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Scientific Dating

Arden Mill, Hawnby, Near Helmsley, North Yorkshire

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 16-2016

Cover: Arden Mill, east face, after demolition of the miller's house in 2005.
Photograph Alison Arnold

Research Report Series 16-2016

ARDEN MILL
HAWNBY
NEAR HELMSLEY
NORTH YORKSHIRE

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SUMMARY
Analysis undertaken on 12 of the 23 samples taken from the mill roof, main structure, hurst frame and waterwheel resulted in the construction of a single undated site sequence. This site sequence demonstrates that several of the roof timbers are coeval but that a cross rail from the hurst frame was felled several decades later.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
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ARCHIVE LOCATION
North York Moors National Park Historic Environment Record
National Park Office
The Old Vicarage
Bondgate
Helmsley
North Yorkshire
YO62 5BP

DATE OF INVESTIGATION
2014–5

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CONTENTS

INTRODUCTION

The Grade II* listed Arden Mill is a water-powered corn mill located just under 2½km to the north-west of the village of Hawnby, near Helmsley, in the North York Moors National Park (Figs 1–3). The information presented below is summarised from Harrison (2008) and Watts (2012).

The site is thought to be medieval in origin, once serving St Andrew's Priory (the Benedictine nunnery at Arden) with the existence of a mill here being hinted at in AD 1189 and securely documented in AD 1536.

The current mill is a three-bay, single storey structure, orientated roughly north-south (Fig 4). The southern bay houses the waterwheel (Fig 5) and is separated from the central bay by a stone wall. The central bay contains the driving gears, hurst frame, and millstones (Fig 6), whilst the northern bay was floored and was used for grain storage. Attached to the north of the mill is what remains of the miller's house, a smoke bay with inglenook fireplace with chamfered bressumer beam, and a salt box.

The roof over the mill consists of two cruck trusses, between which are two tiers of staggered trenched purlins and modern common rafters (Fig 7).

The mill was thought to have been refurbished by Charles Tankred in the early eighteenth century, around the time of the expansion of Arden Hall (AD 1700–10) to supply fine flour for the hall. In AD 1846 the then miller, William Megginson, is documented as carrying out repairs. He is also believed to have made some modifications to the mill machinery in the AD 1850s. The mill ceased working in 1912, since which time the mill building has suffered extensive damage from flooding and changes in its hydrology.

Arden Mill is of special interest as a water-powered corn mill of possibly medieval origin that retains a near complete set of early-eighteenth century mill machinery with only minor mid-nineteenth century modifications and repairs.

SAMPLING

A dendrochronological survey of the mill was requested by Keith Emerick to inform its long term future of possible dismantlement and potential relocation.

A total of 23 timbers was sampled by coring. Samples were taken from those timber elements thought to have the best dendrochronological potential from throughout the mill. Two cores were also taken from the floor frame but, as these were clearly not oak (*Quercus* spp), no further sampling of this floor frame was undertaken. These two samples were subsequently identified as ash (*Fraxinus excelsior* L; Flintoft *pers comm*).

Each sample was given the code ARD-M and numbered 1–23. The location of all samples was noted at the time of sampling and has been marked on Figures 4 and 8–12. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

Nine of the oak samples had less than 40 rings making them unsuitable for analysis and so these were discarded prior to measurement, as were the two ash samples. This rejection rate is disappointing but reflects difficulties experienced during sampling with cramped conditions hindering clear access to timbers as well as the issue of various timbers being rather damp leading to the loss of a significant portion of the outer rings. The remaining 12 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 samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in six samples matching each other.

These six samples were then combined at the relevant offset positions to form ARDMSQ01, a site sequence of 112 rings (Fig 13). Attempts to date this site sequence and the ungrouped samples by comparing them against a series of relevant reference chronologies for oak, initially from throughout the British Isles and subsequently from elsewhere in Europe and the United States and Canada, were unsuccessful and all remain undated.

DISCUSSION

It is unfortunate that neither the site sequence nor any of the ungrouped samples have been dated. Generally, the longer and better replicated a site sequence is, the greater the chance of successful dating. Site sequence ARDMSQ01 contains six samples and is 112 rings long and so might usually be expected to have a good chance of dating. However, it may be that the timbers represented belong to the late post-medieval period, a period less well represented within the network of reference chronologies. In addition, it may be that the trees used were subject to highly localised conditions which have unduly influenced the growth pattern necessary for matching against reference chronologies. The mill is located in an area which is not well represented in the chronological network and an area that has proven problematic with respect to successful dendrochronological analysis. Thus, the production of a replicated 112-year site chronology is of importance for future analyses in this area. In addition should the decision be taken to dismantle and relocate the mill then this would provide an opportunity to enhance the sampling already undertaken which proved problematic and, thus, potentially increase the likelihood of successful dendrochronological analysis.

Although undated, it is clear that the five samples from the roof included in site sequence ARDMSQ01 are coeval with heartwood/sapwood boundaries varying by only nine years. Two of these samples, representing a principal rafter and a purlin, have complete sapwood and, thus, based on the high level of cross-matching, it is possible to suggest that all five of the timbers represented were felled in the same relative year of 110. It is notable that the cross-matching between ARD-M01 and ARD-M02 (t = 10.7) and ARD-M04 and ARD-M05 (t = 12.0) raises the possibility that each pair of principal rafters was derived from a single tree. The sixth sample, ARD-M17, included in site sequence ARDMSQ01 represents a cross rail in the hurst frame. With a last measured ring at relative year 112 it was clearly felled at a later date than the roof timbers. Using a sapwood estimate of 15–40 rings (the usual 95% confidence interval), an estimated felling date in the relative year range of 121-146 is obtained. This indicates that this cross rail was potentially felled several decades later than those timbers in the roof.

BIBLIOGRAPHY

Harrison, J K, 2008 *Eight Centuries of Milling in North East Yorkshire*. North York Moors National Park Authority

Watts, M, 2012 *Arden Mill, Hawnby, North Yorkshire: A condition survey and report for The North York Moors National Park Authority*

TABLES

Table 1: Details of samples from Arden Mill, Hawnby, 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)
Roof & structure						
ARD-M01	East principal rafter, truss 1	81	19C	----	----	----
ARD-M02	West principal rafter, truss 1	100	15	----	----	----
ARD-M03	Tiebeam, truss 1	NM	--	----	----	----
ARD-M04	East principal rafter, truss 2	61	h/s	----	----	----
ARD-M05	West principal rafter, truss 2	95	03	----	----	----
ARD-M06	Tiebeam, truss 2	NM	--	----	----	----
ARD-M07	East upper purlin, wall to truss 2	99	11C	----	----	----
ARD-M08	Lower lintel, south wall	99	h/s	----	----	----
ARD-M09	Window lintel, east wall	NM	--	----	----	----
ARD-M10	Bresummer, mill house	NM	--	----	----	----
ARD-M11	Joist 4 – not oak	NM	--	----	----	----
ARD-M12	Joist 8 – not oak	NM	--	----	----	----
Hurst frame						
ARD-M13	Top beam	108	19	----	----	----
ARD-M14	Axial beam	70	15	----	----	----
ARD-M15	East post	NM	--	----	----	----
ARD-M16	West post	64	--	----	----	----
ARD-M17	Cross rail	107	06	----	----	----
Waterwheel pit						
ARD-M18	Horizontal beam	NM	--	----	----	----
ARD-M19	Spoke 1	NM	--	----	----	----
ARD-M20	Spoke 2	63	--	----	----	----
ARD-M21	Spoke 3	NM	--	----	----	----
ARD-M22	Rim 1	64	--	----	----	----
ARD-M23	Rim 2	NM	--	----	----	----

NM = not measured
h/s = heartwood/sapwood boundary is the last-measured ring
C = complete sapwood retained on sample, last measured ring is the felling date

FIGURES

Figure 1: Map to show the general location of Arden Mill, arrowed. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

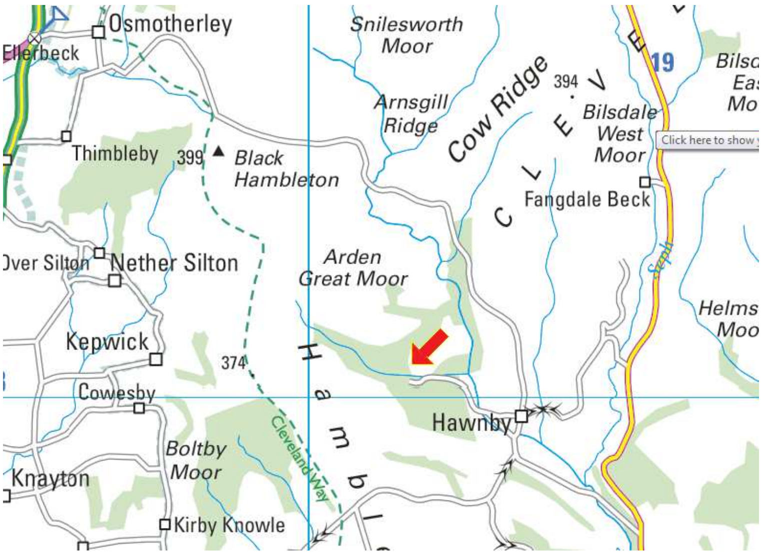

Figure 2: Map to show the general location of Arden Mill, arrowed. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the location of Arden Mill. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

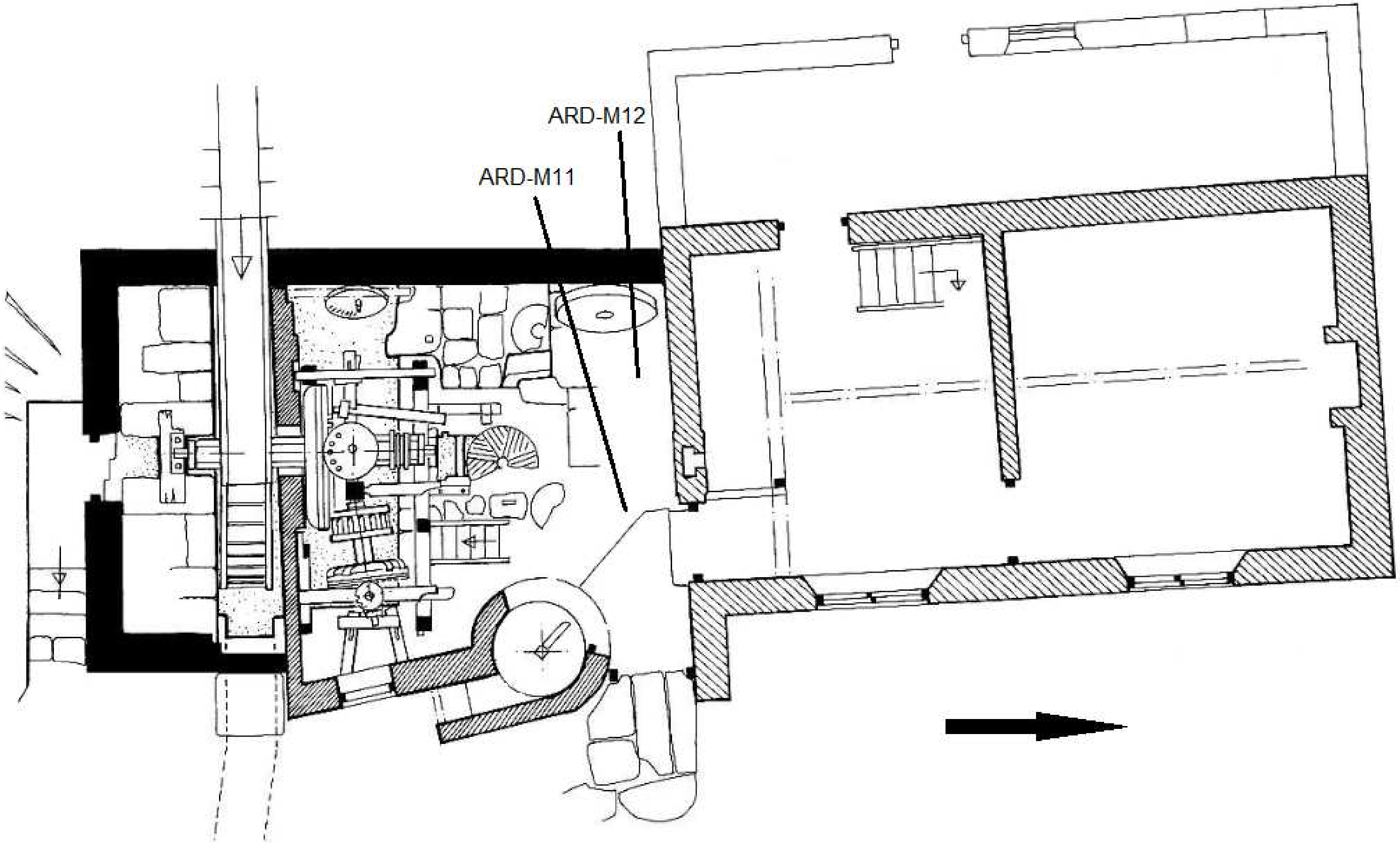

Figure 4: Plan of the mill and miller's house (prior to the demolition of the majority of the miller's house in 2005), with the approximate position of samples ARD-M11 and ARD-M12 (after Harrison 2008)

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Figure 5: The waterwheel, photograph taken from the south-east (Alison Arnold)

Figure 6: Hurst frame and gears, photograph taken from the north (Alison Arnold)

Figure 7: Truss 1, photograph taken from the south (Alison Arnold)

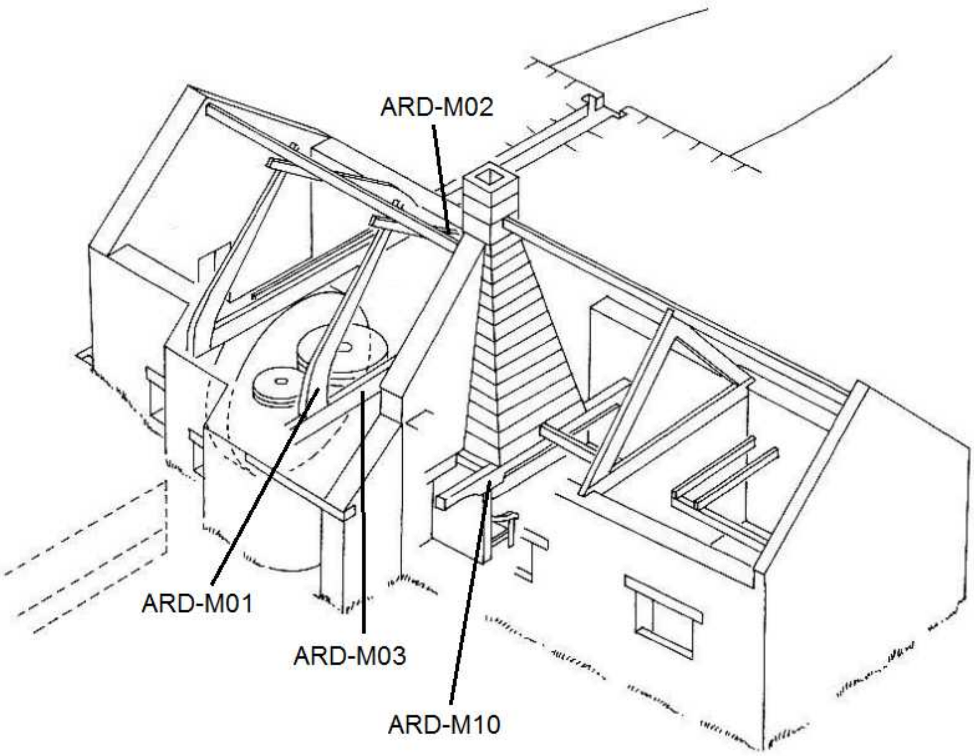

Figure 8: Arden Mill, showing the location of samples ARD-M01–03 and ARD-M10 (after Harrison 2008)

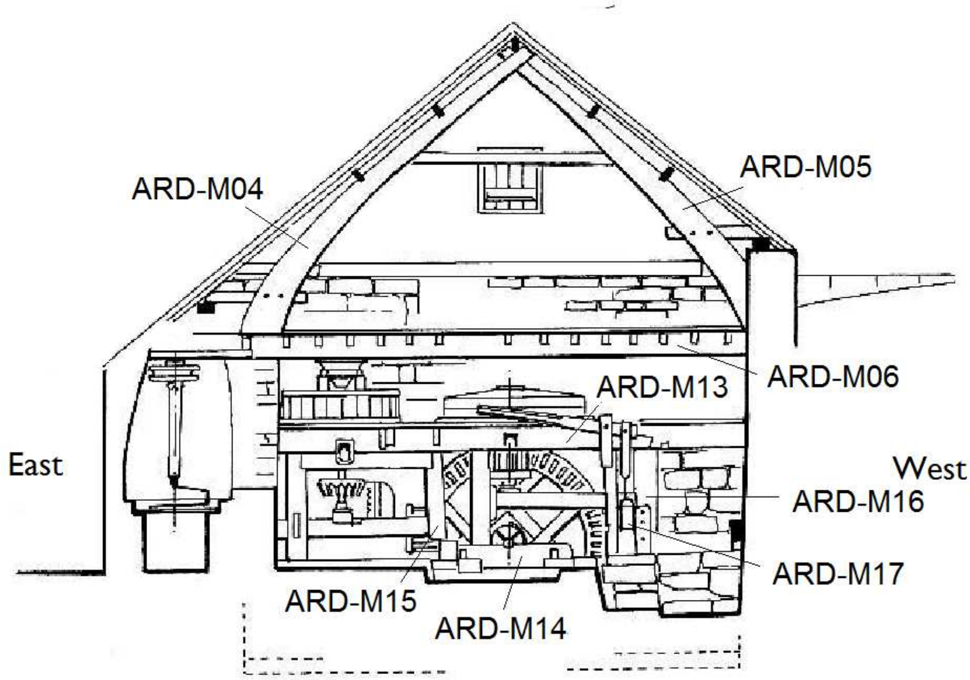

Figure 9: Section through the mill, showing the location of samples ARD-M04–06 and ARD-M13–17 (after Harrison 2008)

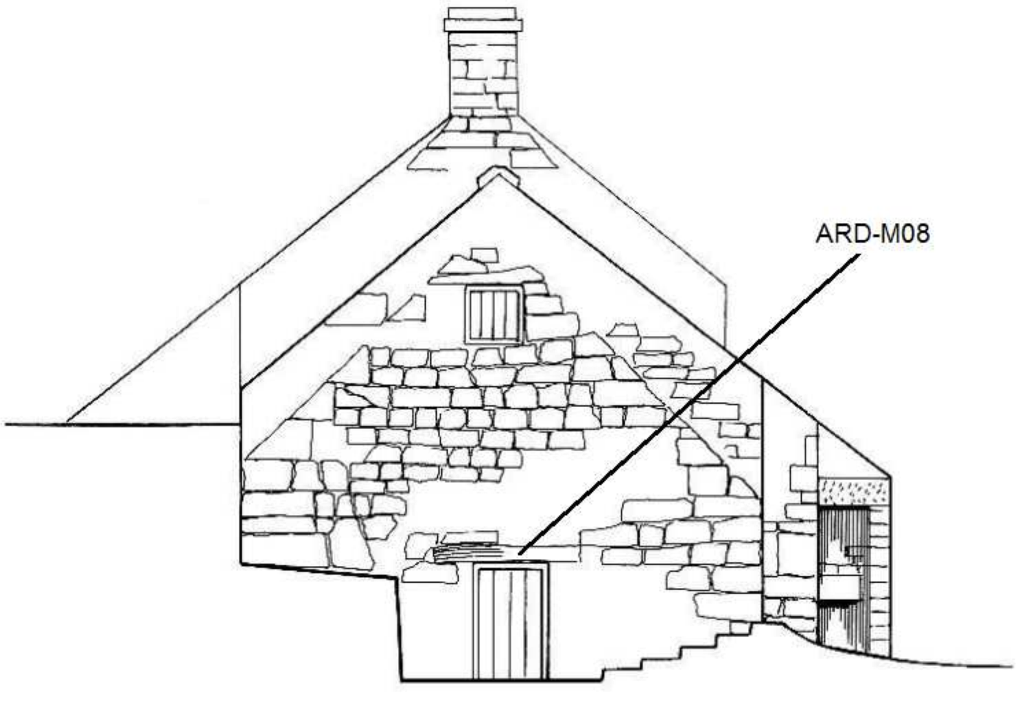

Figure 10: South elevation, showing the location of sample ARD-M08 (after Harrison 2008)

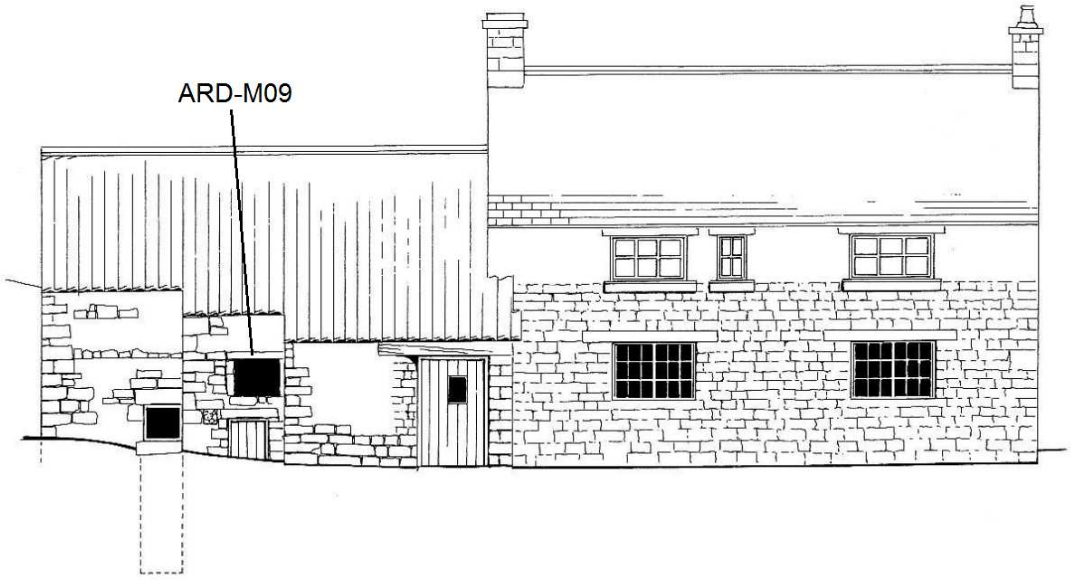

Figure 11: East elevation, showing the location of sample ARD-M09 (after Harrison 2008)

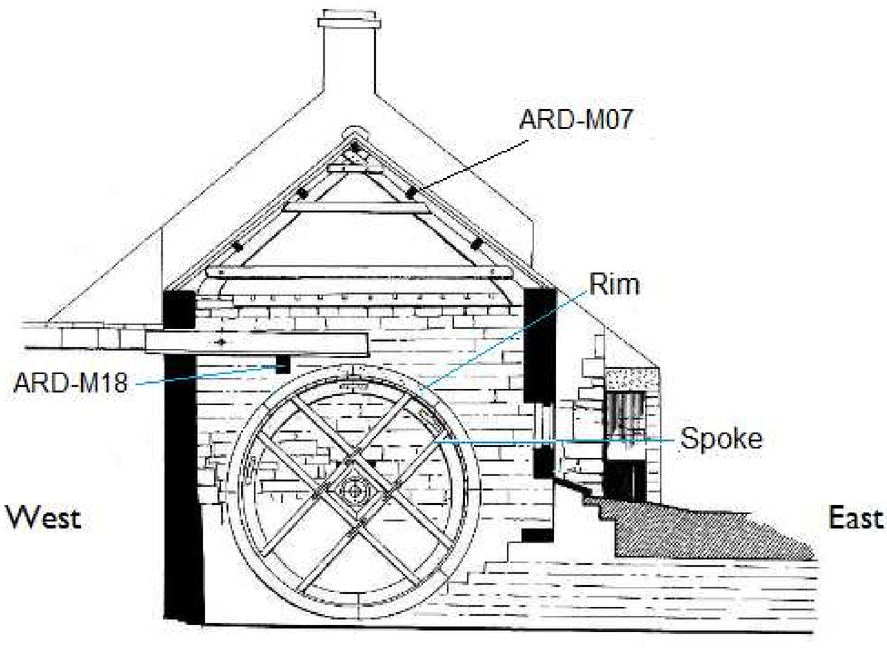

Figure 12: Section through the mill, showing the location of samples ARD-M07 and ARD-M18, and to identify those sampled elements described as 'rim' (ARD-M22, ARD-M23) and 'spoke' (ARD-M19–21) (after Harrison 2008

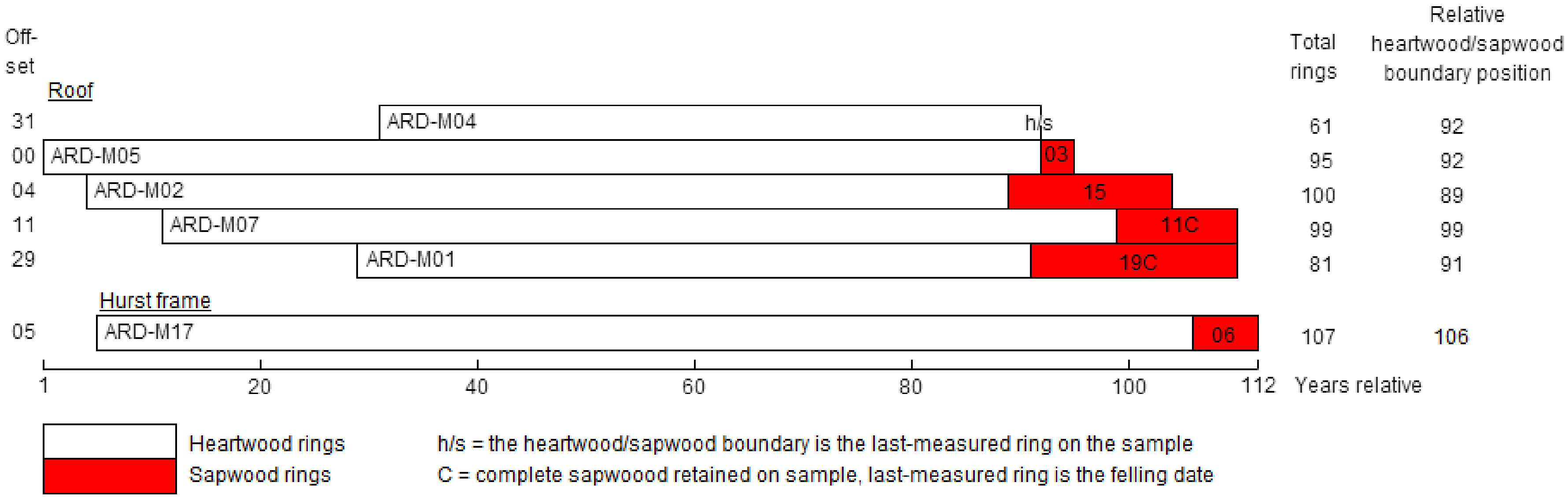

Figure 13: Bar diagram of samples in site sequence ARDMSQ01, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

ARD-M01A 81
348 215 248 193 160 237 234 263 233 185 164 212 160 194 142 198 194 205 262 209
187 160 173 161 95 110 129 124 179 187 173 137 114 74 54 80 88 113 145 112
86 132 118 115 156 175 122 118 125 150 168 158 176 168 127 127 142 137 78 79
58 73 137 121 131 155 205 208 284 258 192 186 180 214 149 130 124 132 81 58
65
ARD-M01B 81
344 211 253 198 163 232 238 262 239 188 153 206 182 175 170 188 189 179 270 245
189 171 165 168 92 108 116 121 189 191 161 153 112 69 50 79 105 124 131 121
82 122 126 130 160 164 130 133 110 149 169 155 172 173 124 113 130 133 76 77
67 73 137 130 136 146 204 203 291 255 186 194 181 250 170 140 143 153 83 73
58
ARD-M02A 100
277 126 244 190 115 163 143 254 153 220 161 196 170 246 243 218 220 170 204 181
167 179 161 186 180 204 143 210 146 143 193 179 193 147 128 123 160 122 171 152
177 191 185 248 194 202 174 223 191 119 134 145 153 210 205 205 192 131 88 73
73 86 126 154 110 108 168 126 115 147 166 140 125 141 148 178 167 176 199 126
107 127 129 99 93 89 81 123 151 113 126 166 225 230 232 210 185 160 185 205
ARD-M02B 100
272 133 241 202 138 156 170 221 167 222 159 207 163 242 249 227 230 183 208 172
172 195 162 183 179 217 124 201 152 139 193 183 187 150 140 124 161 118 157 144
172 191 194 246 202 204 178 229 198 113 141 138 160 216 204 205 196 137 86 65
78 84 133 141 111 100 160 141 106 151 182 144 121 140 146 177 173 175 197 124
117 123 124 101 94 96 70 136 143 117 126 162 211 248 223 222 188 180 189 205
ARD-M04A 61
229 170 180 221 143 193 139 114 116 177 121 104 84 82 60 97 123 126 123 110
127 163 106 139 149 185 231 140 208 113 90 82 120 130 139 223 158 149 47 94
92 132 128 146 157 105 103 109 154 140 115 180 105 98 111 139 86 111 93 121
159
ARD-M04B 61
202 172 166 215 175 188 135 113 119 170 124 96 94 75 71 96 121 130 115 112
137 164 95 146 148 187 229 162 198 124 80 93 116 128 137 226 161 137 55 92
97 123 135 141 162 98 106 111 148 147 114 158 125 90 112 143 81 112 84 112
150
ARD-M05A 95
159 162 176 107 80 59 79 62 77 134 120 115 87 97 81 99 89 139 171 187
160 160 170 158 168 179 125 125 140 185 147 170 134 98 131 117 161 85 85 87
128 95 90 61 53 54 74 127 115 115 116 107 132 64 89 82 130 176 119 144
97 65 61 84 109 119 195 162 132 55 100 71 110 108 142 158 73 110 91 119
131 121 142 93 83 72 102 50 61 47 75 121 96 81 107
ARD-M05B 95
187 153 174 107 79 63 65 78 65 139 112 112 102 79 113 79 95 127 163 185
160 149 173 158 166 174 129 138 122 141 148 169 128 102 133 121 158 82 85 86
128 94 86 63 57 55 81 113 114 116 115 121 124 69 75 73 119 160 124 144
94 67 62 81 107 119 193 152 132 60 99 75 111 116 145 147 68 106 94 113
130 130 139 96 80 69 96 57 63 54 75 109 98 81 115

ARD-M07A 99
228 141 146 212 351 262 365 306 326 251 196 206 152 274 153 124 145 206 225 131
176 158 155 197 203 227 96 100 105 137 119 149 124 107 94 156 152 199 174 206
240 192 111 126 153 150 220 141 155 106 75 71 60 57 57 90 99 110 47 50
50 51 43 63 89 56 62 57 97 116 117 135 92 72 76 112 51 83 53 98
156 170 117 145 192 132 233 181 193 214 220 258 245 175 147 147 154 115 178
ARD-M07B 99
219 151 146 207 342 265 351 319 321 259 202 201 152 253 152 137 139 204 239 139
173 171 155 191 201 223 108 100 101 154 129 144 119 102 91 143 142 191 178 204
237 189 110 123 149 147 218 139 160 102 80 70 60 55 61 88 99 110 51 48
50 52 45 62 88 58 55 63 95 118 116 133 91 75 72 107 61 82 50 95
155 167 114 147 190 136 232 173 203 211 227 253 252 177 139 146 146 119 189
ARD-M08A 99
92 153 135 163 248 172 149 229 329 303 356 309 270 177 246 150 319 249 207 180
170 174 152 122 57 128 129 158 118 104 109 117 113 116 123 141 147 101 52 40
53 72 50 48 68 74 83 99 92 64 59 67 56 68 74 109 133 113 72 67
67 51 73 77 82 73 83 71 110 60 56 54 60 73 71 90 100 86 128 102
91 128 118 93 108 126 108 97 118 103 94 123 124 113 119 114 127 121 96
ARD-M08B 99
108 160 140 167 316 187 151 236 317 312 350 314 272 175 244 154 325 251 201 180
174 170 153 117 59 133 134 162 124 98 111 118 118 106 129 138 137 105 49 41
50 64 49 43 65 72 84 88 83 66 57 68 58 68 76 108 135 106 71 70
59 59 72 66 86 74 77 75 106 61 53 55 60 73 65 93 99 80 130 100
81 125 118 88 112 123 106 100 119 102 90 123 129 108 119 114 127 112 112
ARD-M13A 108
230 239 395 290 229 238 254 340 275 282 422 317 230 315 392 396 506 356 257 264
221 285 219 249 252 207 241 313 304 270 199 301 193 339 376 354 318 256 223 294
215 99 122 161 182 173 220 161 179 214 195 199 176 194 167 188 238 156 205 154
196 234 270 195 182 232 208 184 135 185 220 303 228 239 203 188 176 115 134 144
202 183 222 222 169 159 128 118 147 121 130 179 128 163 172 145 183 108 182 104
59 57 55 33 33 26 46 41
ARD-M13B 108
222 237 395 288 220 246 242 337 282 271 412 314 232 323 363 382 502 362 258 252
211 290 215 251 252 197 250 309 304 274 194 301 200 349 372 341 307 262 219 302
211 94 136 154 179 170 227 156 179 211 191 195 169 191 176 195 255 161 203 168
198 244 257 208 179 224 205 185 135 182 231 294 225 243 203 184 177 118 130 143
203 180 222 222 168 166 113 126 153 124 125 193 118 156 175 143 180 102 187 108
56 62 50 34 38 29 34 42
ARD-M14A 70
433 462 408 369 344 254 360 243 332 222 300 245 284 250 184 207 181 187 242 325
218 217 192 192 142 141 104 89 131 188 109 69 74 66 69 67 81 84 106 108
94 109 72 100 99 100 112 144 120 163 140 135 90 130 126 131 71 66 97 35
55 51 79 114 100 111 87 89 84 82
ARD-M14B 70
432 456 409 359 339 253 355 242 329 228 298 246 284 237 168 208 176 189 235 327
214 211 187 178 153 125 101 84 125 188 103 73 68 61 78 60 80 91 103 97
96 109 80 99 99 96 110 146 121 158 137 132 92 127 122 130 75 66 94 37
67 46 84 106 86 123 80 94 83 85
ARD-M16A 64
400 356 265 248 209 251 178 150 79 128 139 163 199 195 189 223 263 271 158 152
180 200 258 188 215 269 234 147 158 186 263 143 122 177 204 233 115 65 65 47
54 87 114 77 59 99 64 71 69 123 118 89 80 79 73 76 112 144 140 99
148 162 377 358

ARD-M16B 64
393 353 283 223 241 263 172 136 57 135 146 163 198 212 195 227 289 281 168 157
191 209 254 188 238 291 280 144 162 190 262 148 123 193 198 243 109 66 74 51
62 92 108 73 63 88 79 71 71 118 119 83 79 81 78 68 114 126 158 97
148 162 289 376
ARD-M17A 107
226 522 357 327 263 238 365 325 282 330 226 199 279 217 361 365 215 226 176 159
89 60 103 91 85 70 91 63 62 115 103 133 92 101 65 91 71 58 43 76
65 73 87 57 54 59 57 52 39 41 35 32 35 25 30 26 28 27 26 29
59 56 64 42 36 61 65 56 70 96 120 103 94 75 102 133 140 147 101 113
106 133 88 106 153 178 342 226 219 167 192 166 258 162 131 126 142 179 166 153
149 99 100 72 55 89 70
ARD-M17B 107
222 521 358 332 263 228 372 312 283 315 219 193 252 193 369 375 204 228 170 157
90 65 98 97 84 70 82 70 64 113 122 143 121 118 65 101 60 52 45 72
69 64 80 56 54 58 57 51 47 35 34 31 36 23 30 27 27 27 27 28
59 63 53 44 35 66 63 49 75 101 120 102 92 80 103 131 137 149 104 111
97 147 86 107 146 162 350 229 219 160 193 160 254 156 127 136 141 173 145 141
133 116 90 71 56 93 68
ARD-M20A 63
188 107 143 109 90 98 62 124 102 153 186 180 216 172 144 207 162 223 198 173
174 265 249 225 214 204 194 210 265 198 217 223 255 241 256 213 197 200 228 202
224 204 159 146 153 144 147 153 182 163 191 141 107 124 144 143 156 128 188 174
188 167 139
ARD-M20B 63
173 108 135 112 116 91 69 119 101 166 186 182 212 176 150 199 168 221 203 167
178 261 243 226 208 209 189 202 259 194 209 219 263 245 243 213 193 217 231 204
222 205 168 141 148 143 152 147 177 168 187 140 110 120 149 133 166 126 196 171
191 170 136
ARD-M22A 64
32 28 29 24 28 29 41 48 67 93 78 127 153 137 157 153 147 165 224 192
188 191 286 245 188 163 160 144 111 128 120 92 95 102 84 72 94 91 110 105
138 117 108 134 173 258 242 268 286 274 332 311 322 342 350 376 370 396 456 354
311 409 494 346
ARD-M22B 64
29 27 35 26 30 34 31 50 71 84 88 136 144 140 161 153 151 168 210 199
190 202 276 239 193 164 161 146 124 132 114 95 81 106 88 76 92 99 109 98
145 115 99 147 182 247 247 266 287 280 339 320 334 347 346 371 372 388 456 349
316 410 498 325

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 Building* (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.

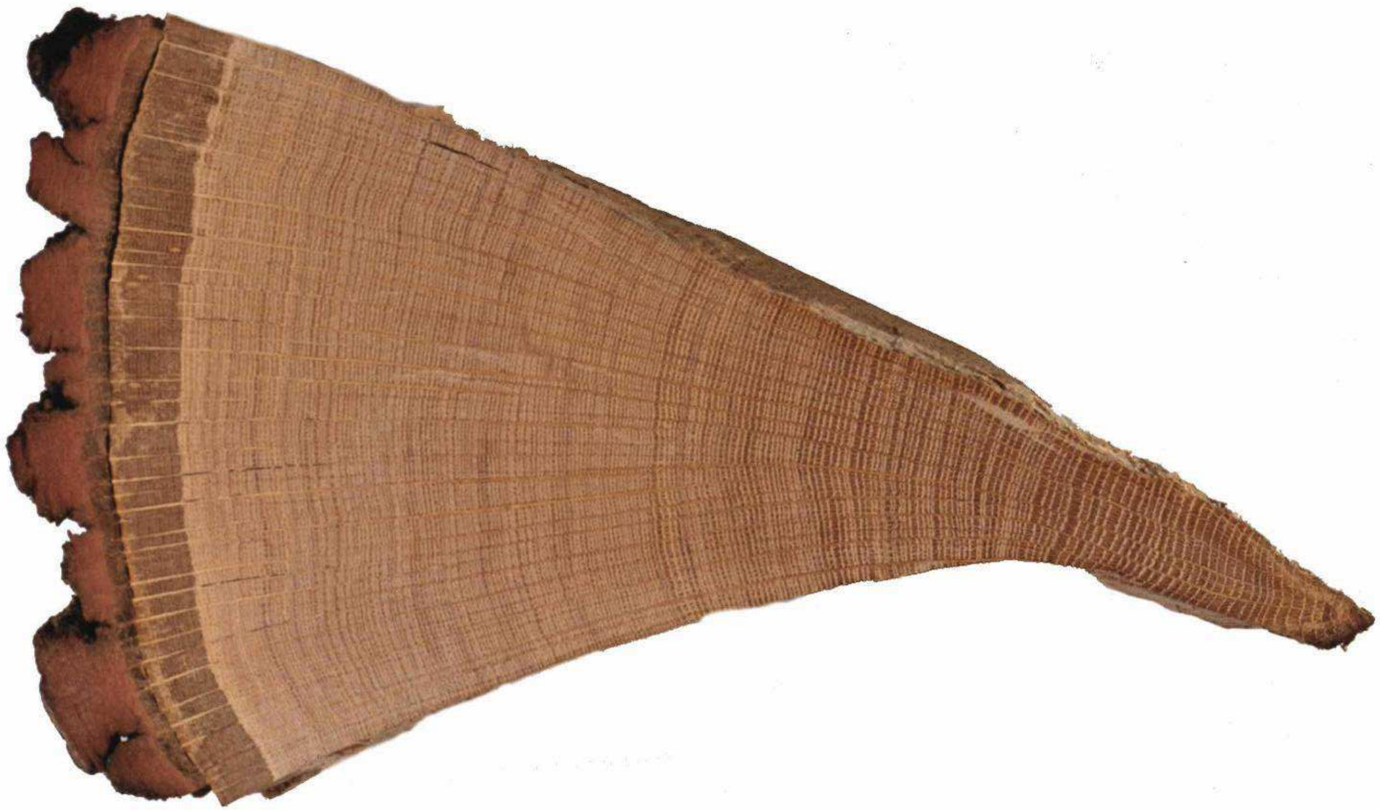

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

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

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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

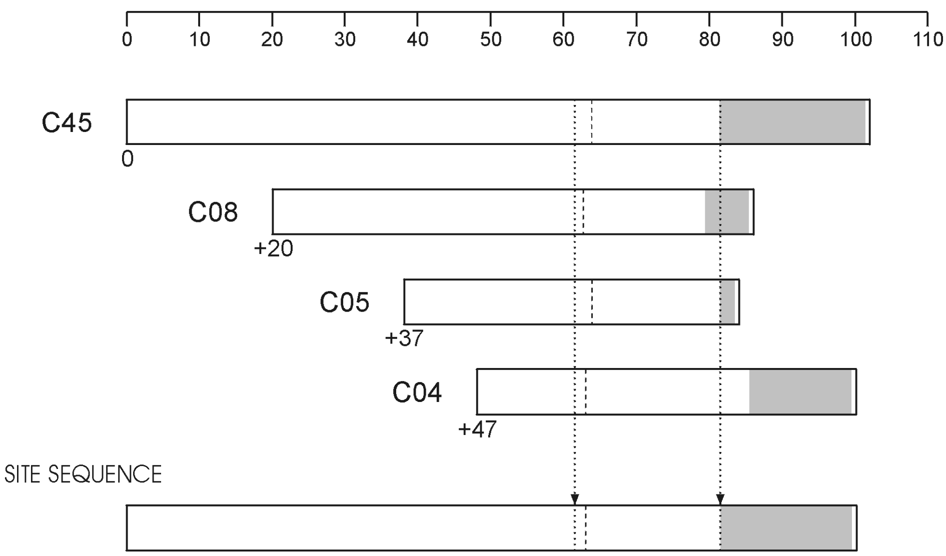

Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

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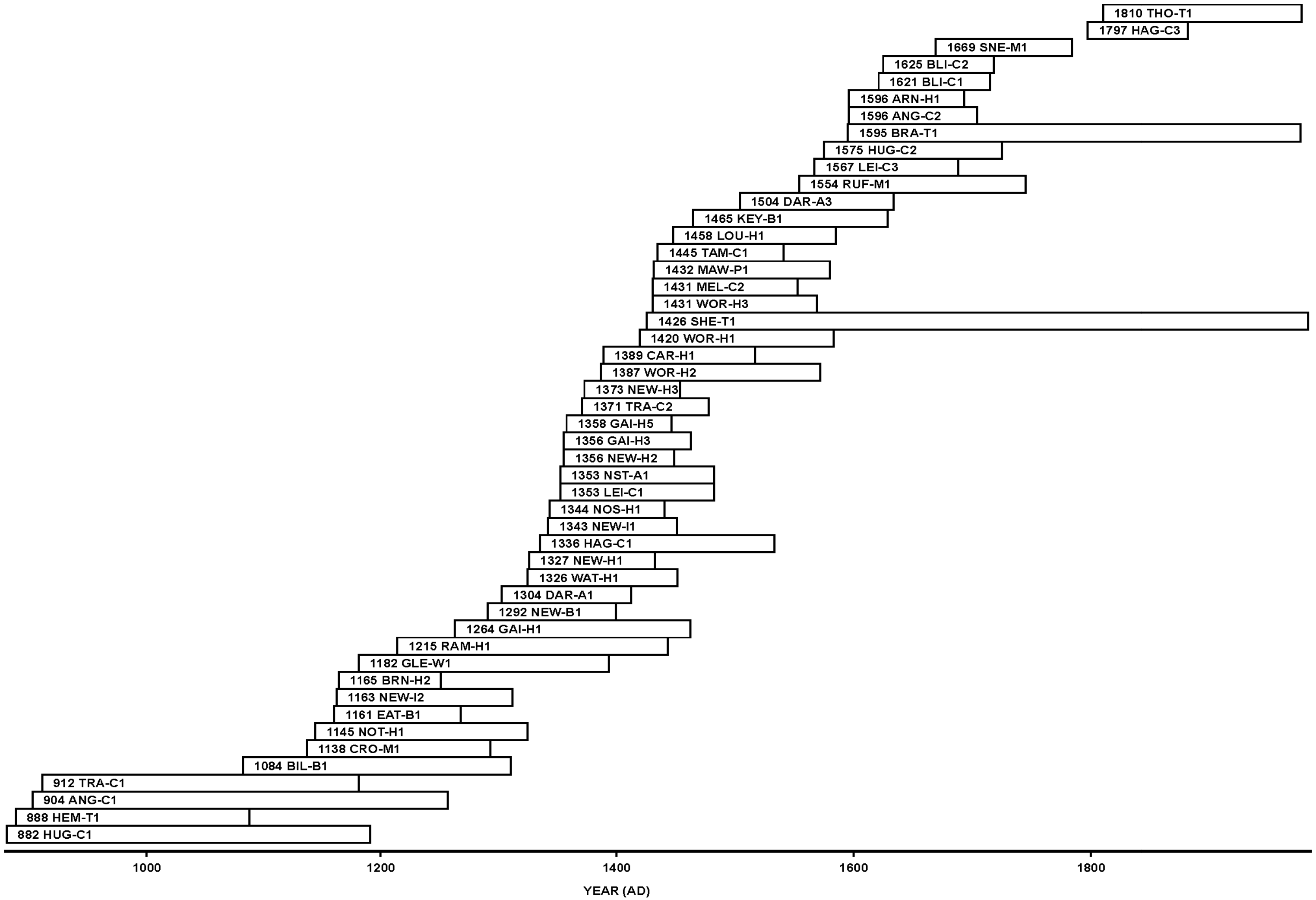
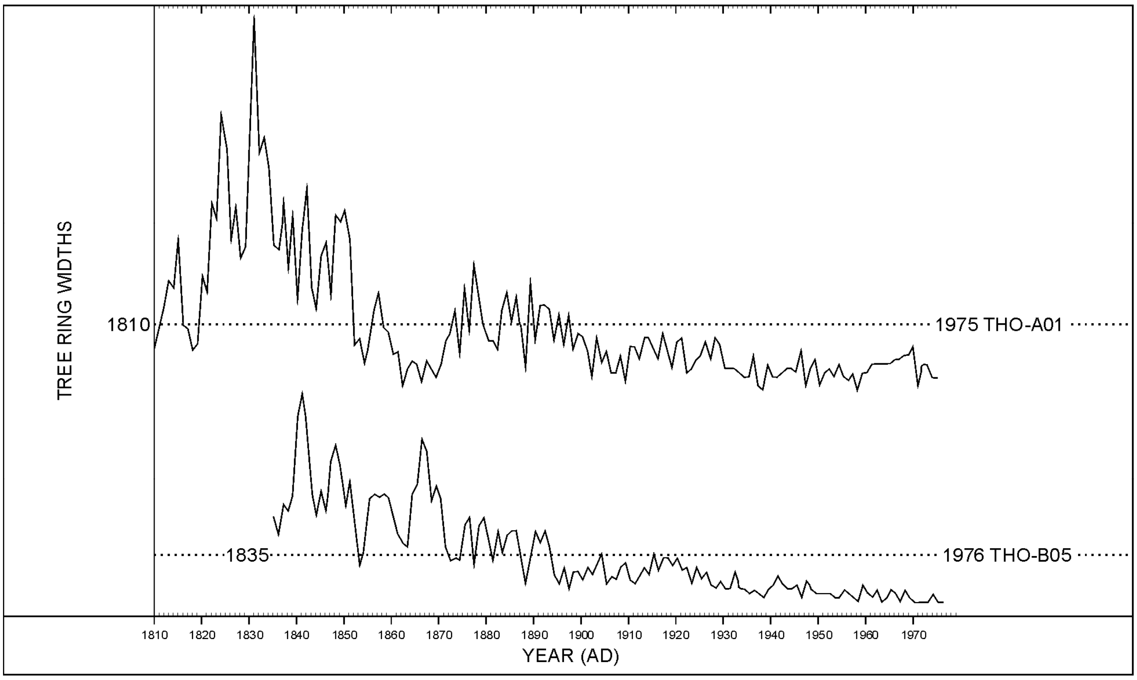


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

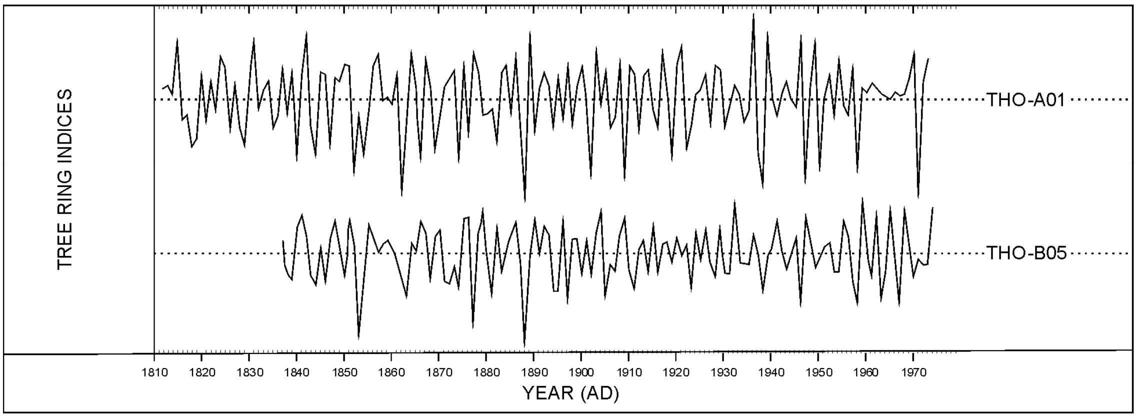


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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