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HIGH BEECHES AND THE HOLLIES, THURSTONFIELD, BURGH-BY-SANDS, CUMBRIA
TREE-RING ANALYSIS OF TIMBERS FROM THE BARN

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard and Cliff Litton

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

Summary

The timbers within this cruck barn at Thurstonfield, Cumbria, possibly represent three separate phases of construction, each potentially of a different date. From these timbers a total of 16 core samples was obtained. Of this number 12 were measured whilst four samples were rejected as having too few rings for reliable analysis. From the data of the measured samples, a single site chronology, BBSDSQ01, comprising two samples, could be created, having an overall length of 140 rings.

Despite being compared to an extensive collection of reference chronologies neither site chronology BBSDSQ01, nor the 10 remaining measured but ungrouped samples, could be dated.

Keywords

Dendrochronology
Standing Building

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Introduction

The clay barn at High Beeches and The Hollies, Thurstonfield (NGR NY3158156673, Figs 1 and 2), is a long tall structure of 13 unequal bays formed by seven cruck trusses and four relatively modern, probably twentieth-century, sawn softwood trusses. There are several stone and brick extensions, both gables have been replaced in brick, and the building is now divided between two residences. While it is possible that the variation in bay width is the result of the removal of some cruck trusses, several factors suggest that the barn may in fact be of three phases, or was at one time three separate structures. These factors include the grouping of differently formed trusses along the length of the barn, the thick divisions between some bays which might at one time have been external walls, and a slight difference in the alignment of the barn along its length.

Of interest at this particular site are the timbers of the seven cruck trusses which appear to vary in form along the length of the barn forming one group of three trusses, A–C, and two groups of two trusses, D–E, and F–G, these latter trusses each represented by a single cut-off blade (Figs 3–5). It is believed that there might be differences in date between these forms.

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 16 core samples was obtained, the samples being spread as widely and as evenly as possible between the seven trusses. This total, which comprised all of the suitable timbers, might have been considered insufficient to date three separate phases, but these timbers were sampled on the basis that they were part of the pilot project. Each sample obtained from was given the code BBS-D (for Burgh by Sands, site 'D') and numbered 01–16. The positions of these samples are marked on Figures 3 and 6a–e. Details of the samples are given in Table 1. In this Table all the trusses are identified from west to east following the schema on the plans provided.

The Laboratory would like to take this opportunity to particularly thank Mr and Mrs Allison and Mr and Mrs Gray, joint owners of the barn, for their help and cooperation during sampling. We would also like to thank Nina Jennings for her indefatigable efforts in establishing 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 16 samples obtained was prepared by sanding and polishing. It was seen at this time that four samples, BBS-D04, D05, D10, and D16, 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 all the remaining 12 samples were, however, measured, the data of these measurements being given at the end of the report.

The growth-ring widths of all 12 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 samples with a combined overall length of 140 rings could be formed. The cross-matching samples were combined with each other at their indicated positions (Fig 4) to form site chronology BBSDSQ01.

Site chronology BBSDSQ01, plus the remaining 10 measured but ungrouped samples, was then compared to an extensive collection of reference chronologies for oak. There was, however, no satisfactory cross-matching at any position. All the samples must, therefore, remain undated for the moment.

Interpretation and conclusion

Although there is no dating for any site chronology or any of the individual samples, it would appear very likely that the grouped samples in site chronology BBSDSQ01 represent timbers felled at the same time. The two cross-matching samples, BBS-D13 and D14, from cruck blades E and E1 respectively, have very similar relative heartwood/sapwood boundary positions. Such similarity is indicative of timbers being felled at the same time. There was no evidence, such as mirrored knots, centre-line shakes, or shape of the timbers, that would indicate that the blades of truss E – E1 are derived from the same tree, each being formed from separate trees. Indeed, this can be said for all the trusses, each blade of which appears to be formed from a separate whole tree, which has been subject to varying degrees of trimming and squaring-up.

This unfortunate lack of cross-matching and dating may be due to a number of factors. The most likely is the low numbers of rings found in many of the samples. Whilst all the measured samples have sufficient rings for reliable analysis, the numbers are towards the lower end of the acceptable scale; as can be seen in Table 1, although the longest ungrouped sample, BBS-D11 has 74 rings, most of the others have less than 60 rings. Also of note in Table 1 is the fact that the four samples with the highest number of rings all come from truss groups D and E, which, although not dated, may signify that the trees used represent a distinct group, possibly from a different source and of a different date.

Other compounding factors adversely affecting the dendrochronological potential of this group of timbers might be the possible variability in date and/or source of the timber within each group of trusses. Truss group A – C, the timbers for which might be of one date and from one source, is represented by only seven measured samples. Whilst this is not an unacceptably low number of samples it is not as high as generally recommended for successful dating (English Heritage 1998). Trusses D – E, and F – G, whose timbers might be of a second and third date or source, are represented by only four and one measured sample respectively. Smaller numbers of samples, which sometimes do not contain sufficient climatic data, are often more difficult to date 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.

References

English Heritage, 1998 *Dendrochronology. Guidelines on producing and interpreting dendrochronological dates*, London (English Heritage)

Table 1: Details of samples from High Beeches and The Hollies barn, Thurstonfield, Burgh by Sands, Cumbria

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
BBS-D01	Cruck blade A	58	h/s	------	------	------
BBS-D02	Cruck blade A1	56	2	------	------	------
BBS-D03	Collar A – A1	55	h/s	------	------	------
BBS-D04	Cruck blade B	nm	---	------	------	------
BBS-D05	Cruck blade B1	nm	---	------	------	------
BBS-D06	Collar B – B1	57	h/s	------	------	------
BBS-D07	Cruck blade C	57	4	------	------	------
BBS-D08	Cruck blade C1	61	6	------	------	------
BBS-D09	Collar C – C1	54	h/s	------	------	------
BBS-D10	Cruck blade D	nm	5	------	------	------
BBS-D11	Cruck blade D1	74	30C	------	------	------
BBS-D12	Collar D – D1	101	34C	------	------	------
BBS-D13	Cruck blade E	112	19	------	------	------
BBS-D14	Cruck blade E1	127	9	------	------	------
BBS-D15	Cruck blade F	59	h/s	------	------	------
BBS-D16	Cruck blade G	nm	no h/s	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
nm = sample not measured
C = complete sapwood retained on the sample

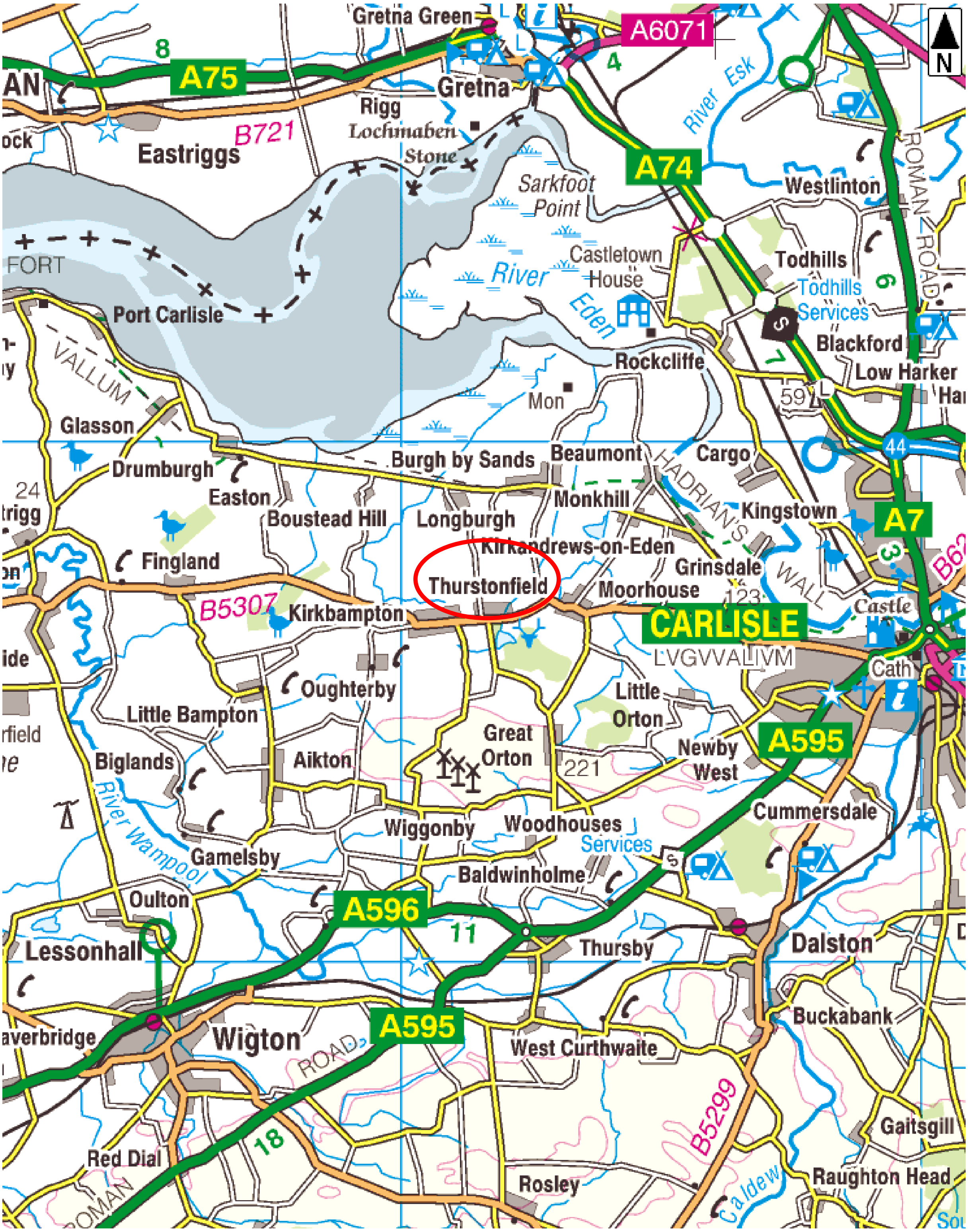


Figure 1: map showing the location of Thurstonfield, Cumbria.

Figure 2: map showing the location of the barn at High Beeches and The Hollies, Thurstonfield, Cumbria.

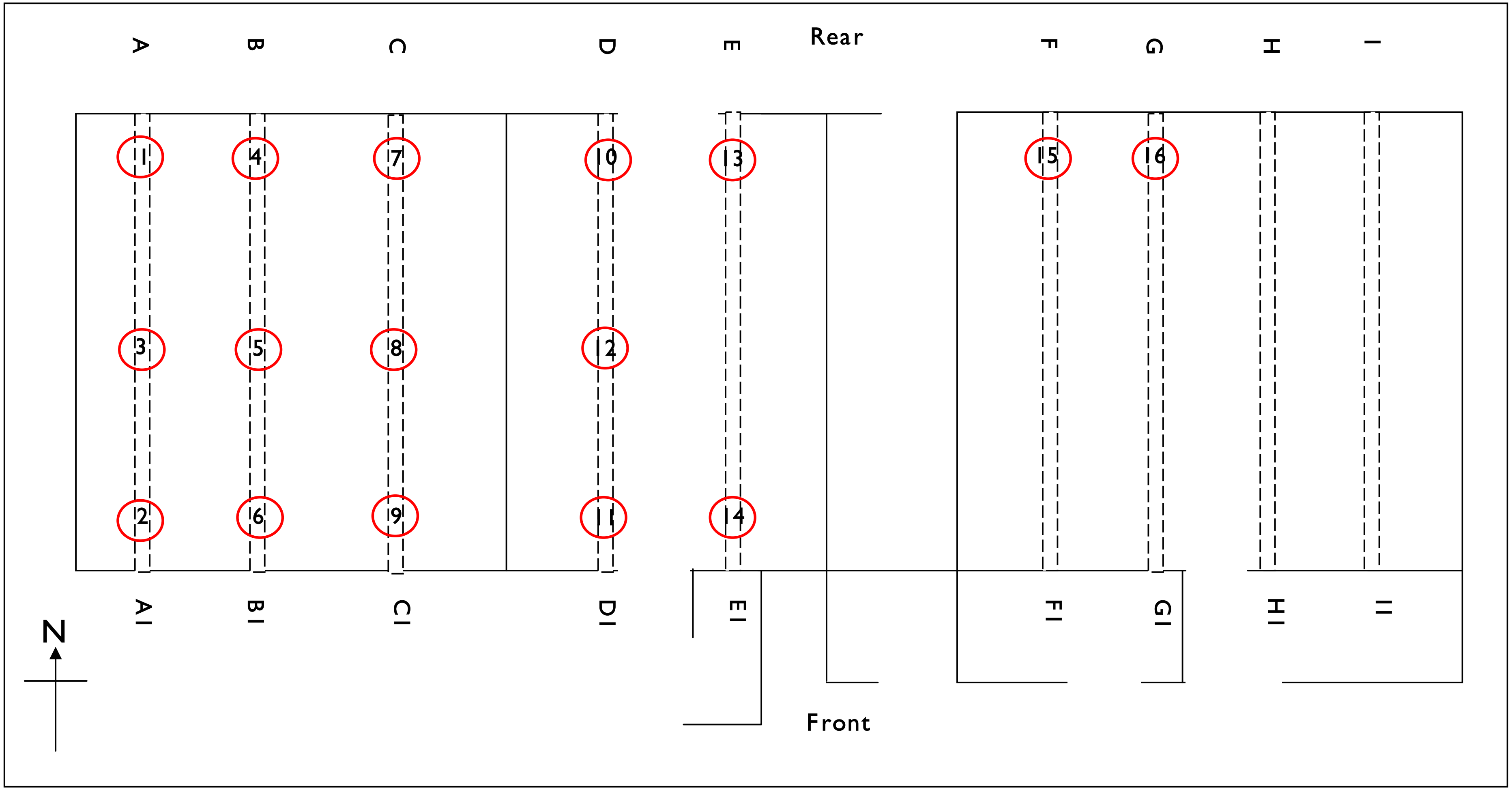


Figure 3: plans of clay buildings at High Beeches and The Hollies, Thurstonfield, indicating the positions of the timbers sampled for dendrochronology. Based on original drawings by Nina Jennings

Figure 4: Cruck truss E-E1 at High Beeches and The Hollies, Thurstonfield

Figure 5: Truncated cruck blades F (left) and G, High Beeches and The Hollies, Thurstonfield, which were sampled for dendrochronology

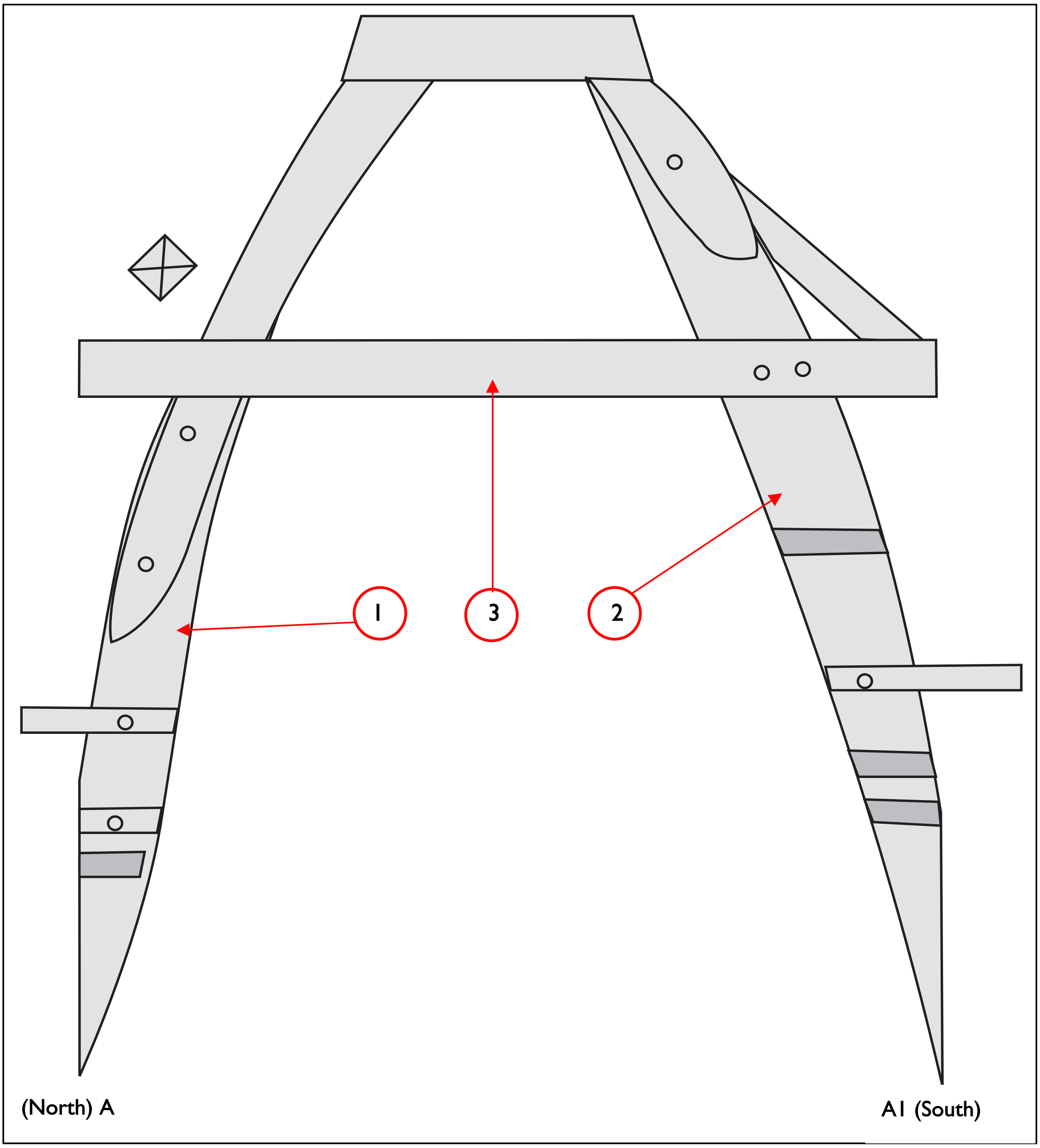


Figure 6a: Schematic section of truss A-A1 to show sampled timbers. Dark shading indicates empty half-lap joints (viewed from the west looking east)

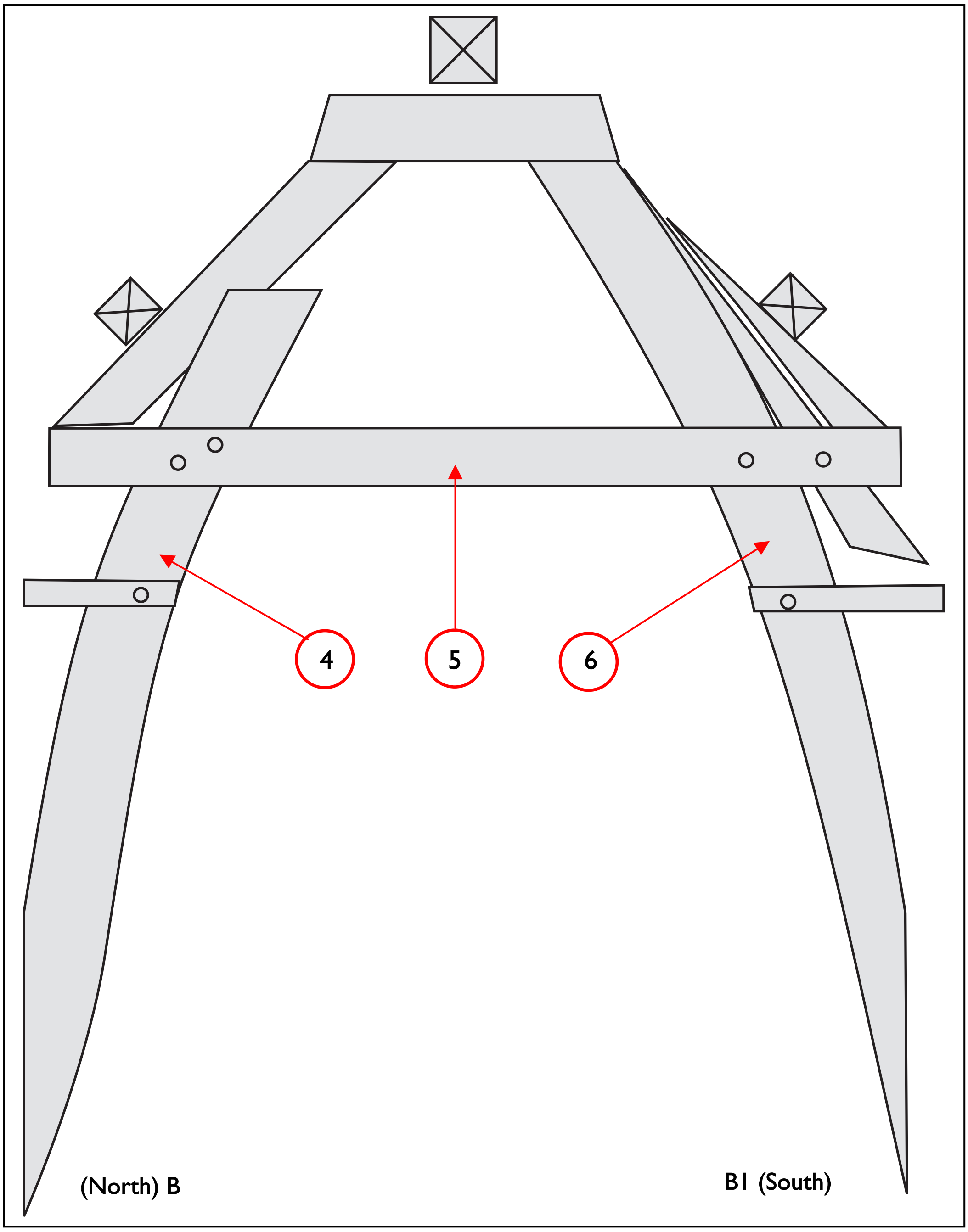


Figure 6b: Schematic section of truss B-B1 to show sampled timbers
(viewed from the west looking east)

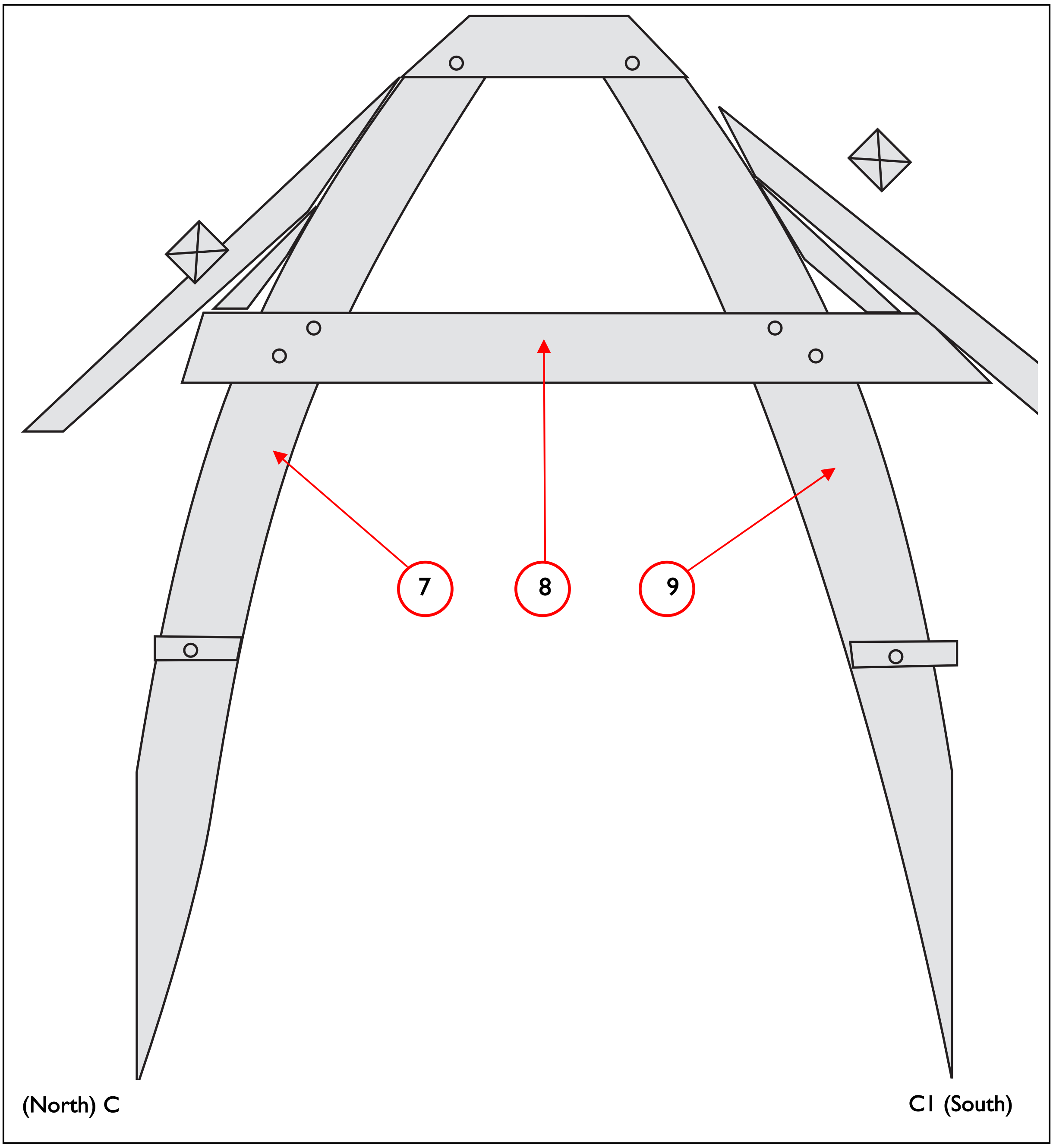


Figure 6c: Schematic section of truss C-C1 to show sampled timbers
(viewed from the west looking east)

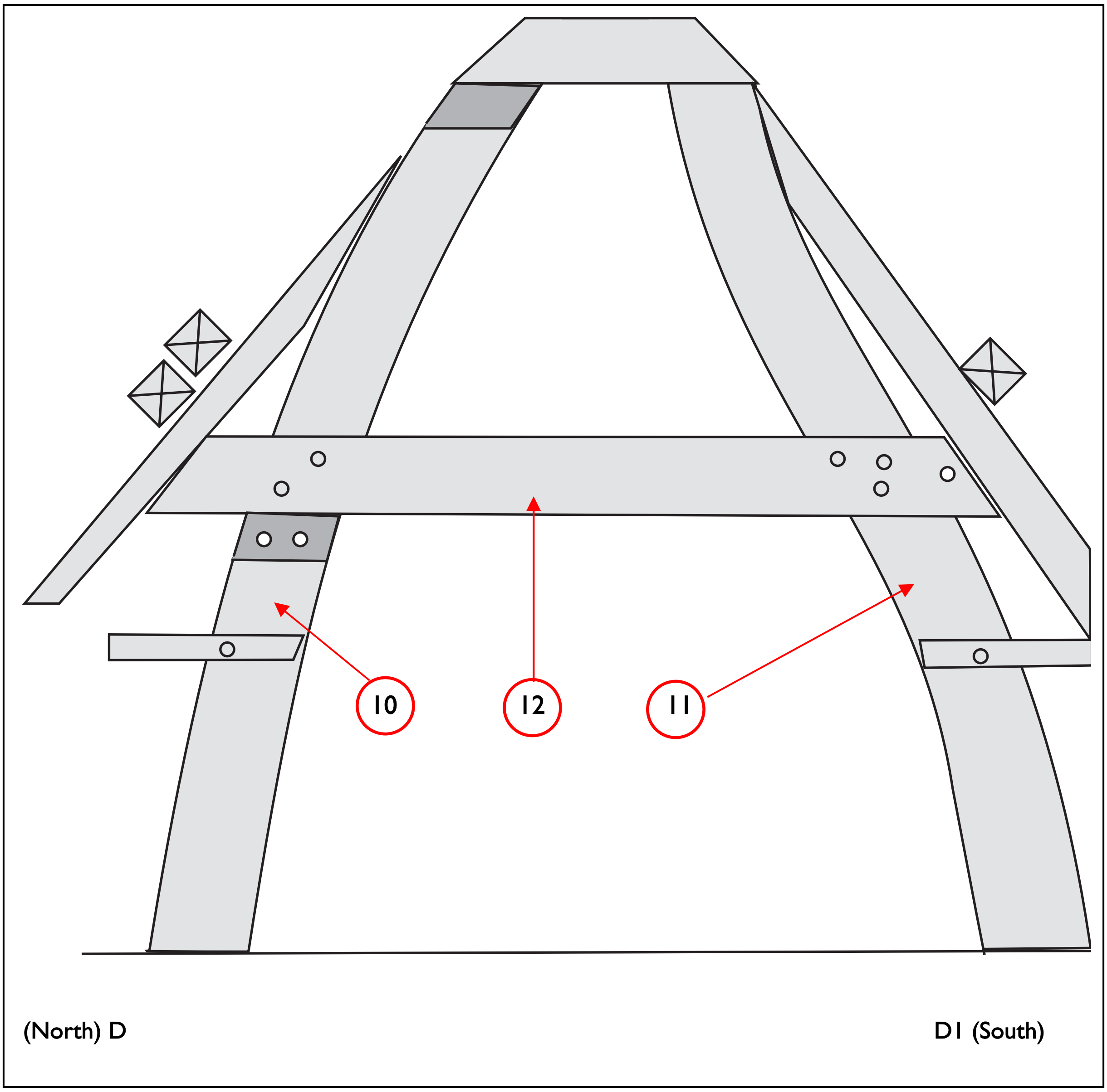


Figure 6d: Schematic section of truss D-D1 to show sampled timbers. Shaded areas indicate redundant half-lap joints; cruck blades should continue through inserted floor (viewed from the west looking east)

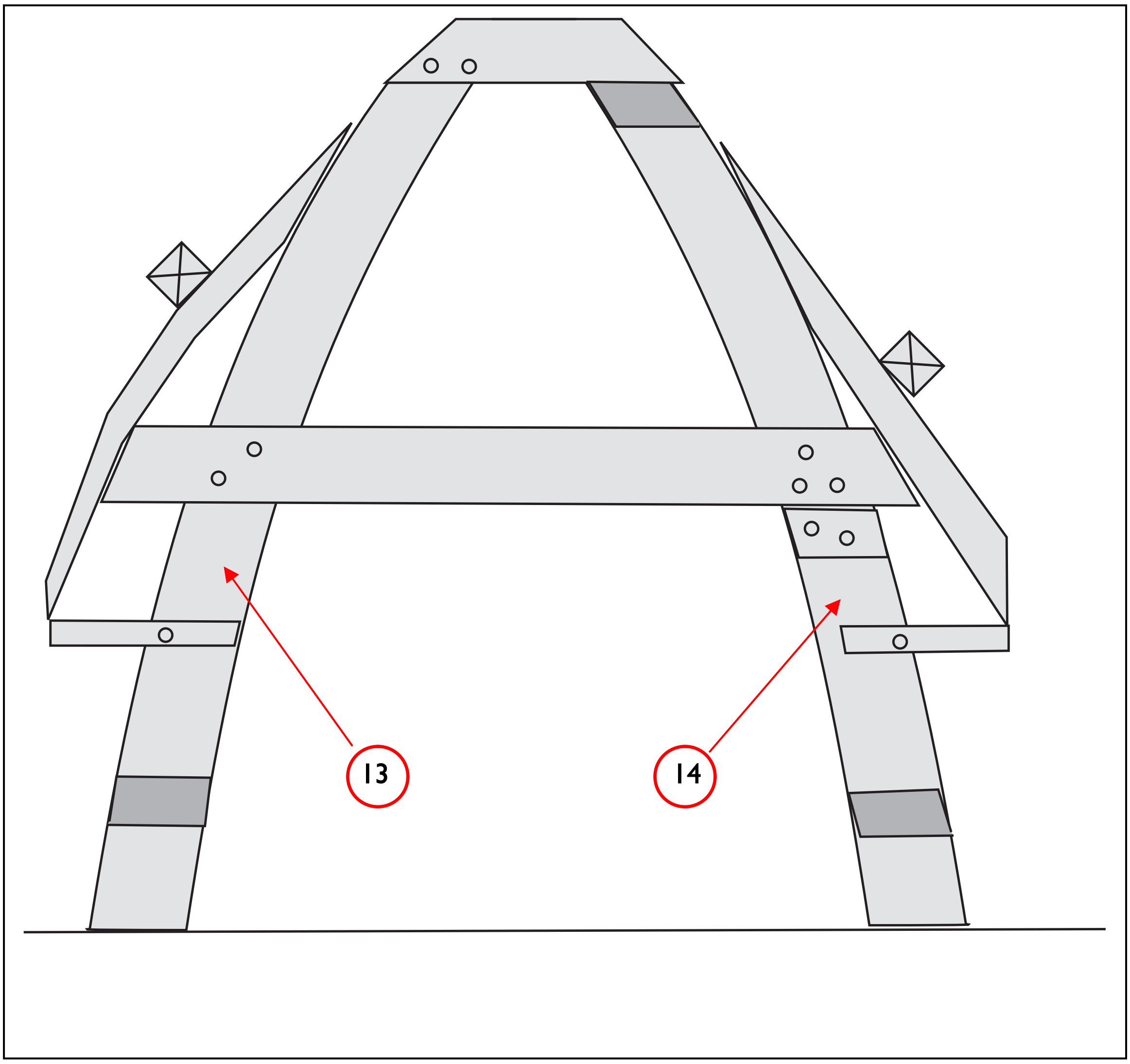
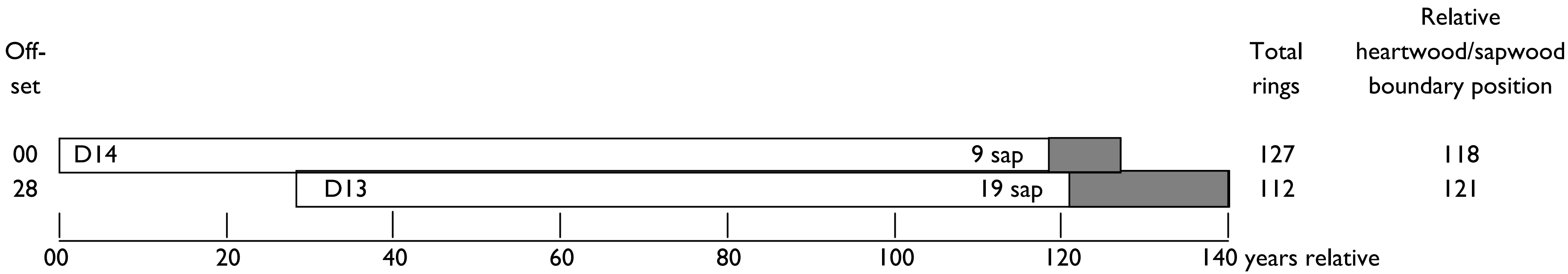


Figure 6e: Schematic section of truss E-E1 to show sampled timbers. Shaded areas indicate redundant half-lap joints; cruck blades should continue through inserted floor (viewed from the west looking east)



white bars = heartwood rings, shaded area = sapwood rings

Figure 7: Bar diagram of the samples in site chronology BBSDSQ01

Data of measured samples – measurements in 0.01 mm units

BBS-D01A 58
227 290 317 173 347 242 315 398 312 289 323 297 252 225 185 220 199 261 258 284
196 188 191 179 237 157 98 294 261 338 312 324 244 102 99 82 70 96 136 165
79 88 88 91 150 112 117 101 105 99 107 90 119 97 105 71 71 61
BBS-D01B 58
227 284 321 166 378 243 318 396 320 321 320 252 259 219 175 219 212 255 258 267
186 197 184 180 247 147 89 296 247 341 311 335 247 95 90 86 80 92 142 162
67 89 93 95 143 112 114 108 106 109 95 87 114 107 105 66 74 58
BBS-D02A 56
84 438 457 462 352 437 411 390 333 289 278 285 243 231 265 56 45 72 92 60
68 45 55 59 68 39 72 60 121 88 68 72 74 77 47 44 33 37 36 40
71 70 76 84 82 80 70 43 59 26 43 35 97 106 100 100
BBS-D02B 56
72 442 458 463 361 427 414 395 330 282 277 294 234 251 252 53 51 65 103 61
63 46 54 48 73 50 67 65 114 92 74 76 60 80 45 42 32 34 42 41
68 79 69 85 87 72 73 49 49 35 45 43 92 110 100 99
BBS-D03A 55
76 81 65 103 112 52 56 112 129 109 116 94 115 133 174 203 183 112 90 103
77 98 43 62 66 66 62 61 91 83 73 88 80 93 60 90 58 46 39 31
44 66 39 55 73 73 35 35 48 69 116 95 85 75 53
BBS-D03B 55
78 71 65 104 115 49 62 111 123 109 121 88 120 135 183 198 179 114 89 103
77 98 43 58 68 67 61 65 93 85 77 98 83 92 63 89 60 44 37 27
45 62 41 60 69 70 42 33 46 70 118 100 82 72 54
BBS-D06A 57
231 176 219 199 252 262 279 375 407 418 388 358 341 352 331 279 272 196 153 185
137 159 139 169 159 107 157 143 171 132 64 68 48 78 87 141 151 188 154 116
86 113 115 108 131 238 196 160 218 176 113 114 133 130 107 117 99
BBS-D06B 57
244 171 220 199 239 268 268 366 416 423 399 365 351 339 319 284 267 210 142 186
135 163 140 169 148 109 156 152 164 120 61 70 52 68 88 134 146 169 162 127
87 110 114 110 135 225 226 145 238 171 110 112 112 123 109 100 87
BBS-D07A 57
66 41 78 68 85 91 61 54 70 67 81 82 108 100 100 88 65 90 76 61
78 89 88 63 53 60 48 63 52 74 72 68 45 63 55 38 56 79 63 62
73 51 46 61 61 40 58 58 48 39 50 40 51 28 56 81 64
BBS-D07B 57
67 40 78 67 75 92 63 49 77 66 84 77 100 95 99 88 78 78 91 51
74 85 89 66 49 58 53 64 53 81 62 70 52 58 52 43 59 73 70 60
69 49 44 60 62 39 53 59 49 43 47 38 56 25 55 78 62
BBS-D08A 61
450 300 221 302 277 308 333 318 308 313 320 283 294 255 262 258 187 251 282 214
292 243 198 172 185 182 173 165 153 194 176 309 362 287 325 152 106 66 85 48
95 149 121 129 128 131 111 153 139 123 130 120 140 122 107 111 267 295 202 260
219

BBS-D08B 61
451 300 214 307 288 308 338 313 316 317 303 301 290 256 248 262 189 247 283 208
295 258 199 171 197 154 192 177 159 197 172 323 369 289 338 148 120 54 85 48
95 147 116 120 134 128 112 141 137 131 122 122 126 125 104 117 280 282 201 269
210
BBS-D09A 54
62 53 59 66 73 49 71 43 57 47 59 31 25 31 29 90 94 97 74 57
51 76 77 85 81 73 73 86 86 62 55 61 57 61 37 43 48 51 46 38
32 40 42 28 35 23 24 22 39 32 20 47 64 67
BBS-D09B 54
59 54 60 59 71 39 62 53 57 48 63 30 26 30 33 89 92 95 74 55
69 79 81 86 83 71 71 86 86 65 52 79 68 78 38 42 40 55 40 38
31 38 37 32 38 25 24 31 32 39 20 43 63 61
BBS-D11A 74
267 168 186 191 220 177 198 225 262 201 295 278 317 224 187 181 131 163 153 179
127 122 141 111 99 97 112 125 148 162 158 162 157 170 140 140 121 103 120 126
208 134 125 111 73 66 93 108 132 145 93 118 103 111 101 101 94 146 131 138
164 98 128 126 130 161 184 238 142 137 115 138 178 220
BBS-D11B 74
302 169 183 194 228 172 211 223 263 193 308 281 272 204 201 183 131 162 157 178
118 129 140 103 107 94 113 134 142 155 156 166 146 180 140 143 127 93 123 131
212 140 128 118 73 72 90 103 122 137 92 112 91 104 106 97 97 128 140 143
138 93 152 110 137 145 200 212 130 158 124 161 181 212
BBS-D12A 101
162 178 173 126 139 92 110 124 163 217 255 252 317 264 218 208 283 213 193 115
93 192 173 200 176 208 248 227 156 74 70 74 75 67 60 74 65 59 64 48
37 55 45 63 76 56 50 41 39 53 46 39 56 55 41 71 53 69 67 58
57 44 26 19 29 25 50 43 49 46 31 39 27 29 34 25 43 65 40 40
51 25 20 33 32 38 35 42 43 34 42 39 51 48 88 96 60 62 48 64
64
BBS-D12B 101
131 206 175 118 136 97 102 131 160 186 248 263 304 252 252 199 271 258 193 119
96 186 175 199 178 211 238 228 161 87 67 76 71 66 69 68 63 65 57 42
45 54 43 60 84 57 51 44 37 52 45 44 45 59 47 67 62 74 60 64
54 42 20 27 24 29 49 47 55 48 29 36 28 34 34 25 40 71 41 38
55 25 27 30 30 37 36 38 48 31 35 43 50 42 98 95 61 62 46 67
66
BBS-D13A 112
542 491 374 307 287 258 282 295 282 242 167 180 198 218 312 268 278 208 96 94
150 181 217 266 225 223 182 266 345 297 342 243 260 206 221 156 161 170 209 198
152 120 138 116 86 77 135 51 58 47 42 32 39 55 36 62 40 61 46 64
54 78 65 63 78 57 66 62 63 80 55 75 64 69 62 49 44 43 42 35
39 36 57 49 34 46 52 47 68 67 46 50 60 90 110 62 54 61 47 138
174 148 164 130 121 92 94 121 141 157 113 115
BBS-D13B 112
525 498 387 313 294 257 304 284 275 245 174 185 205 207 317 270 282 203 105 95
154 185 217 266 236 221 178 261 354 316 372 246 247 209 201 140 161 167 205 194

147 136 133 122 84 80 123 55 44 35 40 34 48 54 47 43 47 75 57 64
51 81 71 78 75 70 71 62 62 95 46 90 63 79 64 54 46 45 30 35
33 36 56 50 36 48 49 50 63 64 42 60 61 86 108 60 63 48 56 141
160 157 164 136 112 98 83 124 144 160 96 120
BBS-D14A 127
233 181 181 183 107 232 208 250 128 281 263 190 182 175 227 209 162 164 175 357
255 253 156 170 178 157 218 198 222 282 213 255 232 247 316 171 171 141 136 170
189 146 238 186 227 175 106 148 210 237 194 229 173 179 210 277 443 348 248 200
217 224 232 128 165 154 191 211 221 231 181 258 169 153 206 151 123 90 88 72
45 60 64 69 70 93 65 79 100 73 81 110 133 101 72 110 109 128 108 139
115 124 110 92 58 57 41 39 44 54 69 82 63 75 71 61 81 44 57 84
76 137 138 110 48 77 144
BBS-D14B 127
216 184 226 201 127 244 204 265 118 319 284 203 170 191 192 192 141 178 245 369
239 259 154 178 173 156 218 193 240 303 197 259 232 245 308 177 173 140 128 157
149 154 244 185 225 174 103 148 220 231 187 194 162 170 205 260 433 359 231 230
244 190 225 136 146 154 187 219 224 206 164 272 163 146 219 139 124 91 89 83
41 54 67 71 59 101 65 92 91 84 71 103 123 95 94 90 88 128 99 116
113 122 109 96 61 51 50 36 47 52 81 100 58 68 77 63 76 56 57 93
68 132 132 110 47 90 138
BBS-D15A 59
46 85 79 44 67 66 61 73 57 38 36 65 40 61 49 43 49 57 77 53
83 60 113 70 56 87 85 102 91 71 61 62 72 59 67 53 65 78 48 46
65 71 89 102 83 84 75 70 47 90 86 40 67 58 63 83 73 72 66
BBS-D15B 59
47 82 77 43 62 63 60 69 53 35 36 64 44 57 56 40 51 48 70 59
84 68 108 74 58 88 83 90 88 69 61 54 72 58 70 55 64 64 65 42
63 65 93 104 80 89 71 77 55 58 88 37 68 60 69 90 69 66 63

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	

Bar Diagram

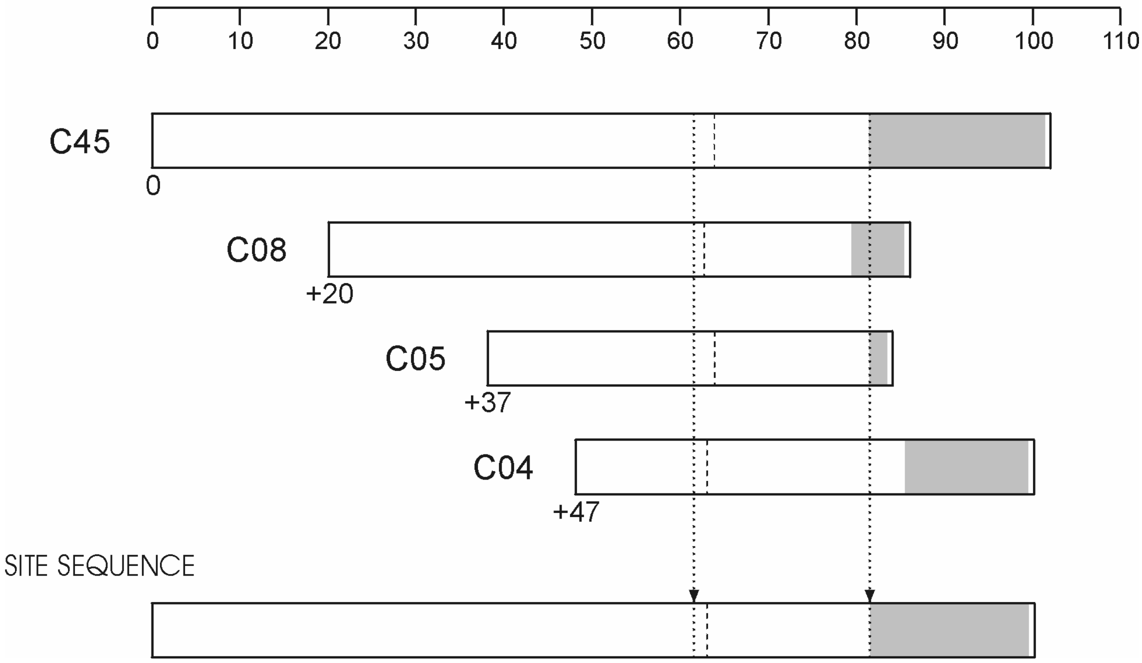


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

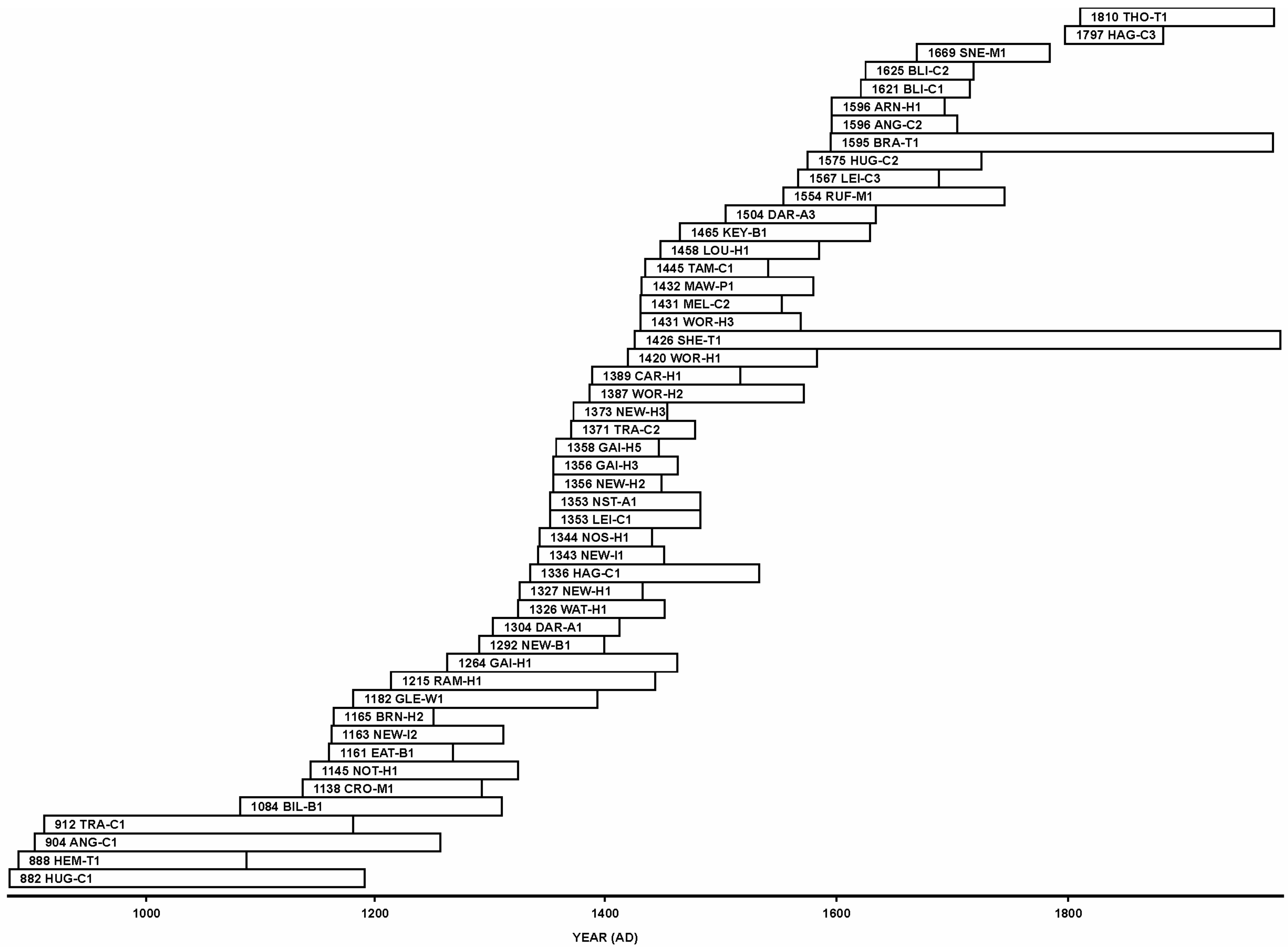
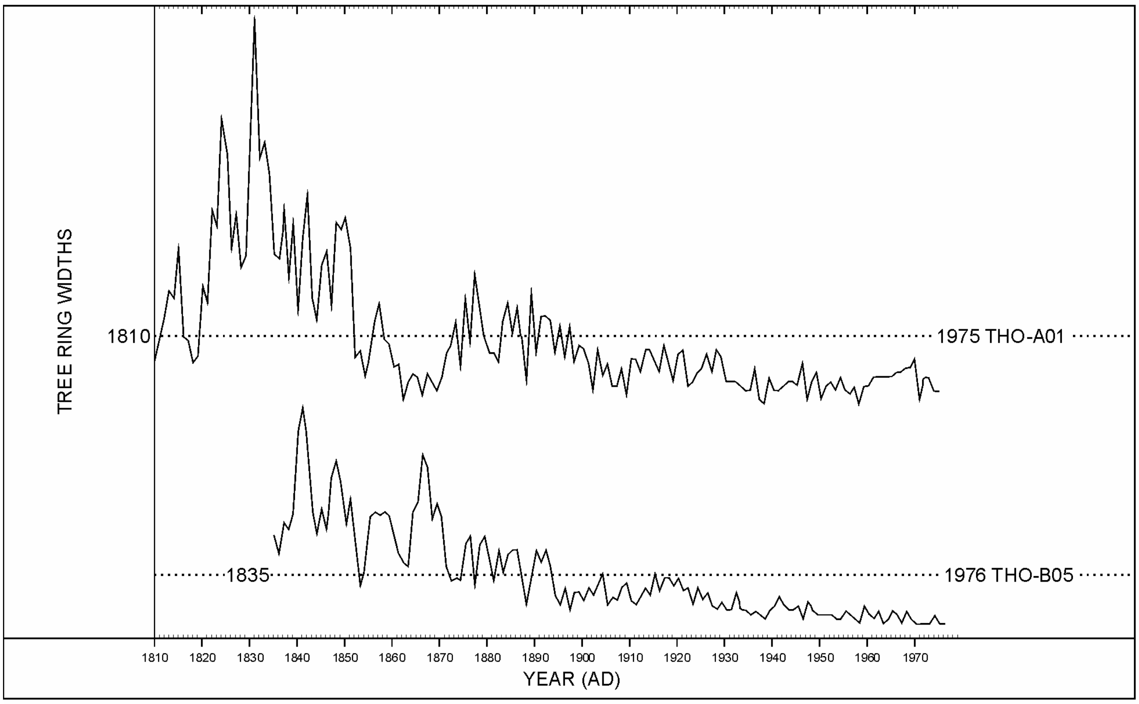


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

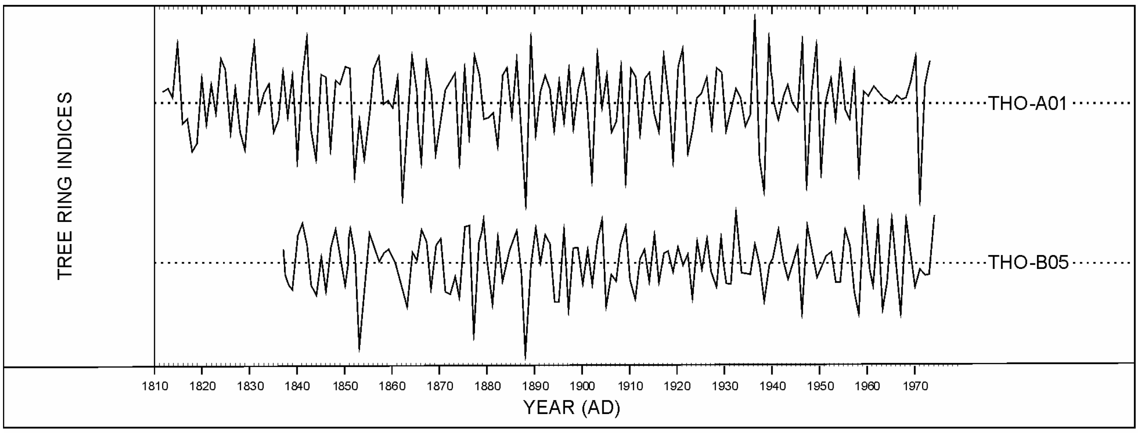


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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