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Ancient Monuments Laboratory
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TREE-RING ANALYSIS OF TIMBERS FROM HEADSTONE MANOR TYTHE BARN, PINNER VIEW, HARROW, LONDON

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Summary

Sixteen samples from the principal timber members of this barn were analysed by tree-ring dating. This analysis produced a single site chronology of thirteen samples, the 132 rings it contains spanning the period AD 1374 - AD 1505. Interpretation of the sapwood, and the relative positions of the heartwood/sapwood boundaries on the dated samples, suggests that the entire barn is of a single phase of construction using timber felled late in AD 1505.

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Introduction

The tithe barn at Headstone stands adjacent to and west of the Manor House here (TQ 141897; Figs 1 and 2), though outside the moat. It is an impressive weatherboarded structure being approximately 45 metres long and 15 metres wide; the ridge reaches some 9 metres above floor level.

Internally the barn is of ten bays divided by eleven trusses. The trusses consist of principal wall-posts with tiebeams and rafters. Each principal rafter carries two butt-purlins, only one of which, the lower, is jointed and pegged to the rafter. From the tiebeams queen posts rise to collars. Each principal wall-post has a brace, very slightly arched, to the tiebeam, but only on the northern side of each post does a brace rise to the wall plate.

The walls of the barn are of box-frame construction with sills, mid-rails, and wall plates forming the horizontal members. Each bay is divided into two by an intermediate wall-post, from sill to wall plate. To either side of the intermediate wall-post, above and below the mid-rails, are smaller stud posts. The wall-framing also contains diagonal bracing, though this is a rather inconsistent feature. The barn has two large wagon entrances on its south side, one at bay four, the other at bay 8. There is evidence that truss 8, immediately before the second wagon entrance, was at one time closed by studding. The barn is currently occupied by Harrow Museum and Heritage Centre.

Sampling and analysis by tree-ring dating was commissioned by English Heritage as part of an on-going historical research project. The purpose of this was to verify and refine the construction date and possible phasing of the barn. The accounts of the Archbishop of Canterbury for the year ending AD 1506 refer to payments made for sundry repairs at Headstone and for the making of one barn, suggesting that the building dates from at least this time. Stylistically however, it is believed that the barn may be later than the early sixteenth century. Furthermore, given the positions of the wagon entrances, and evidence for internal partitions it is believed that although the first or eastern-most seven bays may be of primary construction, the last or western-most three bays could possibly be a later addition.

Establishing a construction date for the barn would provide information on the post-medieval up-grading of the site during the late-fifteenth to early-sixteenth as evidenced by structural changes made to the Manor house during this time. It was hoped that it might be possible to link the building of the barn to one or more phases of the Manor house.

The Laboratory would like to take this opportunity to thank Richard Bond for his help in interpreting the building, his assistance with sampling, and for providing drawings. The Laboratory would also like to thank Harrow Council for allowing sampling and in particular Jan Strode, David Whorlow, curators of the Centre, plus staff for their help, cooperation, and hospitality during sampling.

Sampling

After discussion with Richard Bond on the possible phasing of the building and the timbers available, and in conjunction with the brief provided by English Heritage, a total of sixteen core samples was obtained. Each sample was given the code HED-B (for Headstone, site "B") and numbered 01 – 16.

Ten samples, HED-B01 – 10, were obtained from timbers in the east section of the barn, the remainder, HED-B11 – 16 being taken from timbers in the western section. For the most-part the sampled timbers were major elements of the framing, main posts, tiebeams, rails, etc, and appeared to be integral to the structure as a whole, representing the primary phase of construction. The positions of the samples have been recorded on drawings produced by Richard Bond, shown here as Figure 3. Details of the samples are given in Table 1. The trusses and bays have been numbered from site east to west.

Analysis

Each of the sixteen samples was prepared by sanding and polishing, and the growth-ring widths measured; the data of these measurements are given at the end of the report. The growth-ring widths of all the samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a minimum *t*-value of 4.5 thirteen samples cross-matched with each other at relative positions as shown in the bar diagram Figure 4. The growth-ring widths of these thirteen samples were combined at these relative off-set positions to form HEDBSQ01, a site chronology of 132 rings. Site chronology HEDBSQ01 was compared with a series of relevant reference chronologies giving it first ring date of AD 1374 and a last measured ring date of AD 1505. Evidence for this dating is given in the *t*-values of Table 2.

Site chronology HEDBSQ01 was then compared with the three remaining ungrouped samples. There was, however, no further satisfactory cross-matching. All the ungrouped samples were therefore compared individually with a full range of relevant reference chronologies. Again, however, there was no satisfactory cross-matching for these individuals.

Interpretation

Three of the samples contained in site chronology HEDBSQ01, HED-B08, B15, and B16, retain complete sapwood, that is, they have the last ring that the tree produced before it was felled. Each last measured complete sapwood ring, has the same date, AD 1505. The relative position of the heartwood/sapwood boundaries on the other dated samples in this site chronology would suggest that AD 1505 is the felling date for all the timbers represented.

On each of those three samples with complete sapwood it is possible, under the microscope, to see that in the final growth-ring, all the spring cell growth and a large amount of summer cell growth for the year AD 1505 has taken place. This would suggest that the timbers represented were felled late in AD 1505, and certainly before the spring of AD 1506.

Conclusion

Analysis by dendrochronology has been able to provide a very precise date for the felling of the timber used in this building, AD 1505. Dendrochronology has also been able to show that both parts of the barn are of a single phase of construction, not two different phases as was thought possible. Thus, the date obtained by tree-ring analysis is very close to the documentary reference for the site of late AD 1506. Such dating indicates that this building is an early example of its type as stylistically the barn was thought to be later.

It is of interest to note that the felling date of the timber obtained through tree-ring analysis and the construction date implied from the documentary sources is identical. This shows that the timbers at Headstone barn were green and unseasoned when used. The analysis reported upon here supports the general assumption made by dendrochronologists that, at least up to about AD 1600 for larger structural timbers, builders generally used unseasoned wood.

Three samples remain undated. One of these, HED-B04, has only 45 rings, rather too few for satisfactory analysis.

A second undated sample, HED-B01, shows in its later rings a distinct repeated growth pattern. Bands of narrow rings widen gradually over a period of 10 years or so and then suddenly reduce in width before widening slowly again. This pattern, illustrated in Figure 5, is unlikely to have been caused by climate. The wider rings may represent periods of reduced competition when surrounding trees or bushes were cleared, the rings narrowing as competition gradually increased.

In any case sample HED-B01 is from a timber that is almost certainly a later insertion of unknown date. The lack of dating may in part be due to the absence of local reference material for the period of the source timber's growth.

The third undated sample is HED-B13. There appears to be no problem with this sample, it shows no distortion or stress, which might make cross-matching and dating difficult.

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Table 1: Details of samples from Headstone Manor Barn, Headstone, Middlesex

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
HED-B01	South intermediate wall-post, bay 1	154	26C	------	------	------
HED-B02	South main wall-post, truss 2	114	h/s	AD 1377	AD 1490	AD 1490
HED-B03	South intermediate wall-post, bay 2	90	h/s	AD 1396	AD 1485	AD 1485
HED-B04	South mid-rail (to west), bay 2	45	h/s	------	------	------
HED-B05	South main wall-post, truss 3	84	2	AD 1404	AD 1485	AD 1487
HED-B06	South intermediate wall-post, bay 3	86	10	AD 1414	AD 1489	AD 1499
HED-B07	South main wall-post, truss 4	113	4	AD 1376	AD 1484	AD 1488
HED-B08	North mid-rail (to west), bay 3	93	21C	AD 1413	AD 1484	AD 1505
HED-B09	Tiebeam, truss 8	113	h/s	AD 1374	AD 1486	AD 1486
HED-B10	Tiebeam, truss 7	98	h/s	AD 1392	AD 1489	AD 1489
HED-B11	North main wall-post, truss 9	82	h/s	AD 1403	AD 1484	AD 1484
HED-B12	Tiebeam, truss 9	68	h/s	AD 1417	AD 1484	AD 1484
HED-B13	South intermediate wall-post, bay 9	76	h/s	------	------	------
HED-B14	North intermediate wall-post, bay 10	93	2	AD 1397	AD 1487	AD 1489
HED-B15	North main wall-post, truss 11	113	18C	AD 1393	AD 1487	AD 1505
HED-B16	North intermediate wall-post, truss 11	94	29C	AD 1412	AD 1476	AD 1505

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on sample, last measured ring date is felling date of timber

Table 2: Results of the cross-matching of site chronology HEDBSQ01 with relevant reference chronologies when first ring date is AD 1374 and last ring date is AD 1505

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	9.2	(Laxton and Litton 1988)
England	AD 401 – 1981	7.5	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	8.3	(Bridge 1988)
Kent-88	AD 1158 – 1540	10.3	(Laxton and Litton 1989)
England London	AD 413 – 1728	12.8	(Tyers and Groves 1999 unpubl)
MC10---H	AD 1386 – 1585	9.3	(Fletcher 1978)

Figure 1: Map to show general location of Headstone

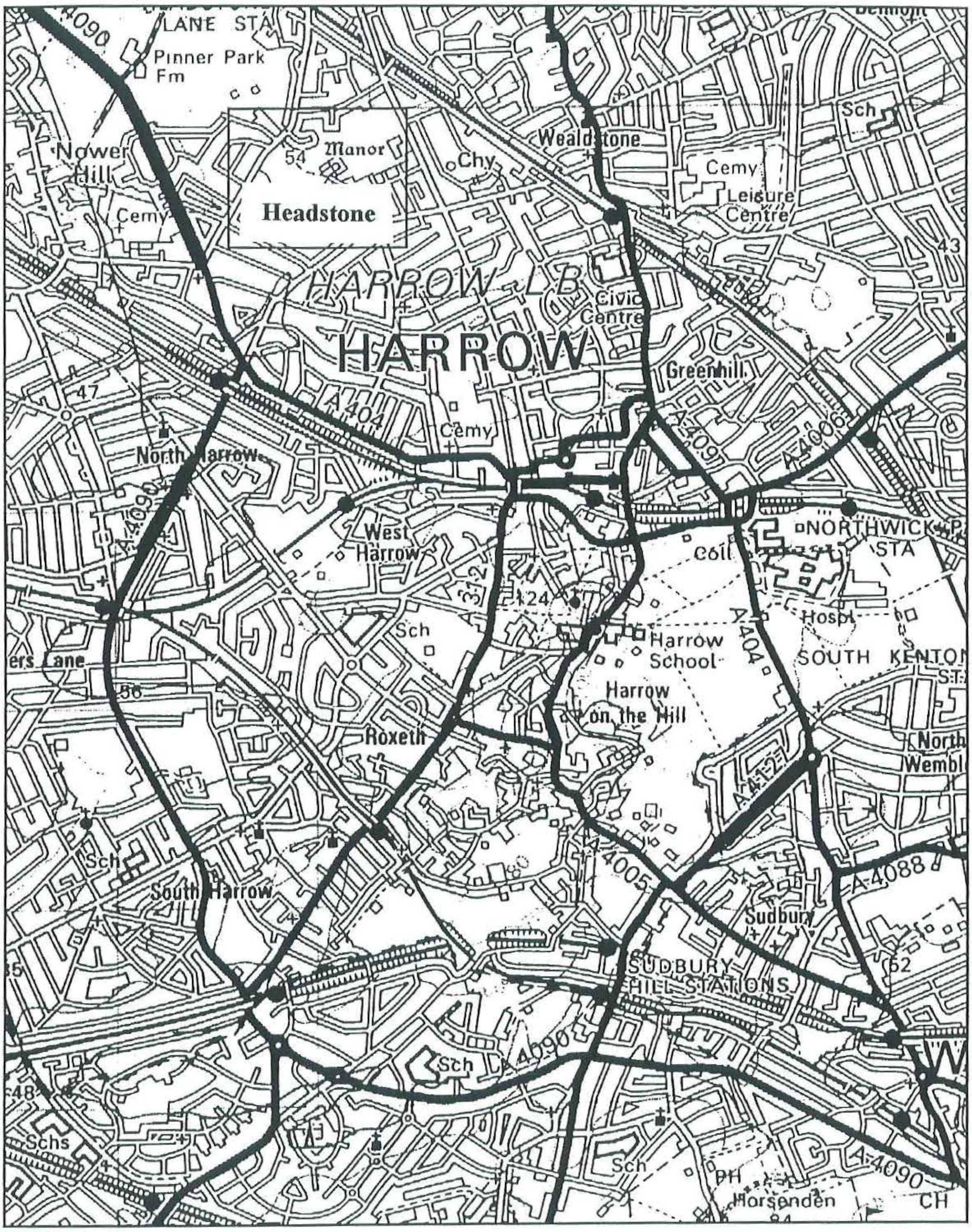


Figure 2: Map to show position of buildings at Headstone Manor

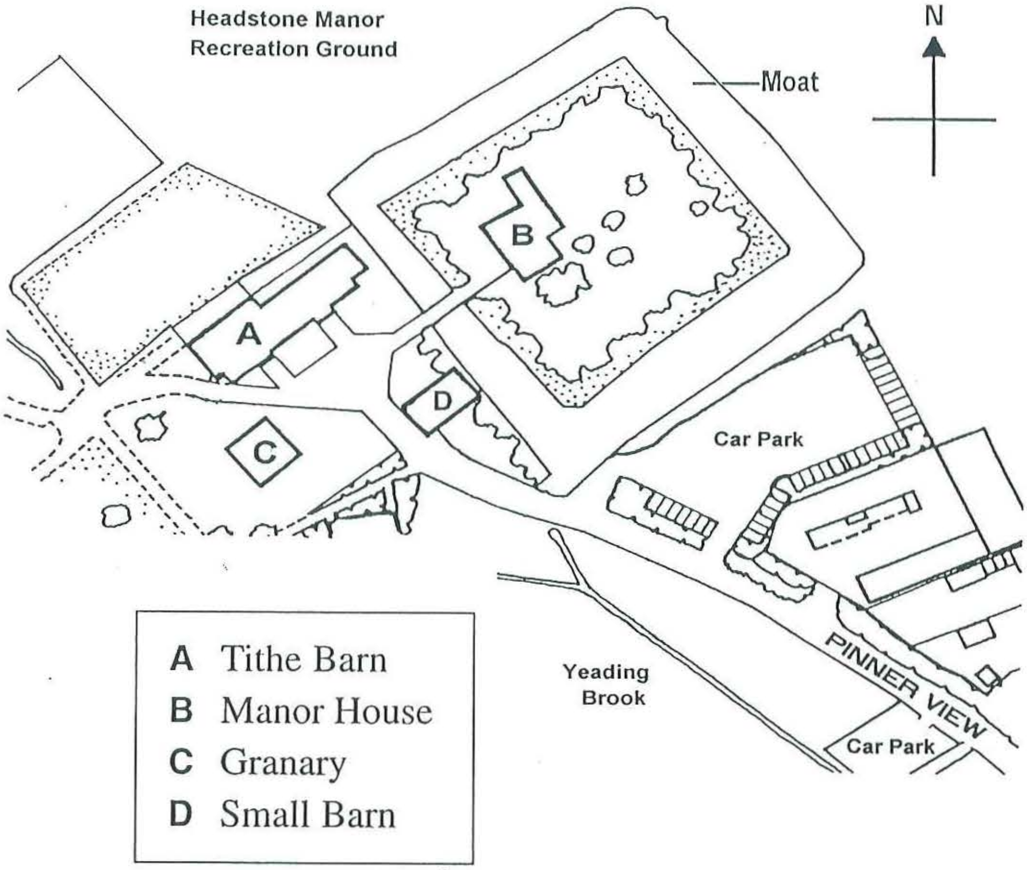
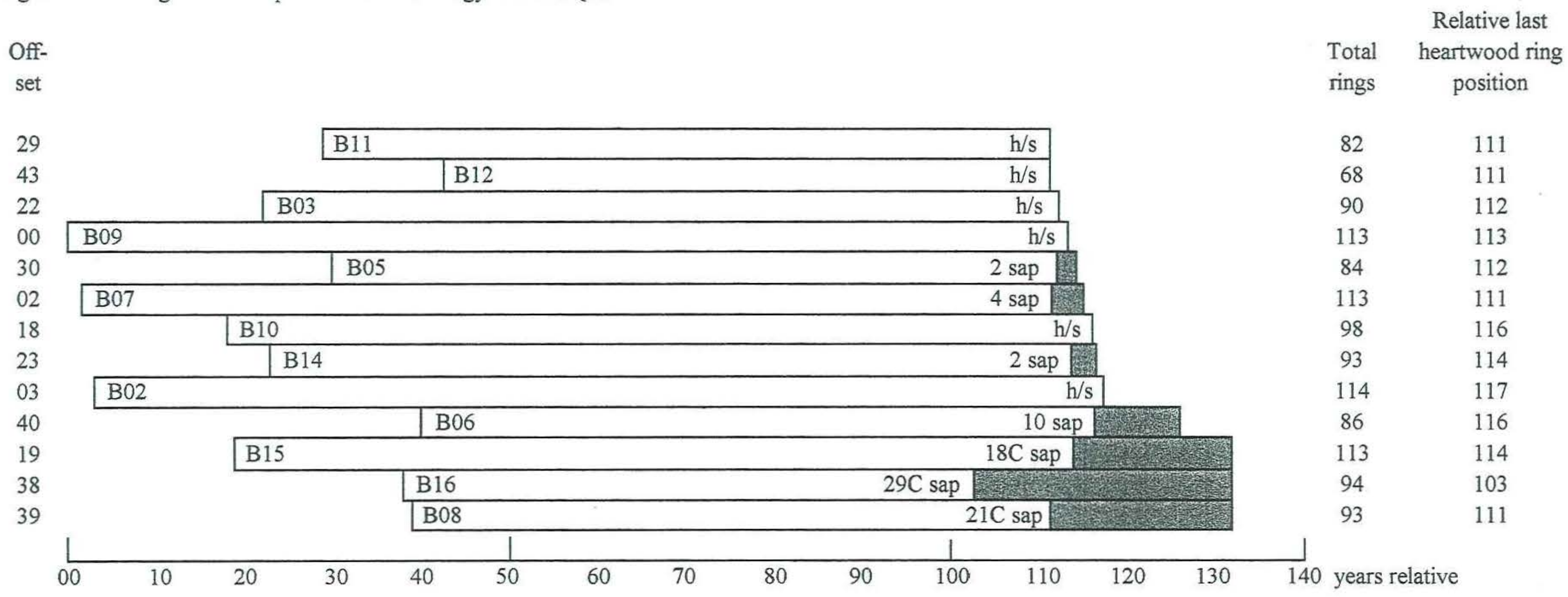


Figure 4: Bar diagram of samples in site chronology HEDBSQ01



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 5: Illustration of erratic growth-ring pattern in undated sample HED-B01

Data of measured samples - measurements in 0.01 mm units

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HED-B01A 154
 386 292 357 281 296 303 294 385 510 429 311 225 256 298 331 507 427 414 380 114
  55  76  92 147 175 219 177 185 183 197 253 342 431 337 351 337 240 289 332 316
 366 386 314 148  49  57  81  75  87 111 122  78  95 109 165 186 146 169 132 196
 196 185 144 245 107  55  59  62  75  67  76  58  66 112  66  40  28  36  43  65
  79  94  77  97 129  50  46  36  52  55  62  56  66  70  76 103  70  60  52  62
  72 118  93 125 127 113  77  29  52  53  74  71  65  81 109 193 160  71  47  42
  29  62  56  80  94  85  98 131 138 127  35  38  52  41  35  53  73  89  80  47
  31  35  34  57  45  78  79  92  71  43  25  46  54  57
HED-B01B 154
 388 307 347 268 303 291 289 409 474 460 324 245 256 303 359 505 416 423 379 110
  57  70  87 149 185 231 179 177 186 194 258 338 444 351 347 331 260 287 341 322
 354 415 320 144  50  50  91  71  85 109 122  83  98 110 165 187 151 168 137 182
 216 176 161 244 107  59  54  64  71  66  74  60  67 125  55  35  35  44  41  61
  78  96  86  95 126  66  39  34  48  55  66  59  65  74  97  97  57  62  56  69
  73 109  95 125 126 121  81  23  45  61  74  65  77  72 112 194 160  71  44  32
  42  45  69  84  90  87  98 120 152 122  48  37  37  45  50  50  55  87  74  50
  33  28  47  51  53  73  86  95  75  44  35  31  54  60
HED-B02A 114
 317 275 398 308 244 304 193 237 254 282 419 343 259 243 213 209 171 240 262 253
 215 263 256 253 218 192 244 258 211 248 175 186 146 152 121 159 118  93  70  69
  69 106  73 106 151 153 105  94  86  80  99 120 140 152 160 189 105  54  92  79
 107 132  78 114 112 131 139 108  99  61  75  75  83  83  82  99  97 107 100 128
 116  93  72 102  93  92 113  91 103 108  76  71  54  66  66 125 134 193 130 122
  74 105 144 120 191 312 325 267 226 210 200 220 254 236
HED-B02B 114
 239 270 389 307 252 317 197 247 271 275 424 337 261 227 212 186 189 238 252 235
 214 247 258 249 217 183 269 274 198 248 172 192 146 147 131 142 108  96  71  72
  78  99  77 111 133 160 109  95  92  82  99 115 144 157 161 195 101  56  91  92
 100 126  84 122 119 119 121 118  92  84  68  67  89  87  83  80  88  99 100 118
 111  92  78 106  86 102 110  97 114  99  81  66  66  54  84 112 142 182 134 121
  70 111 142 126 206 299 322 256 224 218 213 209 274 222
HED-B03A 90
 436 289 391 313 326 237 188 289 339 350 327 289 346 278 259 230 246 176 153 157
 112 164 197 128 223 187 155 206 187 129 157 120 153 158 179 144 211 133 100 117
 105 116 121  82  96  92 121  92  96  77  67  78  73  80  81  82  78 102  89 100
  86  91  96  80  66  69  85  87  70 123  76  69  66  77  78  72 107 160 158 200
 169  80  96 140 155 232 125 118 125 148
HED-B04A 45
 301 328 300 185 349 272 264 289 281 300 238 356 280 354 406 396 429 370 247 237
 352 213 249 294 229 326 269 245 215 178 169 165 234 217 123 140 153 156 223 185
 178 186 229 224 282
HED-B04B 45
 234 364 280 177 349 280 260 278 309 275 231 356 285 345 409 402 411 361 236 244
 354 210 244 285 211 342 279 259 206 181 180 181 229 219 118 144 170 159 218 174
 169 194 221 226 258
HED-B05A 84
 514 560 571 439 360 261 166 325 380 298 341 266 316 344 354 266 384 326 285 348
 310 260 292 232 349 328 287 317 377 201 126 225 184 217 185 194 173 205 206 165
 232 148 119 133 145 153 146 191 155 159 181 184 178 195 167 129 143 134 135 132
 135 142 152 131 107 154 119 125 140 150 136 186 119  77  99 125 159 166 150 163
 178 161 160 189
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HED-B05B 84
526 569 610 436 363 271 161 328 379 335 357 273 322 369 361 256 338 325 265 365
321 276 304 250 325 306 273 306 361 170 145 227 187 217 196 190 168 205 200 190
219 156 109 131 147 153 139 197 146 163 182 186 179 198 155 129 145 139 123 149
116 142 154 114 119 162 124 126 135 151 128 214 115 82 91 121 148 171 147 168
178 160 175 204
HED-B06A 86
226 183 141 212 238 167 279 282 208 314 294 207 200 214 251 234 221 231 362 253
196 220 225 197 224 153 174 177 214 207 223 193 115 134 155 135 142 180 151 133
162 185 169 172 150 107 120 128 125 107 119 148 136 89 91 116 141 123 108 179
181 209 296 195 253 190 203 379 193 182 150 138 174 259 185 199 221 182 138 167
136 213 319 227 196 282
HED-B06B 86
202 180 144 214 232 172 283 269 204 323 288 200 206 202 249 236 218 247 369 246
195 204 245 186 233 140 197 176 227 195 220 201 114 138 150 124 148 184 142 123
170 178 167 161 145 117 139 132 110 111 120 142 128 106 91 108 141 126 122 170
182 201 298 206 250 190 203 370 187 186 174 151 201 250 192 195 223 179 134 136
154 217 327 238 196 279
HED-B07A 113
590 409 600 718 591 639 618 451 509 426 672 654 526 340 228 275 348 291 313 296
298 396 339 315 453 190 173 287 293 279 283 234 252 311 261 221 221 250 248 229
150 126 141 127 229 178 150 185 145 156 142 126 182 202 223 251 223 126 101 147
161 153 112 123 145 174 148 169 148 107 74 88 102 89 107 117 94 92 223 165
211 160 155 130 126 135 145 207 168 187 222 137 84 72 100 81 94 127 139 107
115 86 143 199 220 259 221 211 177 189 249 309 276
HED-B07B 113
584 413 633 713 505 535 541 532 634 453 627 602 458 363 232 252 329 285 301 318
284 385 334 326 454 190 177 293 298 272 283 233 267 307 262 221 238 242 251 222
150 128 143 135 235 156 155 198 146 162 155 138 167 206 218 254 213 134 91 140
148 163 104 100 144 156 167 166 147 102 79 93 100 92 101 127 90 94 207 178
202 173 140 139 123 136 147 200 113 194 225 134 83 65 102 87 97 129 136 109
117 95 139 208 217 272 246 204 231 143 246 307 288
HED-B08A 93
181 196 177 101 174 315 120 317 265 208 267 214 157 111 98 195 203 138 115 194
133 147 161 170 213 187 103 156 135 182 112 160 114 119 108 171 160 155 225 136
124 148 110 151 137 136 102 112 117 106 125 89 148 131 107 149 153 169 93 113
83 93 110 105 79 102 127 116 180 142 145 129 108 120 137 130 144 137 113 85
84 93 77 161 98 111 99 104 75 122 75 70 73
HED-B08B 93
184 196 184 101 162 320 122 311 273 214 281 222 163 118 98 187 207 126 116 200
131 149 167 171 212 190 114 163 133 183 108 158 117 102 127 187 164 145 231 125
130 140 118 154 123 142 94 111 127 104 126 92 131 144 110 147 152 171 95 112
88 101 114 112 83 92 127 108 185 131 150 118 110 110 151 138 129 161 94 91
85 112 79 157 99 118 96 100 83 93 102 63 82
HED-B09A 113
253 172 238 230 318 439 277 316 299 270 202 197 219 278 238 216 210 220 182 204
171 192 201 163 245 212 231 198 220 197 238 198 188 149 191 210 196 190 179 135
160 128 106 128 211 96 172 150 109 135 153 151 101 102 163 157 156 139 204 120
95 127 108 119 161 141 109 103 130 128 112 100 65 94 109 118 128 151 113 102
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100 123 117 76 81 103 92 100 85 82 83 70 99

HED-B09B 113
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93 133 105 90 77 112 90 107 91 76 94 70 98
HED-B10A 98
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232 121 86 156 93 136 79 105 149 144 141 157 153 110 74 59 61 92 86 140
92 77 113 114 103 92 60 68 45 52 60 55 59 63 83 44 36 71 80 52
80 147 149 258 101 91 147 264 224 188 234 199 135 125 190 229 203 266
HED-B10B 98
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278 210 146 187 116 164 198 110 292 215 285 213 213 135 115 62 142 248 250 165
222 132 95 160 107 138 81 126 131 154 151 156 155 114 82 64 54 106 81 138
87 79 120 106 109 92 62 60 47 51 61 64 55 62 76 46 40 67 79 58
82 144 146 260 101 97 141 269 220 187 219 204 145 112 193 231 203 288
HED-B11A 82
399 439 405 462 370 413 361 299 363 263 343 300 318 290 225 327 213 365 271 225
276 253 216 211 182 230 225 174 177 183 151 141 129 111 130 157 167 197 151 180
184 188 223 151 225 192 235 210 214 197 201 254 157 257 225 163 138 160 203 204
191 112 158 177 113 174 178 198 197 167 135 166 227 156 102 150 166 154 211 167
189 175
HED-B11B 82
428 423 407 457 350 423 361 286 376 257 345 301 323 284 228 313 237 388 235 211
286 246 227 224 181 255 210 151 181 179 157 136 137 116 132 144 168 191 145 191
166 186 225 154 248 204 251 202 204 184 195 254 156 240 201 169 131 153 184 229
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185 203
HED-B12A 68
560 755 476 610 357 310 723 594 466 376 274 600 381 507 446 576 375 407 421 358
217 241 170 151 125 186 139 125 133 131 112 160 136 123 138 116 113 130 103 76
87 98 151 158 180 218 272 169 303 262 222 239 234 281 206 265 231 239 253 198
139 107 147 150 206 144 142 122
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565 722 472 604 367 317 699 576 479 368 279 543 351 509 453 572 377 406 410 360
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HED-B14B 93
378 507 360 493 409 429 361 511 453 579 445 438 463 376 389 268 308 255 149 126
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70 48 48 80 96 95 72 74 73 77 95 118 134
HED-B15A 113
455 331 251 270 289 312 303 261 249 187 250 317 274 364 334 342 260 196 239 302
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217 135 241 187 172 183 165 219 159 242 140 117 155 116 209 162 189 186 217 160
182 149 140 214 187 174 170 149 129 133 178 128 202 154 127 151 190 236 172 185
155 165 247 144 123 143 178 158 256 156 182 170 105 163 188 180 170 160 115 90
105 122 105 181 127 149 102 136 94 94 76 78 82
HED-B15B 113
459 326 244 280 286 311 301 258 252 189 272 331 258 340 345 346 261 189 233 302
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153 170 247 138 129 146 177 157 256 159 130 133 102 153 215 187 166 156 113 92
112 131 96 182 128 126 131 137 87 96 76 81 87
HED-B16A 94
322 330 363 230 168 210 236 142 265 270 257 237 264 237 240 240 265 219 207 204
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160 150 106 139 113 103 106 102 78 143 98 94 71 82 89 133 105 116 56 85
87 87 74 105 119 90 97 120 111 121 144 144 104 157
HED-B16B 94
292 336 354 232 174 205 228 184 272 263 230 268 262 273 217 218 254 193 190 203
236 163 142 178 228 188 205 140 193 196 196 205 214 192 167 192 158 234 215 162
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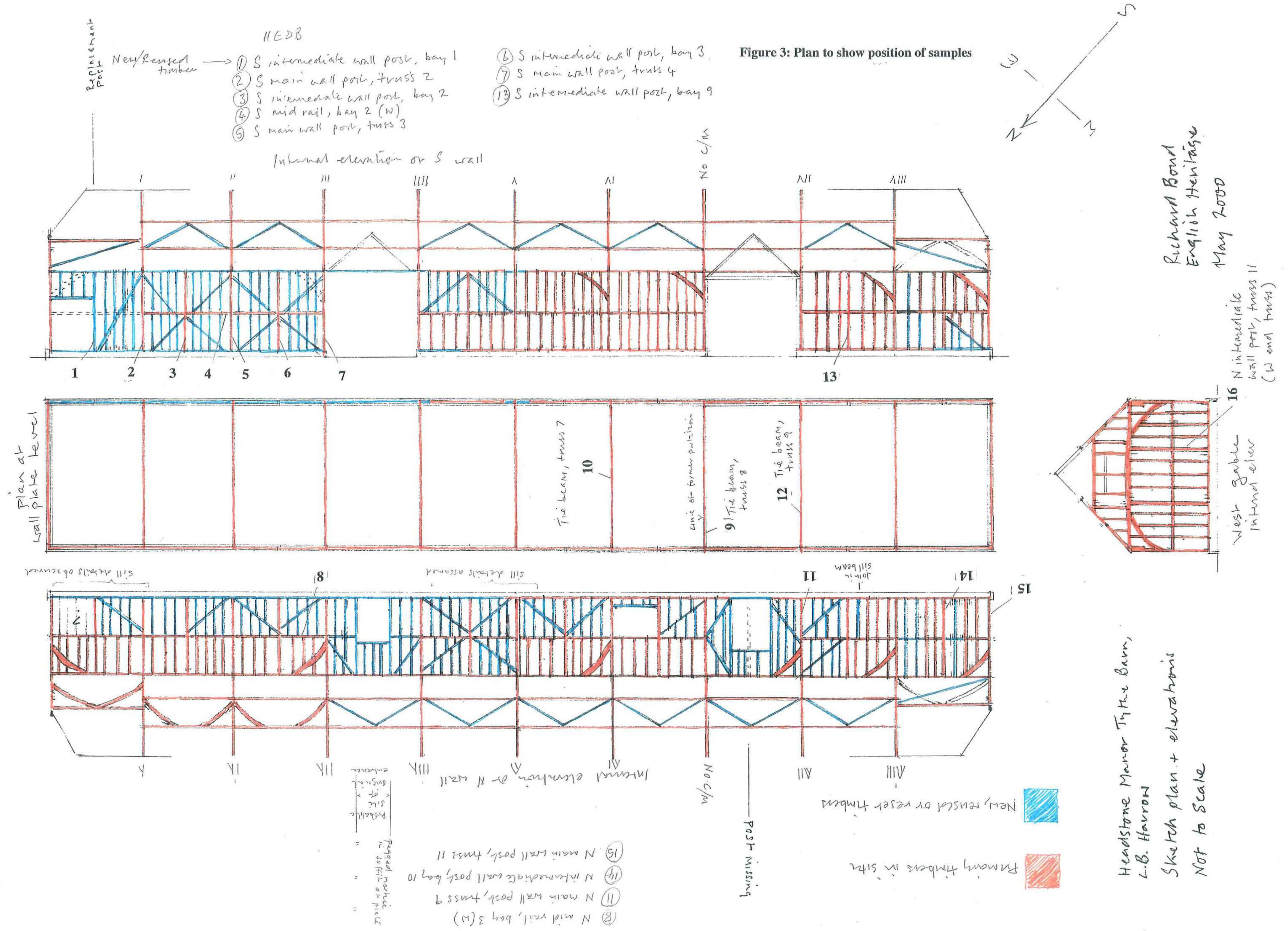

Figure 3: Plan to show position of samples

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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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. 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 we inspect the timbers in a building 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. Similarly the core has just over 100 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.

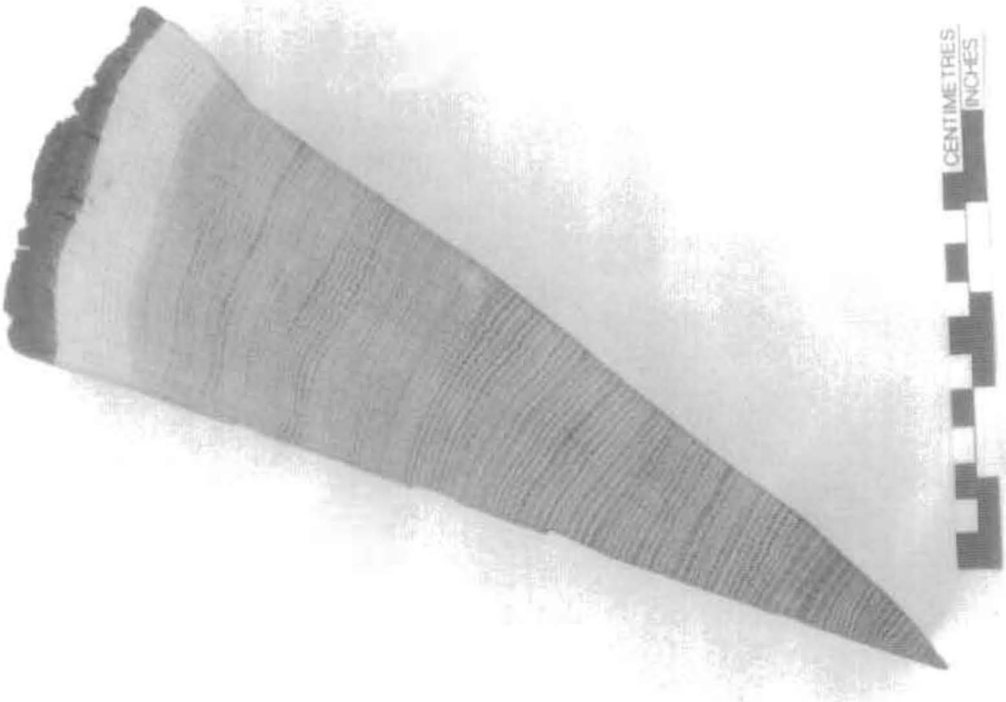

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

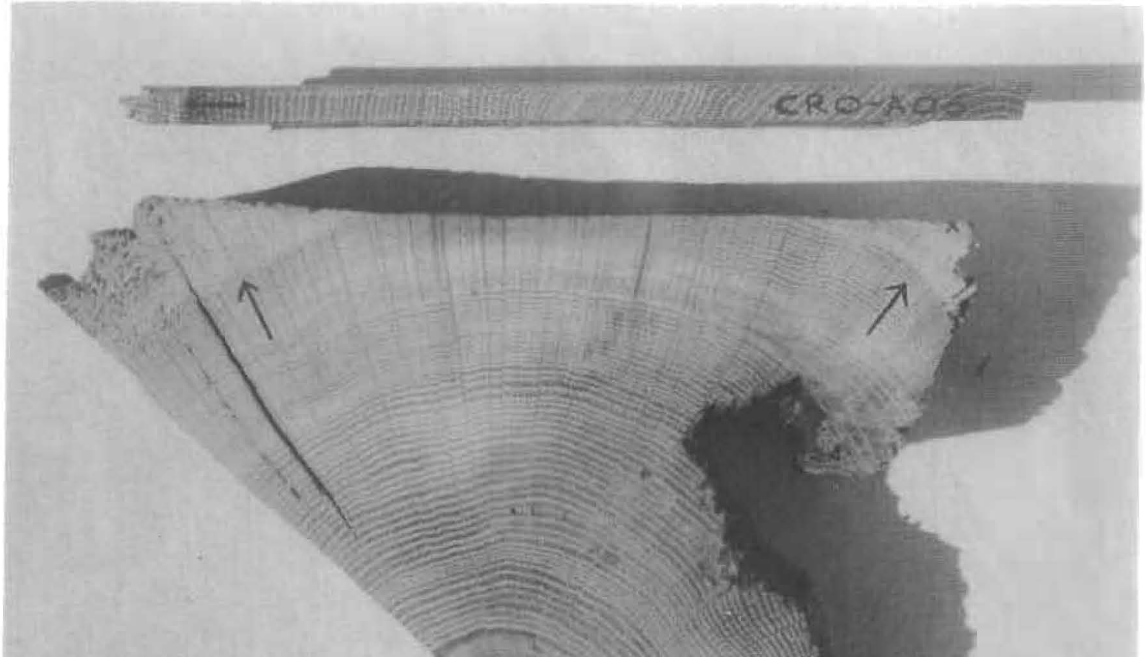

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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 measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

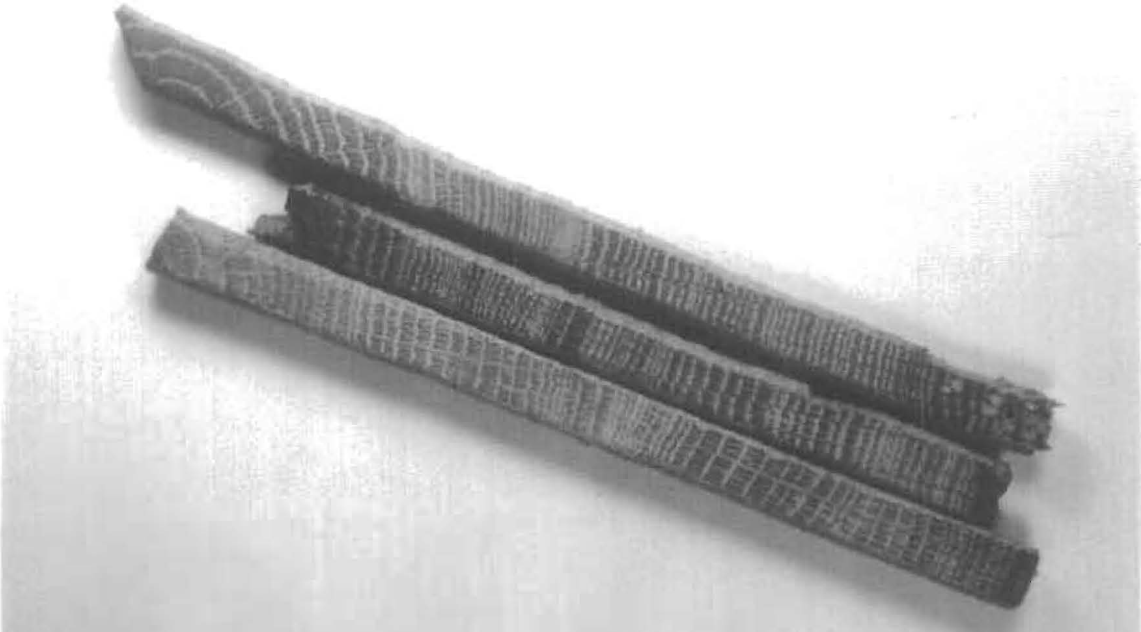

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 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 inspecton 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 is insured with the CBA.

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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, 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 between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the 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 from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

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. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

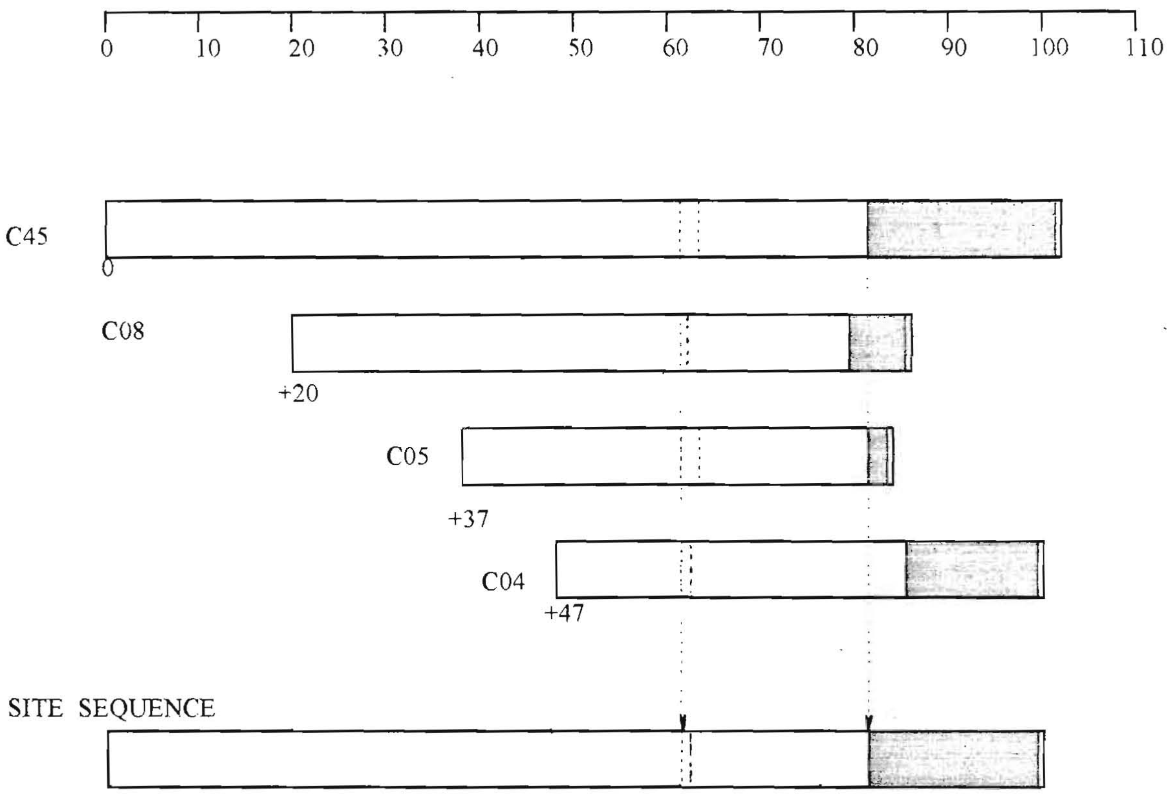

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ,* and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 1988b, 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* 1988a). 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 (1988b) 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 (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

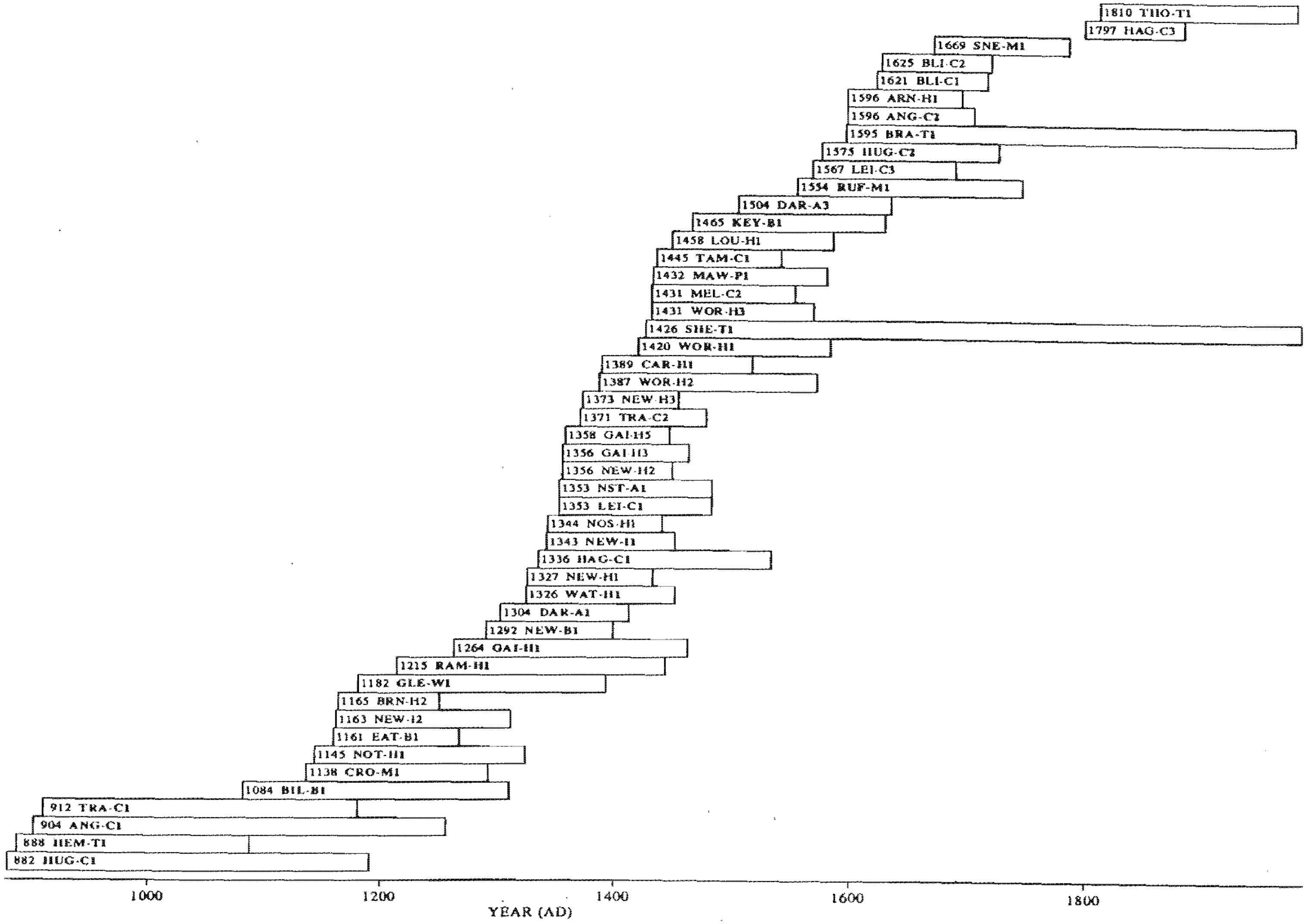

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

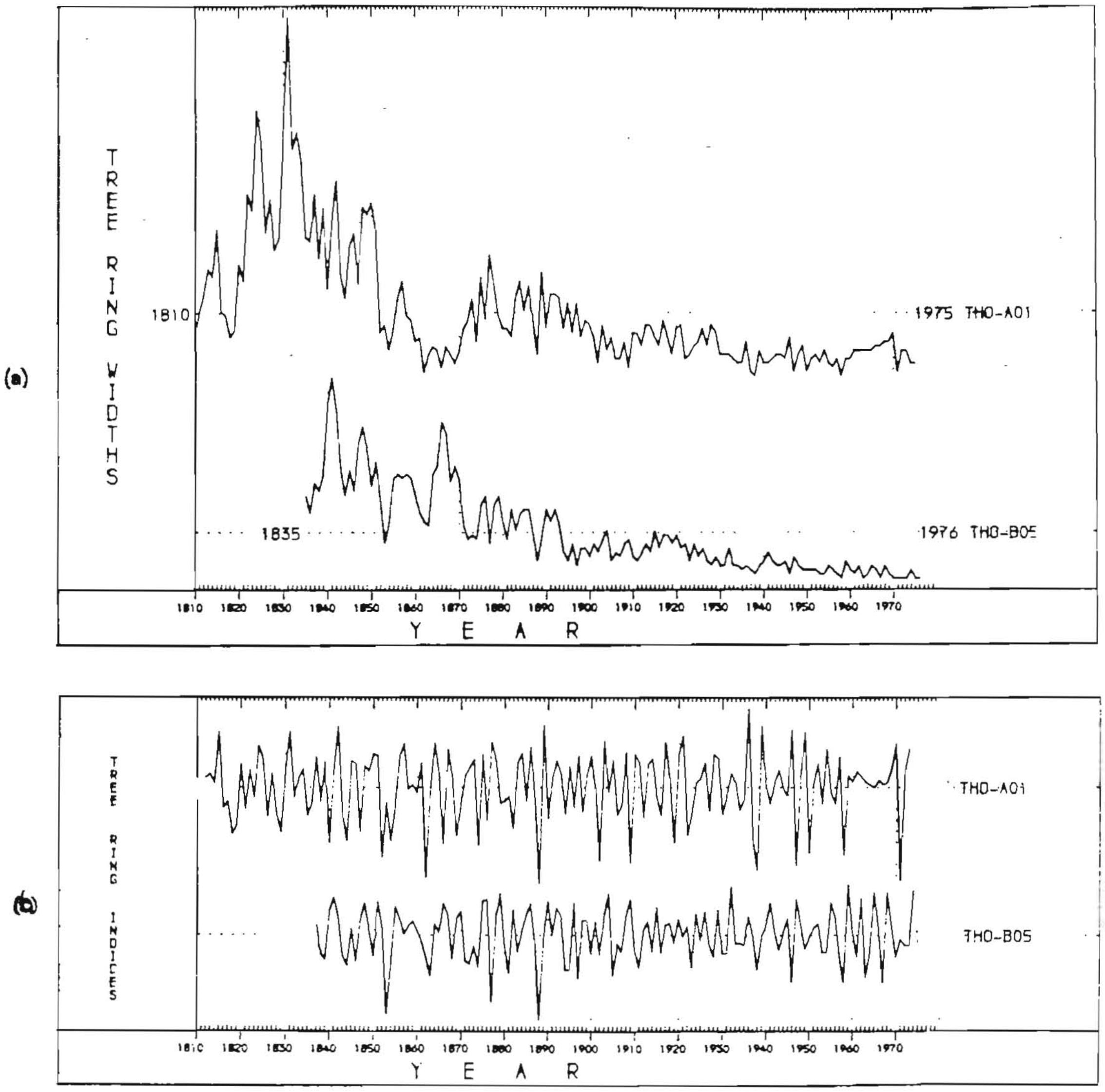

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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