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TREE-RING ANALYSIS OF TIMBERS FROM THE MALTINGS, SEYMOUR HOUSE HOTEL, CHIPPING CAMPDEN, GLOUCESTERSHIRE

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Summary

Dendrochronological analysis was undertaken of samples from twelve oak timbers within The Maltings at the rear of the Seymour House Hotel in Chipping Campden. This resulted in the production of three site chronologies of two samples each, with 61, 54, and 68 rings, respectively. Although these were compared with a wide range of reference chronologies there was no satisfactory cross-matching. None of the single samples cross-matched with the reference chronologies and the timbers from this site must, therefore, remain undated for the moment.

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Introduction

The Maltings at Chipping Campden (SP 149389, see Figs 1 and 2) form a rear extension to the Seymour House Hotel, itself a rather fine building of Cotswold stone which faces on to the broad high street. This rear extension is a two-storey building of coursed and dressed rubble with a Cotswold stone roof. As a maltings, it is a rare survival of its type. There are very few architectural features by which to date it except for the form of the trusses, which strongly suggest it is of mid-eighteenth century date. With recent work for conversion to conference facilities came the need for more accurate dating to inform the process of repair.

Within the building, the roof consists of four bays formed by three principal-rafter trusses. These have tiebeams and collars, and support double purlins. The purlins support rather small, two-by-four inch common rafters. These run up from a wall-plate to a ridge beam. At one end of the roof the purlins run into a stone gable wall that does not have a timber truss. At the other end the roof runs into the rear of the Hotel. Between, and on either side of the tiebeams of the principal trusses, are other intermediate lateral beams which, with the tiebeams, act as joists for an attic floor. Below this are another series of lateral beams which act as joists for a first-floor level.

It was noted at the time of sampling that many of the timbers of this building are of elm. These included the principal rafters and collars of two of the trusses and those parts of the purlins which remain. The ridge beam, most of the common rafters, and the intermediate floor joists, are of oak. The timbers of the third truss are also of oak, but these were rather small and so badly decayed that they would not provide usable samples. It was apparent also that these timbers had very wide rings. For these reasons the timbers of truss 3 were not sampled.

Sampling and tree-ring analysis were commissioned by English Heritage to establish the date of the roof timbers and the attic and first-floor joists.

Sample analysis and dating

Cored samples were obtained from twelve different oak timbers from this site. Each sample was given the code CHC-A (for Chipping Camden, site "A") and numbered 01 - 12. Seven core samples, CHC-A01 - 07, were obtained from the intermediate floor joists at attic and first-floor levels. Five core samples, CHC-A08 - 12, were obtained from common rafters which had been removed from the roof and labelled. The positions of all the cores taken were recorded at the time of sampling and are shown on Figure 3, with details of the samples being given in Table 1. The trusses and other timbers are numbered from west to east, or from the rear of the building towards the front, following those given on drawings provided by Reg Ellis, Architects and Planners of Chipping Campden.

All twelve samples were prepared by sanding and polishing. At this initial stage one sample, CHC-A12, was seen to have less than 50 rings and was rejected as having too few rings for satisfactory analysis. The growth-ring width sequences of the remaining eleven samples were measured and compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

At a value of t=5.0 three groups of samples formed. The two samples of the first group, CHC-A09 and A11, cross-match at the relative off-set positions shown in the bar diagram Figure 4. At these off-sets the relative positions of the heartwood/sapwood boundaries are consistent with a group of timbers having a single felling date. Because of this and the satisfactory cross-matching of the samples, the ring widths from these two were combined at these relative offset positions to form CHCASQ01, a site chronology of 61 rings. Site chronology CHCASQ01 was compared with a wide range of relevant reference chronologies for oak, but there was no satisfactory cross-matching at any position.

Figure 1: Map to show general area of Chipping Campden

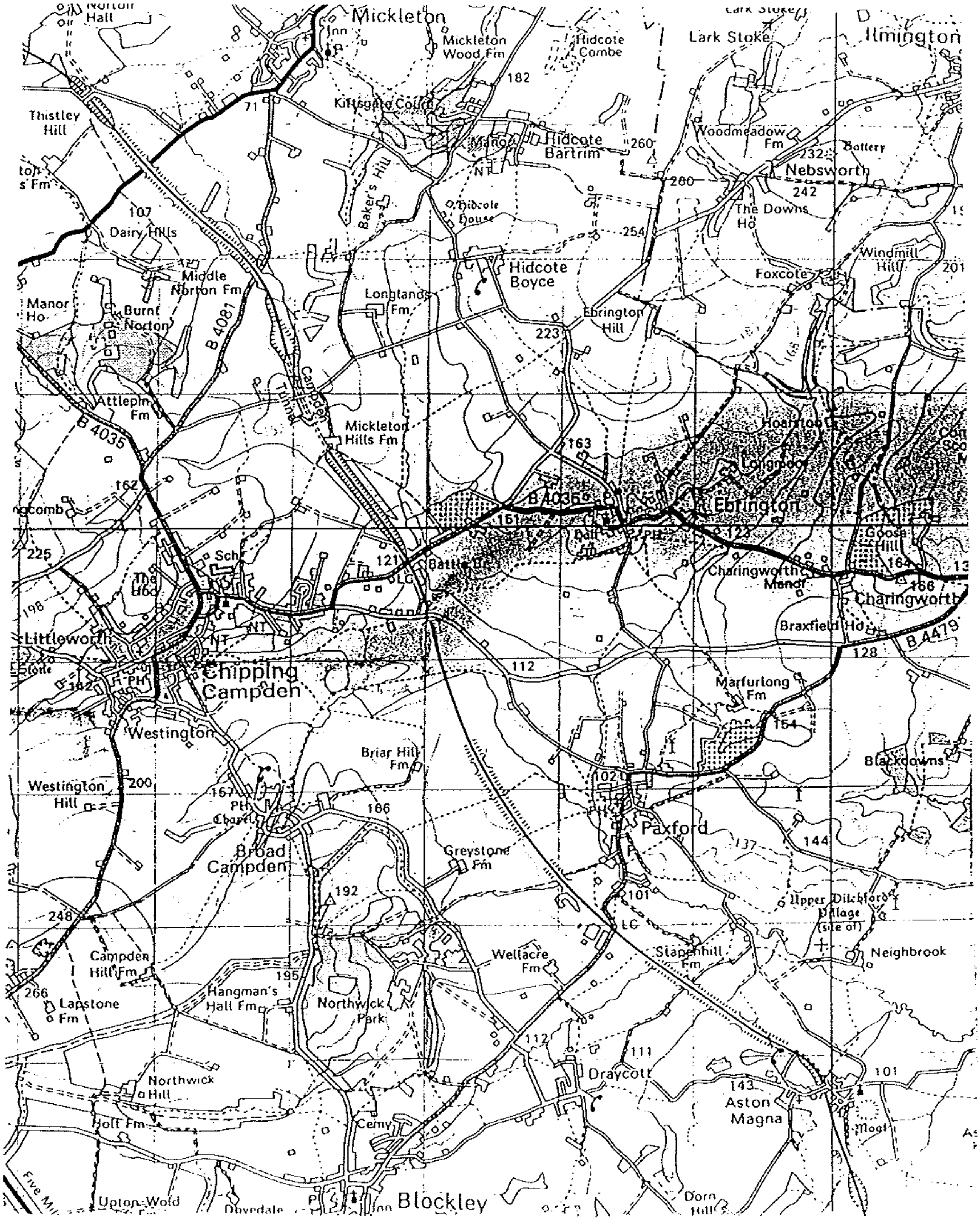
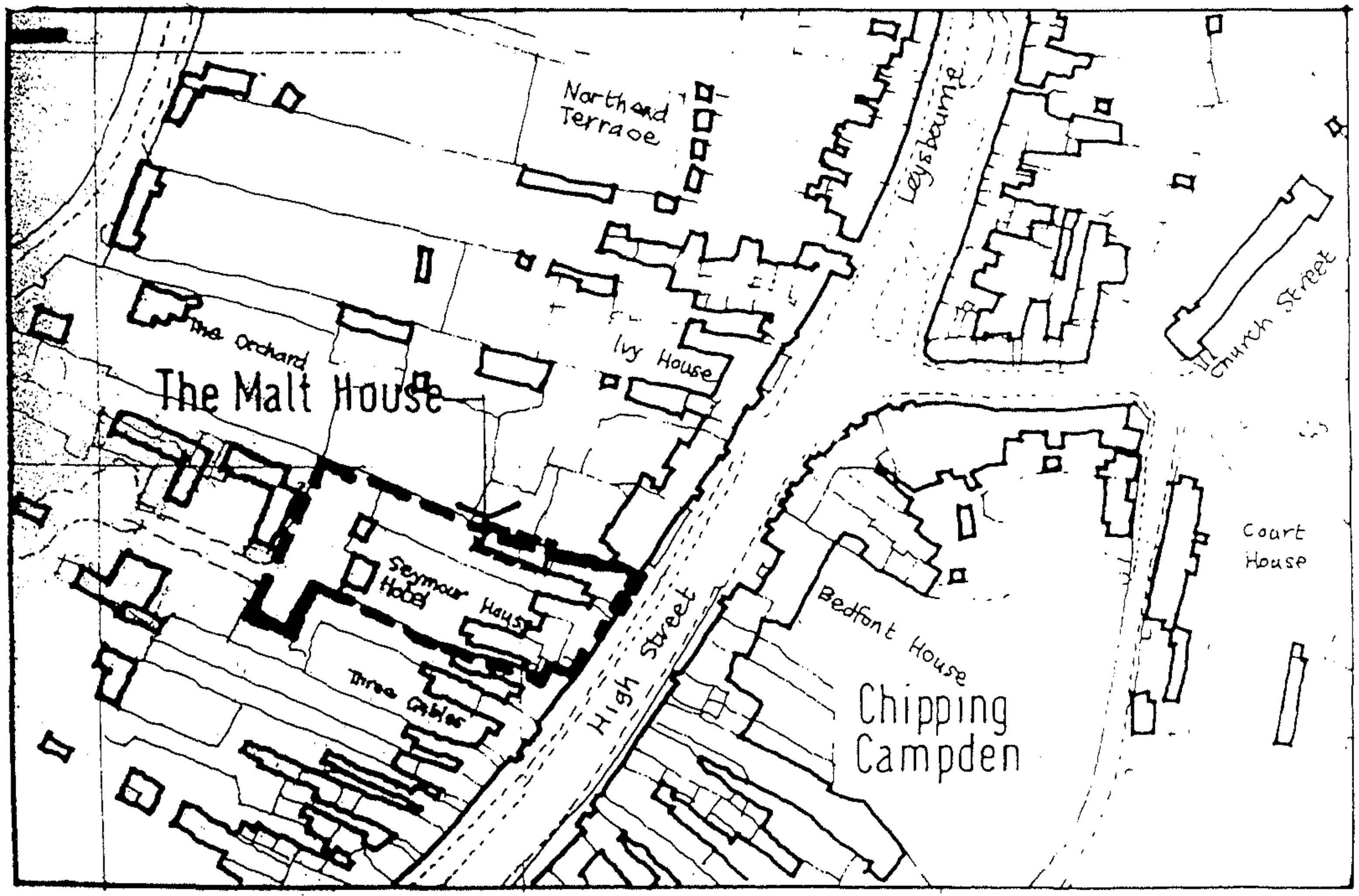


Figure 2: Part map of Chipping Campden to show location of The Maltings



The two samples of the second group, CHC-A01 and A03, cross-match at the relative off-set positions shown in the bar diagram Figure 5. At these off-sets the relative positions of the heartwood/sapwood boundaries are consistent with a group of timbers having a single felling date. Given the high t-value cross-match between these two samples it is possible that the timbers they represent are from the same tree. The ring widths from these two samples were combined at these relative offset positions to form CHCASQ02, a site chronology of 54 rings. Site chronology CHCASQ02 was also compared with a wide range of relevant reference chronologies for oak, but again there was no satisfactory cross-matching.

The two samples of the third and final group, CHC-A05 and A07, cross-match at relative off-set positions as shown in the bar diagram Figure 6. At these off-sets the relative positions of the heartwood/sapwood boundaries are consistent with a group of timbers having a single felling date. Because of this and the satisfactory cross-matching of the samples, the ring widths from these two were combined at these relative offset positions to form CHCASQ03, a site chronology of 68 rings. Site chronology CHCASQ03 was compared with a wide range of relevant reference chronologies for oak, but there was no satisfactory cross-matching.

The three site chronologies thus formed were compared with each other but there was no satisfactory cross-matching. Each site chronology was then compared with all the other samples. A cross-match was found between site chronology CHCASQ03 and sample CHC-A06 but as the sample has only 50 rings it was not combined to make a new site chronology. Each of the five remaining ungrouped samples was then compared individually with the reference chronologies, but again without success.

Conclusion

It has not been possible to date any of the site chronologies nor any of the individual samples from this site. It is possible that this is in part due to the shortness of the samples, the shortest having 50 rings, the longest only 68 rings. However, it is also probably due in large measure to the lack of relevant reference material for this area at the date expected on the basis of stylistic evidence; there are relatively few chronologies from Gloucestershire later than the sixteenth century. None of the samples show any narrow or distorted rings which might make cross-matching difficult. There is indeed more of a tendency to complacency, the growth-rings being quite wide and having little variation.

Figure 3: Diagram to show sample locations

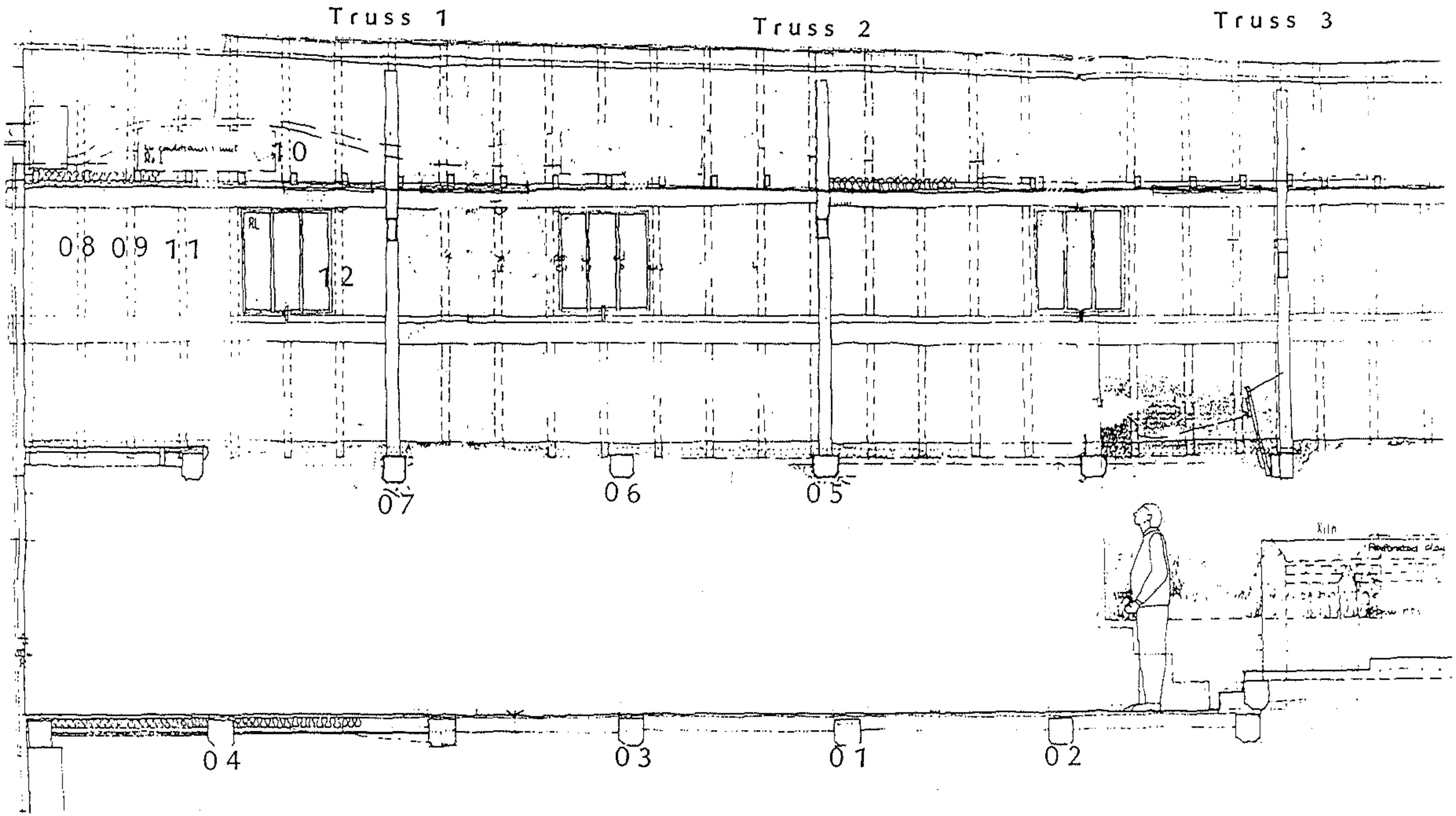


Figure 4: Bar diagram of samples in site chronology CHCASQ01

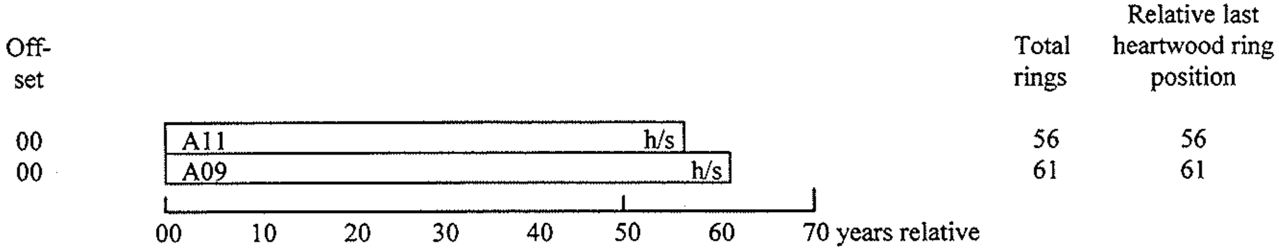


Figure 5: Bar diagram of samples in site chronology CHCASQ02

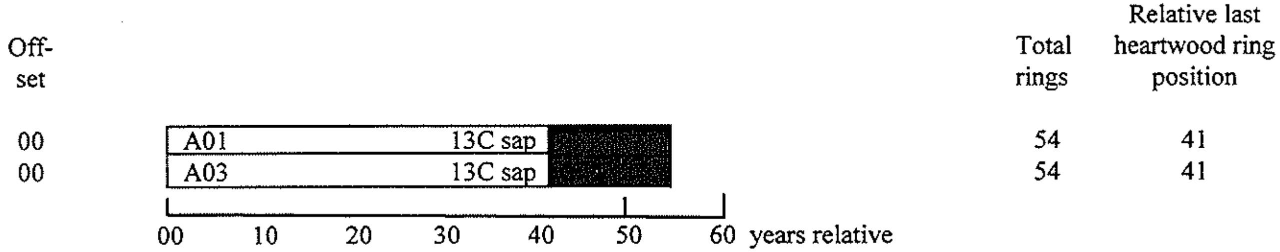
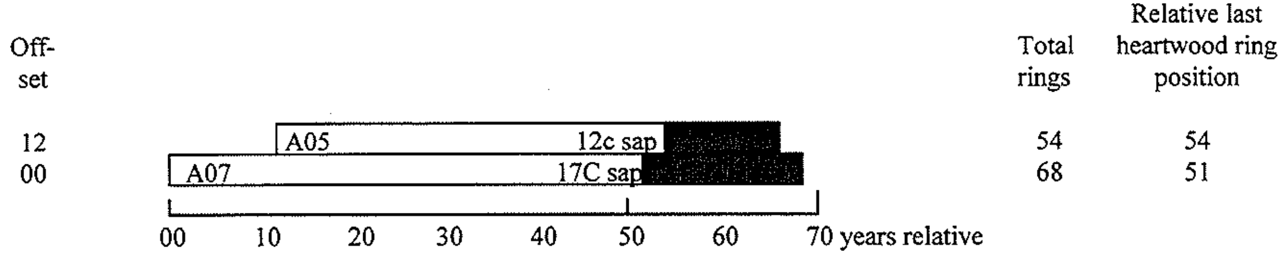


Figure 6: Bar diagram of samples in site chronology CHCASQ03



White bar = heartwood rings, shaded area = sapwood rings
C = complete sapwood retained on sample
c = complete sapwood on timber, all or part lost in sampling
h/s = the heartwood/sapwood boundary is the last ring on sample

Data of eleven measured samples - measurements in 0.01mm units

CHC-A01A 54
254 292 220 167 196 230 239 287 335 181 207 197 235 213 190 190 233 247 260 226
209 188 208 181 92 68 109 157 244 269 331 328 254 204 206 269 232 251 179 222
301 230 248 240 240 122 189 197 241 144 130 140 212 163
Chc-A01B 54
211 285 197 164 182 239 237 223 326 201 186 202 243 211 210 203 248 267 254 224
210 198 207 186 96 70 98 160 248 262 355 313 253 205 208 270 216 251 182 223
298 229 224 270 210 111 217 183 254 161 110 141 214 164
CHC-A02A 59
100 236 412 340 397 284 281 359 370 189 347 306 355 362 331 387 329 345 188 324
328 256 339 312 342 344 377 459 357 223 253 263 284 396 344 192 186 197 327 246
307 311 229 261 219 191 225 196 209 131 223 174 175 209 244 196 236 166 209
CHC-A02B 59
106 366 396 342 405 296 324 322 372 219 357 322 351 354 333 384 320 331 195 341
334 254 335 315 339 356 376 456 368 220 246 278 274 392 341 198 188 188 335 240
308 310 217 250 230 193 224 199 214 137 214 163 185 211 235 194 245 153 202
CHC-A03A 54
209 295 191 159 196 236 234 299 289 197 186 154 202 209 204 213 221 228 202 202
212 219 203 218 117 82 101 196 276 251 331 300 300 235 257 324 279 269 255 248
276 256 234 252 272 174 229 176 238 164 116 145 212 185
CHC-A03B 54
232 291 198 163 188 245 241 292 277 193 204 162 201 216 212 212 222 198 208 205
183 207 195 214 118 84 90 196 288 252 332 307 275 241 246 329 268 272 255 264
281 247 244 251 259 151 196 180 220 148 113 136 201 178
CHC-A04A 66
284 373 464 514 475 206 318 313 386 328 361 338 489 354 370 391 171 129 113 133
140 116 243 361 253 290 373 353 320 270 166 161 221 363 291 280 373 353 283 209
240 268 240 214 219 214 213 223 235 239 257 284 262 192 237 254 217 257 246 159
189 158 214 230 192 237
CHC-A04B 66
289 376 483 476 465 201 339 309 353 358 369 333 501 354 363 396 161 131 109 142
120 108 251 368 254 302 385 345 308 284 174 162 217 362 289 276 387 362 284 216
226 266 239 222 218 208 210 223 234 230 264 282 271 173 246 249 204 272 236 167
169 163 223 230 196 237
CHC-A05A 54
109 132 306 460 334 243 260 207 266 224 257 279 326 386 392 484 420 357 330 375
575 461 469 264 107 77 83 144 192 209 195 356 86 63 90 147 112 252 235 241
229 264 311 416 147 72 74 141 205 307 204 205 264 339
CHC-A05B 54
119 144 308 463 343 238 264 206 262 231 249 285 319 391 387 492 417 360 322 377
577 454 480 267 94 78 92 138 200 208 213 355 94 65 88 147 114 250 237 240
216 263 313 416 147 75 76 149 183 318 205 211 255 317
CHC-A06A 50
140 270 217 160 136 157 173 206 254 265 365 261 347 396 327 404 344 438 354 329
235 332 336 519 477 359 451 154 90 92 114 78 137 145 120 139 198 206 269 131
86 93 200 279 380 225 410 295 234 168
CHC-A06B 50
151 274 160 162 139 154 169 208 269 265 365 252 364 389 357 380 347 424 356 321
237 327 325 515 489 378 450 151 93 87 108 77 139 134 118 138 195 196 258 123
86 97 225 280 368 238 389 283 236 179
CHC-A07A 68
194 298 489 342 320 300 359 361 376 287 300 246 332 261 297 329 313 262 197 204
245 262 310 278 224 328 270 310 303 253 236 214 99 59 135 128 98 118 170 212
200 208 144 172 66 35 38 69 62 101 105 112 132 112 137 161 70 62 45 59
61 73 65 111 109 90 72 64

CHC-A07B 68
171 290 463 345 331 308 366 367 375 286 314 255 325 272 298 350 306 257 207 195
247 255 314 284 219 318 278 318 289 256 231 224 90 57 146 111 110 117 177 197
206 206 144 169 65 37 37 72 64 94 108 100 137 118 140 152 64 53 56 61
66 82 70 100 105 91 80 82
CHC-A08A 68
120 234 186 159 154 145 170 101 76 89 86 70 56 58 76 81 83 121 88 100
68 115 119 107 120 171 132 177 161 186 116 184 186 162 238 141 224 63 96 70
53 52 70 65 62 64 64 68 89 79 72 79 88 60 55 72 58 114 82 62
59 63 62 103 59 92 95 115
CHC-A08B 68
139 238 180 164 149 144 168 101 68 94 84 74 48 55 81 85 84 113 93 96
75 110 115 112 117 168 136 176 165 184 122 182 172 164 224 158 228 73 92 72
53 41 79 68 63 66 57 75 81 75 75 83 91 61 54 68 56 114 91 55
63 65 72 89 65 93 96 119
CHC-A09A 56
212 314 335 216 175 87 90 91 154 212 204 315 183 159 156 187 172 149 166 258
179 210 164 177 124 98 105 80 48 74 111 115 67 89 72 74 88 84 69 61
68 61 69 112 109 93 89 95 103 118 160 134 124 130 97 163
CHC-A09B 61
183 307 340 224 177 84 110 100 150 186 193 322 168 173 177 192 174 147 160 244
177 201 174 177 127 97 110 70 48 75 93 107 73 82 83 72 79 91 75 66
62 60 72 106 126 83 94 99 113 111 151 129 117 137 100 170 67 79 59 63
68
CHC-A10A 50
174 194 300 466 316 204 202 151 181 174 176 180 252 340 223 222 275 192 255 256
152 264 212 202 130 170 194 132 424 338 176 146 75 47 45 50 96 75 139 96
176 118 76 69 116 78 96 82 121 90
CHC-A10B 50
196 179 292 471 334 202 201 147 195 184 182 174 247 360 210 217 286 182 254 258
156 265 212 201 134 171 187 132 421 336 176 151 74 52 39 53 92 84 135 101
166 131 74 62 112 87 88 83 114 84
CHC-A11A 56
300 329 302 221 169 79 85 142 160 143 210 241 218 182 265 124 275 149 177 275
152 200 151 186 163 141 154 83 68 65 87 104 66 98 78 70 92 62 94 73
126 89 141 150 188 137 182 165 166 116 182 146 125 150 108 201
CHC-A11B 56
271 337 305 209 174 78 88 139 149 147 198 251 205 178 270 113 283 164 175 269
146 197 156 185 152 144 151 99 58 66 87 101 69 98 74 68 89 71 80 85
111 104 143 147 189 132 187 168 169 123 191 141 124 149 117 204

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.

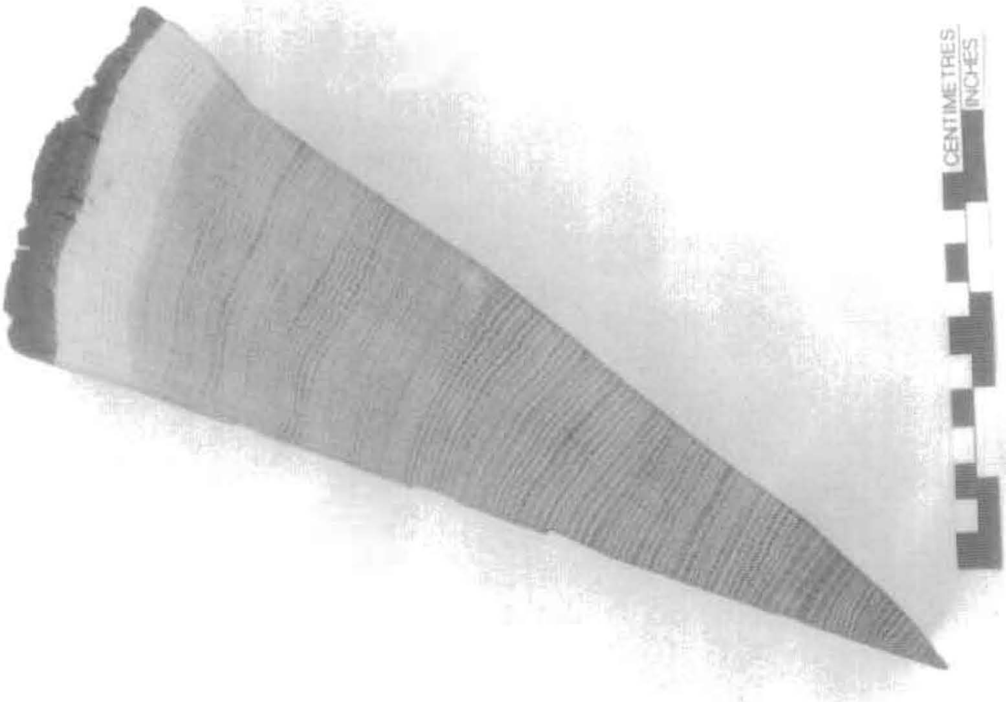


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

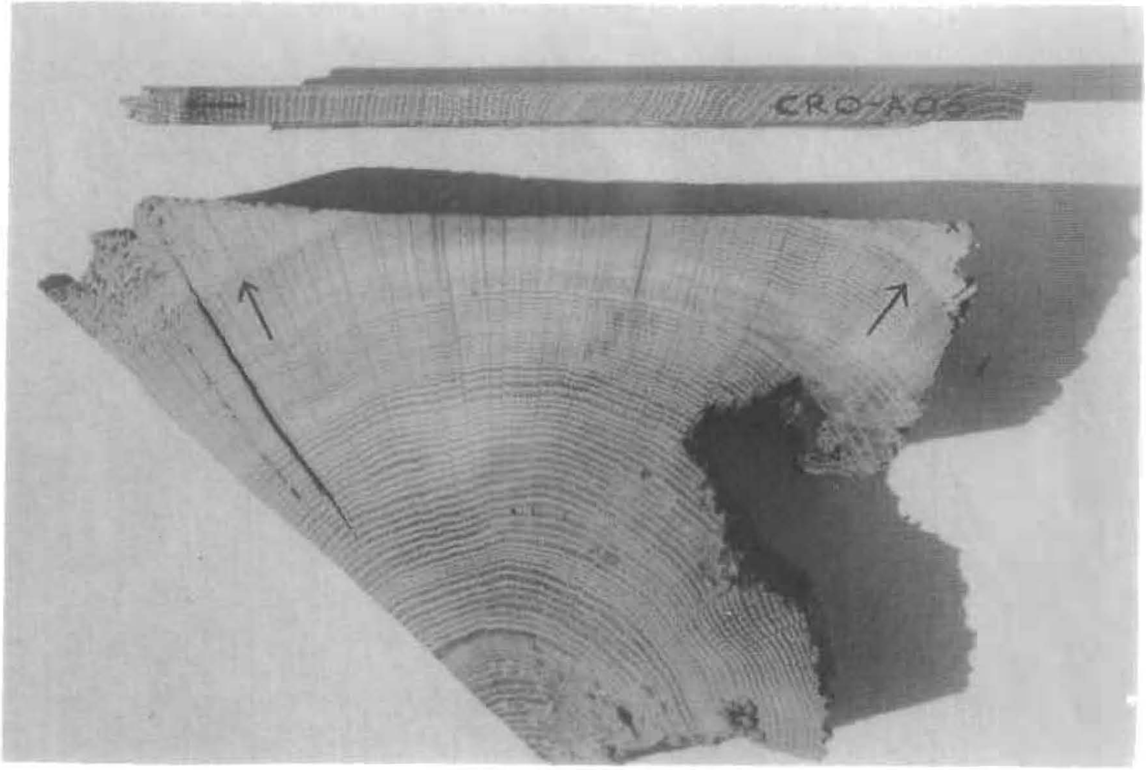


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood: again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

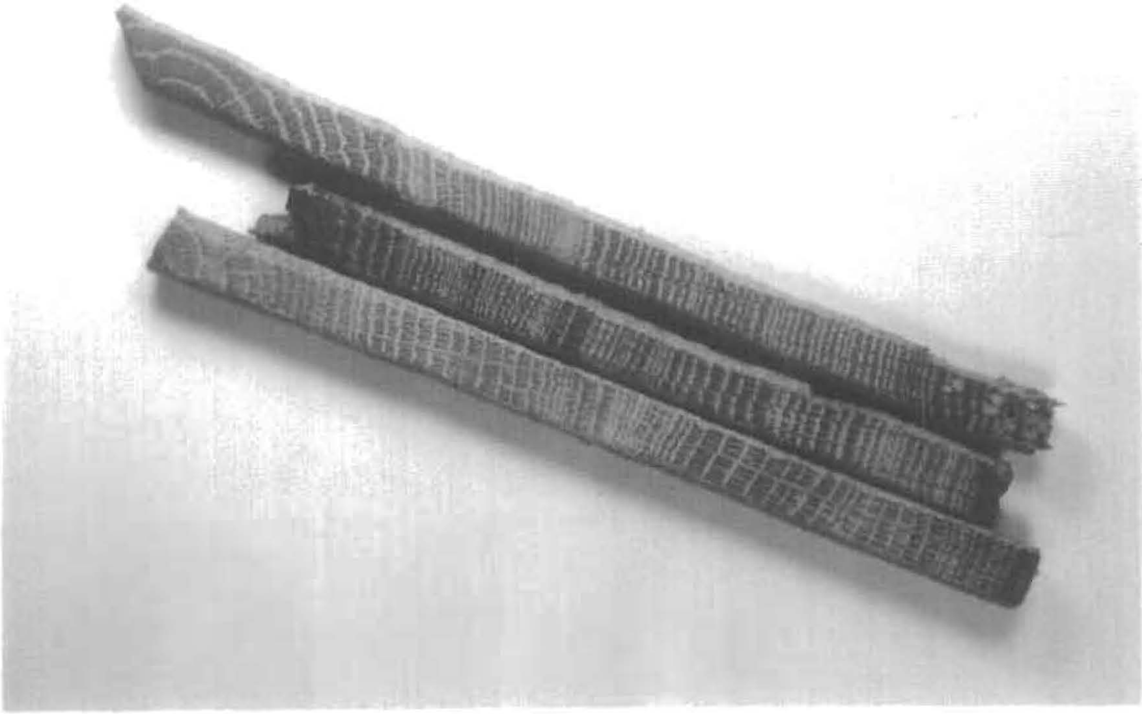


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

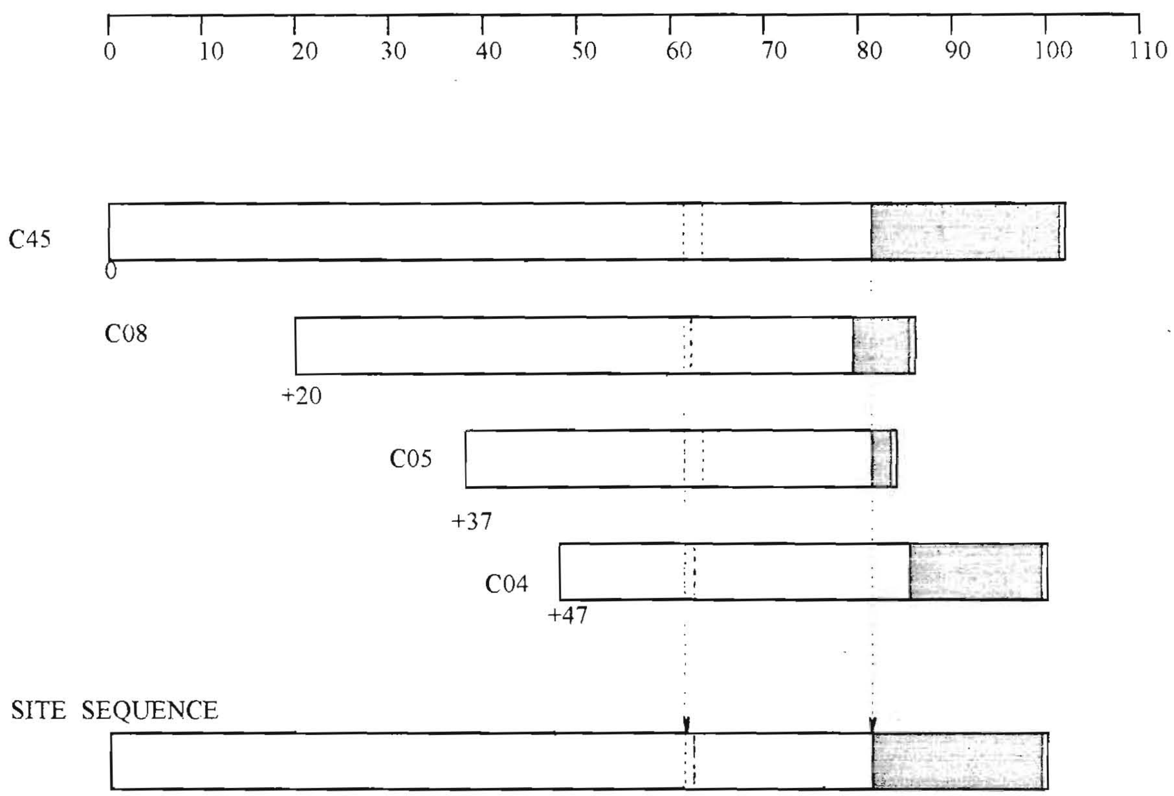


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

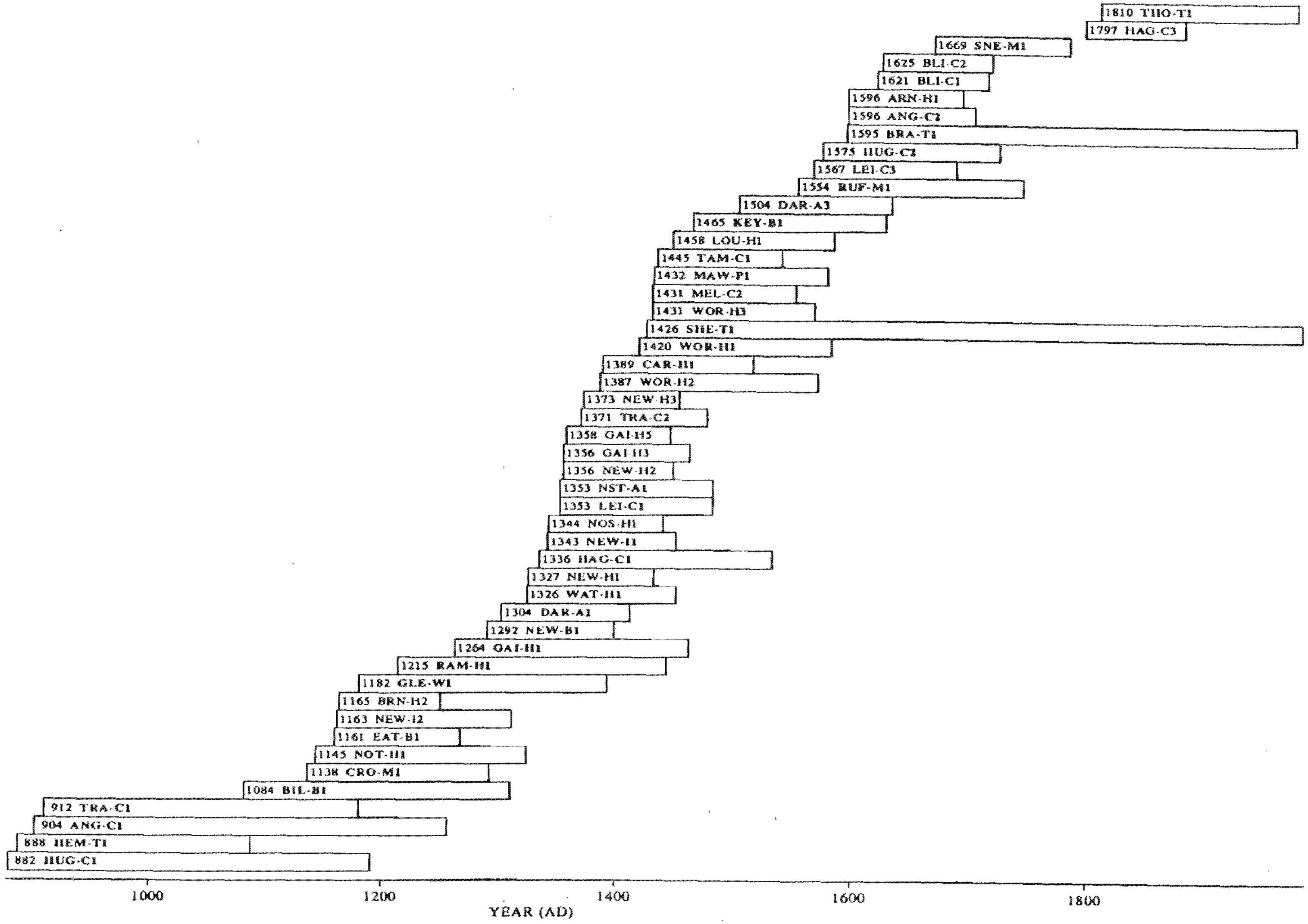


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

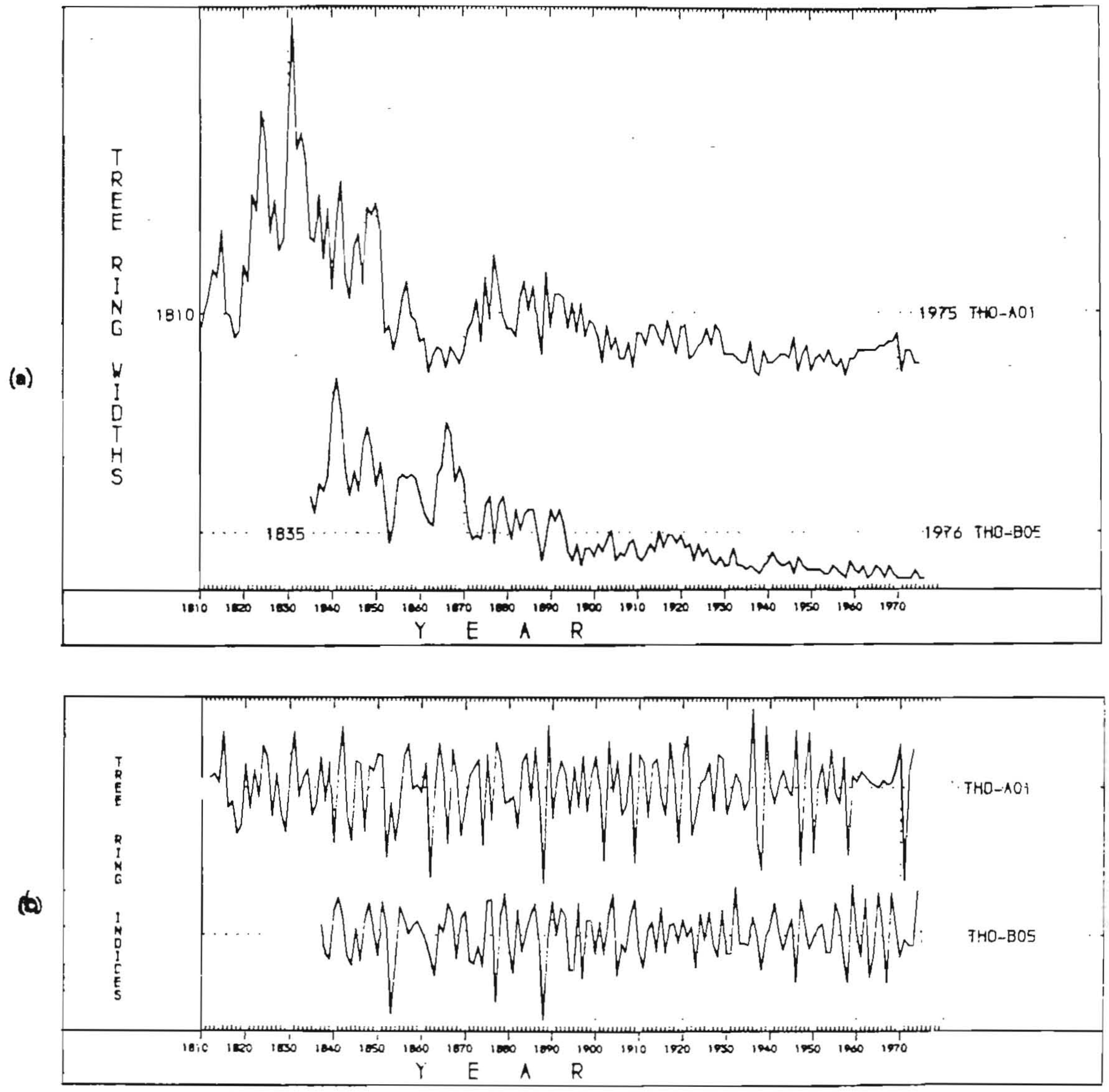


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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