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Summary

Core samples were obtained from 14 different beams at this site, these mainly being the major basal timbers, with some of the upper timbers being sampled too. Of these cores 13 were analysed by tree-ring dating. The analysis of these produced a single site chronology, KIBASQ01, comprising all 13 samples, and having a combined overall length of 192 rings. This site chronology was dated as spanning the years AD 1582 to 1773. Interpretation of the sapwood would indicate that all the dated timbers were cut in a single phase of felling in AD 1773. The analysis of the timbers would suggest that the mill may not be as old as had been believed.

Keywords

Dendrochronology
Standing Building

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Introduction

Kibworth Harcourt Windmill is the only surviving post-mill in Leicestershire, and one of only 48 of the type in the entire country. It is a listed Grade II* building and a Scheduled Ancient Monument, as well as being designated as a building at risk. It stands on high ground to the east of the village at Windmill Farm, adjacent to the lane between Kibworth and Tur Langton (SP 689 944, Figs 1 and 2). It has two common sails and two sprung sails, upon a mid- to late-nineteenth century brick roundhouse at its base. A drawing of the mill is given in Figure 3.

The history of milling in Kibworth Harcourt is better recorded than in most villages because the hamlet was owned by Merton College, Oxford, from *c* AD 1270. As Lord of the Manor, the Warden of the College maintained records of all the village activities, including mill-related ones, up to the time they transferred ownership in AD 1936.

The earliest reference to a mill in Kibworth Harcourt is dated AD 1286. Its exact location is, however, not given. In AD 1356, except for the sailyards, the timber of a mill in the village was sold and a new one constructed. From the documentary sources it is believed that the mill was moved at this time to a higher position north east of the village. Today this area is known as 'Old Mill Hill'. The documents further indicate that the mill was repaired in AD 1448, and rebuilt again, possibly at its present location, in AD 1515. A map of AD 1609, however, does not show a mill in the village at all, either where it now stands or at Old Mill Hill. It is only on a map of AD 1635 that a mill, at its present location, can be seen. The central mill-post is inscribed 'Daniel Hutchinson, Miller, 1711'

Although not having been used commercially since AD 1914 the mill and its machinery have been maintained. It was repaired in AD 1936, when it was given by Merton College to the Society for the Preservation of Ancient Buildings, and again in the early AD 1970s. The most recent repairs were undertaken in AD 1989. Currently the day-to-day administration of the mill is in the hands of the Kibworth Harcourt Windmill Charity.

The structure of the mill comprises basal timbers of two horizontal beams forming an 'X'. From the centre of the 'X', where the two horizontals cross each other, rises the central mill-post. This is an extremely large timber some 2.75m in diameter. The surface of this timber is covered in whorles and bosses from which small branches must have once grown. It is also badly split, and, from the evidence of coring, may be badly rotted within. Straight struts run from the four arms of the 'X' to the central mill-post.

The central mill-post supports two parallel north-south beams (connected by short east-west cross-beams either side of the central mill-post), which run to wall plates at their north and south ends. The north and south wall plates in their turn support further wall plates to east and west. Upon these four wall plates stand four corner posts which form the basic box-like structure of the upper portion of the mill.

The upper portion of the mill contains two floors. The first floor is where the flour was bagged via a chute from above. The second or top floor contains the grinding wheels themselves, the gears, and other drive machinery. The structure of the upper levels of the mill is of simple close-studded framing comprising the four principal corner posts, smaller wall posts, and studs. These walls are clad in what appears to be a mixture of relatively modern, possibly some nineteenth-century and some twentieth-century, oak and softwood weatherboard cladding. It was seen that none of the weather-boards appeared to be particularly suitable for tree-ring analysis, having too few rings, ie less than 54, for reliable analysis.

Sampling

Sampling and analysis by tree-ring dating of the timbers of the windmill were commissioned by English Heritage. The purpose of this was to identify the earliest elements of the mill, establishing if possible its construction date and the date of any repair material, in advance of a major repair programme funded by English Heritage.

After an examination of the mill, and in conjunction with the sampling brief, 14 different timbers were sampled, with 15 cores, the maximum allowed under Scheduled Monument Consent, being taken. Two attempts were made to sample the central mill-post, but no suitable core could be obtained, the core appearing to reach rotted material and breaking a short way below the surface. The short sections of core obtained appeared to show very wide ring growth

Each sample was given the code KIB-A (for Kibworth, site "A") and numbered 01 – 14. All the timbers sampled appeared to be primary and integral with each other, all being jointed and pegged. Other timbers were potentially available, but many of them appeared to be more recent, possibly related to twentieth century repairs. Furthermore many of these more recent timbers appeared to have too few rings for reliable analysis.

The positions of these samples are marked on plans and drawings produced and provided by J Kenneth, Architects. These are reproduced here as Figures 4a-c. Details of the samples are given in Table 1. In this Table, all timbers are identified on a north - south or east - west basis as appropriate.

Analysis

Each of the 13 suitable samples obtained was prepared by sanding and polishing and their annual growth-ring widths were measured. The growth-ring widths of all 13 samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum value of t=5.0 a single group comprising all measured samples could be formed, the samples cross-matching with each other at relative off-set positions as shown in the bar diagram Figure 5. The samples were combined at these off-sets to form KIBASQ01, a site chronology of 192 rings. Site chronology KIBASQ01 was then dated by comparison to a number of relevant reference chronologies for oak as spanning the years AD 1582 to AD 1773. The evidence for this dating is given in the t-values of Table 2.

Interpretation and conclusion

Analysis by dendrochronology has produced a single site chronology, KIBASQ01 comprising 13 samples, its 192 rings dated as spanning the years AD 1682 to AD 1773. Three samples in this site chronology, KIB-A06, A07 and A12, retain complete sapwood. This means that they each have the last ring produced before the tree, or trees, they represent were felled. In each case the last measured ring date is the same, AD 1773, this thus being the felling date of the timbers.

The relative position of the heartwood/sapwood boundary, where it exists, on the other dated samples in site chronology KIBASQ01, is very similar, varying by 13 years from relative position 165, AD 1746, on sample KIB-A12, to relative position 178, AD 1759, on sample KIB-A06. Such consistency is indicative of a single phase of felling, and it is almost certain that all the other timbers represented were felled in AD 1773 as well. There is no clear indication of any earlier timbers represented in the sampled material.

The only possible exceptions to this consistency might be represented by samples KIB-A03 and A04. The rings sequences of these two samples start over 60 years before any of the others, and they finish earlier too. There is no heartwood/sapwood boundary on either of these timbers, which are probably derived from the same tree, and it is thus not possible to be certain about their felling date. However, using a 95% confidence limit of 15 for the minimum number of sapwood rings that the timbers might have had means that they are unlikely to have been felled before AD 1716, and thus still post-date the AD 1711 inscription. It is likely that the two timbers represented by these samples are felled in AD 1773 too, but are derived from the inner portions of the tree. There is no clear indication of any earlier timbers represented in the sampled material

The date of AD 1773 for the felling of the timbers would suggest that the sampled timbers at least are not as old as had been believed. A mill is shown at the present site on a map of the village dated AD 1635, with a date of AD 1711 also being carved in to the central mill-post. Given that the central mill-post itself did not provide a useable sample, it is possible that this element is more ancient. It is a sizeable timber and hence potentially valuable. Consequently it could have been reused in a late-eighteenth century phase of construction. Alternatively, the AD 1773 felling phase may represent a major repair or renovation to an earlier structure.

Judging by the *t*-values of the cross-matching between some of the samples, it is very likely that many of the sampled timbers represent trees growing very close to each other in the same copse or stand of woodland. Some samples, for example, cross-match with each other with values of *t*=6.7, 7.4, and 8.8. Indeed it is very likely that some timbers, those represented by samples KIB-A03 and A04, struts to the central mill-post, are derived from the same tree, cross-matching with each other, as they do, with a value of *t*=17.2. A cross-match with a value of *t*=12.3 is found between samples KIB-A02 and A08. The two timbers represented by these samples are also, probably, derived from a single tree.

Information from a detailed structural survey may aid the interpretation of the dendrochronological results. However, it may also be worthwhile considering undertaking further sampling during repair works which might result in the removal of whole beams or sections of timber. This is particularly relevant to the central mill-post with the AD 1711 inscription. As indicated above, this timber could not be successfully cored due to decay, knotting and cracking. A cross-sectional slice of this timber might prove useable, though it is not of course possible to guarantee that it would be dated.

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Table 1: Details of samples from Kibworth Harcourt post-mill, Leicestershire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
KIB-A01	North east strut to central mill-post	87	6	AD 1677	AD 1757	AD 1763
KIB-A02	South west strut to central mill-post	93	no h/s	AD 1643	------	AD 1735
KIB-A03	South east strut to central mill-post	120	no h/s	AD 1582	------	AD 1701
KIB-A04	North west strut to central mill-post	110	no h/s	AD 1583	------	AD 1692
KIB-A05	Upper east central beam	102	h/s	AD 1656	AD 1757	AD 1757
KIB-A06	Upper west central beam	99	14C	AD 1675	AD 1759	AD 1773
KIB-A07	North base-beam / wall plate	129	18C	AD 1645	AD 1755	AD 1773
KIB-A08	North central cross-block	71	no h/s	AD 1660	------	AD 1730
KIB-A09	South central cross-block	82	no h/s	AD 1660	------	AD 1741
KIB-A10	Central mill-post	nm	---	------	------	------
KIB-A11	South west corner post	111	7	AD 1648	AD 1751	AD 1758
KIB-A12	Upper main wall post, west wall	70	27C	AD 1704	AD 1746	AD 1773
KIB-A13	Stud post, east wall, first floor	55	no h/s	AD 1664	------	AD 1718
KIB-A14	Stud post, east wall, first floor	61	h/s	AD 1691	AD 1751	AD 1751

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

Table 2: Results of the cross-matching of site chronology KIBASQ01 and relevant reference chronologies when first ring date is AD 1582 and last ring date is AD 1773

Reference chronology	Span of chronology	*t*-value	
Stoneleigh Abbey, Warwicks	AD 1646 – 1813	11.5	(Howard *et al* 2000)
East Midlands	AD 882 – 1981	10.6	(Laxton and Litton 1988)
Quenby Hall, Leics	AD 1575 – 1724	9.7	(Howard *et al* 1993 unpubl)
Main Street, Cosby, Leics	AD 1642 – 1734	7.8	(Alcock *et al* 1991 unpubl)
Old Barn, Stratford upon Avon, Warwicks	AD 1591 – 1735	7.8	(Howard *et al* 1996)
Chicksands Priory, Beds	AD 1646 – 1813	7.7	(Howard *et al* 1998)
Bolsover Castle Riding School, Bolsover, Derbys	AD 1494 – 1744	7.2	(Howard *et al* forthcoming)
England	AD 401 – 1981	6.9	(Baillie and Pilcher 1982 unpubl)

Figure 1: Map to show general location of Kibworth Harcourt

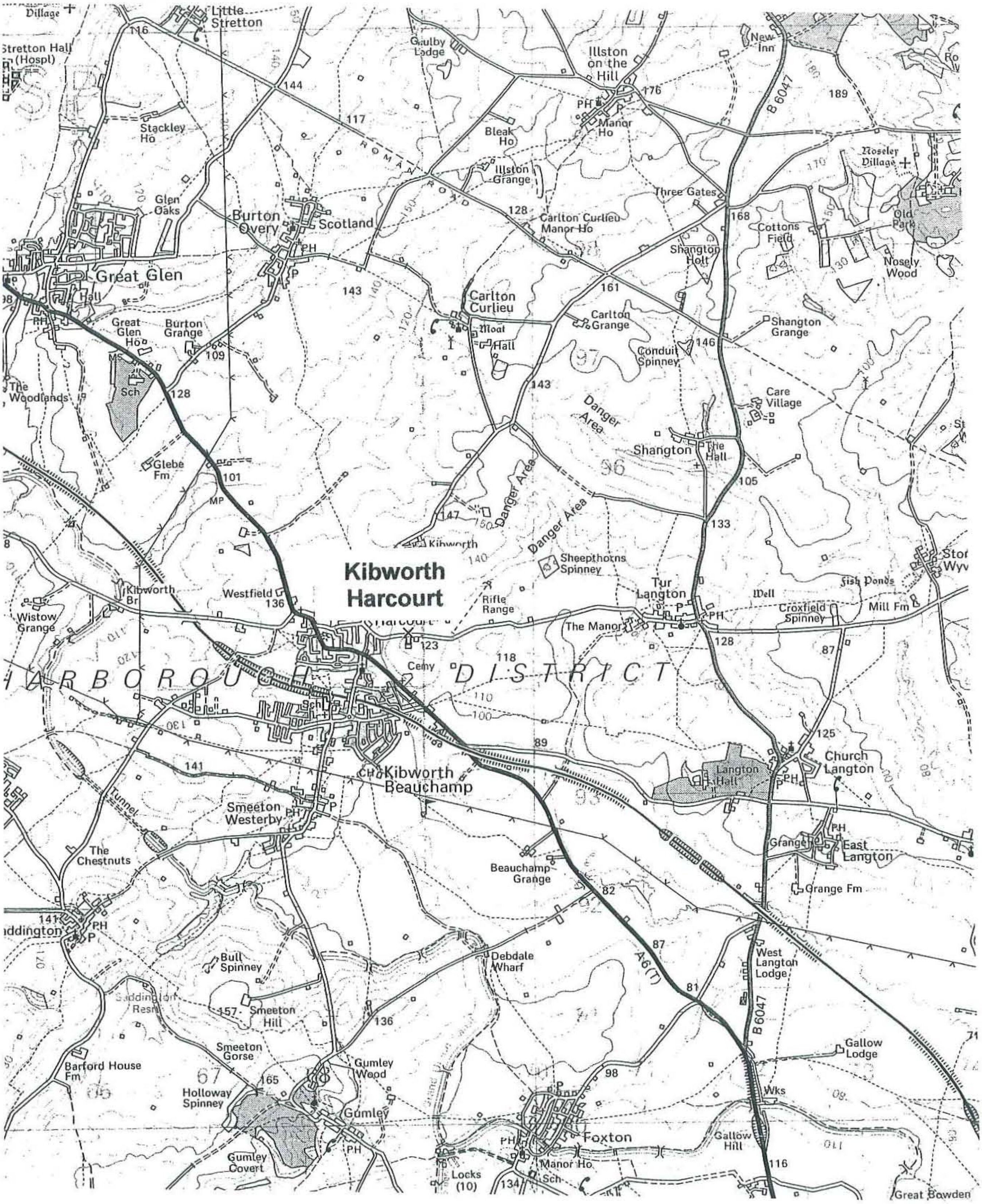


Figure 2: Map to show specific location of post mill

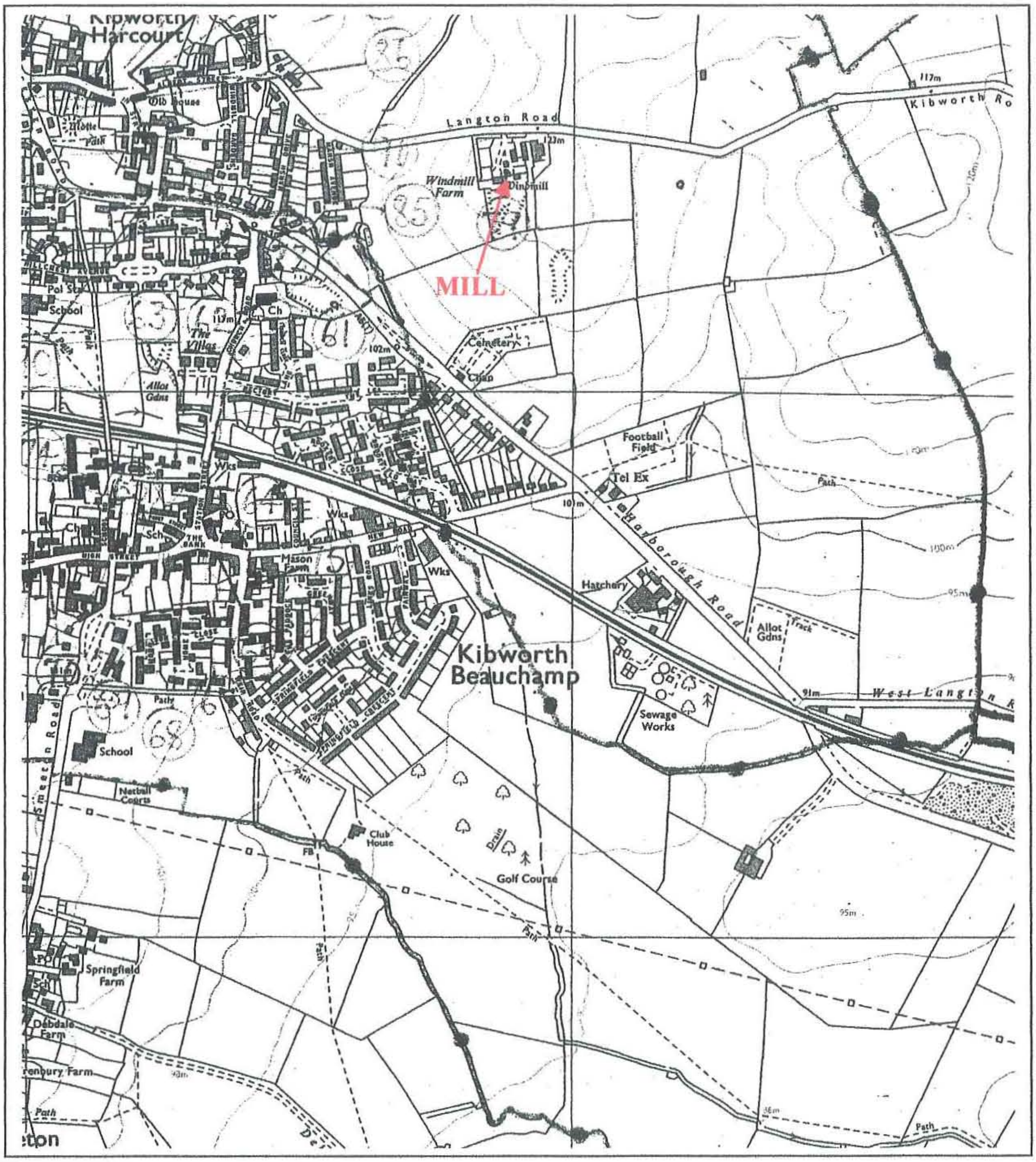


Figure 3: Drawing of Kibworth post-mill from the south

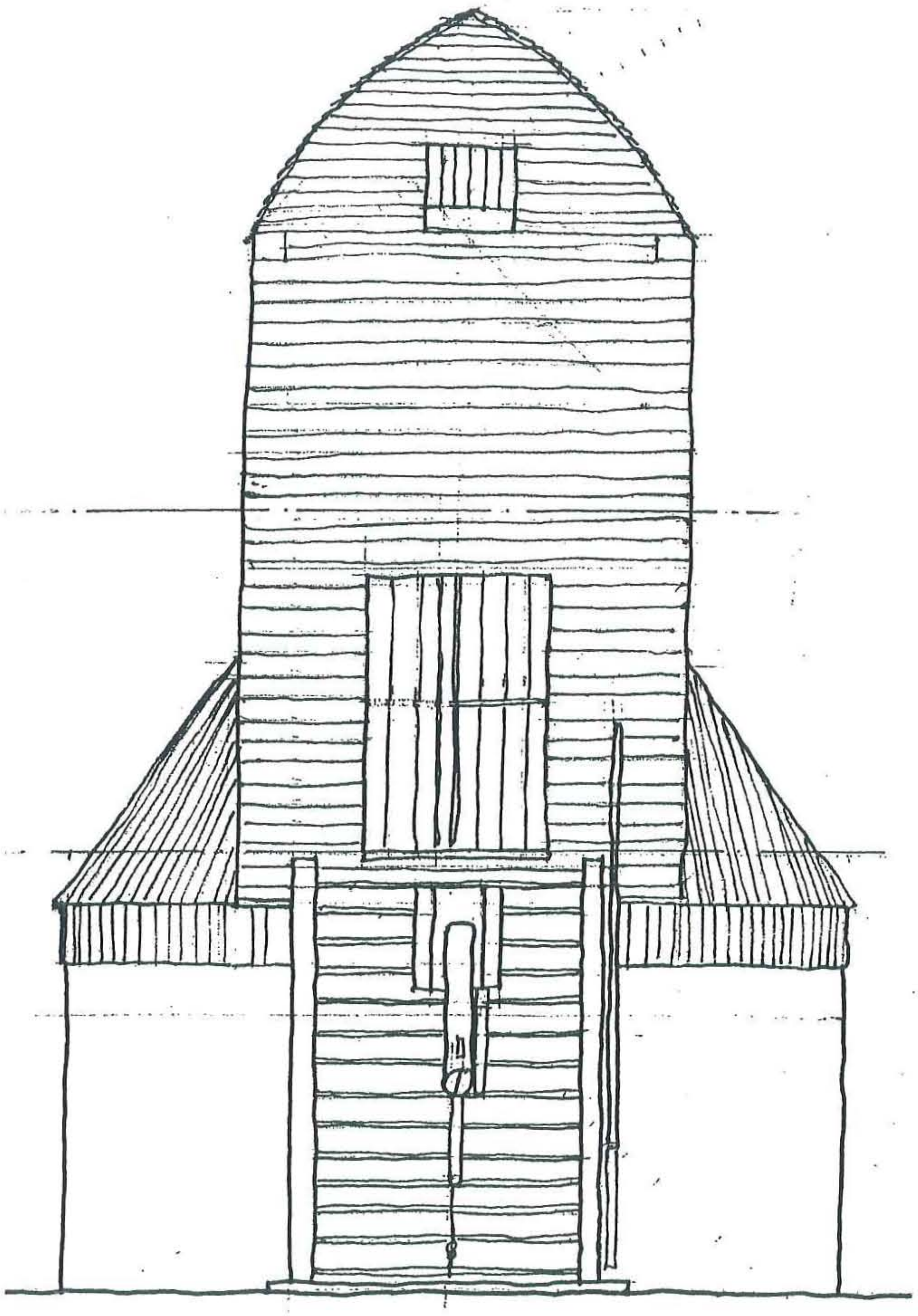


Figure 4a: Plan to show location of timbers sampled

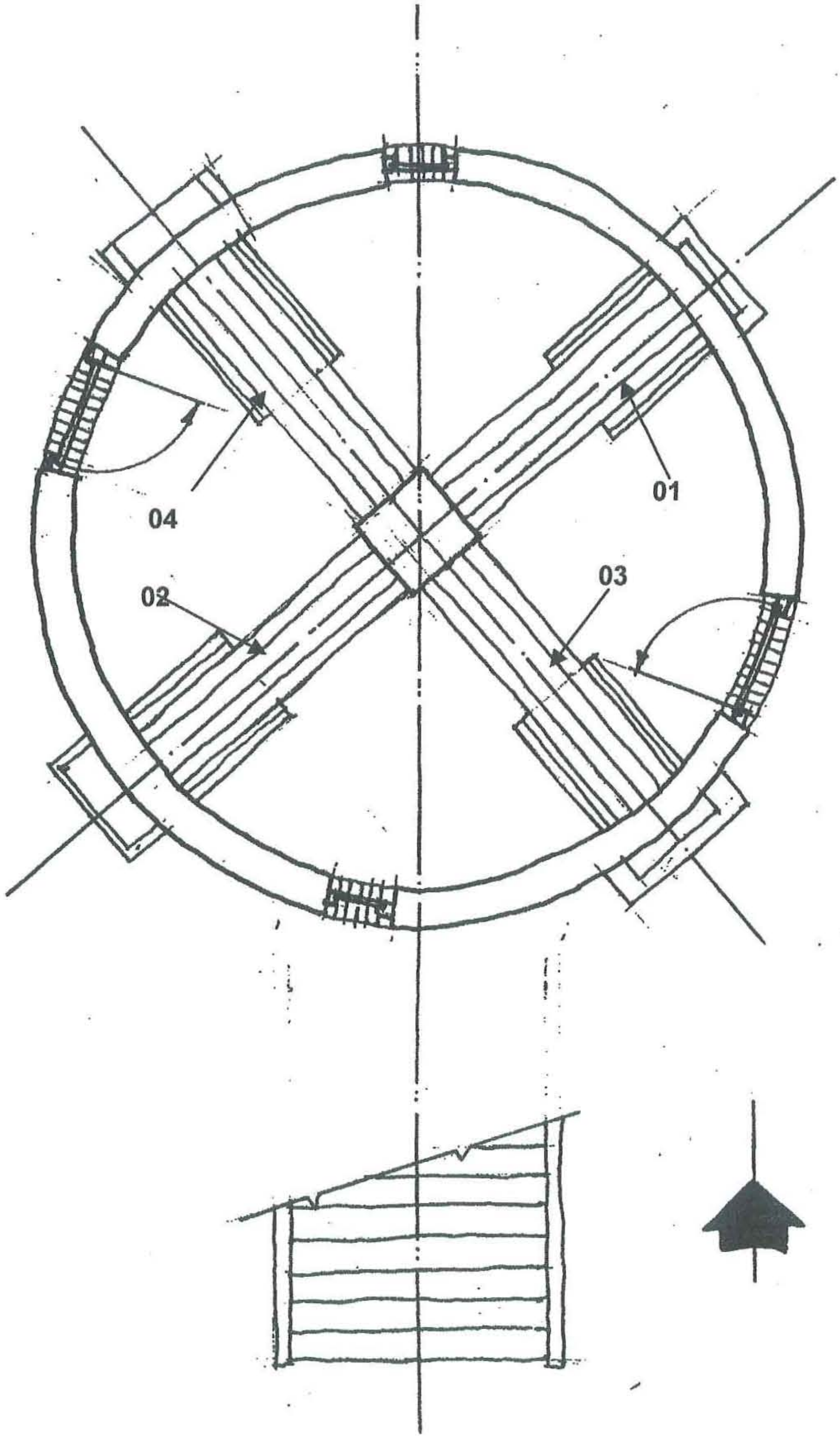


Figure 4b: Plan to show location of timbers sampled

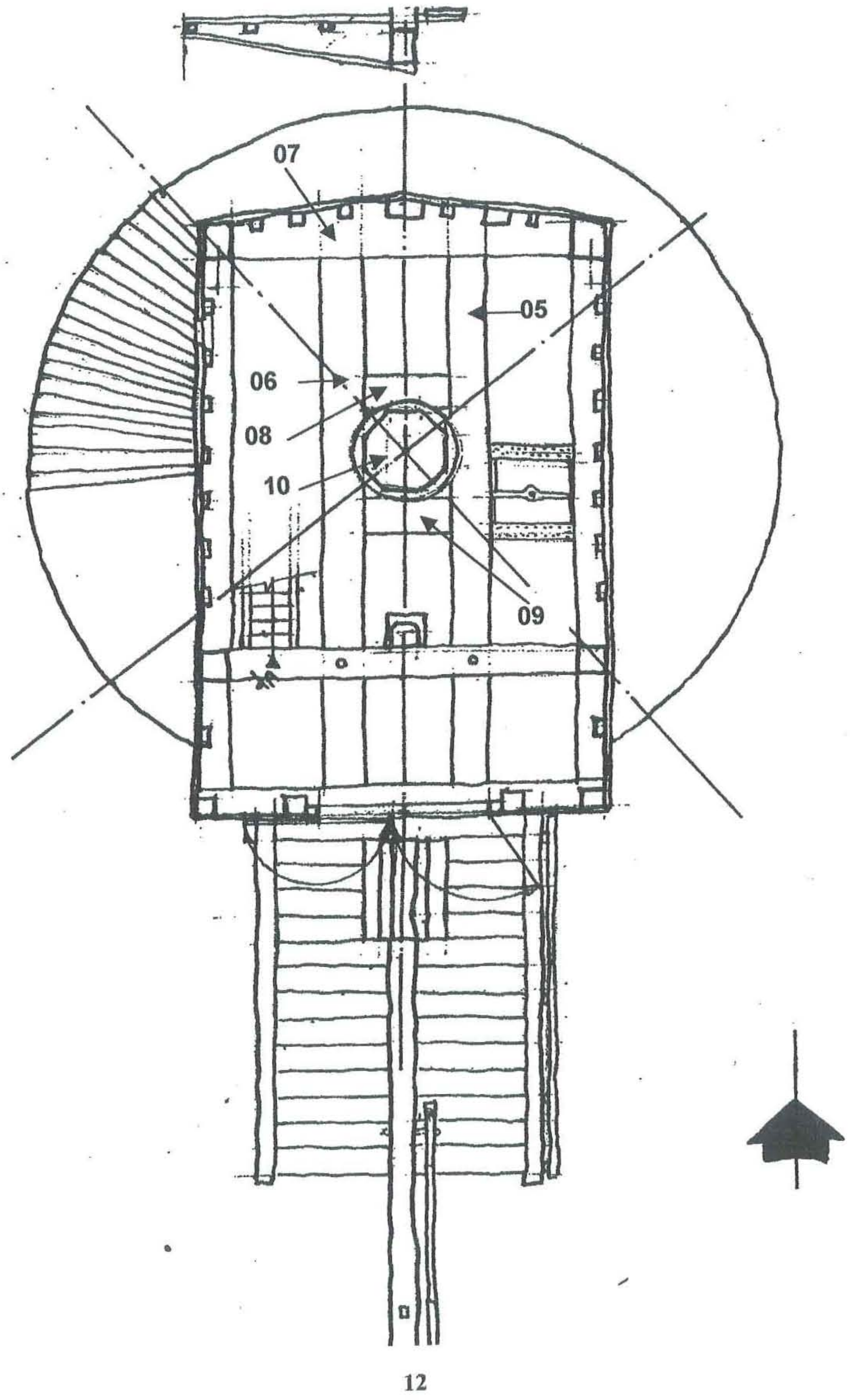


Figure 4c: Cross-section to show timbers sampled (viewed from the west looking easr)

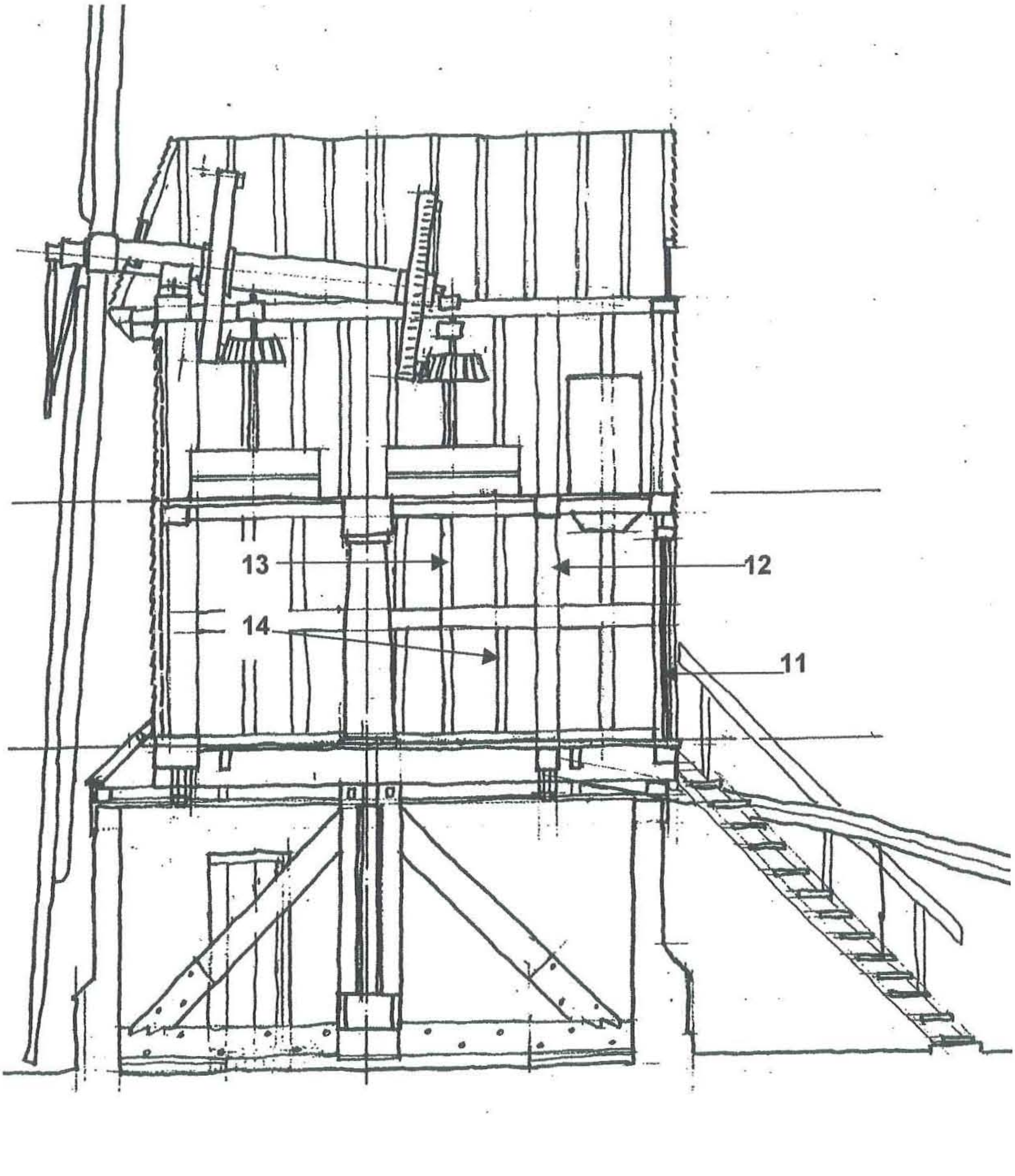
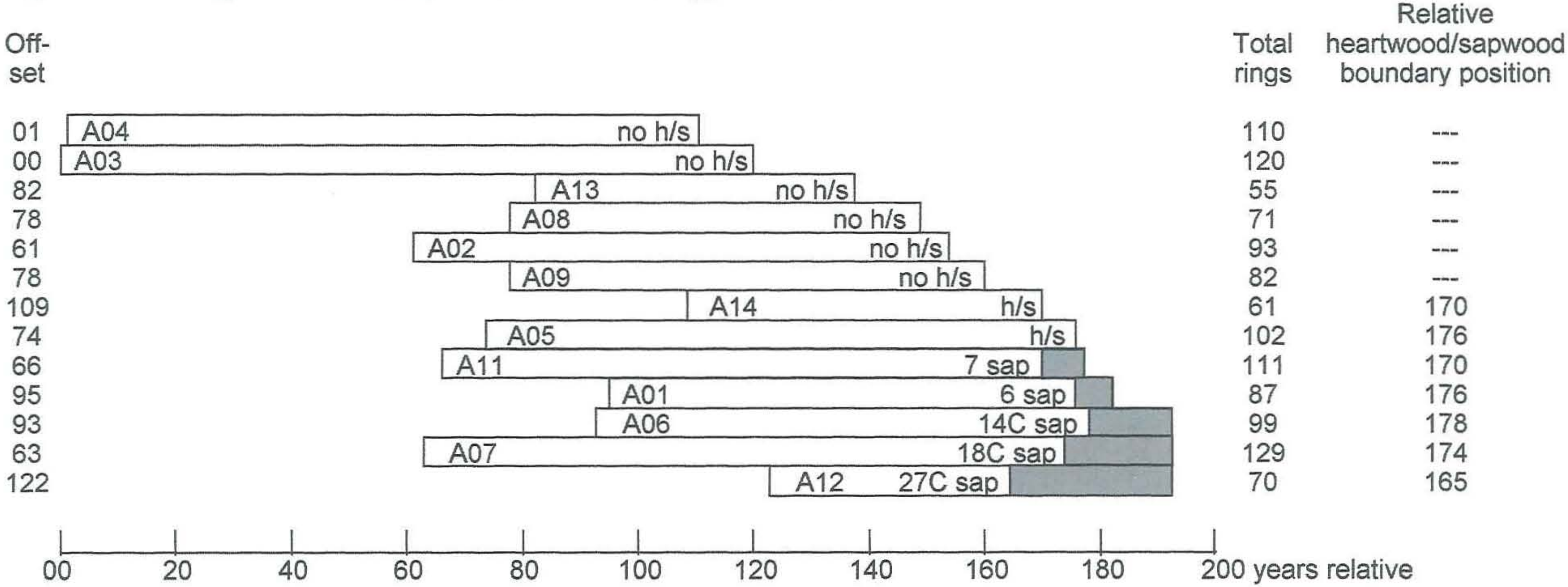


Figure 5: Bar diagram of the samples in site chronology KIBASQ01



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample, the last measured ring date is the felling date of the timber

Data of measured samples – measurements in 0.01 mm units

KIB-A01A 87
165 278 209 326 197 260 272 195 283 287 316 319 337 294 344 271 229 248 251 294
261 145 75 81 92 120 142 138 142 176 105 137 162 105 183 194 208 150 232 211
251 155 131 201 290 270 208 317 165 179 242 203 218 197 203 250 205 195 190 218
169 252 320 145 123 141 189 135 146 195 202 182 134 138 146 191 194 239 210 218
230 238 227 273 197 192 262
KIB-A01B 87
184 331 234 292 208 287 247 159 233 298 331 329 325 298 336 267 272 204 292 287
275 155 76 76 104 125 142 125 141 175 105 127 161 122 171 210 183 155 235 227
251 157 136 195 310 256 205 340 173 174 224 195 215 193 207 270 224 179 189 223
200 256 322 137 121 148 180 149 141 196 193 180 136 138 155 200 213 246 217 214
223 284 224 266 247 203 201
KIB-A02A 93
375 274 234 347 250 401 248 405 278 319 257 236 385 246 291 290 272 191 200 235
196 134 169 157 174 275 221 263 313 251 240 184 164 140 165 235 186 257 154 297
328 178 161 393 310 295 236 170 239 145 214 106 133 187 206 205 155 158 130 211
306 287 156 181 133 175 181 94 132 132 129 83 122 120 136 142 90 122 156 136
79 78 86 79 112 104 105 179 120 166 120 158 132
KIB-A02B 93
319 329 175 255 240 293 229 399 288 305 238 212 396 247 297 288 265 203 199 212
190 147 160 160 168 275 218 271 312 244 243 185 172 132 162 229 188 247 167 299
334 171 164 385 303 281 229 179 228 160 209 106 135 188 205 208 146 167 114 226
293 296 165 188 136 182 180 94 129 134 130 89 125 112 138 142 83 132 154 138
77 86 88 81 95 108 101 185 118 175 126 128 157
KIB-A03A 120
356 332 356 352 318 403 422 376 247 253 231 170 286 295 281 239 291 257 210 188
149 169 235 176 357 419 283 242 307 337 282 317 270 342 302 399 382 254 232 139
247 335 238 214 200 137 173 298 143 174 225 203 186 159 139 136 156 166 183 301
241 232 213 228 265 217 213 174 122 219 163 171 207 255 281 242 217 207 332 189
255 237 134 99 129 174 215 249 220 326 206 239 170 126 161 241 233 230 159 157
215 202 152 149 301 223 207 139 111 167 117 184 139 94 156 151 172 133 145 182
KIB-A03B 120
330 350 349 340 310 411 433 360 240 257 228 175 264 310 282 244 299 268 207 192
141 174 232 167 361 420 290 253 313 337 283 318 263 352 309 380 383 275 232 144
248 321 255 207 200 135 175 306 141 177 220 206 171 170 133 145 146 169 180 306
235 245 220 206 277 222 211 164 132 200 175 154 206 272 289 246 212 215 331 180
258 238 134 91 138 166 220 253 213 321 222 229 175 132 155 231 248 222 180 151
216 188 155 168 284 232 185 152 110 163 108 168 134 135 143 149 178 144 101 170
KIB-A04A 110
234 301 342 314 394 377 300 210 213 193 170 261 293 240 221 218 227 169 135 139
146 242 138 225 310 215 213 218 306 242 238 223 353 279 355 347 262 152 126 220
296 261 166 218 158 166 305 173 191 230 221 107 106 64 67 77 127 143 218 203
177 173 173 234 177 176 132 119 152 152 132 192 267 260 243 223 237 300 213 263
247 137 107 162 175 215 273 255 291 210 229 188 184 162 219 200 239 173 184 192
180 145 142 271 235 205 162 127 98 124

KIB-A04B 110
256 298 348 287 398 403 310 200 209 207 172 256 292 253 196 223 222 172 150 128
157 224 147 248 296 212 199 214 283 241 220 230 349 276 354 356 243 152 129 218
324 251 163 218 160 165 295 172 186 234 221 100 97 82 65 80 118 144 221 198
181 168 177 232 187 176 144 108 147 161 137 180 268 255 241 227 237 307 207 276
246 143 109 148 165 228 260 260 284 224 215 199 175 156 232 206 235 161 180 197
188 143 144 262 236 210 164 116 73 150
KIB-A05A 102
223 224 250 334 305 297 231 305 322 233 281 245 298 205 326 280 218 251 241 178
156 245 196 250 276 314 335 282 200 309 345 301 410 362 233 453 369 314 231 239
308 291 299 220 261 207 170 238 231 162 199 198 311 307 203 242 303 234 136 151
190 174 153 182 133 158 141 115 129 109 91 135 117 98 92 92 108 82 161 178
170 104 143 179 137 114 120 150 150 178 175 114 115 143 154 201 175 210 185 223
224 199
KIB-A05B 102
226 212 238 332 280 302 202 293 332 220 330 229 314 218 358 255 232 247 247 172
162 245 201 229 271 304 352 269 204 305 333 326 401 347 267 447 360 318 234 256
286 276 305 228 255 213 177 221 243 138 210 186 296 302 215 259 277 252 150 156
177 167 146 178 124 172 157 95 129 105 83 127 109 92 98 91 100 79 164 186
163 102 147 181 137 109 118 156 157 175 171 110 110 149 161 195 168 217 185 219
226 212
KIB-A06A 99
228 136 337 325 284 285 156 298 282 151 131 243 324 364 326 227 246 191 179 129
189 301 299 246 207 150 169 212 378 297 191 208 179 220 167 123 185 271 213 180
251 214 150 173 164 207 217 162 152 174 133 176 199 235 250 219 175 227 224 208
218 177 127 197 199 137 108 138 160 155 200 189 203 196 210 146 200 144 156 192
161 176 174 207 213 143 186 189 175 234 174 173 180 200 180 182 151 174 200
KIB-A06B 99
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184 304 291 259 192 152 165 215 378 287 195 224 173 227 186 137 192 249 226 182
259 201 160 165 160 201 218 156 151 166 124 159 187 243 212 217 182 232 224 209
201 157 138 202 180 141 113 126 146 166 173 186 167 190 191 155 195 168 168 192
162 181 175 204 212 153 178 185 190 229 168 178 171 203 175 179 138 170 201
KIB-A07A 129
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188 162 240 454 265 286 337 267 221 123 183 110 157 154 73 119 96 211 144 109
74 210 162 162 147 81 99 108 84 66 63 127 157 141 83 90 97 93 213 159
199 262 237 306 259 180 281 333 320 216 307 263 303 254 239 225 322 316 175 283
244 192 343 226 242 344 241 257 280 307 334 294 115 278 286 180 179 197 217 237
304 258 236 234 231 174 213 301 217 247 231 203 191 196 174 116 138 125 226 224
193 192 166 245 191 151 142 149 160
KIB-A07B 129
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193 157 230 460 264 279 343 267 209 139 183 98 161 162 73 103 109 213 162 100
88 204 169 158 137 95 102 105 91 69 59 122 158 136 90 78 102 98 224 151
184 269 243 308 281 177 264 344 322 224 294 268 290 248 253 228 326 323 166 294
253 184 347 217 224 333 258 257 275 299 345 292 110 286 287 186 181 190 225 239
304 260 237 232 226 181 207 309 205 245 233 203 203 179 177 125 147 128 209 217
209 188 166 242 205 144 161 150 160
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118 81 96 136 148 118 123 108 145 156 90 115 137 107 73 124 90 104 84 94
111 162 110 60 67 76 89 114 131 124 137

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160 135 220 235 152 142 284 286 289 250 189 183 97 147 109 124 112 140 127 99
112 75 104 169 150 105 121 102 137 142 91 122 131 110 69 116 100 99 89 88
118 166 108 73 64 75 90 126 135 108 125
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122 76 93 166 198 137 148 81 99 108 64 89 111 96 76 86 98 83 83 74
109 104 110 62 90 102 96 128 96 95 129 92 132 94 119 83 87 79 138 110
98 135
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439 197 388 407 152 107 278 315 263 242 174 338 208 294 164 139 138 148 131 108
109 74 102 167 192 131 150 88 103 119 61 97 111 97 67 96 91 84 93 77
107 96 123 62 79 99 105 119 96 110 114 110 124 96 111 80 101 77 142 119
93 130
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122 173 138 214 248 131 154 207 144 156 185 133 101 94 61 77 81 68 70 150
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303 214 128 190 127 144 93 132 234 250 268 185 184 142 118 233 249 228 311 268
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197 240 372 307 200 185 251 290 308 370 522 481 186 113 111 153 221 148 143 125
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294 223 131 192 116 144 96 141 228 255 293 186 199 137 111 229 241 241 290 290
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206 256 379 307 220 179 262 282 340 358 510 485 190 95 128 157 209 149 157 125
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KIB-A12A 70
136 83 139 99 115 133 117 156 162 225 137 136 119 95 101 94 122 164 233 108
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KIB-A13A 55
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136 133 120 127 142 127 104 119 155 105 74 111 103 101 136 160 106 123 145 147
204

KIB-A14B 61
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202 259 283 162 192 223 235 219 219 186 200 240 166 170 165 167 165 165 224 140
145 125 103 134 154 137 86 129 148 112 95 98 101 100 138 146 108 144 128 141
223

APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building*' (Laxton and Litton 1988) and, *Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. ***Inspecting the Building and Sampling the Timbers***. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

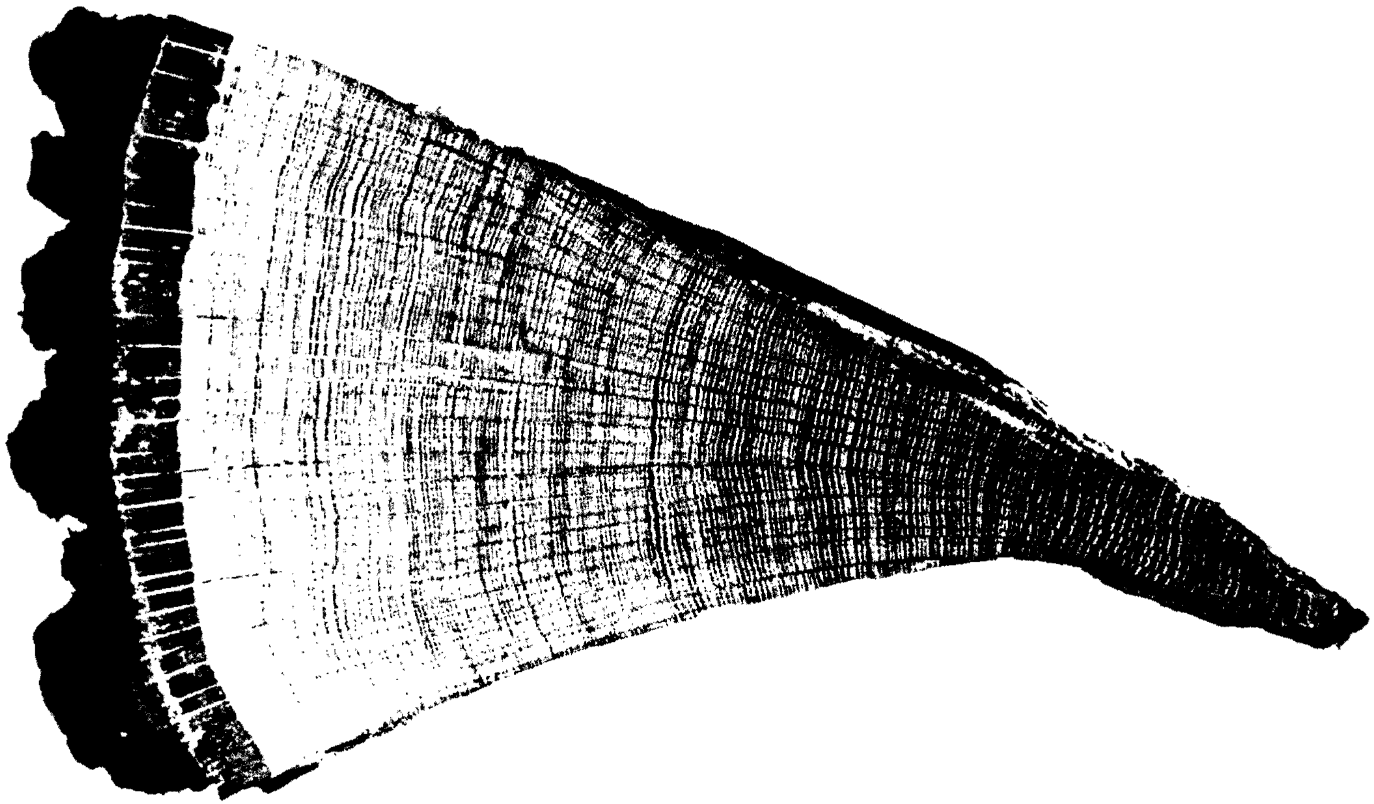


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

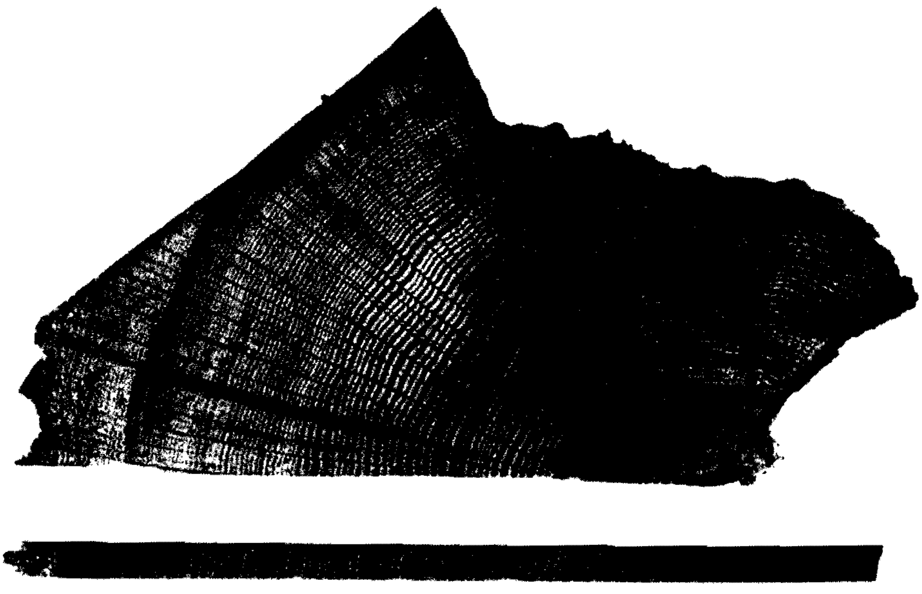


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig. 3 Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure 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.

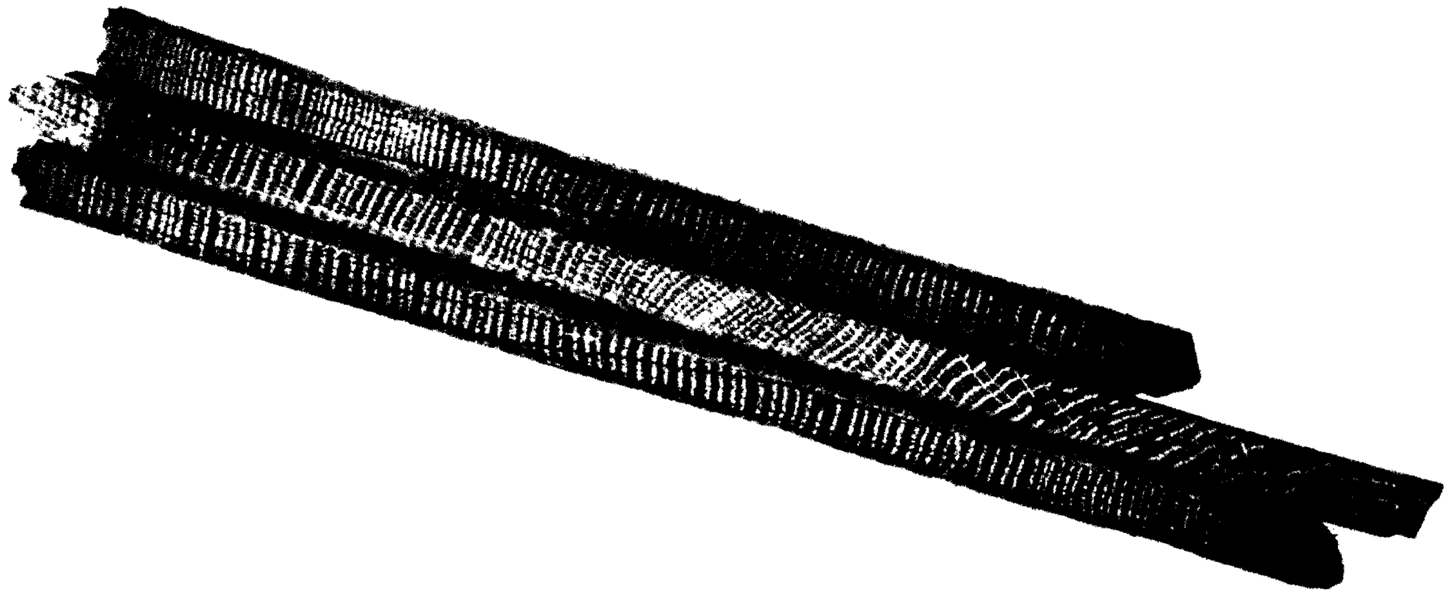


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

2. ***Measuring Ring Widths***. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples***. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984-1995).

This is illustrated in Fig 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a *site sequence* of the building being dated and is illustrated in Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

4. ***Estimating the Felling Date***. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree. Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases. The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called *sapwood* rings, are usually lighter than the inner rings, the *heartwood*, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to *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

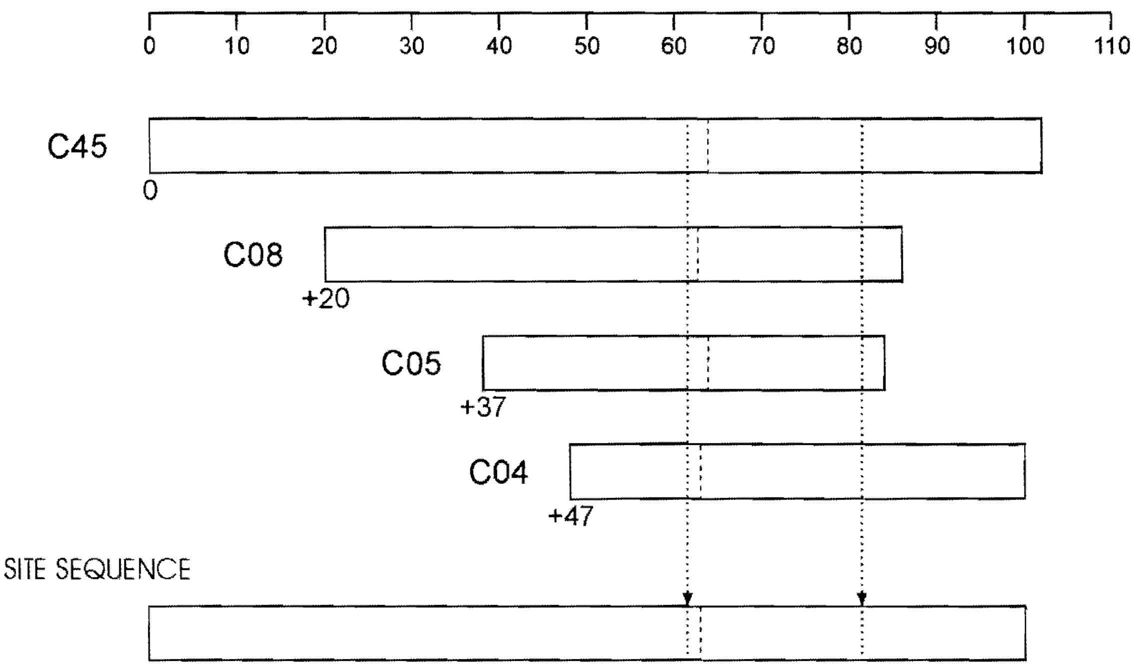


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t*-values.

The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

5. ***Estimating the Date of Construction***. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. ***Master Chronological Sequences***. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. ***Ring-width Indices***. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomena 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.

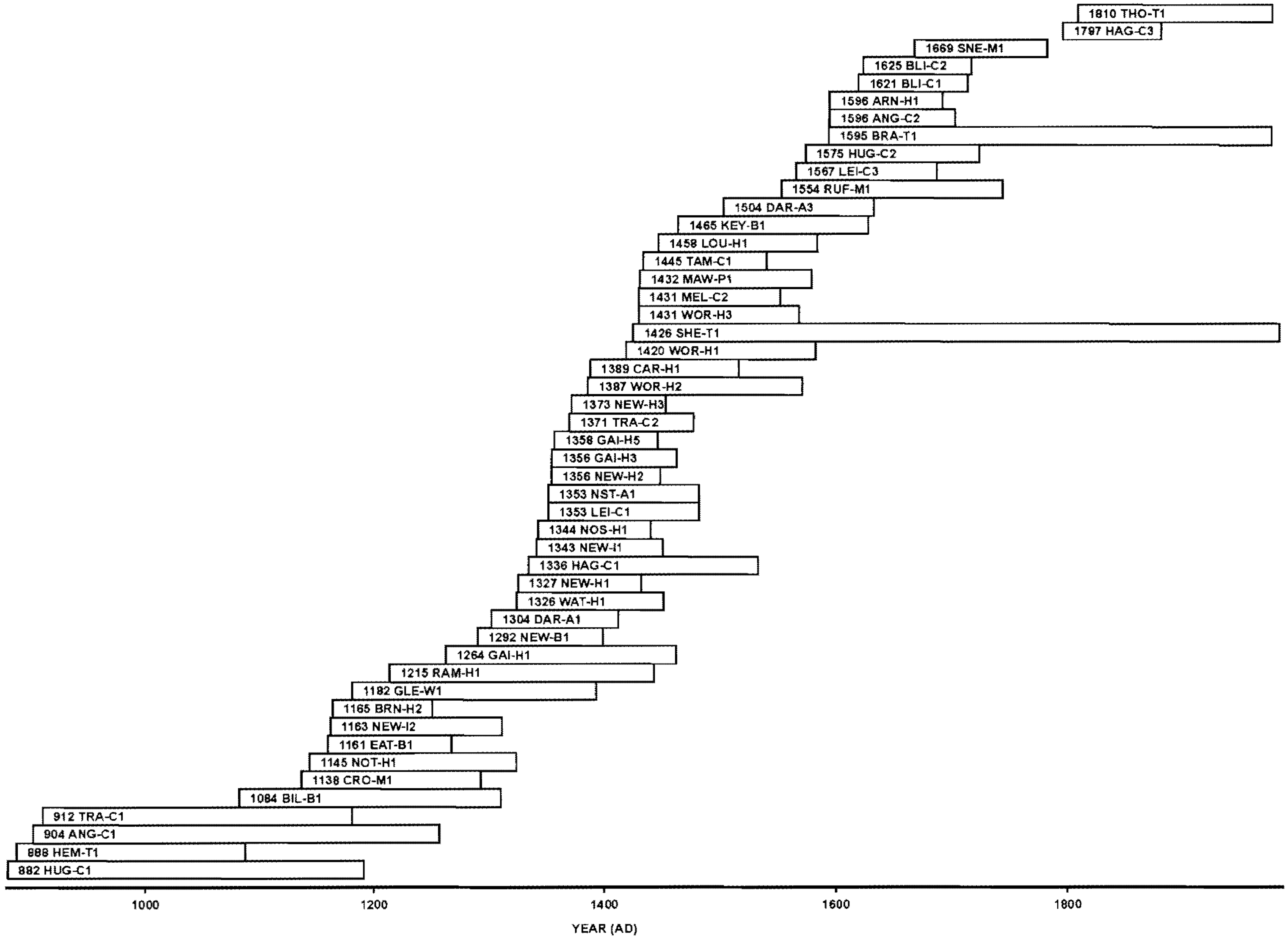
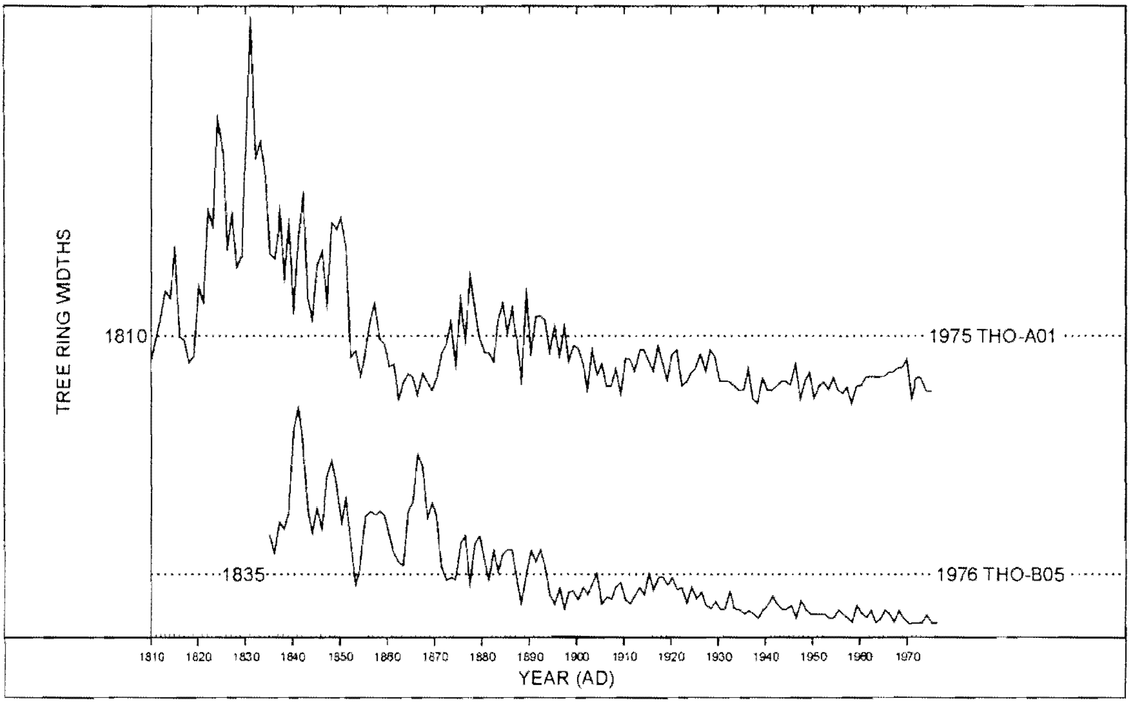


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

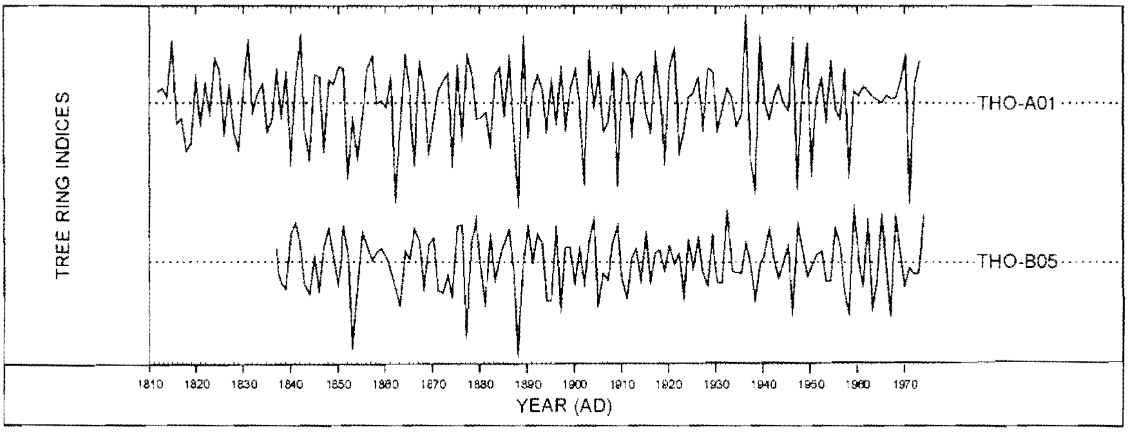


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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