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Summary

Twenty samples were obtained from what were believed to be primary construction phase timbers of the ground and first-floor frame, and what were potentially later timbers of the roof of this building at Fell Close.

The analysis of these samples produced two site chronologies. The first comprises 12 samples from ground, first-floor frame, and roof timbers, with a combined overall length of 156 rings, and dated as spanning the years AD 1496 to AD 1651. Interpretation of the sapwood would suggest that at least some of the ground and first floor frame timbers are contemporary with the roof timbers which were felled at the same time in AD 1651.

The second site chronology consists of two samples, both from ground floor timbers, with a combined overall length of 80 rings. The site chronology cannot be dated.

This programme of tree-ring analysis has not found any evidence of timbers with different felling dates. Fell Close thus appears to be a single-phase, mid-seventeenth century, structure.

Keywords

Dendrochronology
Standing Building

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Introduction

Fell Close is an isolated, and now deserted and much dilapidated, Grade II listed building of two-storeys, lying between Castleside and Waskerley, near Consett, in County Durham (NZ 067 477; Figs 1 and 2). The walls are of clay bonded rubble, with long and short quoining and with a flat projecting foundation course. The main access is through a slightly off-centre door in the south wall with a plain lintel and jambs. An opposing door in the north wall is now blocked. A third door gives access to a porch structure attached to the west gable at a later date. An elevation and a general ground-floor plan of the house are given in Figure 3.

The ground-floor ceiling / first-floor frame comprises five heavy, north-to-south, main joists supporting several much smaller common joists, the lower arrises of which are decorated by very slight chamfering. A wooden plank floor is laid over these common joists. Projecting from the walls just above the first floor are two pairs of crucks, which divide the upper level into three not quite equal bays. Truss 1 has a collar and a saddle or yoke, but truss 2 has a collar only. The trusses carry single purlins. An illustration of the trusses is shown in Figure 4.

A number of internal furnishings exist such as chimneys and hearths to east and west gables. These retain cast-iron fire-places, set-pots, and box ovens. There is also a brick built dome, which may have served as a bread oven. At one time the cottage was covered in a heather thatch. This has now largely disappeared, its place being taken by the partial remains of a rusting corrugated iron roof.

Sampling

Sampling and analysis by tree-ring dating of the timbers of Fell Close were commissioned by English Heritage. It is believed, on the stylistic evidence of the form of the lintel to the west door, that the building might date to the seventeenth century, and there is some supporting documentary evidence, at least for the plot of land on which the building stands, for such a date too.

However, the heavy first-floor structure, the clay-bonding of the walls, and window and roof features suggest that the building may be older than generally believed. It is also thought that alterations to the roof may have subsequently taken place with the insertion of the cruck trusses; the relationship of these to the floor structure was not recognised at the last inspection. This analysis was requested to help establish the construction date of the building, to help identify any possible subsequent alterations, and to establish the relationship between the floor and roof structures. It was hoped that this programme of tree-ring dating would assist in a possible listing upgrade and help inform future repairs to the roof structure.

From the timbers available a total 20 core samples was obtained. Each of these samples was given the code HFD-A (for Healeyfield, site "A"), and numbered 01 – 20. Timbers were selected for sampling on the basis of their appearing to be related to the possible phases under investigation, and for appearing to have sufficient rings for satisfactory analysis by tree-ring dating. Timbers were also selected on the basis of their having sapwood or at least the heartwood/sapwood boundary.

Nine core samples, HFD-A01 - 09, were obtained from timbers of the ground floor, particularly the five main first-floor joists. Unfortunately almost all the common joists appeared to have too few rings for satisfactory analysis and thus only one of these, HFD-A06, was sampled. Two samples were obtained from posts acting as either a support for one of the main floor beams, HFD-A7, or as a jamb to the south door, HFD-A08. Although not integral to the structure it was hoped that these timbers might be reused from the primary phase and thus provide data for tree-ring analysis. Another sample, HFD-A09, was obtained from the lintel of the east fireplace, this appearing to be integral and original to the structure of the building. From the roof structure a total of 11 core samples, HFD-A10 - 21 was obtained. The porch addition did not contain any timbers and tree-ring analysis of this part of the building could not be undertaken.

Plans, based on the drawing of the ground floor, and shown here as Figure 5a/b, give the approximate positions of the 20 timbers cored, with details of the samples being given in Table 1. In this report the joists, cruck, and other timbers have been numbered from east to west, and described on a north - south basis as appropriate.

The Laboratory would like to take this opportunity to thank Mr Stephen Cole for his help in arranging access to Fell Close and to Martin Roberts of English Heritage north-east office for his notes and suggestions on the possible phasing of the site. The Laboratory would also like to acknowledge the use of a published article by Norman Emery (Emery 1986), from which much of the introduction above was taken, and of a drawing of the cruck trusses by Peter Brears.

Analysis

Each of the 20 samples obtained was prepared by sanding and polishing and their annual growth-ring measured. The data of these measurements are given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum *t*-value of 4.5 two site chronologies could be formed.

The first, HFDASQ01, comprises 12 samples, cross-matching with each other at relative positions as shown in the bar diagram, Figure 6. This site chronology has a combined overall length of 156 rings. Site chronology HFDASQ01 was then compared with a large number of relevant reference chronologies for oak. This indicated a consistent cross-match with a number of these when the date of its first ring is AD 1496 and the date of its last measured ring is AD 1651. The *t*-values for this cross-matching are given in Table 2.

The second site chronology to be formed, HFDASQ02, consists of two samples, cross-matching with each other at relative positions as shown in the bar diagram, Figure 7. This site chronology has a combined overall length of 80 rings. Site chronology HFDASQ02 was also compared to a large number of relevant reference chronologies for oak, but unfortunately there was no satisfactory cross-matching.

The two site chronologies were compared with each other, and with the six remaining ungrouped samples. There was, however, no satisfactory cross-matching. Each of the six remaining ungrouped samples was then compared individually with the reference chronologies, but again there was no satisfactory cross-matching, and these samples must remain undated.

Interpretation

Analysis by dendrochronology has produced two site chronologies. The first site chronology, HFDASQ01, comprises 12 samples, with a combined overall length of 156 rings. These rings are dated as spanning the years AD 1496 to AD 1651. The second site chronology, HFDASQ02, consists of two samples, with a combined overall length of 80 rings. Unfortunately this second site chronology cannot be dated.

Four samples in site chronology HFDASQ01 (HFD-A12, A16, A18, and A19) retain complete sapwood. This means that they each have the last ring produced by the trees they represent before they were felled. In each case the last complete sapwood ring date is the same, AD 1651. This is thus the felling date of the timbers represented. The relative position of the heartwood/sapwood boundaries on the other dated samples, where it exists, is strongly indicative of a group of timbers cut in a single phase of felling, and it is almost certain that these other dated timbers were also felled in AD 1651.

Conclusion

Of the 20 samples obtained from this site 12 have been combined in a single dated site chronology. Four dated samples retain complete sapwood, indicating that the timbers they represent were felled in AD 1651. It is highly likely that all the other dated timbers were also felled in AD 1651.

Two of these dated samples, HFD-A03 and A04, are from main joists of the first-floor frame, with a further sample, HFD-A09, a lintel, coming from another timber which is believed to belong to the primary phase. Nine of the dated samples are from the cruck trusses and the roof. It would thus appear that at least some timbers that were believed to be associated with the primary construction phase, that is the floor timbers, and the timbers of the roof, which were thought to be possibly later, are in fact all of the same, mid-seventeenth century date. Tree-ring analysis has found no definite evidence for more than one phase of timber felling and on this basis it appears that the building is a single-date structure. An attempt to show the similarity in felling date of the material from the two areas of the building is given in Figure 8 where the dated samples are sorted by location.

It is perhaps worth noting, however, that six of the supposedly primary phase timbers are not dated, although two, HFD-A07 and A08, which do cross-match with each other, appear to be reused in there present location, and could be from somewhere else altogether. Two samples, HFD-A13 and A14, from the roof structure also remain undated. It is possible that bands of narrow rings seen in these undated samples, and probably caused by stressful growing conditions, account for their not cross-matching and dating. This is particularly so with sample HFD-A02 which has a noticeable band of very narrow rings. Some of the other undated samples also have a low, though still satisfactory, number of rings.

It is probable that four of the samples, HFD-A12, A16, A17, and A18, from the cruck blades, are probably from two trees split in half. As is sometimes found with crucks, the samples from a pair of bladed often cross-match with each other with high *t*-values, in this case values of t=8.4 are found between the blades of truss 1, and a value of t=12.7 between the blades of truss 2. Judging by the *t*-value between samples HFD-A07 and A08 (t=8.4), it is also possible that these elements were derived from a single tree.

It is also worth noting that Fell Close contains a number of other timbers which could not be reached and sampled due to the unsafe nature of the site, this being caused by decay during long-term exposure to the elements. Such timbers include most of the purlins, the ridge beams, the upper collars, and most of the common rafters. While it is not certain that all these timbers were suitable for tree-ring analysis it seems likely that some of them may be. There are also other timbers buried in the walls of the chimney that certainly appeared to have sufficient rings, but which again could not be reached safely. It is not certain, however, that these timbers are primary. The decay of the timbers also meant that even where beams could be reached the maximum number of rings available could not be obtained due to samples breaking during coring. This was particularly a problem with the main joists.

It is therefore very strongly recommended that if, and when, any work is undertaken at the site, and safer access is provided, the potential for further tree-ring sampling is assessed. In particular it should be advised that any timbers, or indeed parts of timbers, that are removed from the building during repairs are labeled and stored for examination before being restored or discarded. This advice is to include both large and small beams, such as joists and common rafters. A number of the smaller timbers in particular were seen to have complete sapwood which, given its now decayed nature, might only be obtainable through the removal of cross-sectional slices rather than more fragile cores.

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Table 1: Details of samples from Fell Close, Healeyfield, near Consett, County Durham

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Ground and first-floor timbers					
HFD-A01	Main first-floor joist 1 (from east)	64	h/s	------	------	------
HFD-A02	Main first-floor joist 2	90	no h/s	------	------	------
HFD-A03	Main first-floor joist 3	110	30	AD 1530	AD 1609	AD 1639
HFD-A04	Main first-floor joist 4	113	2	AD 1501	AD 1611	AD 1613
HFD-A05	Main first-floor joist 5	60	no h/s	------	------	------
HFD-A06	Common joist 6, bay 2	64	2	------	------	------
HFD-A07	South post at main joist 3	79	h/s	------	------	------
HFD-A08	Jamb to south door	70	3	------	------	------
HFD-A09	Lintel to fireplace at east gable	54	no h/s	AD 1551	------	AD 1604
	Roof timbers					
HFD-A10	Collar, truss 1	58	no h/s	AD 1528	------	AD 1585
HFD-A11	Collar, truss 2	62	no h/s	AD 1541	------	AD 1602
HFD-A12	South blade, truss 2	130	30C	AD 1522	AD 1621	AD 1651
HFD-A13	North common rafter 6, bay1	60	h/s	------	------	------
HFD-A14	North common rafter 4, bay 1	60	no h/s	------	------	------
HFD-A15	North purlin, truss 1 to east gable	62	h/s	AD 1562	AD 1623	AD 1623
HFD-A16	North cruck blade, truss 1	141	40C	AD 1511	AD 1611	AD 1651
HFD-A17	South cruck blade, truss 1	135	23	AD 1496	AD 1607	AD 1630
HFD-A18	North cruck blade, truss 2	115	42C	AD 1537	AD 1609	AD 1651
HFD-A19	North common rafter 1, bay 2	80	31C	AD 1572	AD 1620	AD 1651
HFD-A20	North common rafter 5, bay 2	56	no h/s	AD 1522	------	AD 1577

*h/s = the heartwood/sapwood boundary is the last ring on the sample
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 chronology HFDASQ01 and relevant reference chronologies when the date of the first ring is AD 1496 and the last ring date is AD 1651

Reference chronology	Span of chronology	*t*-value	
Dilston Castle, Corbridge, Northumberland	AD 1402 – 1611	6.2	(Arnold *et al* 2003)
Finchale Priory Barn, Brasside, Durham	AD 1449 – 1677	6.2	(Arnold *et al* 2002)
1 Soar Lane, Sutton Bonnington, Notts	AD 1552 – 1651	5.6	(Howard *et al* 1993)
Dovebridge, Derbys	AD 1502 – 1617	5.2	(Howard *et al* 1998 unpubl)
DAR-A3	AD 1504 – 1633	5.0	(Laxton and Litton 1988)
England	AD 401 – 1981	5.0	(Baillie and Pilcher 1982 unpubl)
East Midlands	AD 882 – 1981	4.6	(Laxton and Litton 1988)
Scotland	AD 946 – 1975	4.3	(Baillie 1977)

Figure 1: Map to show general location of Healeyfield

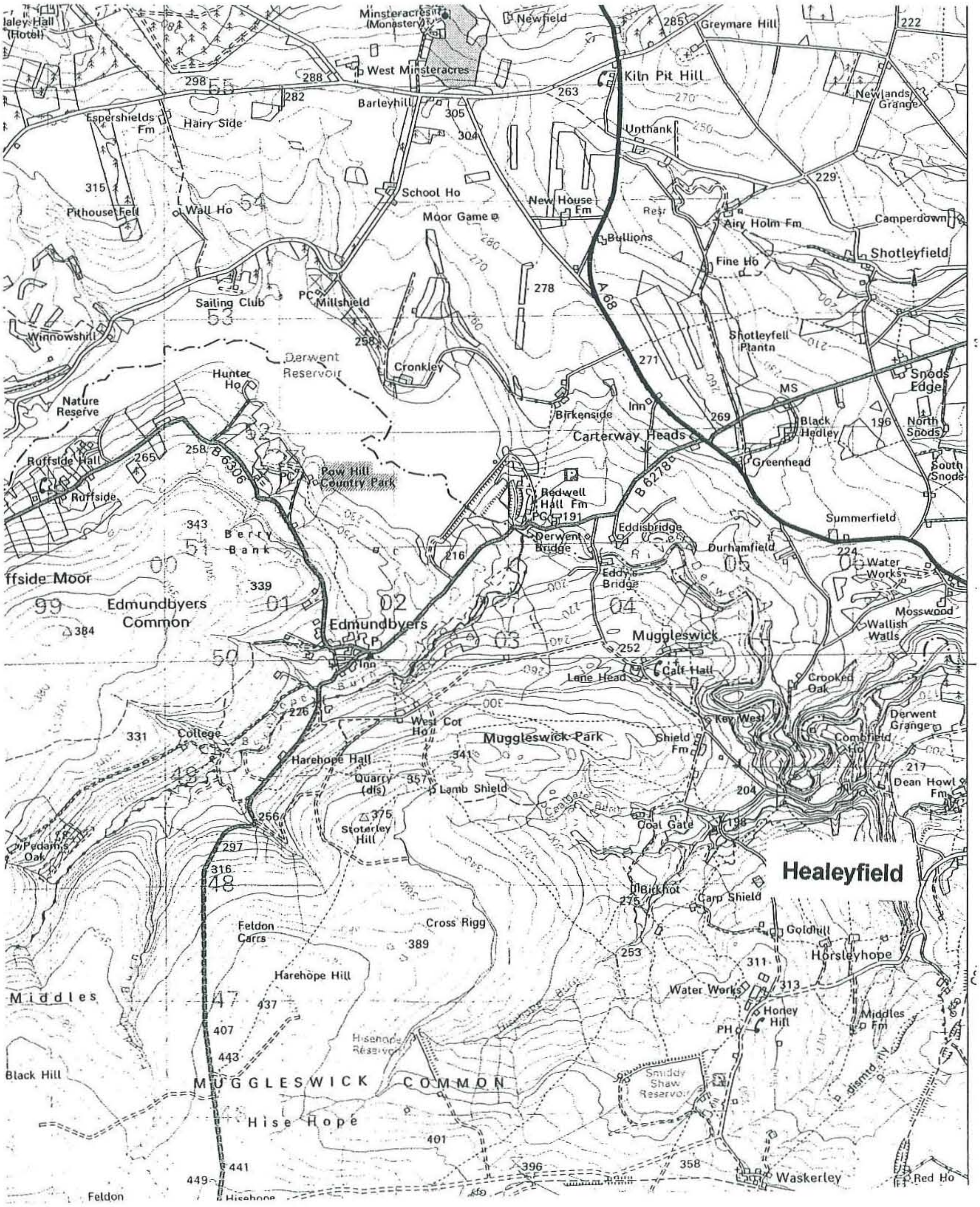


Figure 2: Map to show location of Fell Close

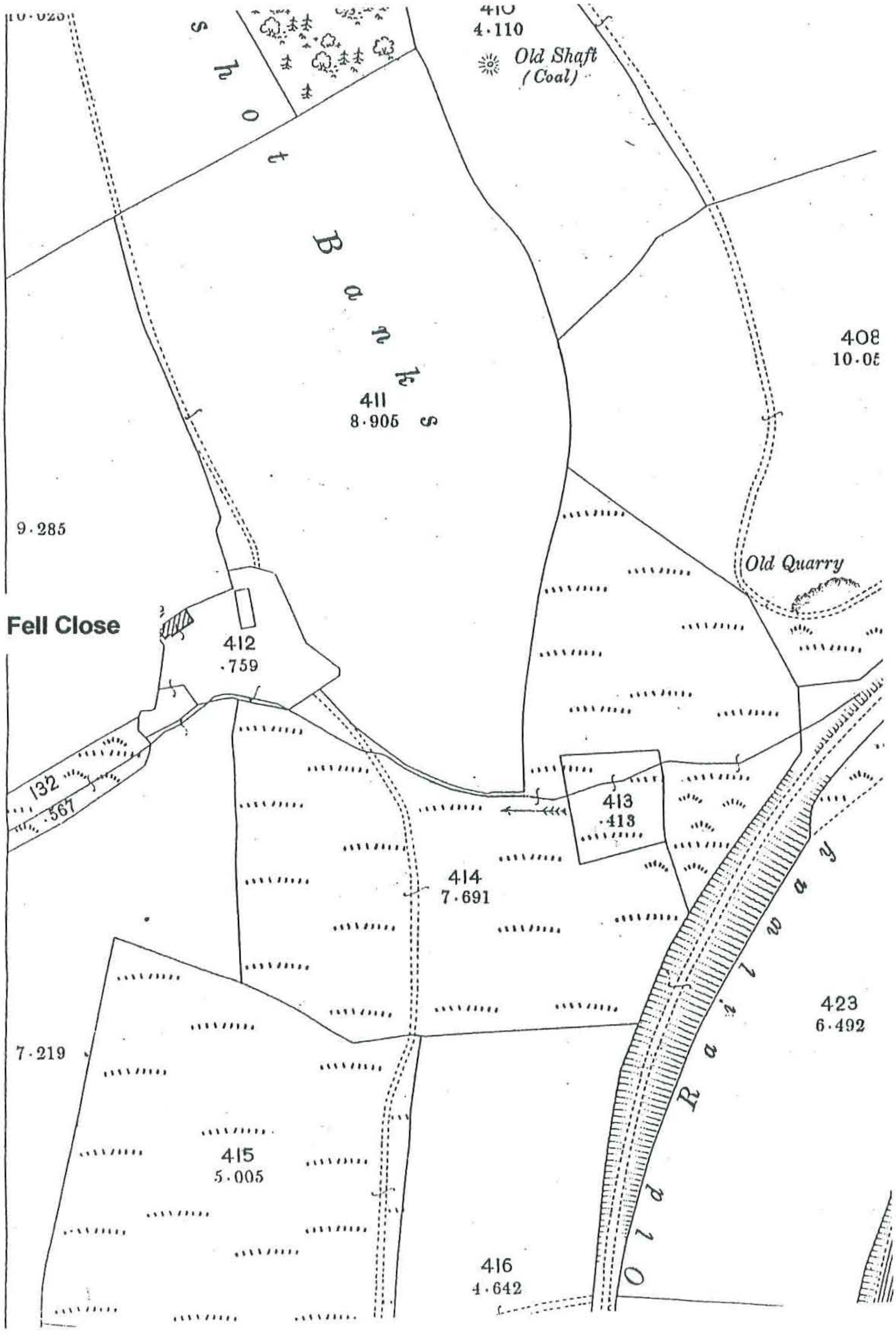
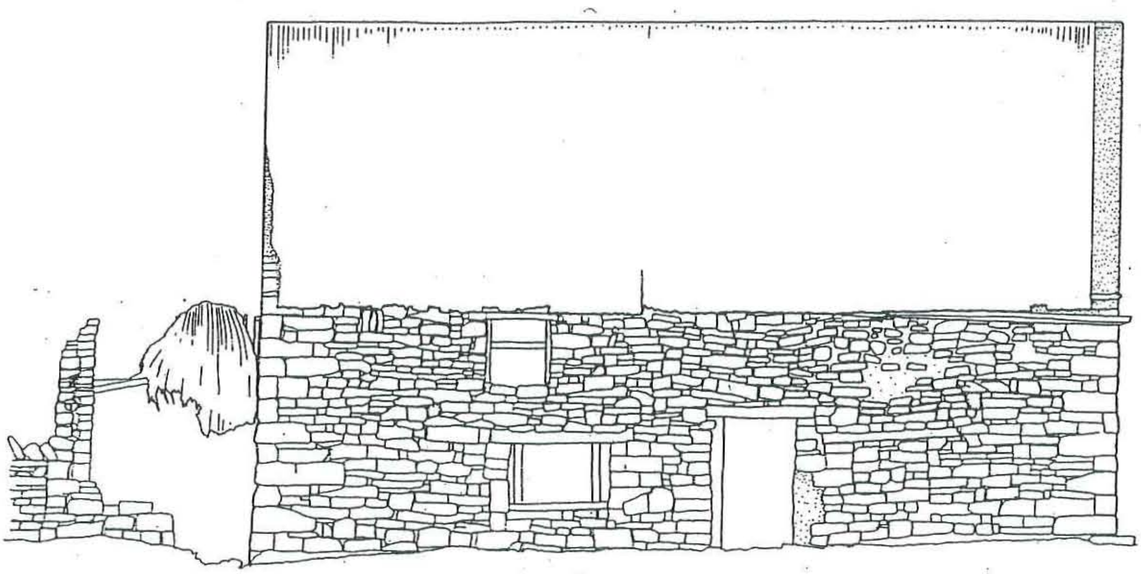


Figure 3: Elevation (viewed from the south) and ground-floor plan of Fell Close (after Emery)



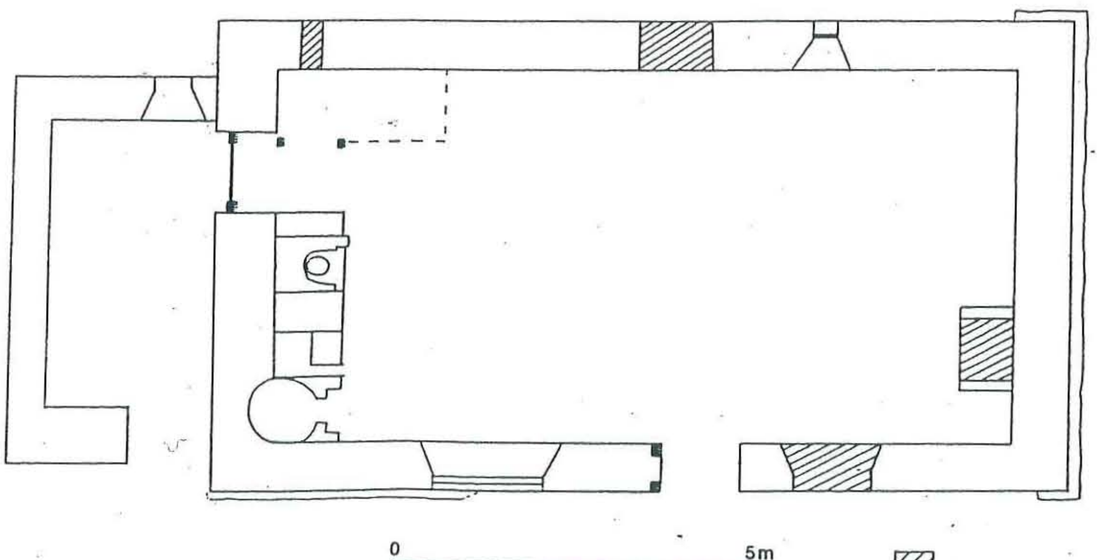
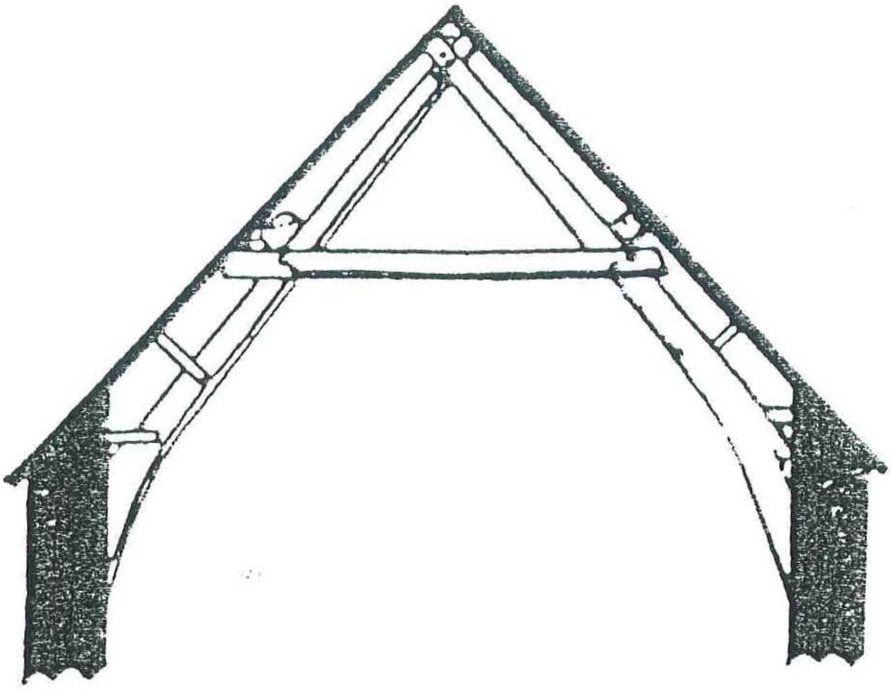


Figure 4: Drawing to show form of the cruck trusses
Truss 2 above, truss 1 below
(viewed from the west looking east)
(after Peter Brears)



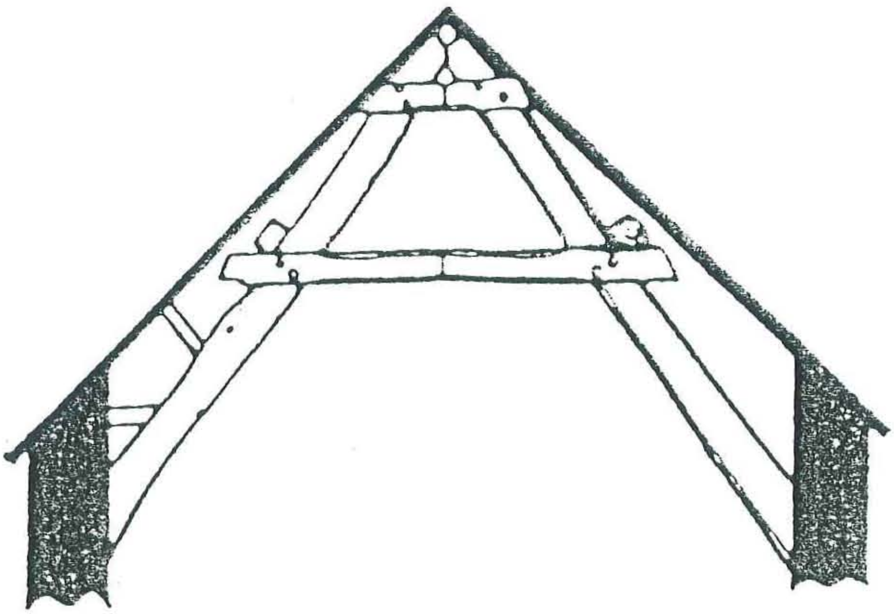


Figure 5a: Plan to show approximate position of ground- and first-floor timbers sampled

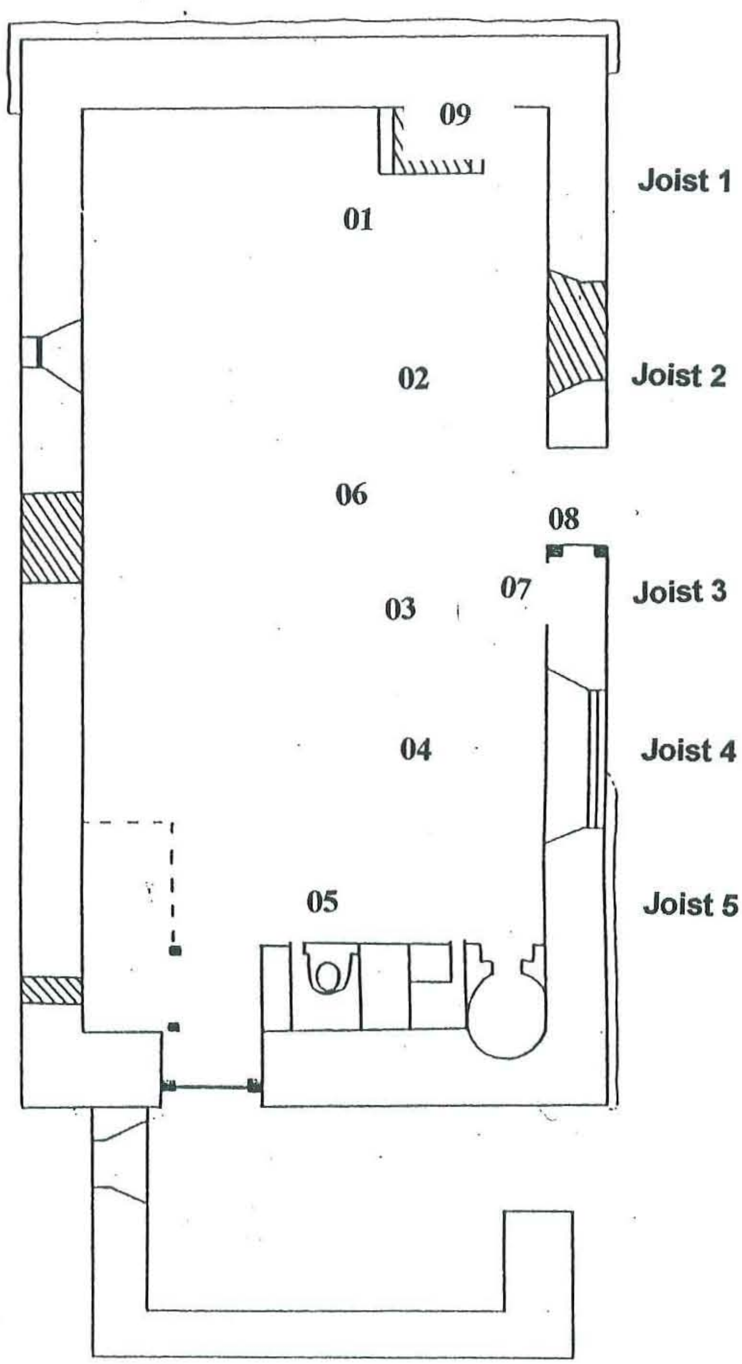


Figure 5b: Plan to show approximate position of roof timbers sampled

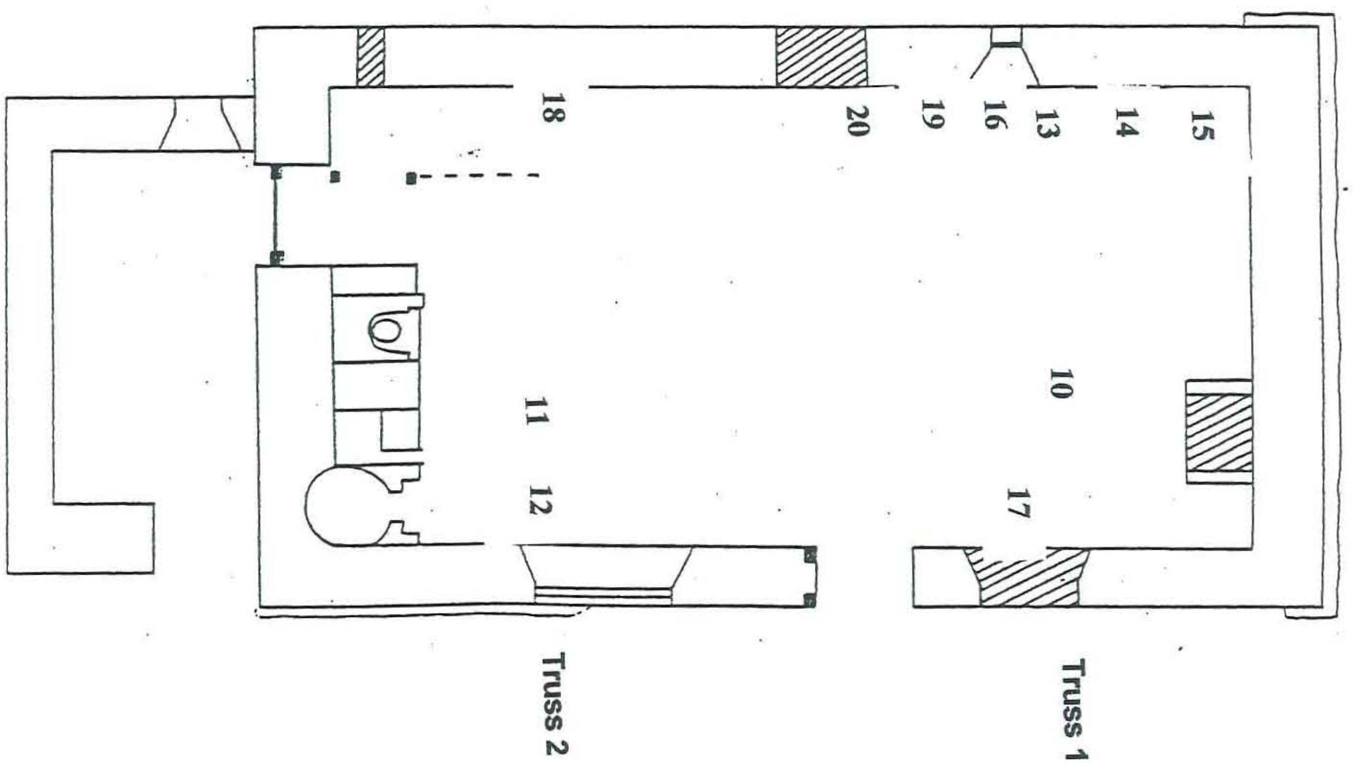
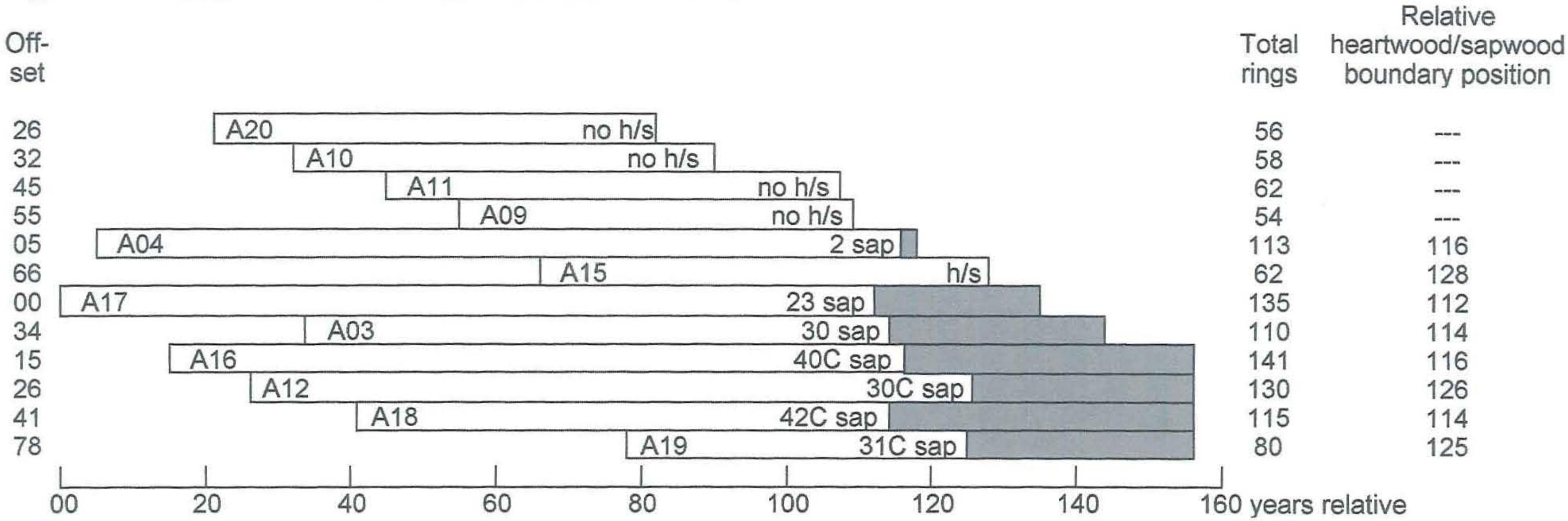
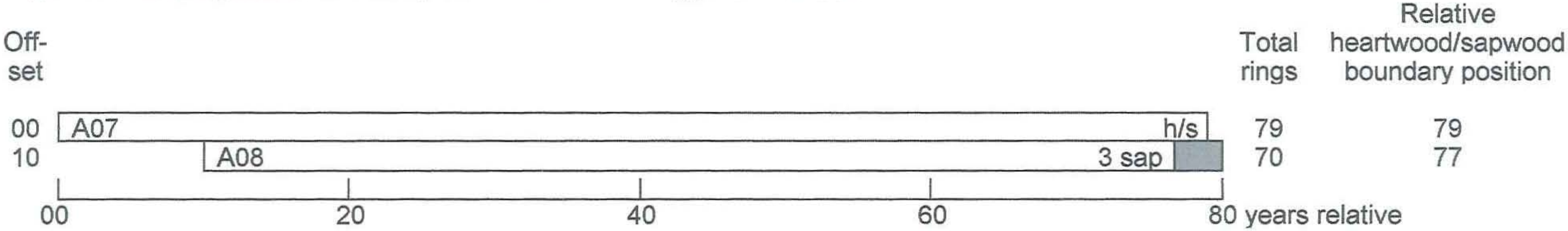


Figure 6: Bar diagram of the samples in site chronology HFDASQ01



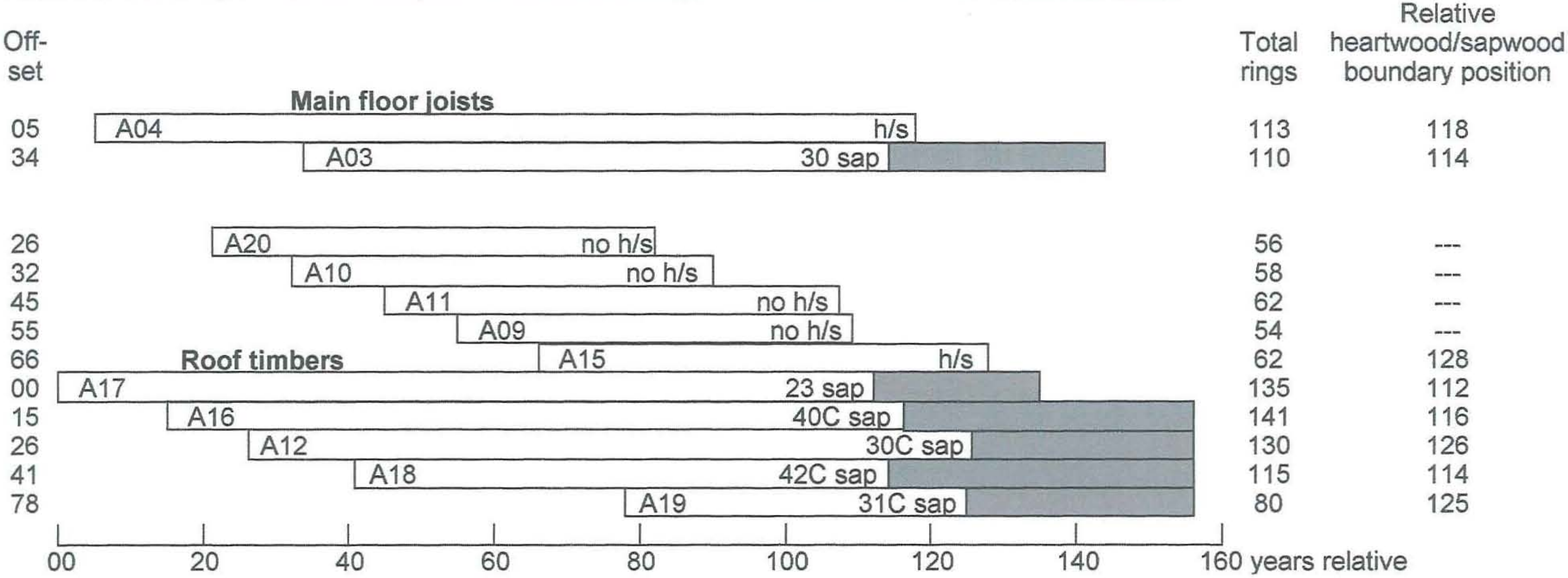
white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on the sample. The last measured ring date is the felling date of the tree

Figure 7: Bar diagram of the samples in site chronology HFDASQ02



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 8: Bar diagram of the samples in site chronology HFDASQ01 sorted by sampling areas



white bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on the sample. The last measured ring date is the felling date of the tree

Data of measured samples – measurements in 0.01 mm units

HFD-A01A 64
522 421 510 366 312 454 364 306 321 321 418 412 336 258 346 461 254 359 290 242
235 176 214 214 199 141 149 137 115 151 112 171 193 166 149 103 84 104 119 125
103 131 134 91 110 119 189 185 217 149 140 105 139 209 151 93 99 59 53 71
75 83 52 80
HFD-A01B 64
529 424 495 389 309 515 392 294 313 332 419 407 328 258 347 441 264 343 317 235
247 169 216 213 185 152 149 130 127 144 112 174 193 162 146 122 79 108 119 124
96 124 156 72 117 131 188 184 208 144 142 100 141 210 145 94 101 56 61 69
71 89 56 79
HFD-A02A 90
332 451 411 471 382 418 495 502 328 419 314 289 316 471 396 348 219 152 204 241
258 205 148 211 170 200 144 89 58 37 42 29 29 27 22 27 24 24 29 32
22 29 23 23 30 36 21 21 25 15 19 26 30 33 36 24 23 37 18 22
40 67 56 49 70 76 61 46 49 67 84 63 59 60 78 87 52 53 46 33
46 61 68 81 61 68 66 48 61 75
HFD-A02B 90
333 497 408 463 386 411 494 503 332 409 325 296 353 443 375 330 228 147 202 223
271 194 155 209 157 198 158 92 55 37 39 31 29 25 23 25 18 22 35 31
23 27 23 26 31 36 25 23 27 17 20 28 32 29 33 23 21 35 22 19
43 68 52 54 63 66 63 52 47 62 77 65 72 47 77 78 57 49 54 36
45 64 69 70 64 74 74 53 53 78
HFD-A03A 110
364 203 80 129 197 291 473 406 410 469 580 574 460 425 360 326 212 206 260 246
233 363 261 274 362 341 310 281 275 284 212 287 256 234 255 289 262 149 154 294
321 270 188 241 201 193 87 58 114 183 281 184 180 242 145 80 99 101 76 108
127 71 41 92 205 218 143 142 135 89 88 116 100 153 57 49 44 45 75 78
102 94 120 121 99 144 105 125 116 168 199 71 52 53 37 46 49 37 29 40
35 38 36 46 31 33 44 38 30 32
HFD-A03B 110
381 166 86 126 187 282 443 415 416 461 595 591 456 434 361 335 223 215 239 259
243 382 289 276 408 310 307 277 267 289 214 262 247 239 273 282 279 164 174 299
312 280 203 233 230 184 80 54 115 179 273 167 179 244 132 91 91 137 77 116
191 70 64 113 233 256 165 160 157 108 88 117 101 162 63 47 47 32 83 75
95 101 112 122 96 147 103 116 127 166 195 77 56 45 42 46 36 37 39 43
36 30 40 40 34 30 38 44 26 36
HFD-A04A 113
195 188 139 207 239 200 167 172 176 255 199 225 232 190 217 234 206 224 278 207
203 174 81 113 141 188 136 165 165 151 149 78 124 124 152 160 166 113 153 201
172 113 179 225 180 151 202 217 139 133 136 135 176 149 154 168 136 122 176 175
260 253 213 234 215 113 58 110 108 100 74 96 112 99 70 52 45 47 74 82
62 64 66 85 75 83 107 68 97 97 79 74 81 96 111 76 70 61 44 45
53 52 63 133 107 85 85 91 75 89 89 81 62
HFD-A04B 113
176 184 147 194 224 187 181 167 188 220 221 200 220 208 207 221 213 217 276 221
188 168 76 112 143 176 144 164 170 151 154 77 104 141 153 162 156 115 163 199
168 110 178 214 203 135 191 234 132 121 148 118 184 149 153 162 142 119 174 174
255 222 211 220 208 116 68 113 102 98 80 93 103 103 65 39 47 54 75 82
59 57 68 89 84 85 106 63 100 92 85 60 76 92 108 70 75 67 33 59
59 53 74 133 120 100 83 100 73 88 93 78 64

HFD-A05A 60
335 480 315 192 217 250 286 271 194 185 257 269 148 150 139 254 224 151 174 142
203 189 179 157 161 148 111 132 98 163 170 151 174 128 59 103 123 148 114 129
153 101 116 138 141 141 166 135 177 111 150 194 130 90 138 129 93 115 143 150
HFD-A05B 60
356 462 304 210 200 248 285 283 193 175 256 257 157 157 143 255 211 145 172 156
225 196 175 156 162 145 108 123 99 167 168 155 176 112 54 111 117 146 107 118
148 105 108 130 152 132 165 139 169 112 155 186 104 93 132 127 94 128 134 146
HFD-A06A 64
303 266 346 339 277 229 300 267 196 210 229 150 229 203 234 216 173 126 83 102
162 170 164 97 164 160 172 90 71 62 96 84 98 112 167 122 159 190 169 159
132 65 136 150 146 145 140 147 148 111 99 118 103 150 171 155 202 204 174 176
229 181 237 199
HFD-A06B 64
267 280 349 353 261 235 306 258 180 209 231 136 226 208 239 212 163 116 74 131
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114 70 127 165 162 160 145 163 131 103 112 123 117 156 192 159 192 199 190 172
239 180 222 174
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257 325 306 240 177 322 309 357 374 400 385 364 306 344 265 210 171 267 204 211
201 231 193 173 184 237 251 235 215 214 195 177 134 197 179 150 182 178 162 174
181 169 181 155 165 134 120 90 92 112 162 174 133 146 180 135 123 169 130 167
148 122 142 77 49 94 118 141 128 159 183 149 58 103 124 89 172 121 159
HFD-A07B 79
291 323 320 229 204 308 327 335 358 395 371 387 362 344 259 204 173 282 195 204
183 229 210 188 189 223 261 239 200 198 215 185 153 201 186 153 178 175 153 183
181 160 182 148 154 141 110 99 86 100 167 184 122 158 178 128 130 175 143 146
140 131 133 75 56 75 125 146 109 166 173 155 58 94 118 103 161 137 154
HFD-A08A 70
279 269 242 267 175 143 213 208 181 187 200 230 236 254 237 251 297 337 279 306
321 262 211 239 282 221 281 259 197 295 250 253 245 202 215 221 168 153 136 190
214 217 188 200 213 185 190 235 181 175 189 163 156 86 58 81 104 117 114 154
176 143 80 84 92 63 93 133 91 79
HFD-A08B 70
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286 261 180 275 270 229 284 251 188 299 257 247 262 205 196 234 165 173 133 166
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149 112 104 67 85 47 121 101 102 86
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196 151 273 294 441 526 294 257 216 202 171 152 244 207 120 130 107 150 197 322
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95 79 124 189 232 171 185 167 169 154 106 52 43 51
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204 152 274 286 436 533 333 253 217 225 200 177 262 204 119 145 78 149 229 314
249 227 223 239 192 273 285 263 221 327 242 220 149 137 123 133 135 99 121 130
100 87 126 188 238 170 185 148 154 147 153 51 43 55
HFD-A10A 58
161 293 226 164 55 79 104 170 201 208 204 219 252 184 162 269 336 347 299 412
414 535 377 675 436 409 457 697 451 314 286 355 211 308 253 292 379 236 179 86
88 151 141 120 111 105 73 81 90 80 100 150 213 176 135 100 76 91
HFD-A10B 58
172 280 231 166 57 68 105 178 207 197 187 199 290 179 157 260 327 353 318 389
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92 152 122 136 106 103 73 85 79 93 93 148 207 169 151 102 71 76

HFD-A11A 62
225 188 239 353 376 267 286 267 247 248 353 330 310 277 268 266 277 245 342 225
146 154 223 179 132 130 57 92 172 262 169 157 223 234 173 153 111 127 152 198
174 189 113 146 87 134 161 143 116 155 87 73 118 159 161 117 155 132 137 118
99 122
HFD-A11B 62
233 186 229 343 372 260 299 272 250 265 325 337 295 283 304 267 281 236 330 242
165 148 203 203 115 139 67 96 167 274 162 152 236 235 177 144 119 118 147 197
182 190 107 143 92 141 161 132 110 143 90 70 114 150 153 129 156 153 115 118
115 109
HFD-A12A 130
230 144 210 157 203 142 152 147 153 103 78 78 83 98 128 112 142 183 225 109
103 78 51 55 70 87 124 84 113 191 130 156 139 177 237 161 143 207 253 320
304 255 280 217 163 89 186 240 270 207 201 197 242 169 189 130 217 253 252 220
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124 191 218 162 182 176 132 119 136 59 42 38 36 52 42 52 53 47 54 49
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42 23 23 33 26 29 32 31 32 43
HFD-A12B 130
228 140 205 162 207 134 156 149 140 101 92 75 75 107 127 119 136 211 238 115
95 66 54 62 75 76 123 81 117 178 129 147 153 178 230 172 139 229 246 301
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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.

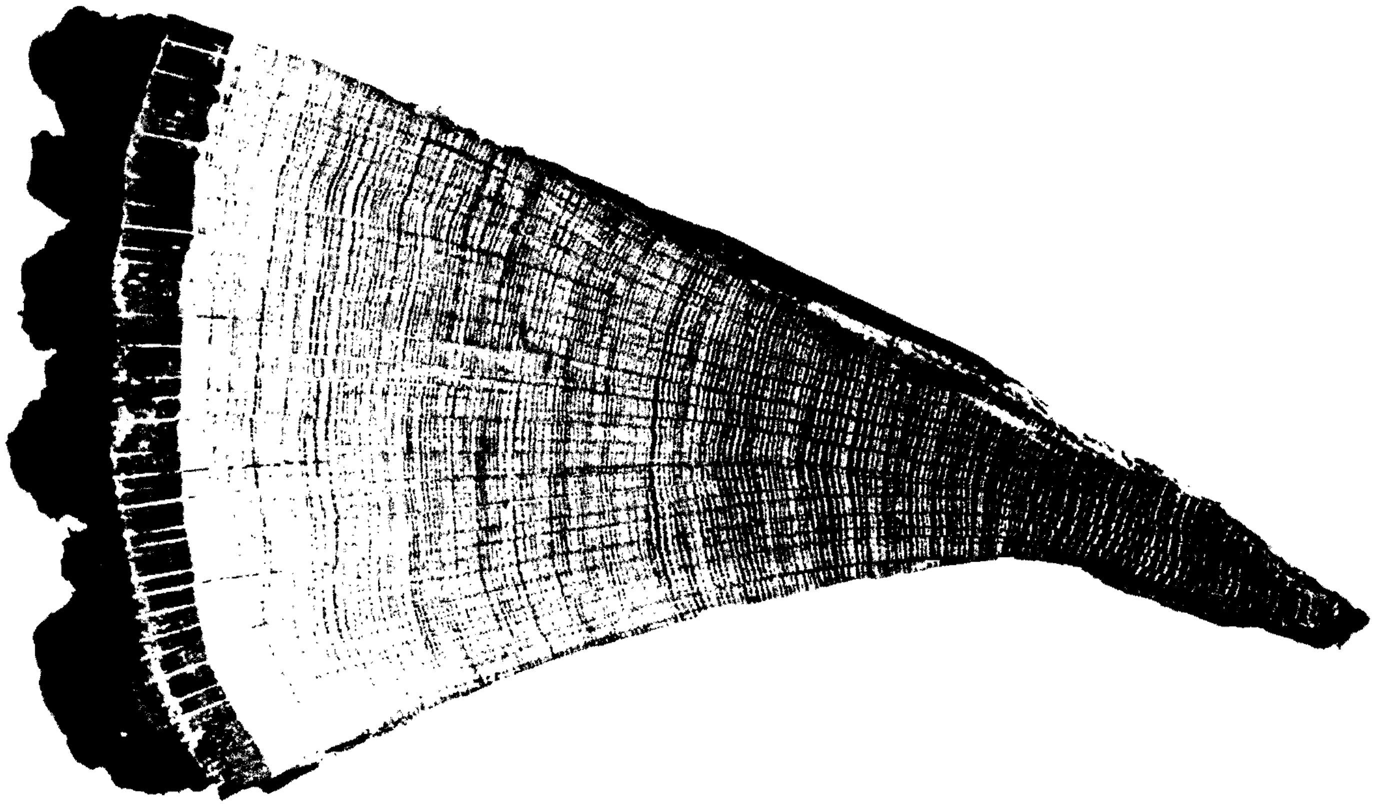


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

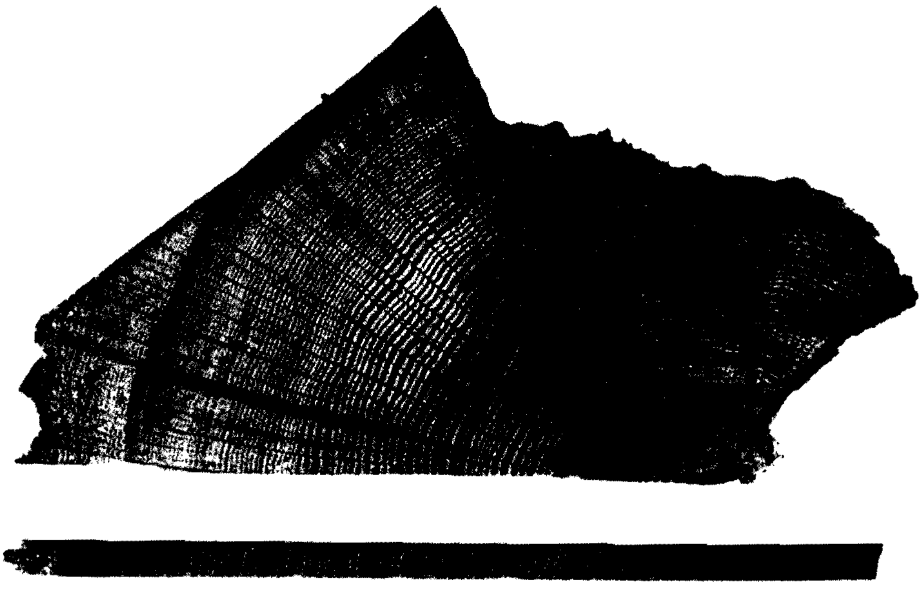


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

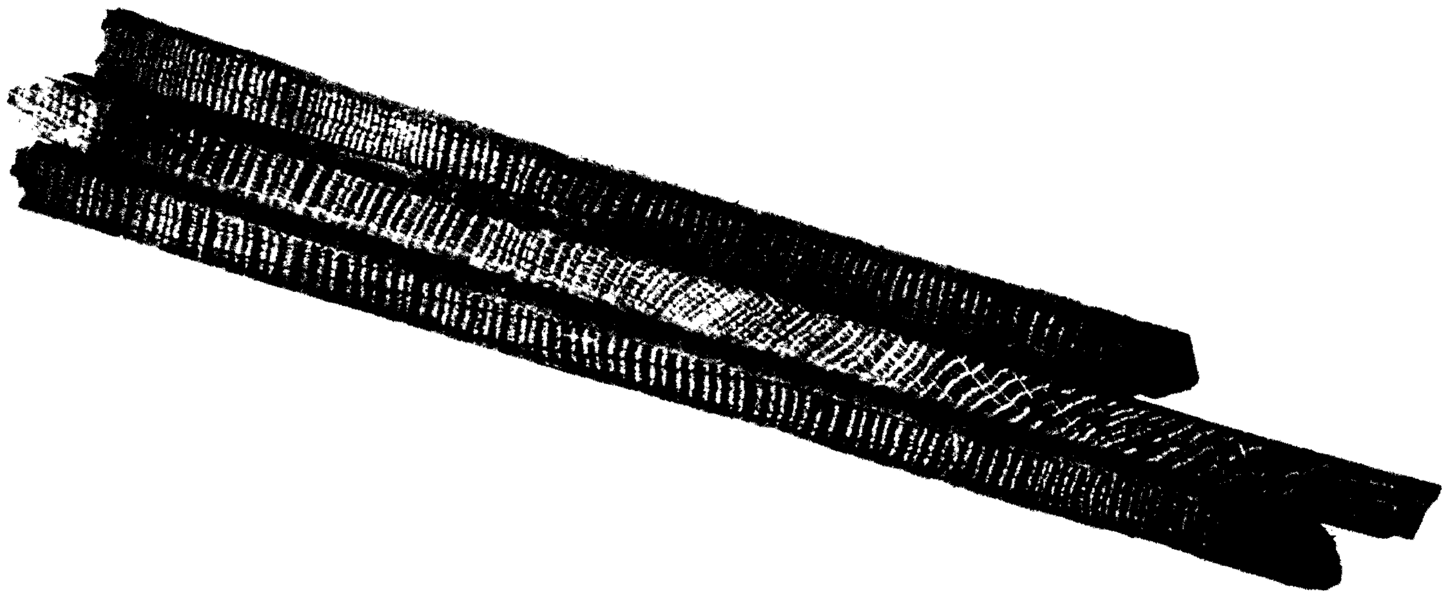


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

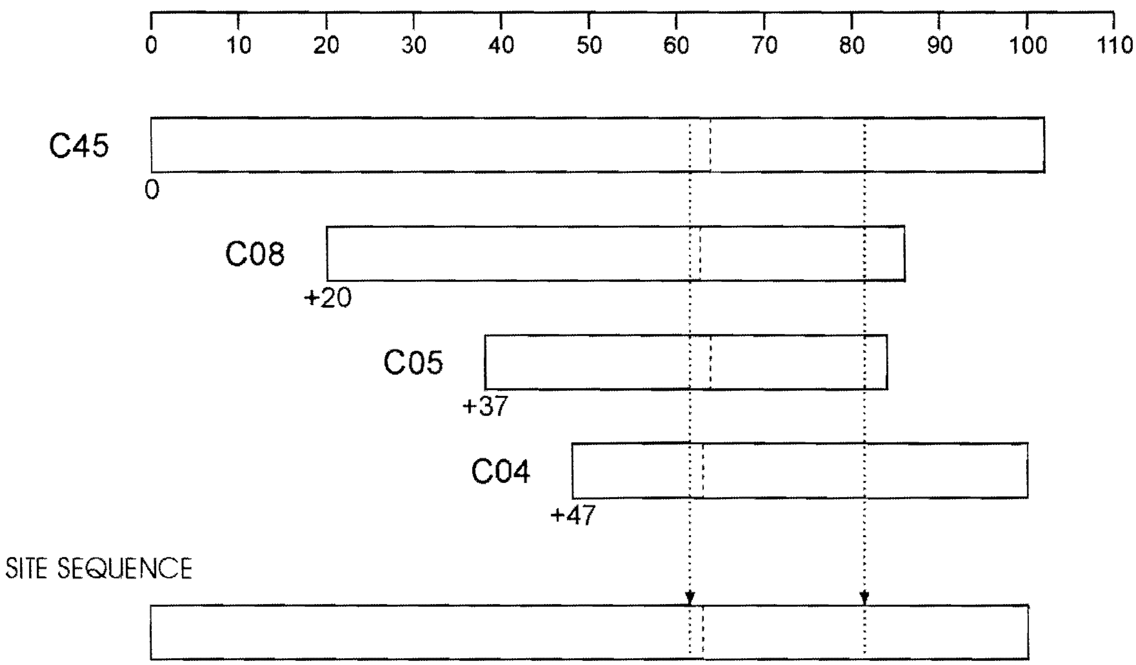


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

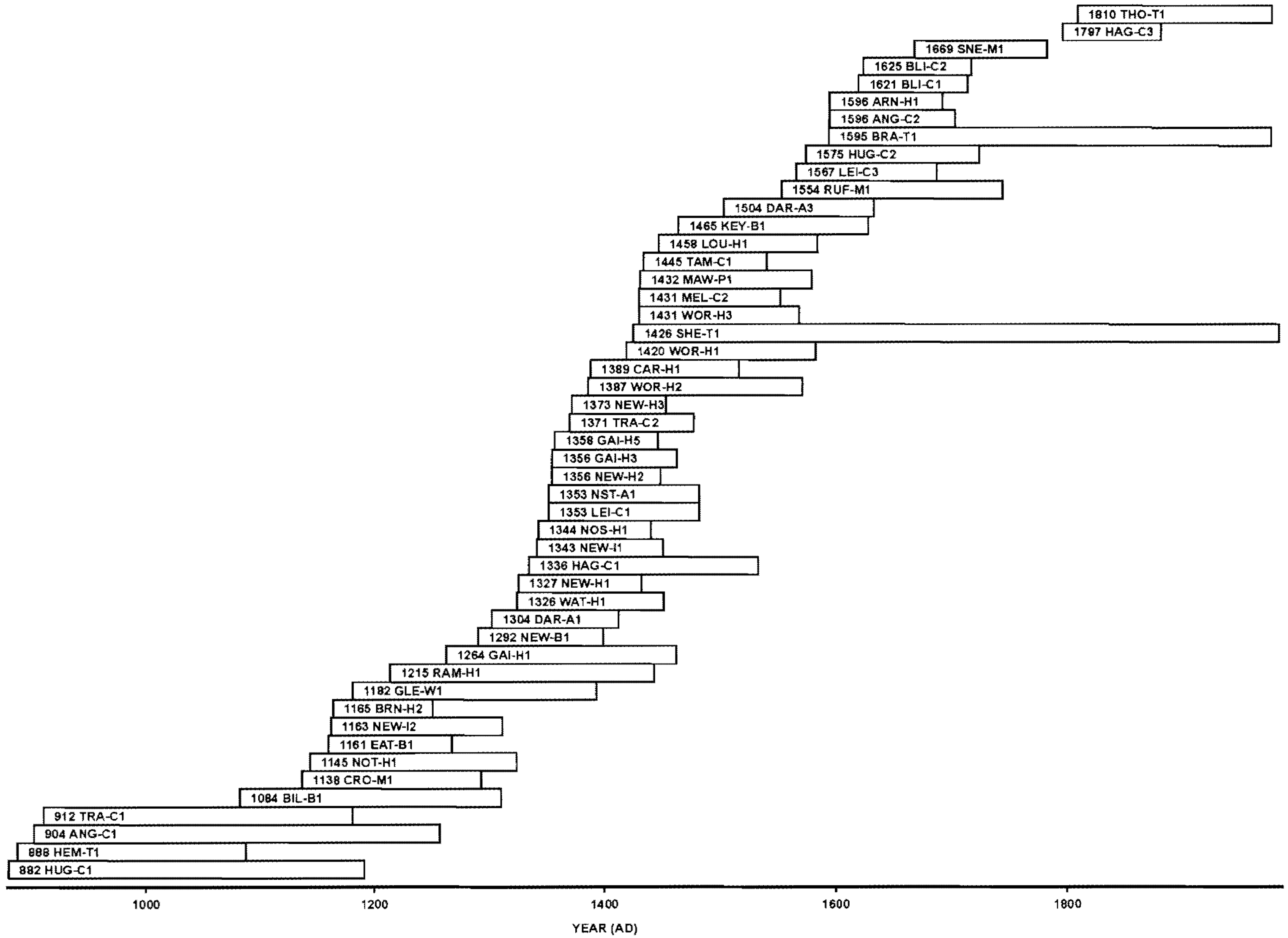
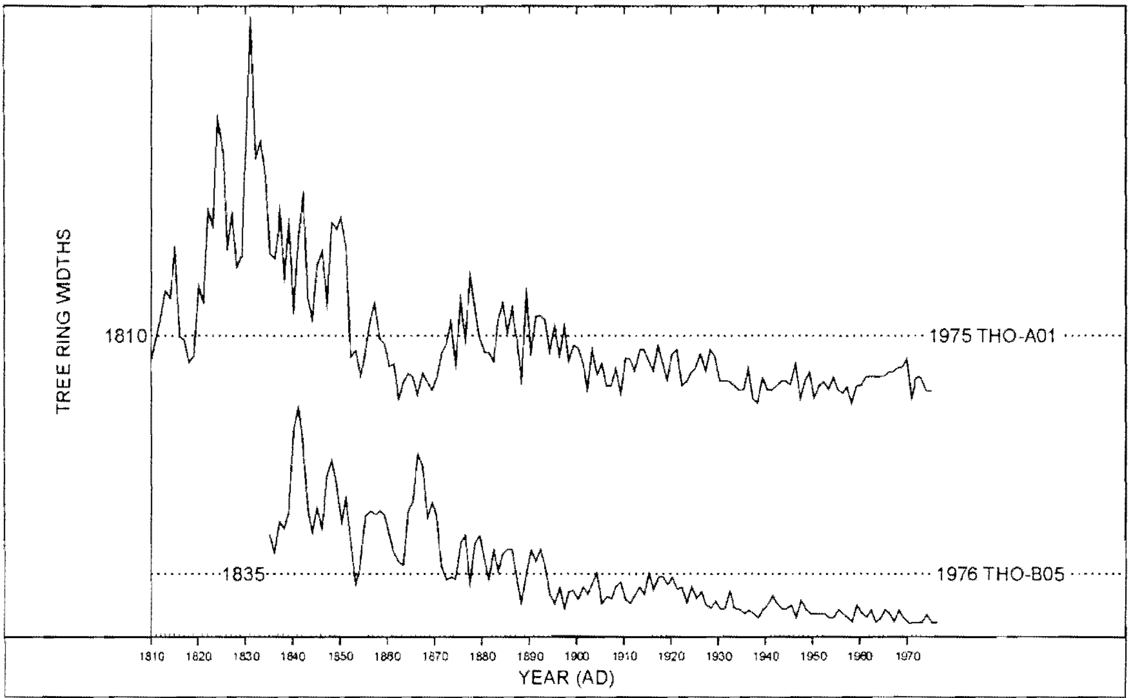


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

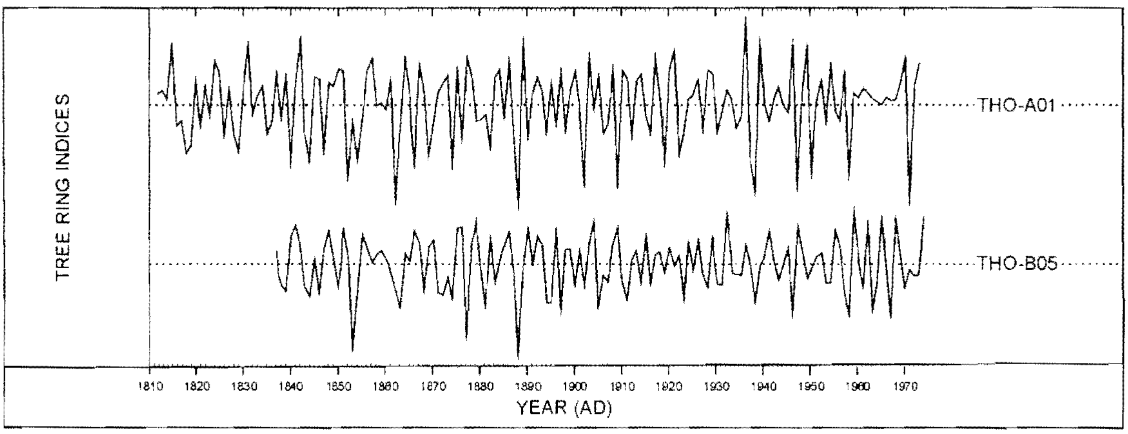


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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