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How Hill Tower and Outbuildings, How Hill Road, Ripon, North Yorkshire

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: How Hill Tower, Ripon in North Yorkshire. © Mr Tim Nichols. Source Historic England Archive IOE01/16345/10

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HOW HILL TOWER AND OUTBUILDINGS
HOW HILL ROAD
RIPON
NORTH YORKSHIRE

Tree-ring Analysis of Oak Timbers

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SUMMARY
Analysis was undertaken on samples taken from this building resulting in the construction of two site sequences, of 108 and 89 rings. Unfortunately, despite comparison with a large number of oak reference chronologies from across the British Isles and elsewhere in Europe and in North America, neither of the site chronologies of any of the ungrouped samples could be matched and all samples remain undated.

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ARCHIVE LOCATION
Historic England Archive
The Engine House
Fire Fly Avenue
Swindon SN2 2EH

HISTORIC ENVIRONMENT RECORD
North Yorkshire Historic Environment Record
Historic Environment Team
North Yorkshire County Council
County Hall
Northallerton
North Yorkshire DL7 8AH

DATE OF INVESTIGATION
2018–9

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INTRODUCTION

The Grade II* listed How Hill Tower, also known as The Chapel of St Michael de Monte (List Entry Number 1293874), is located atop a hill near Ripon, North Yorkshire (Figs 1–2). It is thought to have originated in about AD 1200 and then rebuilt by Abbot Huby *c* AD 1495–1526. It fell into disrepair until incorporated into John Aislabie's garden scheme at Studley Royal Park in the early eighteenth century. It was used as a gaming house in AD 1737–8 and the chapel ruins were converted and reused as farm outbuildings during the later eighteenth century.

The tower was originally a two-storeyed square building with a cantilevered roof of pyramidical form with a projecting stair bay on the west side. Internally, the first floor has collapsed, leaving some of the beams *in situ* (Fig 3). These could range in date from the early eighteenth century to the mid-nineteenth century but may also represent the survival of earlier beams or the use of reused timber (*pers comm* Jonathan Clark). Fireplaces survive at ground-floor and first-floor level.

To the east of the tower itself is a substantial three-storey block with a further lean-to addition to its east. Again, the floors themselves have gone, leaving some surviving floor beams (Fig 4) and a large fireplace in the west wall. This east range is clearly later than the tower itself and is thought to date to the mid-eighteenth to the mid-nineteenth century on the grounds of its architectural detailing (*pers comm* Jonathan Clark). A further building to the north may have served as a stable (Fig 5).

The National Trust has acquired the buildings in a ruinous state with partially collapsed roofs and is at the very early stages of considering their future use and refurbishment. The chapel is located within the Scheduled Monument of How Hill but is exempt from scheduling.

SAMPLING

Dendrochronological analysis was requested by Kerry Babington, Historic England Inspector of Historic Buildings and Areas, Yorkshire Region to provide independent dating evidence for the different range of buildings to understand their development and significance prior to making decisions about the future repair and use of the complex.

Fifteen core samples were taken from oak timbers (*Quercus* spp) of the main and east ranges of this building with a further oak sample being taken from a lintel of an outbuilding, the north range. Each sample was given the code HOW-H and numbered 01–16. Further details relating to the samples can be found in Table 1, and their locations have been marked on Figure 5.

ANALYSIS AND RESULTS

Five of the samples, representing three floor beams and two lintels, had too few rings for secure dating and so were rejected prior to measuring. The remaining 11 core samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. All measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in five samples matching to form two groups.

Firstly, three samples matched each other at a minimum *t*-value of 5.7 and were combined at the relevant offset positions to form HOWHSQ01, a site sequence of 108 rings (Fig 6). Two other samples matched at a *t*-value of 6.4 and were again combined at the relevant offset positions to form HOWHSQ02, a site sequence of 89 rings (Fig 7). Attempts to date these two site sequences and the remaining ungrouped samples by comparing them against a series of relevant reference chronologies for oak, initially from the British Isles but subsequently elsewhere in Europe and also North America, failed to provide any secure dating and all remain undated.

DISCUSSION

The dendrochronology undertaken at this building has demonstrated that three window lintels from the east range are broadly coeval, as are two floor beams, also from the east range. Unfortunately, it has not been possible at this time to provide secure dating for any of the sampled timbers, although tentative dating evidence was noted for both of the site sequences which will be revisited periodically as the network of reference chronologies is enhanced. Although disappointing, this lack of dating is not particularly surprising given the overall characteristics of this site and its timbers, any one of which could have hindered successful matching against the reference chronologies.

Firstly, the timbers are generally relatively fast grown with average ring-widths ranging from 1.3mm to 2.8mm. With the exception of samples HOW-H10 and HOW-H16, which have 89 and 98 rings respectively, the samples do not have particularly long growth ring sequences; five of them being found to be unsuitable due to their low growth ring numbers (<40) and another four of those measured having only 42–53 rings. In addition to the issues of fast-grown timber is the fact that there is likely to be more than one building phase represented amongst the sampled timbers, and so few timbers associated with each phase are available to sample.

These two factors, fast-grown timber and multiple building phases containing few timbers, would have impacted on the intra-site grouping and the construction of long, well replicated site sequences. It is generally accepted that the longer and better replicated a site sequence is, the greater the chance of successful dating. Neither of the two site sequences were either particularly long (being 108 and 89 rings) or well replicated (containing two and three samples).

Alternatively, it may be that the growth patterns of the trees utilised were unduly influenced by factors such as woodland management or growing in an area with a highly localised environmental system, both circumstances which could have masked the climatic signal necessary for successful dating. Finally, given the potentially late date for some if not all of the timbers, it may simply be that the lack of dating is due to a paucity of relevant reference chronologies covering the necessary period for the relevant source areas of timbers.

Previous dendrochronological studies have highlighted the often problematic nature of successful analysis across the Vale of York, the Howardian Hills, and the Yorkshire Wolds. The issues are potentially complex but, as seen with How Hill, include the use of fast-grown young trees, unsuitable for analysis, as well as apparently suitable timbers proving undateable, perhaps relating to localised environmental growth conditions. Hence, it has been recognised that there is the need for a robust local network of reference chronologies to be established in this area, as has proven a successful strategy to enable successful dendrochronology in other problematic areas.

Therefore, although disappointing, sites such as How Hill are important in working towards the provision of such a heavily localised network of reference chronologies in this area and it is hoped that, as further work is undertaken here, one or both of these site sequences may eventually be securely dated.

TABLES

Table 1: Details of tree-ring samples from How Hill Tower and Outbuildings, How Hill Road, Ripon, North Yorkshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Tower range						
HOW-H01	Floor beam 1	NM	--	----	----	----
HOW-H02	Floor beam 2	NM	--	----	----	----
HOW-H03	Floor beam 3	NM	--	----	----	----
HOW-H04	Floor beam 4	42	h/s	----	----	----
East range						
HOW-H05	Door lintel	51	h/s	----	----	----
HOW-H06	Floor beam	67	h/s	----	----	----
HOW-H07	Upper window lintel – east wall	71	--	----	----	----
HOW-H08	Lower window lintel – east wall	NM	--	----	----	----
HOW-H09	Door lintel	42	h/s	----	----	----
HOW-H10	Lower floor beam	89	h/s	----	----	----
HOW-H11	Upper floor beam	53	--	----	----	----
HOW-H12	Upper window lintel – north wall	69	h/s	----	----	----
HOW-H13	Lower window lintel – north wall	NM	--	----	----	----
HOW-H14	Upper window lintel – west wall	71	--	----	----	----
HOW-H15	Fireplace lintel	69	--	----	----	----
North range						
HOW-H16	Lintel	98	h/s	----	----	----

*NM = not measured; **h/s = the heartwood/sapwood boundary is the last-measured ring

FIGURES

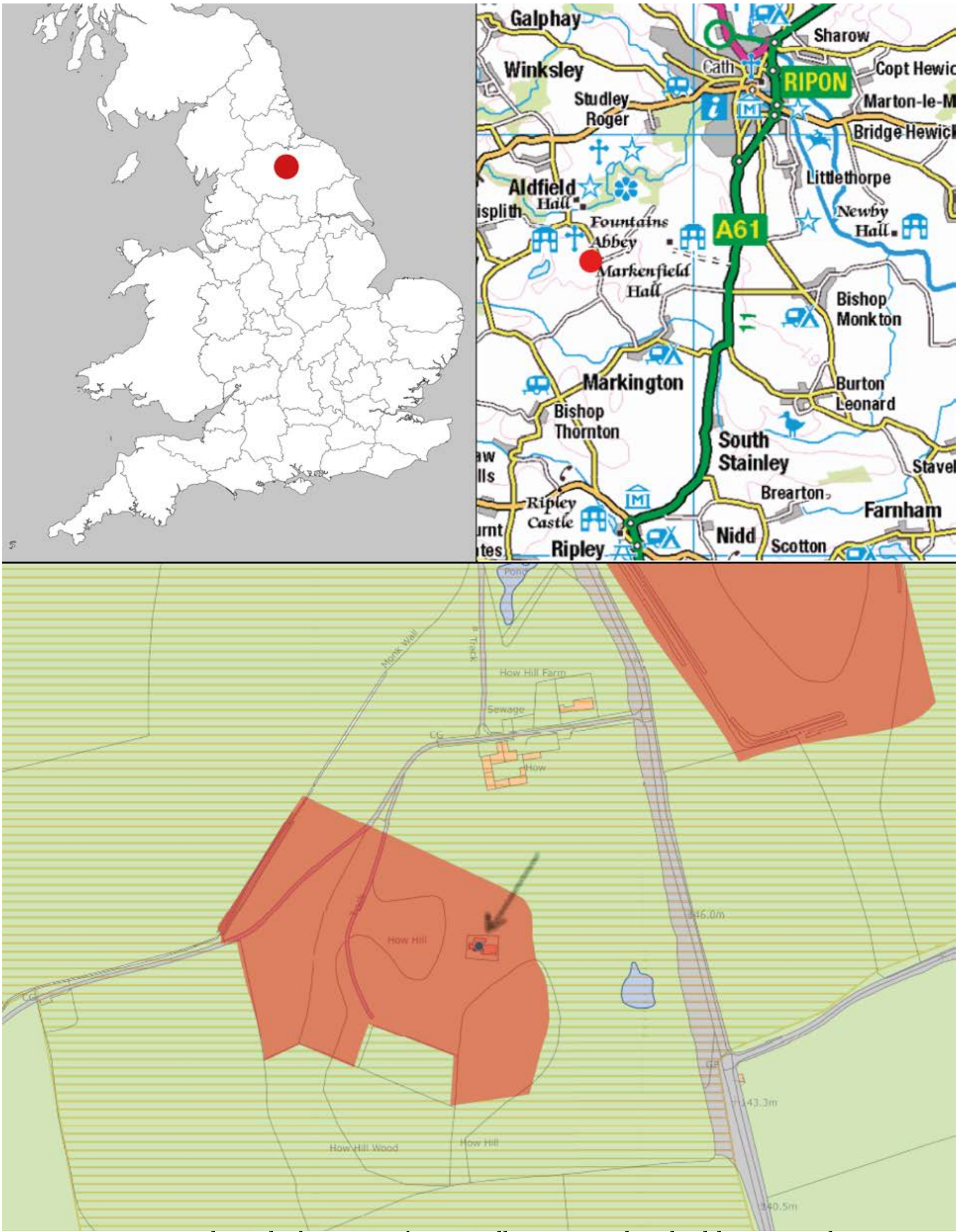


Figure 1: Maps to show the location of How Hill Tower and outbuildings, North Yorkshire, within the Scheduled Monument area of How Hill, marked in red. Scale: top right 1:105,000, bottom 1:3,300 © Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900.

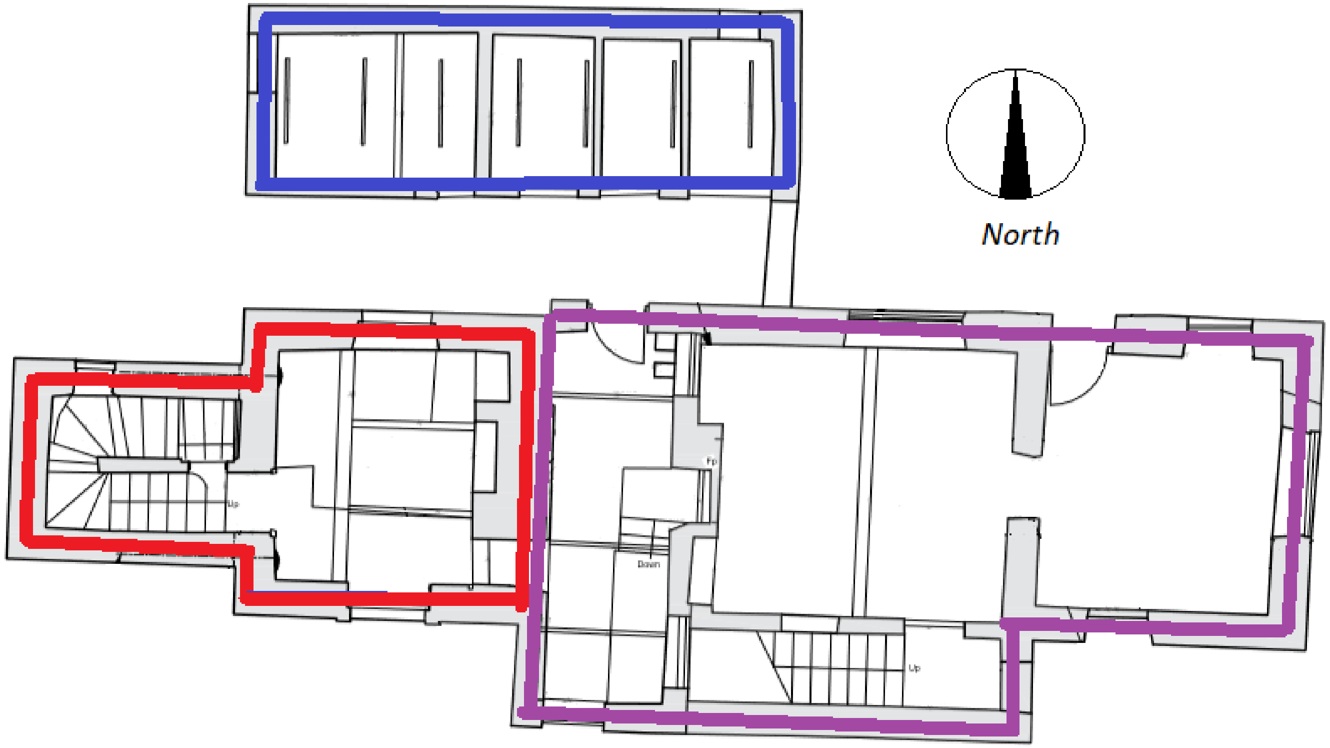


Figure 2: Ground-floor plan, showing the main tower (red), east range (purple), and north range (blue)(Mason Clark Associates)

Figure 3: Tower range; surviving floor beams (photograph by Alison Arnold)

Figure 4: North range, photograph taken from the south-west (by Alison Arnold)

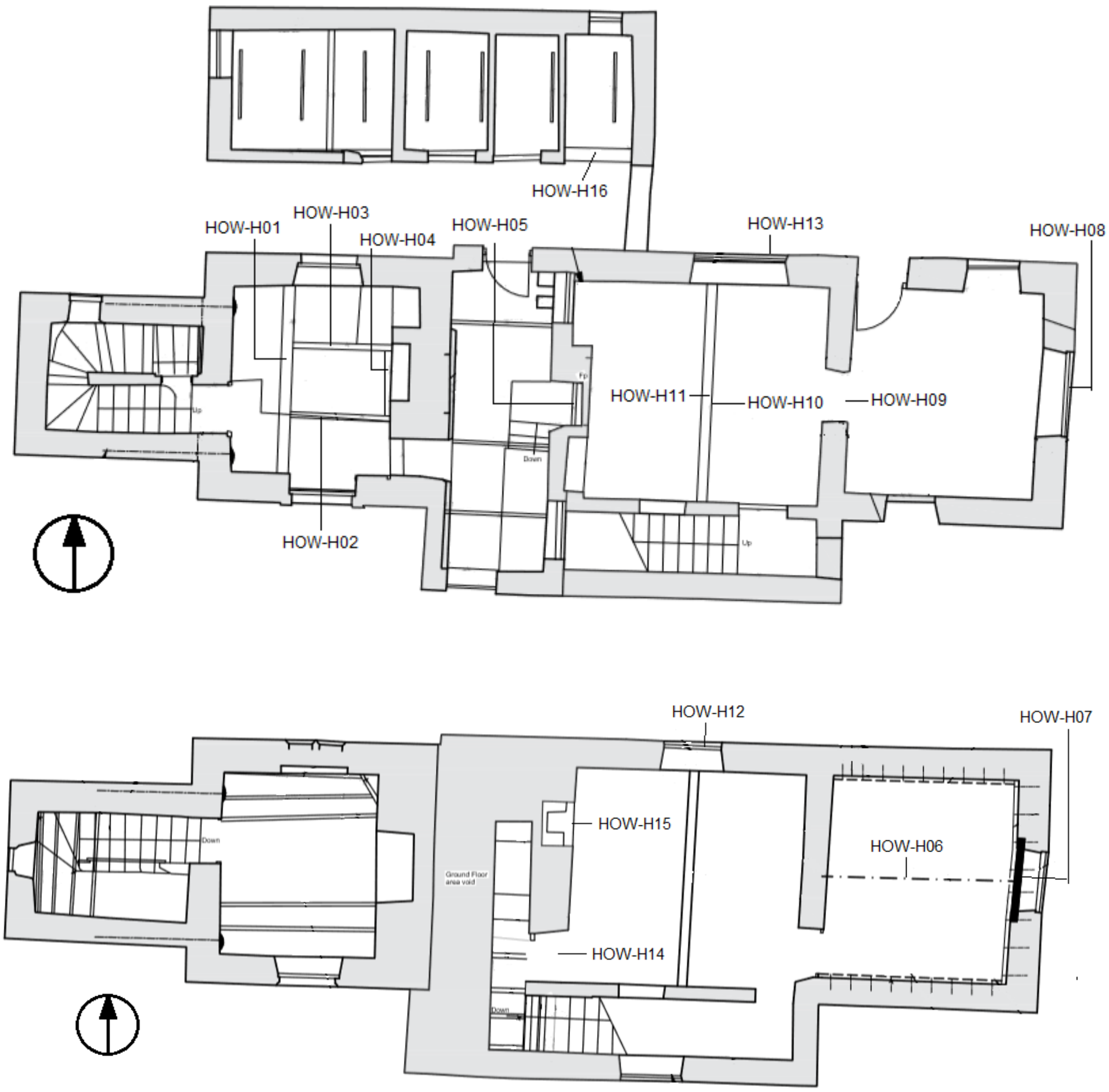


Figure 5: Ground-floor plan (top) and first-floor plan (bottom), showing the location of samples HOW-H01–16 (Mason Clark Associates)

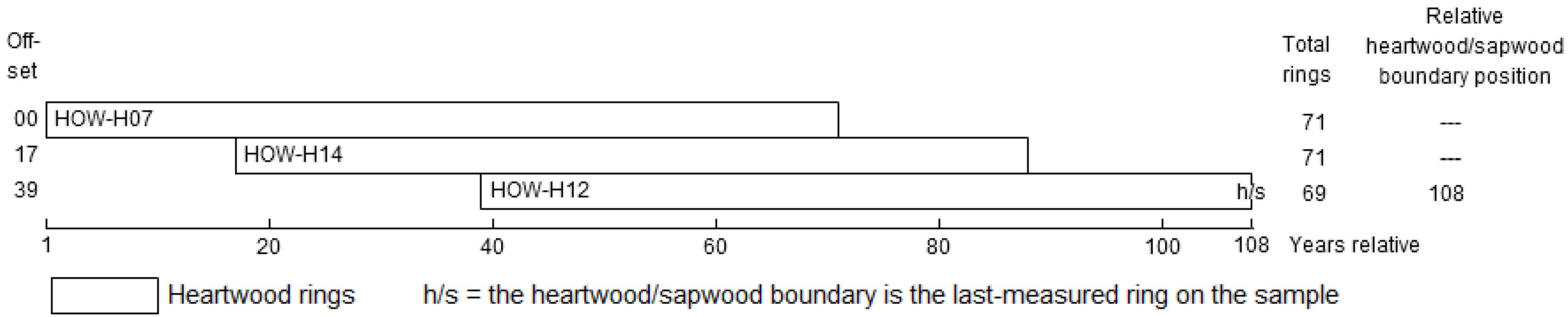


Figure 6: Bar diagram to show the relative position of samples in undated site sequence HOWHSQ01

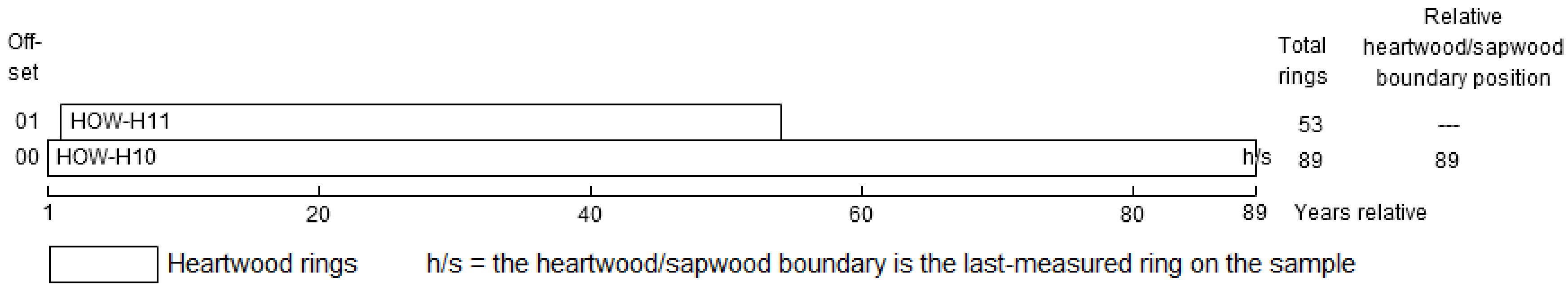


Figure 7: Bar diagram to show the relative position of samples in undated site sequence HOWHSQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HOW-H04A 42
431 417 451 381 466 489 445 365 252 360 326 285 292 287 322 287 252 276 263 218
176 178 177 185 198 186 155 232 124 128 130 132 169 145 162 109 115 85 93 84
103 89

HOW-H04B 42
421 411 442 372 467 485 448 369 249 360 329 286 290 288 307 287 244 286 264 209
183 179 175 190 191 187 157 226 127 130 125 130 169 148 162 108 113 87 91 81
97 95

HOW-H05A 51
159 182 200 250 203 228 209 107 90 77 79 134 122 197 176 102 107 176 230 197
196 234 174 113 74 78 107 120 83 126 88 71 64 42 75 73 92 204 164 96
121 136 94 117 153 89 97 116 143 175 140

HOW-H05B 51
146 178 179 259 204 235 198 118 88 86 77 134 127 194 180 102 112 172 235 191
188 238 178 103 80 79 103 98 82 123 85 65 65 42 73 77 82 212 163 116
104 128 104 116 129 94 87 119 141 171 140

HOW-H06A 67
284 218 344 230 227 298 268 264 220 203 213 210 227 268 222 271 263 343 365 382
322 273 364 269 239 219 209 245 228 271 207 185 210 201 142 170 171 173 209 194
166 232 138 102 88 123 136 166 185 170 193 135 167 135 156 105 91 93 52 57
54 62 70 78 72 67 79

HOW-H06B 67
258 218 330 230 228 303 259 300 235 205 213 204 223 255 212 277 270 350 346 374
320 289 329 251 246 225 205 228 223 285 211 203 203 205 127 153 166 163 216 195
171 233 142 97 78 135 132 160 193 166 174 144 163 148 145 107 93 95 55 54
52 64 66 76 72 65 80

HOW-H07A 71
444 363 410 352 363 354 374 384 374 287 315 296 360 342 291 220 219 171 162 134
69 77 103 99 100 72 84 77 79 66 65 59 57 79 61 76 66 70 104 97
101 106 72 81 138 84 65 116 92 73 73 64 65 69 62 75 72 58 76 67
56 80 59 73 60 70 73 95 47 50 42

HOW-H07B 71
461 353 419 359 364 359 376 376 347 281 314 286 351 352 282 226 223 157 156 128
60 77 108 93 108 77 87 79 77 63 57 59 58 81 47 77 69 73 105 96
98 99 70 80 138 92 72 109 89 78 78 64 61 75 56 73 74 68 72 62
60 80 64 73 52 67 67 100 59 41 30

HOW-H09A 42
233 234 161 164 221 160 180 289 111 125 278 278 250 313 239 207 256 198 308 370
329 361 367 298 207 131 60 46 158 105 147 226 323 385 368 358 392 279 338 341
263 280

HOW-H09B 42
237 230 152 149 223 166 176 292 105 124 269 278 251 322 236 215 250 192 313 359
308 368 364 304 209 132 54 46 145 101 148 235 331 387 377 353 394 281 333 338
274 287

HOW-H10A 89
148 141 270 204 275 220 242 179 206 211 190 250 225 270 210 169 212 280 260 272
269 235 268 211 204 170 179 234 161 201 189 198 202 121 130 145 127 174 187 264

216 201 112 152 217 189 235 211 245 200 129 128 172 257 242 212 220 167 207 162
239 241 206 214 169 257 127 82 56 69 100 107 70 88 76 80 92 97 69 66
81 89 123 88 136 131 106 164 105

HOW-H10B 89
141 151 255 215 278 217 243 189 192 206 196 252 223 270 216 165 214 277 264 281
271 238 271 220 200 184 165 242 174 192 181 179 217 108 137 141 132 174 180 268
213 199 129 138 225 193 224 216 244 206 126 127 169 255 227 230 217 169 193 171
241 245 203 214 169 261 129 82 61 69 100 95 81 93 67 90 82 100 77 60
82 83 125 93 133 131 108 170 93

HOW-H11A 53
308 524 381 498 382 405 302 291 274 239 248 170 178 151 140 144 203 237 255 353
295 357 263 208 259 215 207 237 252 231 268 344 159 199 195 116 140 202 303 271
189 130 114 260 176 147 151 132 111 103 105 115 183

HOW-H11B 53
329 532 385 497 392 412 328 288 280 238 250 171 180 152 137 135 211 221 253 339
289 358 269 221 254 211 216 238 259 229 267 338 160 195 188 113 139 195 308 266
195 127 110 264 168 140 149 134 106 103 104 124 191

HOW-H12A 69
86 71 111 112 105 187 102 130 237 181 186 147 110 118 150 170 138 103 108 169
123 121 153 141 191 126 179 201 284 238 220 219 258 200 336 339 299 219 164 219
366 381 257 258 170 141 146 138 115 196 207 185 145 120 126 118 99 119 76 95
102 107 116 91 85 60 74 112 84

HOW-H12B 69
94 74 108 108 111 188 96 128 235 176 202 147 113 121 153 172 125 101 109 177
118 117 164 140 195 126 172 199 280 240 224 247 274 200 347 351 292 213 150 218
341 331 247 258 168 137 132 142 129 193 217 172 148 120 105 95 85 105 82 98
105 112 121 86 80 62 83 109 99

HOW-H14A 71
310 373 333 151 101 127 88 114 103 92 91 71 81 62 58 50 64 58 69 59
81 111 126 132 156 137 148 186 159 145 193 193 156 211 151 189 313 237 186 202
197 232 181 114 209 195 211 151 173 180 231 165 148 132 183 131 119 121 95 86
85 79 139 131 91 92 127 94 106 113 98

HOW-H14B 71
306 377 324 158 110 128 97 100 91 118 83 81 74 58 60 55 60 59 60 72
84 112 142 120 156 136 138 178 159 143 196 197 150 201 146 169 316 250 188 197
191 228 178 122 202 203 211 159 184 176 217 155 148 126 185 143 132 117 98 92
79 81 156 119 94 92 116 91 104 97 118

HOW-H15A 69
685 588 517 448 343 342 278 358 277 207 179 218 320 250 264 272 343 387 319 301
334 312 348 388 323 308 435 515 425 249 268 299 320 350 284 246 455 305 314 257
260 202 201 252 220 180 164 147 214 229 227 176 187 298 262 273 242 240 221 151
199 252 218 216 120 135 143 134 137

HOW-H15B 69
666 599 527 461 340 338 283 335 253 188 179 237 325 266 263 273 342 383 316 299
333 307 343 394 310 300 434 507 422 250 258 292 322 338 283 241 458 317 304 272
238 201 198 263 213 177 184 151 243 212 227 185 178 310 250 289 239 243 221 142
200 244 213 212 134 130 158 166 130

HOW-H16A 98
194 238 304 214 176 191 187 251 141 274 170 265 273 186 217 281 352 446 378 238
249 150 176 161 138 153 146 137 184 327 222 387 231 277 278 254 143 154 161 243
167 260 260 143 144 128 151 155 82 80 68 80 96 86 121 88 113 82 82 149
102 91 82 82 75 83 91 84 108 129 162 124 76 155 107 112 121 138 100 93

84 97 105 92 96 106 88 123 75 67 61 52 54 69 63 71 50 71

HOW-H16B 98
211 250 264 211 186 189 176 232 143 308 196 245 270 192 215 307 340 494 320 220
251 139 170 157 147 149 155 119 192 322 200 372 237 275 277 253 131 132 173 242
176 232 291 142 145 123 151 147 86 84 70 83 87 88 98 98 114 79 91 151
98 90 81 78 79 75 94 87 102 133 166 130 78 150 123 92 125 143 108 91
73 85 87 75 86 105 88 118 77 67 57 47 53 73 59 73 66 64

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

1. Inspecting the Building and Sampling the Timbers.

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

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

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

4. *Estimating the Felling Date.*

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

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

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

Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

5. Estimating the Date of Construction.

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

6. Master Chronological Sequences.

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

Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices.

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

t-value/offset Matrix

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

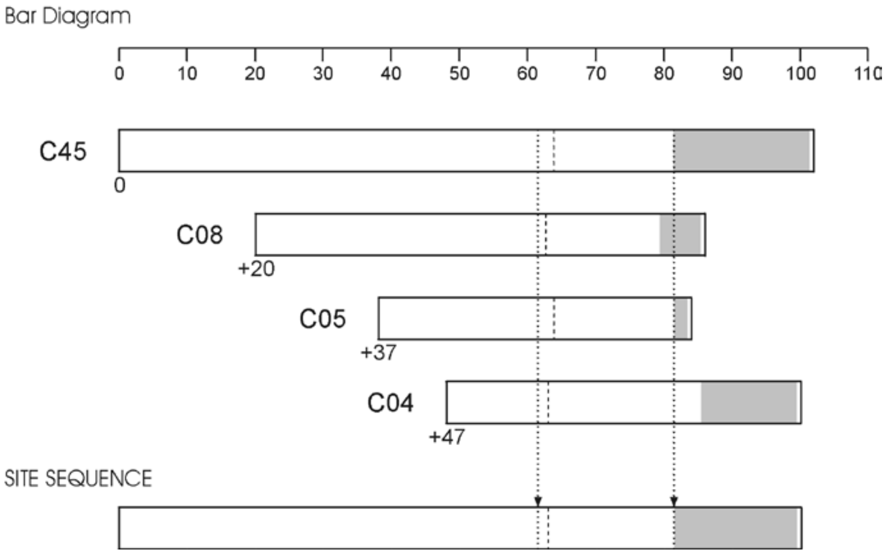


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

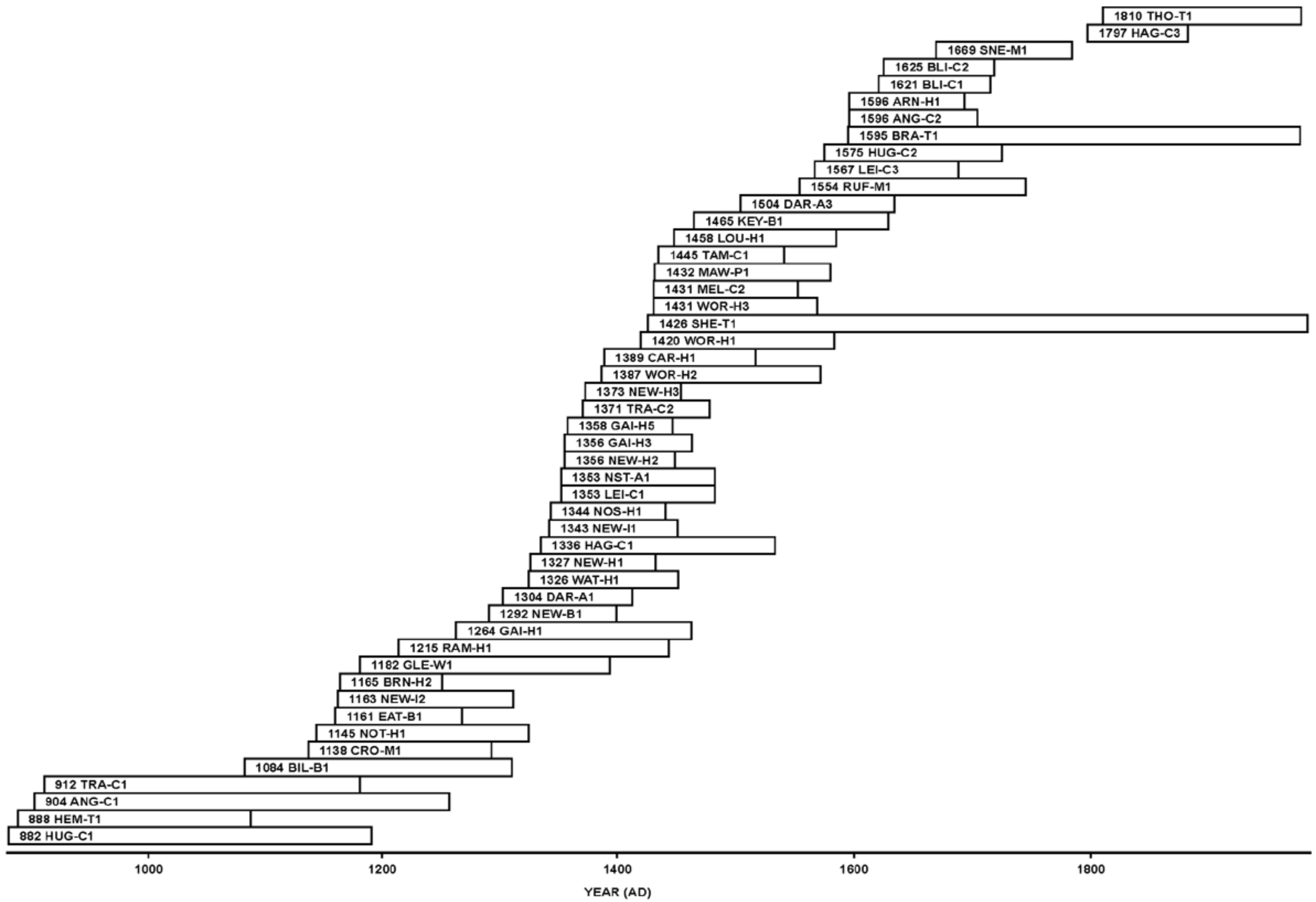
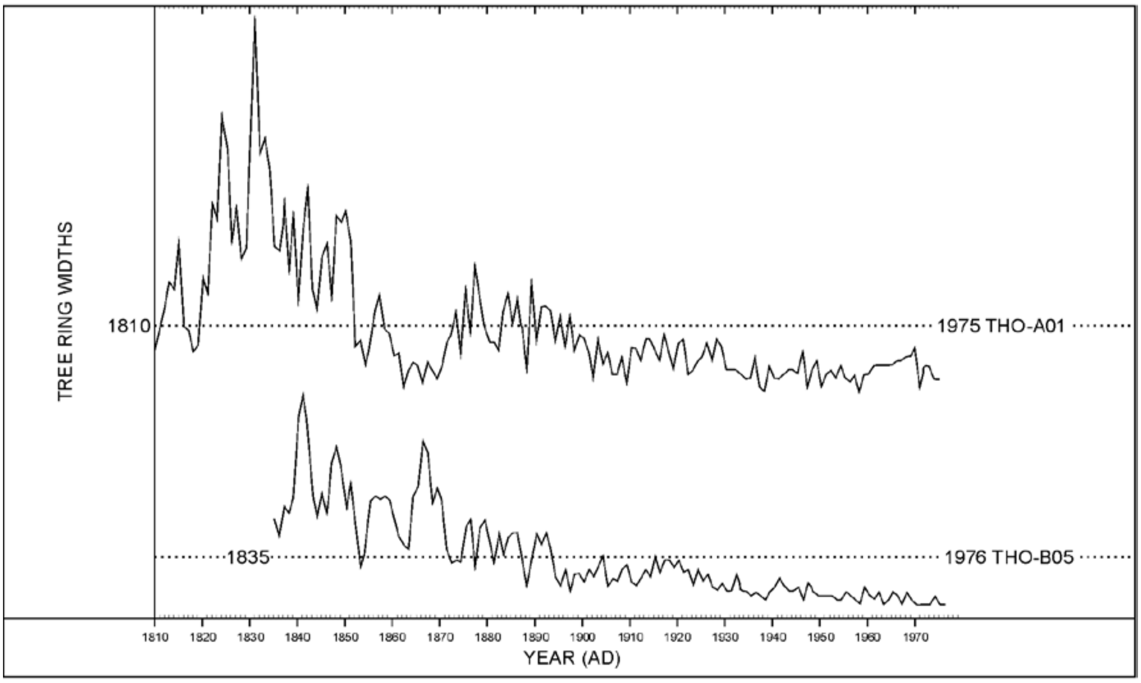


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

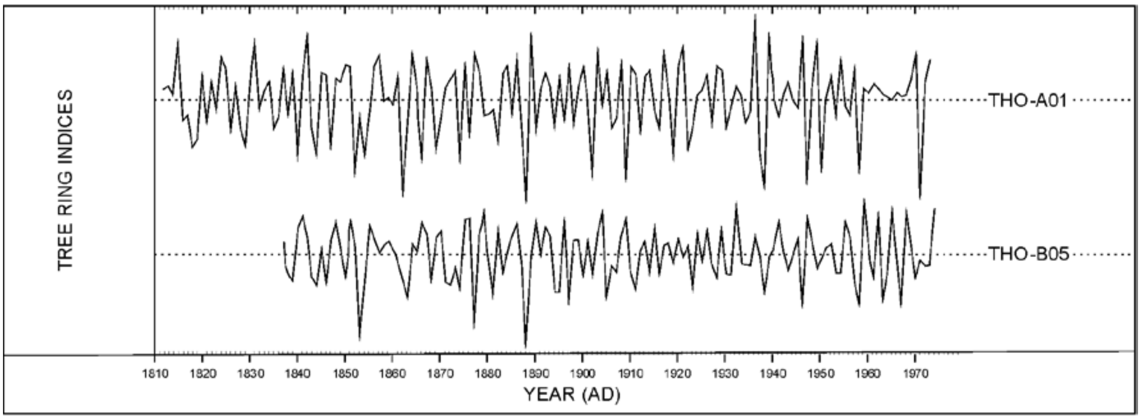


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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