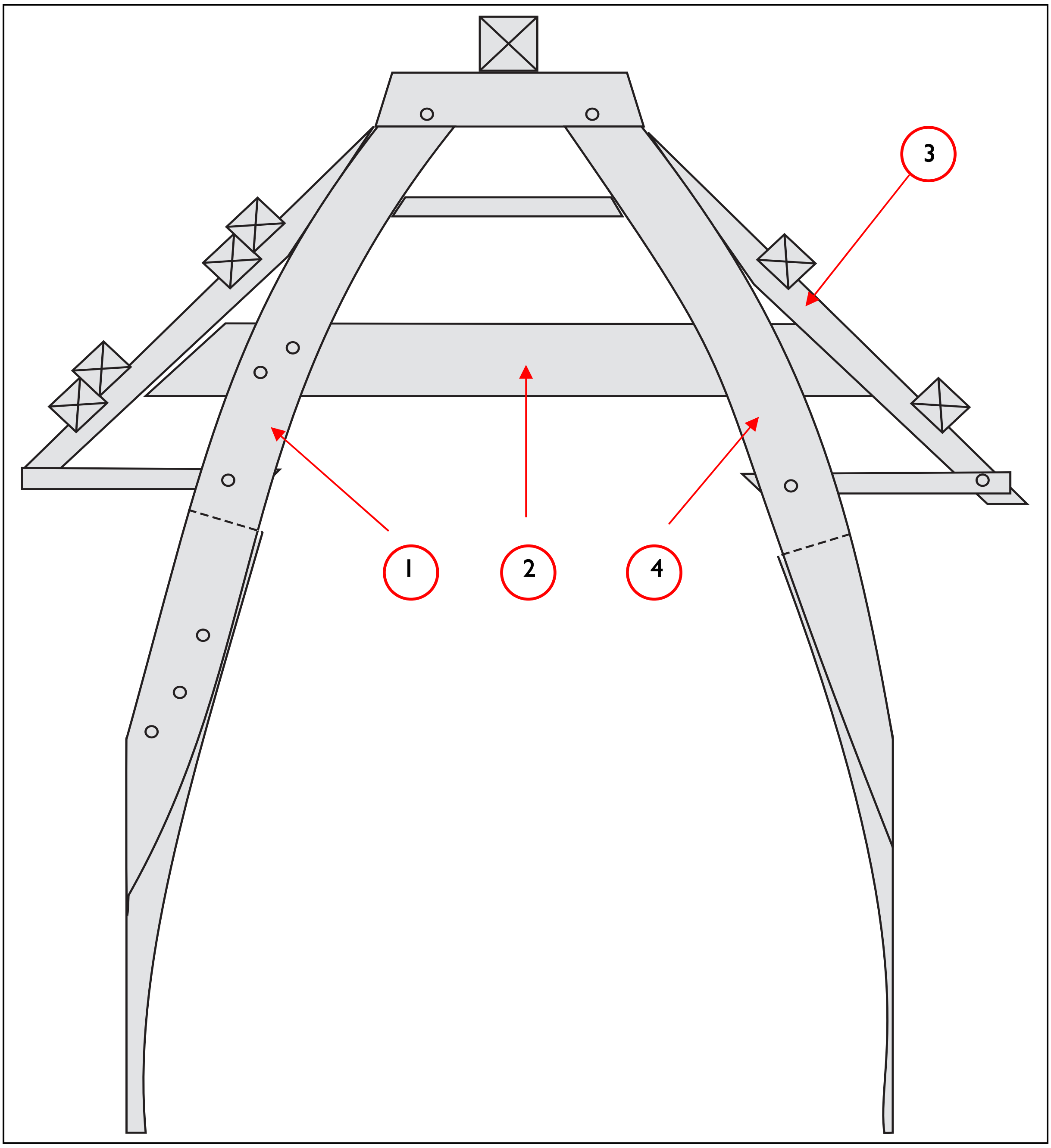


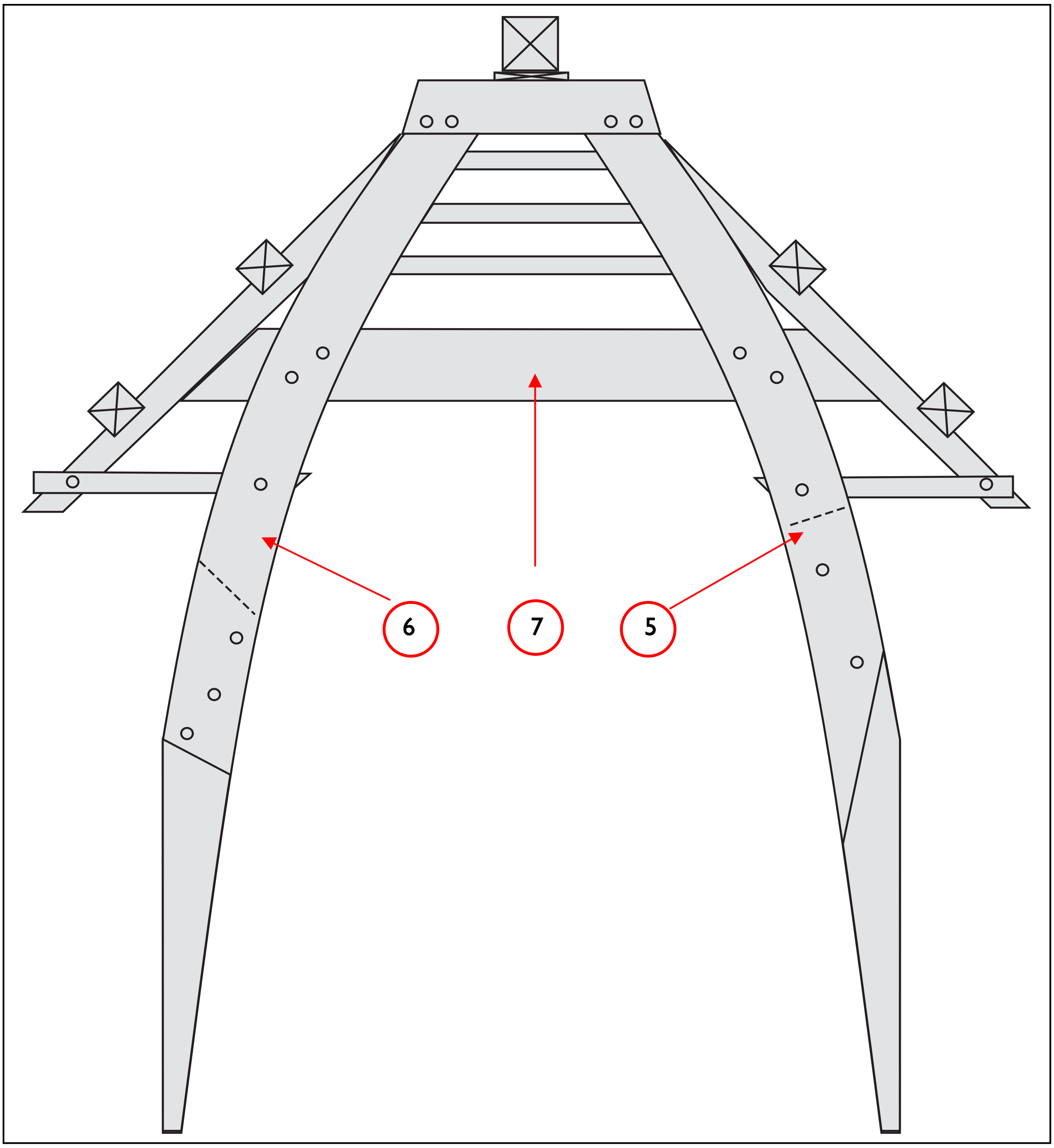
Figure 3: plan of Stonehouse barn, Moorhouse, indicating the positions of the timbers sampled for dendrochronology. Based on an original drawing by Nina Jennings



A (South)

(North) A1

Figure 4a: Schematic section of truss A-A1 to show sampled timbers (viewed from the east looking west)



B (South)

(North) B1

Figure 4b: Schematic section of truss B-B1 to show sampled timbers (viewed from the east looking west)

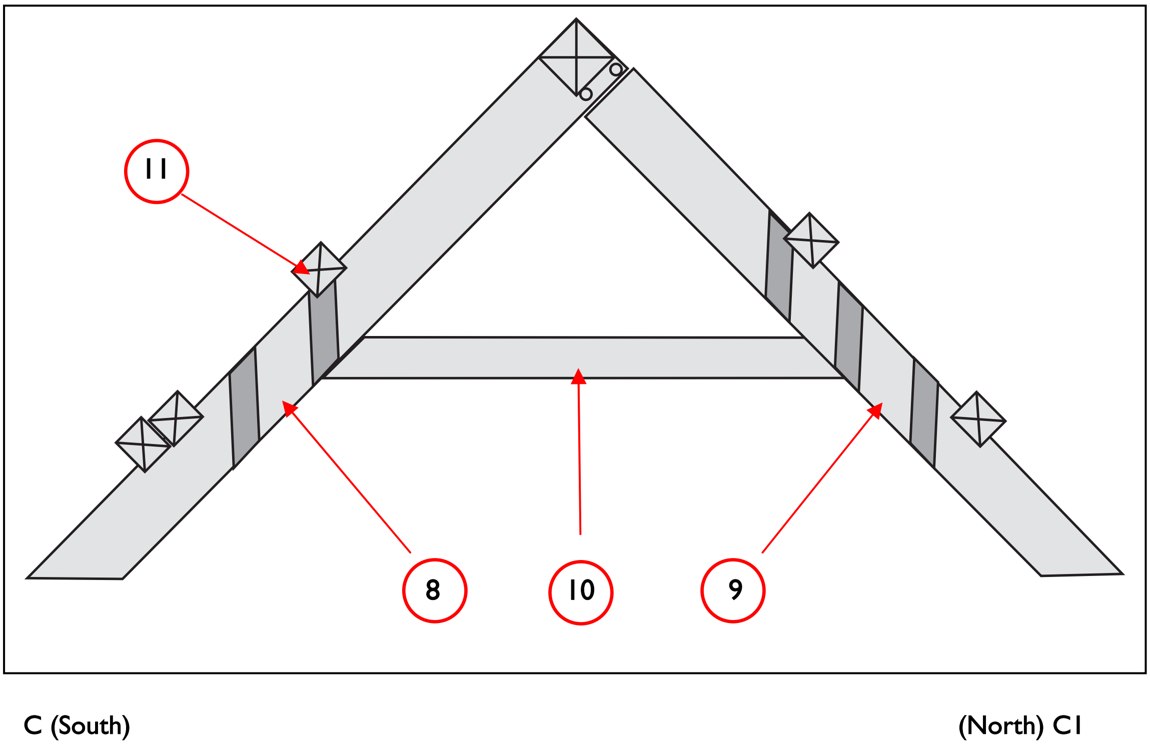
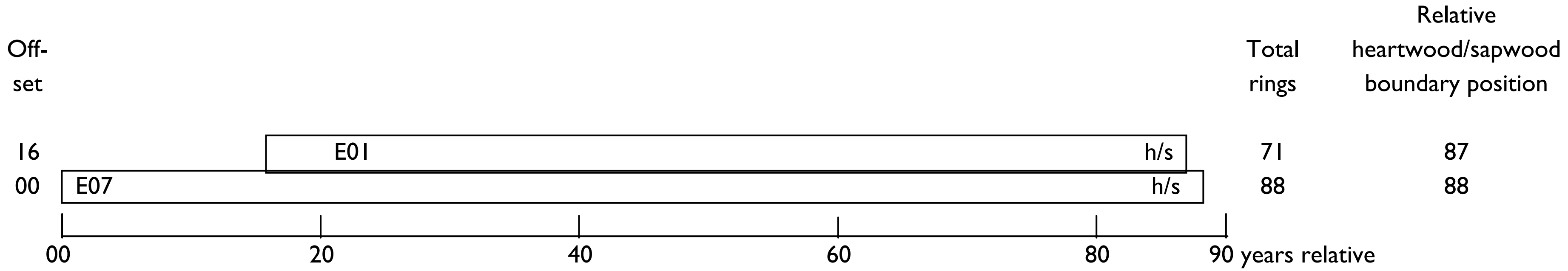


Figure 4c: Schematic section of truss C-C1 to show sampled timbers (viewed from the east looking west)



white bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on the sample

Figure 5: Bar diagram of the samples in site chronology MRHESQ01

Data of measured samples – measurements in 0.01 mm units

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MRH-E01A 71
 135 115 139 154 190 147 151 189 236 224 242 174 139 122  93 157 187 337 244 346
 277 174 218 139 154 169 155 198 214 210 193 213 446 433 314 299 166 215 108  92
 147 138 148 174 214 299 245 115  70 114 143 104 192 285  87  55  76 105  85  89
 115 143 127 134 123 111 100 136 123 186 212
MRH-E01B 71
 142 130 140 153 177 158 155 186 237 224 229 172 148 110  95 165 180 314 213 317
 265 180 204 151 155 154 172 199 219 199 199 214 426 427 314 280 180 239 136 100
 123 153 154 159 212 302 235 104  86 106 147 112 190 293  73  56  81  93  92 109
 102 150 140 166 107 111  89 142 121 188 171
MRH-E02A 89
 474 404 352 356 335 469 304 262 296 276 270 368 330 421 290 309 236 147 192 158
 155 134 112 154 166 125 111 117 132 227 228 237 324 333 240 182 181 206 205 135
 142 185 178 167 135 116 132 157 103 127 136 139 165 161 123 144 194 160 133 121
 104  72  55  57  69  42  33  35  35  44  36  36  40  38  47  36  62  61  55  59
  60  53  48  57  62  53  64  50  56
MRH-E02B 89
 436 419 349 356 331 449 307 263 286 291 263 378 332 421 303 300 230 163 195 155
 149 145 112 149 166 134 101 122 126 225 212 231 330 351 223 189 212 185 200 122
 125 189 185 168 129 127 126 149 111 117 142 148 148 104 136 122 196 153 115 128
 102  73  59  57  66  36  41  29  38  43  39  36  38  38  50  47  59  55  52  62
  64  61  58  48  65  59  56  53  70
MRH-E04A 64
 472 407 570 454 496 523 345 187 130 183 165 195 200 258 230 232 257 190 244 254
 263 126  48  34  38  49  45  76 127  58  42  65  54  51  67  80  42  31  36  32
  53  62  84 101  80  57  81 115 188  83 146  97  70 104  87  74  84 168 124  99
  63 119 143 214
MRH-E04B 64
 477 419 567 454 511 501 356 186 119 194 145 185 207 266 243 268 243 197 238 253
 260 121  55  34  31  45  45  73 130  98  55  67  53  51  65  84  46  43  29  55
  56  70 100 122  87  70 100 106 204 150  95  92  80 109  88  71  97 181 118  94
  73 103 162 219
MRH-E06A 54
 138 138 238 516 497 259 350 250 308 270 273 194 251 366 358 384 369 386 258 332
 310 321 239 138 283 346 290 368 330 317 309 271 176 253 316 306 295 262 339 329
 288 299 308 390 321 341 237 342 200 247 163 209 283 219
MRH-E06B 54
 159 132 246 504 504 252 351 246 303 282 281 186 258 369 352 391 351 394 249 344
 318 325 233 135 298 343 279 355 322 332 304 260 185 271 300 295 300 274 342 314
 293 302 319 393 320 329 255 334 210 215 167 207 274 221
MRH-E07A 88
 194 186 298 328 288 400 334 285 297 319 231 253 458 333 223 200 249 223 151 146
 147 131 136 161 186 168 171 130 119 110  70 113 110 157 175 159  94 114 130 112
 102 133 104 126 117  61  68  89 169 180 152 145 137 135  84  65  81  86  56  84
  82  97 150  62  64  69  50  73  73 106  61  82  72  69  66  51  53  92  81  80
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  52  39  35  47  50  49  49  47
MRH-E07B 88
 218 180 288 322 283 393 326 313 286 305 216 237 463 358 207 199 241 229 141 135
 141 129 149 172 175 178 160 131 110 123  61 114 103 147 148 156 111 111 117 131
  93 132 108 125 118  66  65  82 176 185 158 150 139 141  69  64  94  80  59  69
 105  91 159  69  61  66  54  72  76  99  64  87  70  79  60  42  61  87  94  75
  48  40  34  47  44  51  45  43
MRH-E08A 72
 204 168 197 209 207 120 126 125 156 180 301 242 219 229 327 198 168 177 145 104
  88 159 215 316 399 445 506 267 357 238 247 273 234 338 304 344 260 284 231 335
 316 456 253 217 167 112 163 212 234 431 303 316 261 167 103 152 264 310 282 192
 168 178 153 179 272 304 156 178 173 212 232 242
MRH-E08B 72
 204 171 199 208 207 120 131 112 158 185 308 246 228 222 338 187 177 158 139 102
  99 165 214 305 407 438 565 265 365 214 256 276 243 328 321 344 285 293 213 334
 326 485 280 231 174 100 158 235 221 413 317 324 269 155  99 164 264 316 274 173
 187 185 156 173 269 301 152 179 168 256 211 228
MRH-E09A 54
  94  80 326 142 196  95  29  56  87 164 151 173 119 110 239 247 380 167 230 264
 240 232 122 107 207 253 200 147  89 157 201 209 222 205 239 162 161 207 282 376
 301 240 279 129  69  50  48  40  54  72 122 130 119  99
MRH-E09B 54
  86  83 338 142 205  66  35  56  87 163 165 167 116  96 265 249 362 170 244 252
 257 215 134  90 211 256 190 151  73 159 216 241 263 250 229 163 165 190 308 352
 328 224 278 150  61  48  46  42  53  72 114 134 123 103
MRH-E10A 62
 298 203 293 433 418 394 379 547 349 437 400 457 376 493 429 387 329 399 341 342
 415 334 352 305 254 188 226 271 252 304 297 248 318 293 255 238 173 258 203 247
 218 300 231 300 237 189 102  79 110 241 254 304 235 375 311 291 184 180 174 174
 146 238
MRH-E10B 62
 303 216 320 400 418 396 391 549 377 440 403 462 374 487 437 373 333 389 351 335
 414 339 345 306 264 181 224 264 244 302 296 260 296 291 264 237 197 270 193 231
 224 310 213 313 238 205 105  72 100 250 240 311 241 372 321 300 187 191 187 166
 150 223
MRH-E11A 72
  97  86  49  73  98 164 144 126 110  82 109 116  49  98  70  70  51  50  58  72
  49  57  73  56  63  64  61  55  92  79 117 100  63 101 101  77  44  50 130 280
 203 138 135 128 216 202 115  98  61  69  66  96 176 182 183 138  98  68  71  92
 128 145 188 211 256 257 244 161 145 126 125 150
MRH-E11B 72
  95  78  53  73 100 174 146 131 123  95 102 119  54  95  81  68  50  52  57  68
  53  62  73  57  64  59  78  51  84  94  96  86  62 104 112  61  41  55 116 247
 200 131 134 130 217 201 116  95  67  68  61  89 177 174 193 132 103  65  71  87
 131 141 197 196 245 267 254 159 143 126 120 137
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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 1 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 1, 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 2 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 to 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 2; it is about 15cm long and 1cm 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 1: 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 2: Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Figure 3: 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 4: 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 2. 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 3).

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 4). 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 5 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 5. 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 5 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months 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 2, 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 and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56)).

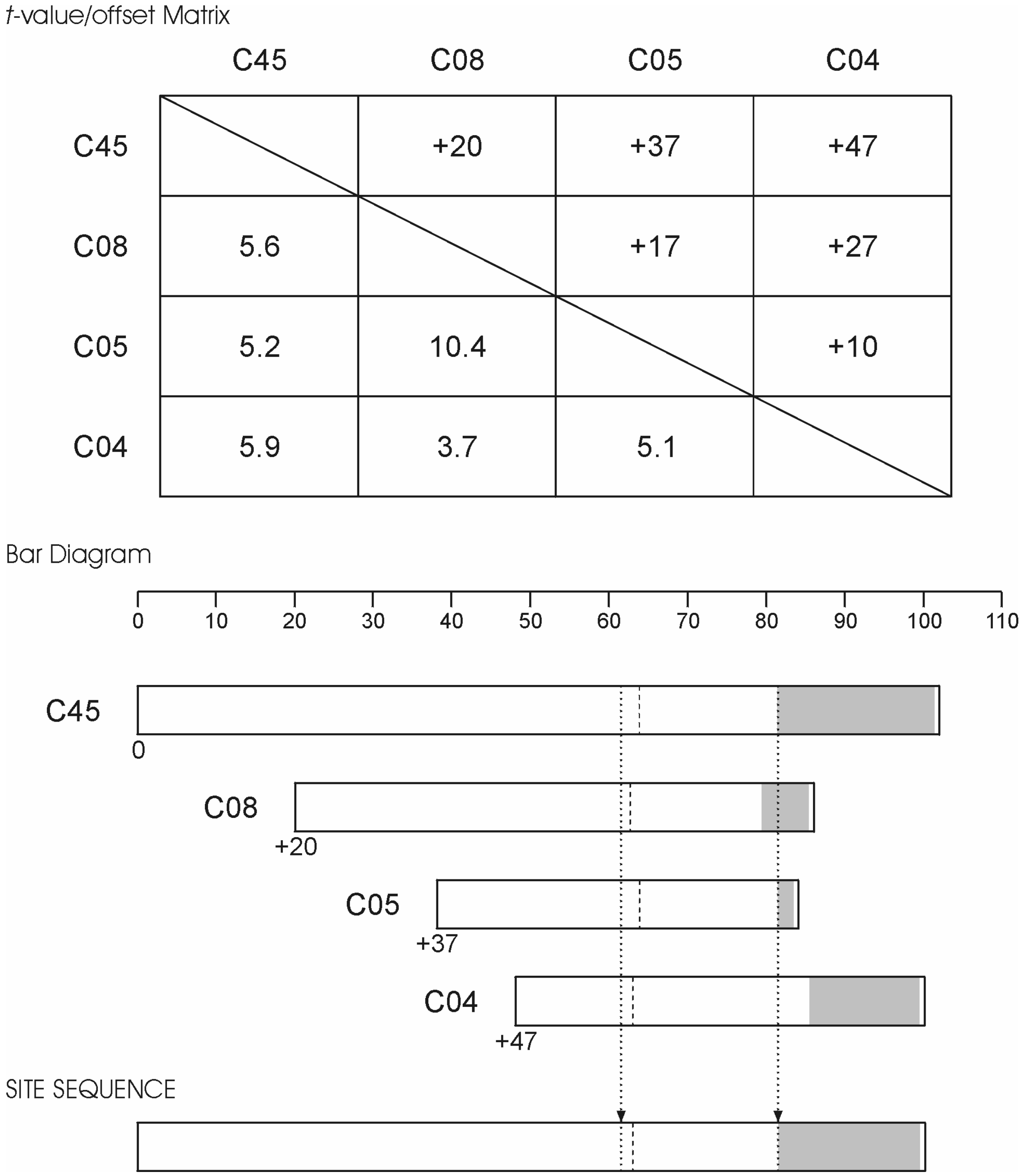
Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still 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 2 cm, 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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 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 Fig 6. 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 Fig 7. 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	

Figure 5: 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.

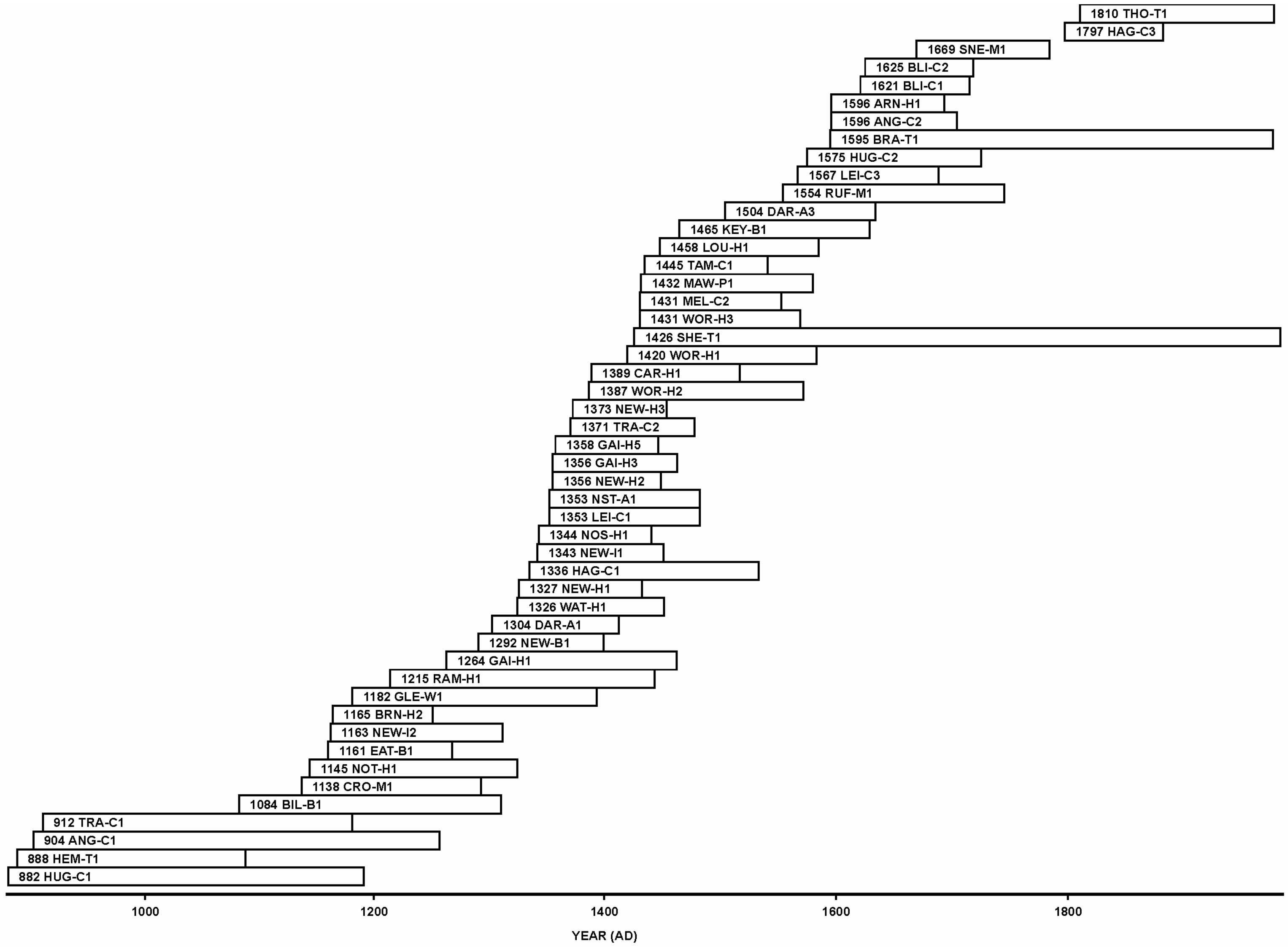
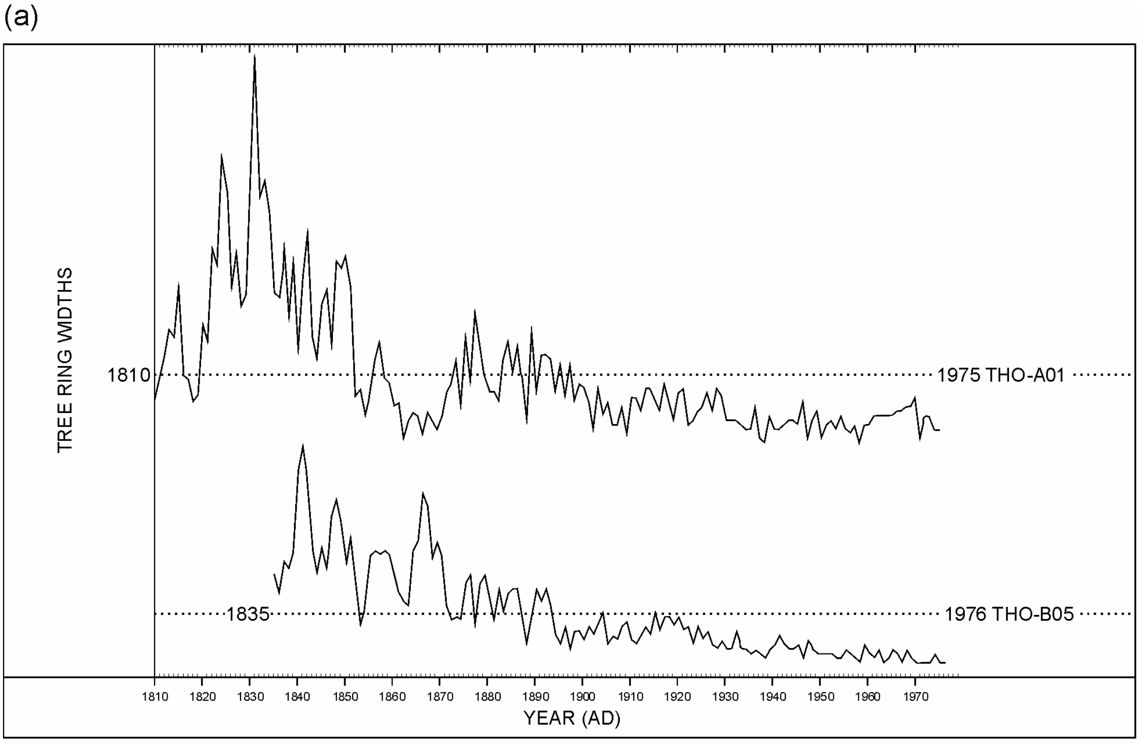


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



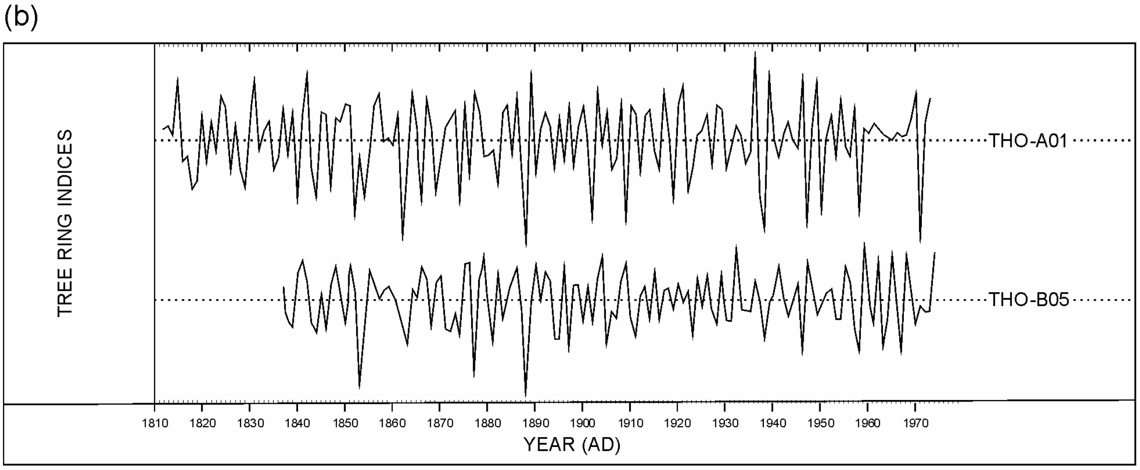


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Figure 7 (b): The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

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