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Outbuilding to Watton Abbey Church Lane Watton East Riding of 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: Watton Abbey outbuilding. © Mr Les Waby. Source: Historic England Archive IOE01/12050/18

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OUTBUILDING TO WATTON ABBEY CHURCH LANE WATTON EAST RIDING OF YORKSHIRE

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SUMMARY
Tree-ring analysis was undertaken on cross-sectional slices from a number of oak timbers removed from the outbuilding during renovations, resulting in the construction of two site sequences.

Unfortunately, neither of the site sequences nor any of the ungrouped samples could be dated ring-width dendrochronology.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank Hugh Bethell, owner of the timbers, for allowing sampling to be undertaken, Andrew Wiles for providing a plan of the building and allowing it to be reproduced in this report, and Rebecca Burns, of the Historic England Scientific Dating Team, for her advice and assistance in undertaking this study.

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

HISTORIC ENVIRONMENT RECORD
East Riding of Yorkshire and Hull Historic Environment Record
The Old School
Northumberland Avenue
Hull HU2 0LN

DATE OF INVESTIGATION
2016

CONTACT DETAILS
Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Cathy Tyers
Historic England
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA
cathy.tyers@historicengland.org.uk

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INTRODUCTION

The Grade II* listed building under investigation is located in the parish of Watton, to the north-east of where the Gilbertine Priory of Watton Abbey once stood (Fig 1; List Entry Number 1083773 https://historicengland.org.uk/listing/the-list/list-entry/1083773). A survey of the building was undertaken by Giles Proctor (2016). It is orientated east–west and is of two-storeys with the upper storey slightly recessed. It consists of 11 bays, and has entrances to the third, fourth, fifth, sixth, seventh, ninth, and between the tenth and eleventh bays (Fig 2). Those to the fourth, fifth, and sixth bays are twentieth-century inserted cart and stable openings, with the other entrances thought to be original but now partly infilled. The ninth bay has an inserted pointed plank door.

The roof is thought to have originally consisted of principal rafter with tiebeam and double collar trusses. Between the trusses were coupled rafters and two sets of purlins to each slope. Wind-braces went from the principal rafters to the lower purlins. This roof was fragmentary in the twenty-first century and has now been replaced. A large number of timbers, thought to have been salvaged from the building during renovations, were recorded, labelled, and retained (Fig 3).

It has been suggested that this building was originally a fulling mill and that after the Dissolution of AD 1539 it was converted into farm buildings. The west gable was rebuilt in AD 1735 and the building converted to stables in the nineteenth century. The building has a number of similarities to the Prior's Lodging which is thought to have been constructed between the AD 1470s and the beginning of the AD 1480s. Other dating puts it as late-sixteenth century with later additions and alterations.

SAMPLING

A dendrochronological survey was requested by Giles Proctor, Historic England Heritage at Risk Architect, to establish a date for the building and subsequent interventions, which will also add to understanding of the site and feed into interpretation.

Seventeen sliced samples were taken from the *ex-situ* oak (*Quercus* spp) timbers. Each sample was given the code WTT-N and numbered 01–17. Where identifying tags were still attached to the timber these particulars were noted and, along with further details relating to the samples, can be found in Table 1.

ANALYSIS AND RESULTS

All 17 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. These measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in four samples matching to form two groups.

Firstly, two samples matched each other (*t*-value = 6.7) and were combined at the relevant offset positions to form WTTNSQ01, a site sequence of 71 rings (Fig 4). Two further samples also matched each other (*t*-value = 10.1) and were again combined at the relevant offset positions to form WTTNSQ02, a site sequence of 54 rings (Fig 5). Attempts were then made to date these two site sequences and the remaining ungrouped samples by comparing them against an extensive range of relevant reference chronologies from both the British Isles and elsewhere in Europe. However, despite some potential matches being noted, none of these were conclusive and all samples must remain undated at present.

DISCUSSION

Unfortunately, it has not been possible to provide secure dating for any of the samples taken from these timbers. There are a number of possible reasons for this lack of dating. The samples do not have particularly large numbers of growth rings with 11 of the 17 (nearly 65%) having less than 70 rings. Having long ring sequences is especially important with sites such as this one, where the intra-site matching is poor, and we are thus attempting to date mostly single samples. Only two site sequences of two samples each were constructed from this site raising the possibility that we are dealing with a disparate group of timbers, perhaps representing several different programmes of work being undertaken in the building rather than a coherent set of timbers of the same date.

The East Riding of Yorkshire is known to be particularly problematic for tree-ring dating (eg Arnold *et al* 2020). Why this might be is currently unclear although it may relate to trees in the area being subject to particularly strong regional influences. Possible dates were noted for a number of the individual samples and also for the two site sequences, however none could be considered secure. Whilst presently unproven, it would be hoped that as further work is undertaken in this problematic region that secure dating may be obtained for at least some of these timbers.

Although it has not been possible to date site sequence WTTNSQ01, by looking at the relative heartwood/sapwood boundary ring positions of the samples in it (Fig 4) one can say that that both timbers represented are likely to have been felled at the same time even if it is not possible to say when this was. The same can be said for the two samples in the site sequence WTTNSQ02 (Fig 5).

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REFERENCES

Arnold, A, Howard, R E, and Tyers, C, 2020 *The Old Friary, Friars Lane, Beverley, East Riding of Yorkshire: Tree-ring Analysis of Oak Timbers*, Historic England Res Rep Ser, 217/2020

Proctor, G, 2016 *The Stable Block, Watton Abbey, East Riding of Yorkshire: Phase II Reinstatement of Roof*, Architect's Report for Historic England, AA 20189/2-2

TABLES

Table 1: Details of samples taken from the outbuilding, Watton Abbey, Church Lane, Watton, Driffield, East Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Ex-situ timbers						
WTT-N01	51427 – Gf 1	62	h/s	----	----	----
WTT-N02	51427 – Gf 1.2	53	h/s	----	----	----
WTT-N03	51427 – Gf 1.28	51	--	----	----	----
WTT-N04	51427 – Gf 1.29	64	h/s	----	----	----
WTT-N05	51427 – Gf 2.14	51	h/s	----	----	----
WTT-N06	51427 – Gf 2.7	90	h/s	----	----	----
WTT-N07	51427 – G 2.28	62	h/s	----	----	----
WTT-N08	51427 – G 2.37	67	h/s	----	----	----
WTT-N09	51427 – Gf 2.6	69	h/s	----	----	----
WTT-N10	51427 – Gf 2.66	54	h/s	----	----	----
WTT-N11	51427 – Gf 4.7	78	h/s	----	----	----
WTT-N12	51427 – G 5.2	89	--	----	----	----
WTT-N13	51427 – Gf 6.1	96	--	----	----	----
WTT-N14	51427 – Gf 6.5	77	--	----	----	----
WTT-N15	51427 Gf ? (number faded)	61	h/s	----	----	----
WTT-N16	No tag	78	h/s	----	----	----
WTT-N17	51427 - G2.20	43	h/s	----	----	----

h/s = heartwood/sapwood boundary retained on sample

FIGURES

Figure 1: Maps to show the location of the outbuilding to Watton Abbey, East Riding of Yorkshire, in red. Scale: top right 1:100,000; bottom 1:5,000. © Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900.

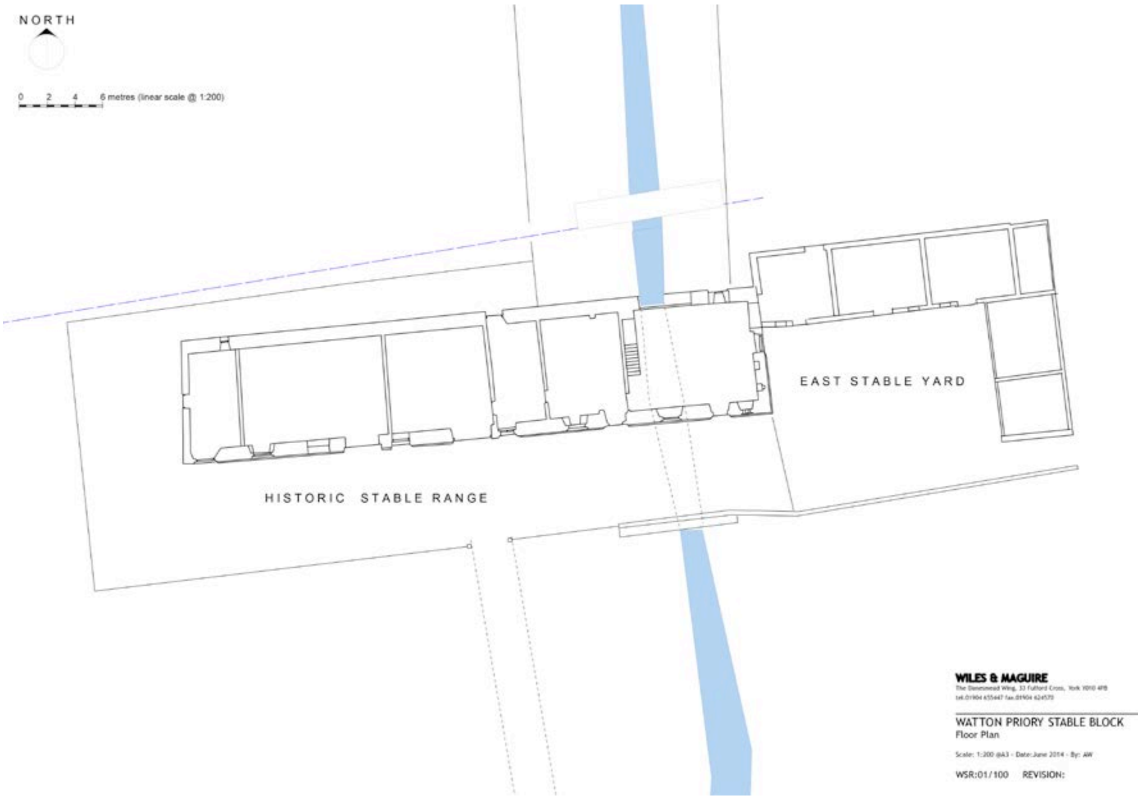


Figure 2: Ground-floor plan (Wiles & Maguire)

Figure 3: Photograph of the ex-situ timbers (Robert Howard)

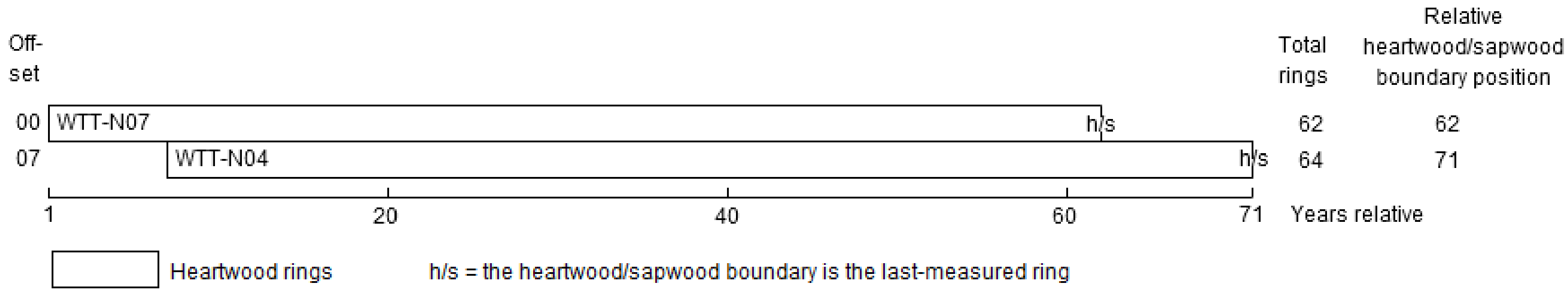


Figure 4: Bar diagram to show the relative position of samples in undated site sequence WTTNSQ01

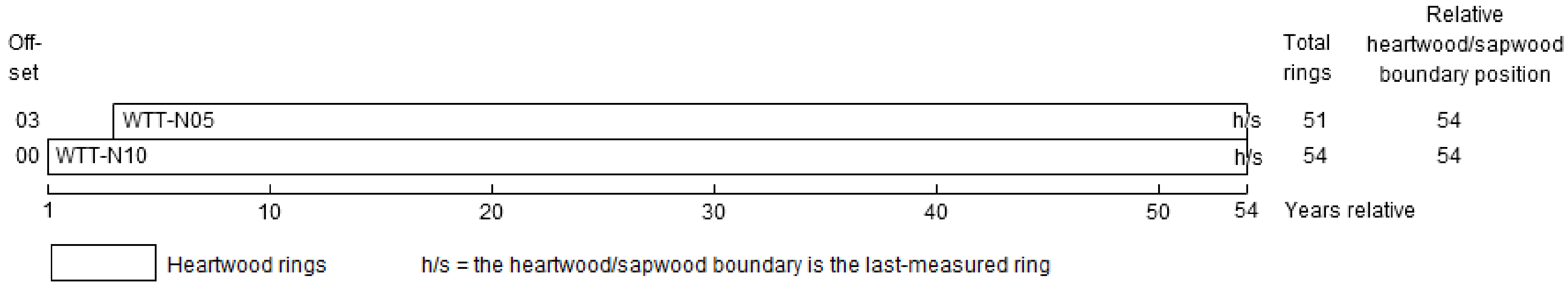


Figure 5: Bar diagram to show the relative position of samples in undated site sequence WTTNQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WTT-N01A 62
90 54 104 118 93 140 125 156 176 185 134 191 269 340 293 249 173 215 111 151
193 295 199 195 143 124 143 90 104 83 94 110 101 83 79 103 87 99 103 85
94 106 90 80 90 191 193 225 262 259 122 203 163 183 212 303 262 237 211 149
257 198

WTT-N01B 62
75 47 89 140 79 133 138 154 165 191 139 192 269 341 303 255 175 223 118 146
197 297 205 198 148 123 147 90 106 80 113 129 113 90 84 110 93 97 109 105
94 101 88 69 100 227 235 222 268 210 134 191 165 190 204 291 286 243 207 162
256 185

WTT-N02A 53
142 193 209 160 116 95 101 160 201 210 153 169 208 146 117 134 96 123 137 110
138 172 106 182 156 118 169 173 146 143 126 146 159 140 261 200 200 169 125 153
110 186 179 170 108 101 150 188 183 174 214 123 152

WTT-N02B 53
153 184 209 164 118 103 96 161 201 218 152 171 212 138 112 140 101 117 143 111
134 176 98 183 152 125 155 182 137 138 126 118 159 131 264 198 199 161 125 154
114 184 178 172 108 108 145 189 183 171 186 135 145

WTT-N03A 51
253 250 264 265 287 144 116 169 257 268 291 259 186 181 160 177 236 255 242 212
269 267 223 238 274 262 196 167 220 244 277 210 297 310 319 352 271 154 181 233
231 203 293 249 289 202 196 230 244 278 239

WTT-N03B 51
210 243 273 267 271 165 144 213 301 293 273 270 182 184 169 173 241 263 251 263
277 232 209 254 272 259 197 168 214 241 277 216 294 314 324 344 279 157 179 235
236 208 291 250 287 208 190 213 243 276 204

WTT-N04A 62
525 391 311 187 277 261 301 414 299 305 294 178 221 231 348 260 245 282 231 202
215 198 211 226 250 228 211 192 240 259 196 182 263 201 254 211 174 317 225 174
161 187 212 195 198 127 214 145 141 119 139 191 163 158 141 162 107 120 167 160
113 117

WTT-N04B 64
341 279 508 399 349 235 308 299 350 415 301 328 318 212 243 269 352 263 261 300
224 202 206 193 212 221 259 215 217 199 238 262 203 172 279 216 294 229 198 320
231 157 142 166 183 186 191 133 213 135 141 114 149 187 173 137 136 164 107 116
151 151 118 105

WTT-N05A 51
176 168 168 257 232 267 335 249 183 231 334 365 242 258 213 347 353 185 160 229
315 331 347 278 336 292 199 216 221 379 341 328 202 196 270 228 221 187 311 273
205 177 267 295 263 212 246 209 257 258 234

WTT-N05B 51
146 177 161 275 239 290 330 243 164 232 325 360 249 255 208 340 337 180 157 229
323 366 359 281 355 300 189 208 238 385 355 328 183 186 255 212 221 194 302 278
200 179 240 298 240 230 237 201 251 262 159

WTT-N06A 90
242 261 297 251 283 190 226 187 188 164 108 214 177 163 102 175 132 115 93 80
39 64 52 68 103 77 73 46 61 57 44 66 41 42 52 42 43 42 47 61

85 59 87 58 45 75 38 61 64 38 41 37 43 39 42 52 36 41 31 32
34 76 195 403 383 440 443 301 224 203 171 156 151 243 238 207 155 128 191 207
188 171 141 267 159 136 165 187 246 259

WTT-N06B 90
230 258 296 249 280 188 225 186 196 157 106 207 176 173 112 185 100 96 84 53
38 48 42 73 95 75 76 52 57 64 53 87 49 46 49 68 66 51 54 78
113 62 92 65 54 75 58 70 98 62 46 48 41 56 56 55 35 31 39 29
25 52 153 319 305 370 380 283 235 210 198 141 135 196 227 210 168 132 184 200
174 159 126 221 164 128 178 193 259 181

WTT-N07A 45
233 297 378 263 193 174 250 214 287 345 270 201 146 130 129 136 218 143 93 92
144 197 142 152 218 160 189 156 174 213 170 120 124 143 162 169 128 154 186 158
139 140 122 183 91

WTT-N07B 49
243 299 329 343 362 336 200 155 207 287 359 260 129 170 161 164 197 194 215 240
119 134 133 277 166 202 218 168 129 96 77 87 153 229 181 129 96 143 158 111
148 173 144 178 165 172 168 149 100

WTT-N08A 67
160 197 178 167 118 160 160 258 198 297 323 212 259 177 161 193 178 257 211 226
161 189 95 118 225 193 241 183 161 133 181 166 144 110 154 158 164 109 113 202
131 190 166 114 124 115 100 120 100 110 160 176 85 86 97 107 128 101 157 187
142 85 98 154 196 124 85

WTT-N08B 67
176 196 177 167 129 166 163 247 216 305 314 214 256 175 154 190 182 242 209 219
161 193 91 119 227 192 244 178 163 148 168 169 141 117 163 154 160 117 120 210
136 186 155 116 122 112 111 128 100 122 155 176 94 95 96 120 131 113 150 190
113 94 95 149 204 138 76

WTT-N09A 69
266 339 297 428 306 251 210 262 302 268 351 437 455 355 335 370 298 378 96 74
116 77 187 180 175 168 171 139 161 117 124 220 194 155 124 87 94 139 218 168
164 163 164 152 176 205 224 165 78 63 62 52 50 46 48 70 74 84 74 81
95 105 121 156 122 96 102 126 136

WTT-N09B 69
263 378 318 546 307 217 192 261 282 250 341 439 452 354 337 377 302 378 95 70
117 75 184 177 189 176 178 155 167 126 127 208 175 145 111 85 88 150 211 172
156 169 159 168 179 206 227 159 85 60 61 54 52 46 55 72 69 72 73 86
95 102 128 133 125 107 103 130 126

WTT-N10A 54
221 245 221 186 168 136 167 160 174 217 224 185 230 287 303 215 224 206 236 252
124 111 189 265 222 201 152 186 147 170 177 176 223 183 203 128 142 155 150 157
151 181 181 128 122 178 204 186 133 145 131 169 166 128

WTT-N10B 54
218 244 223 187 168 134 166 153 177 213 227 179 233 306 294 221 210 213 243 252
143 110 200 258 228 223 158 194 156 184 197 183 225 177 200 123 146 153 157 156
150 180 182 134 123 183 209 180 145 141 140 202 195 139

WTT-N11A 78
174 245 300 314 273 295 227 232 216 309 355 270 259 371 370 273 331 422 379 418
378 274 190 184 108 167 136 119 149 165 143 129 129 106 102 71 80 111 86 79
63 49 63 93 88 89 83 51 80 84 80 77 51 65 59 38 77 44 34 53
52 54 40 32 54 64 73 42 89 121 139 116 179 321 311 320 429 342

WTT-N11B 78

171 255 306 319 257 293 241 211 212 300 359 287 266 334 354 275 320 418 433 421
355 272 167 206 152 210 135 135 132 149 111 113 101 110 101 84 83 115 77 75
70 42 78 95 83 82 81 53 65 68 84 73 54 71 50 46 76 50 40 51
55 48 47 39 53 78 67 57 88 114 143 116 182 321 317 317 432 327

WTT-N12A 89
46 69 62 54 87 90 93 70 65 67 54 52 71 111 119 168 204 196 182 222
178 137 248 187 171 176 198 192 218 117 182 180 92 97 106 84 118 83 111 105
60 116 108 94 109 49 81 71 69 102 122 96 107 127 129 65 39 42 98 94
111 107 58 62 129 159 165 92 81 60 107 153 90 140 87 89 82 169 161 215
207 198 191 161 243 256 290 209 205

WTT-N12B 89
60 62 66 55 84 91 94 75 61 70 56 43 84 102 135 165 171 237 191 231
180 136 251 186 167 174 198 183 222 120 182 168 96 87 106 78 108 73 111 93
61 124 107 97 95 54 77 84 63 86 110 98 107 127 136 63 50 38 90 87
112 102 58 61 119 157 155 95 84 66 108 161 92 143 78 96 87 164 157 202
191 209 189 170 271 253 329 227 189

WTT-N13A 96
467 553 487 411 242 265 150 60 124 118 72 80 100 65 35 78 88 93 89 125
58 46 50 37 26 62 148 203 278 163 231 251 244 230 249 264 301 204 129 136
139 120 128 196 247 211 229 175 109 109 124 172 157 188 144 223 269 191 286 227
215 188 203 277 231 228 217 225 202 262 256 158 145 103 62 80 177 114 136 123
149 177 148 141 78 97 95 94 87 106 98 119 80 115 141 209

WTT-N13B 96
470 557 501 407 271 277 154 77 132 91 75 65 100 60 41 81 80 102 57 107
52 46 38 31 22 52 110 133 188 159 232 247 210 216 187 183 152 199 139 106
122 108 122 179 220 170 238 170 114 107 144 179 168 192 140 227 261 193 278 225
211 207 216 286 225 246 165 215 181 246 260 149 144 95 63 84 174 113 139 126
141 184 143 141 74 101 92 95 85 113 90 120 80 114 139 184

WTT-N14A 77
148 120 67 89 83 82 129 135 90 286 368 281 215 258 207 170 70 57 34 32
58 87 46 76 53 61 46 45 49 39 23 64 290 186 184 193 233 120 164 234
181 291 266 236 190 242 217 444 454 377 281 433 320 345 185 161 274 305 296 316
274 326 373 304 295 247 193 291 233 150 228 260 233 190 185 269 248

WTT-N14B 77
142 111 68 79 91 73 124 137 85 292 375 286 225 260 203 151 76 56 36 35
55 86 51 67 47 71 44 44 47 45 21 59 301 181 183 184 237 119 162 234
190 292 275 225 185 249 212 451 449 355 267 399 306 333 192 164 271 306 259 335
288 332 354 314 292 218 219 294 230 159 233 264 227 177 188 287 269

WTT-N15A 61
366 409 288 290 202 343 308 206 357 343 238 188 177 202 328 321 432 285 184 231
186 102 94 127 202 241 186 172 160 188 98 116 117 128 93 132 56 63 124 194
134 97 59 81 91 123 117 88 64 86 87 171 75 211 169 160 133 95 157 163
110

WTT-N15B 61
371 409 306 259 223 375 283 204 267 284 252 185 161 162 261 233 335 204 150 183
186 117 108 158 238 253 194 165 145 176 100 125 132 117 88 125 58 63 121 186
143 91 58 80 83 125 113 88 65 86 85 167 72 221 171 168 138 93 157 168
153

WTT-N16A 72
271 282 306 294 208 189 145 180 187 106 140 163 113 90 67 147 123 98 195 284
298 311 259 230 189 143 147 159 177 131 150 100 91 102 155 166 125 136 123 117
95 84 67 77 90 152 164 124 77 99 95 82 101 113 146 96 104 142 138 88
88 80 63 116 104 65 57 86 89 106 71 81

WTT-N16B 78
170 276 321 251 253 208 158 189 185 119 140 163 111 100 68 150 139 102 189 282
290 299 230 254 167 152 153 172 195 154 171 112 103 141 157 177 139 198 137 134
145 107 89 95 113 165 135 103 70 88 92 87 93 105 111 92 94 110 139 77
94 82 71 134 93 59 62 93 86 100 77 65 72 66 58 57 64 60

WTT-N17A 43
310 350 366 302 282 258 220 299 185 198 239 270 282 261 236 242 186 160 75 90
121 136 144 164 121 111 98 123 202 264 438 235 331 355 424 372 361 329 242 313
295 242 315

WTT-N17B 43
319 357 366 304 278 258 216 295 191 200 236 270 284 265 233 243 184 155 84 92
114 146 146 168 115 103 109 116 186 269 440 241 320 362 413 376 365 350 248 323
294 243 296

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers.

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.
To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is

complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time. Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

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

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

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

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

2. Measuring Ring Widths.

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

3. Cross-Matching and Dating the Samples.

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

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

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

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

4. Estimating the Felling Date.

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

5. *Estimating the Date of Construction.*

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

6. *Master Chronological Sequences*

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

Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. *Ring-Width Indices.*

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

t-value/offset Matrix

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

Bar Diagram

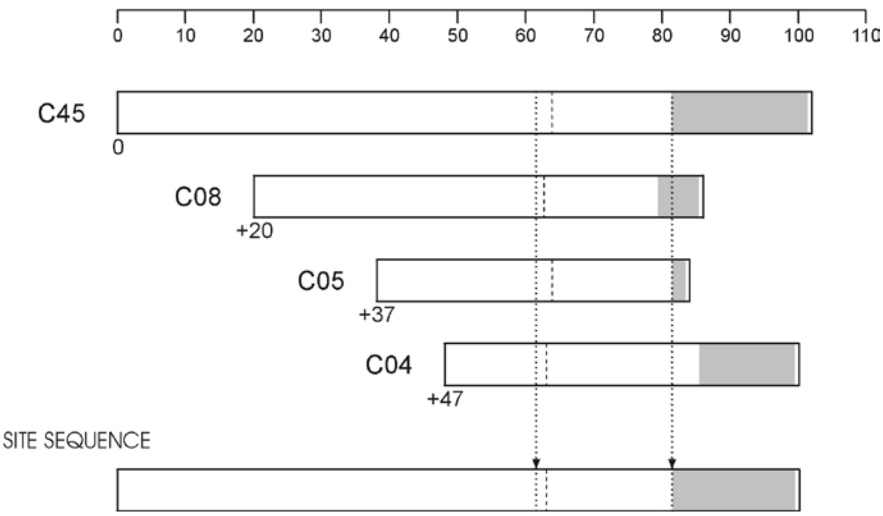


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

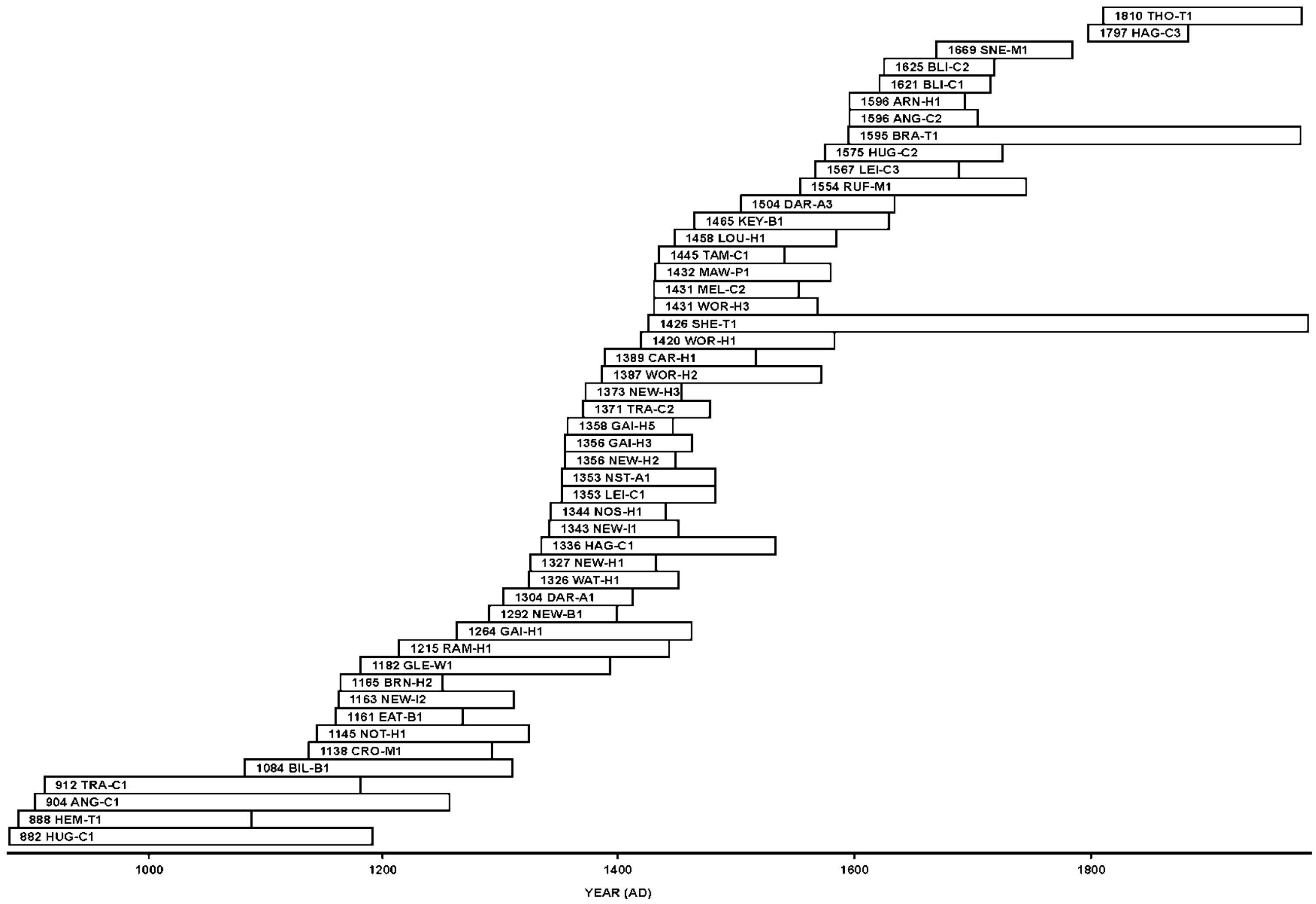
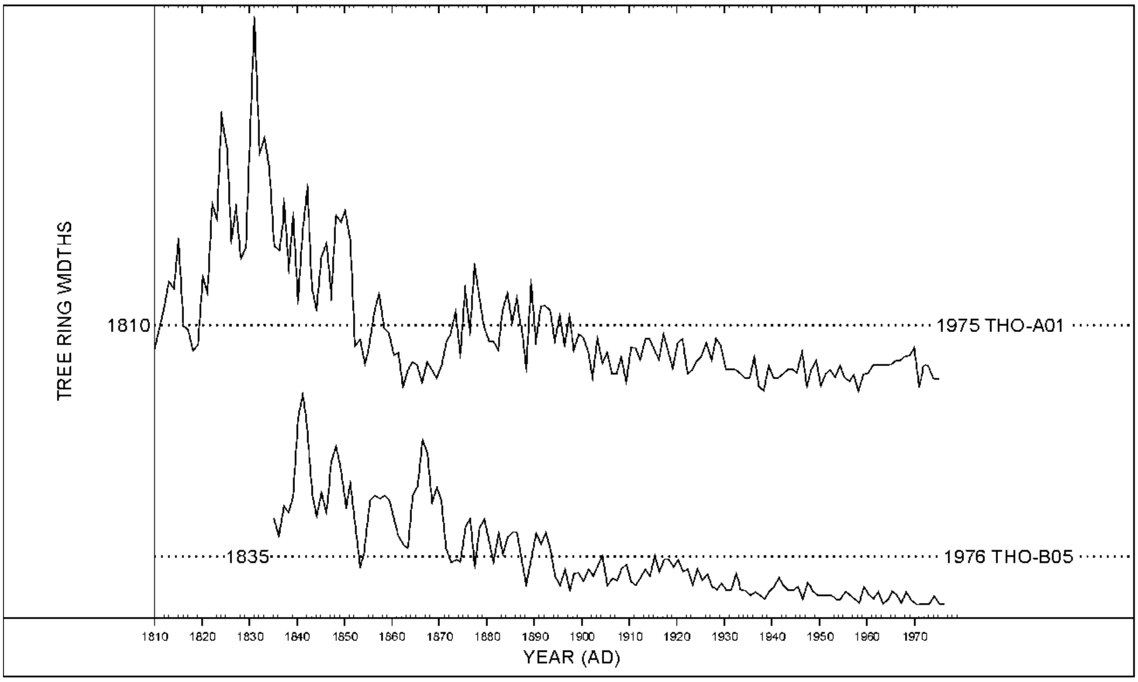


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

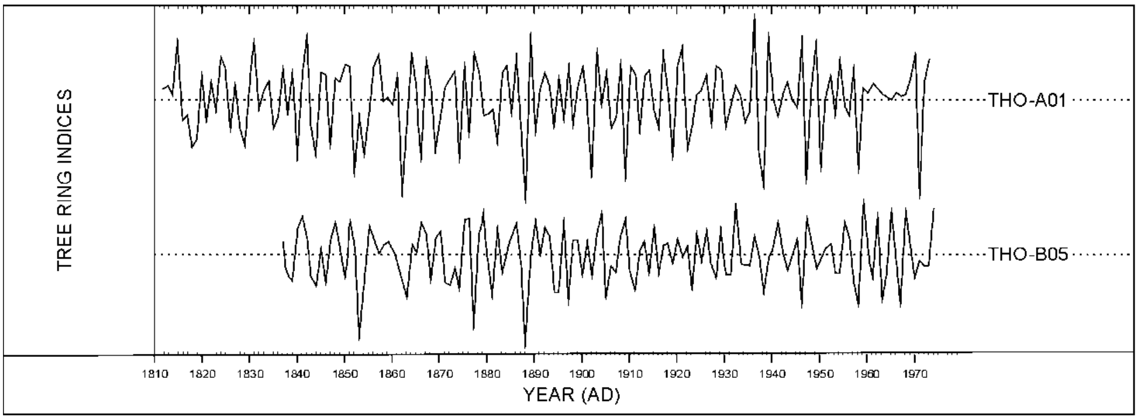


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known
Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely.

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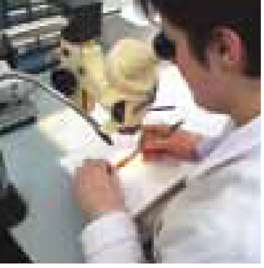 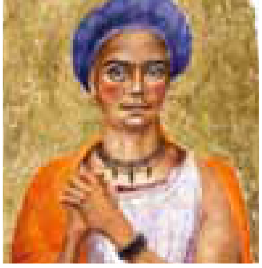   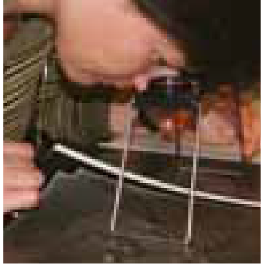 

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