Ancient Monuments Laboratory
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TREE-RING ANALYSIS OF TIMBERS FROM PLACE HOUSE, BLUECOAT YARD, WARE, HERTFORDSHIRE

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Summary

Dendrochronological analysis was undertaken of samples from eight oak timbers from Place House, Ware. A single site chronology of 75 rings, consisting of two samples, was produced spanning the period AD 1179 to AD 1253. One of the samples has a felling date in the range AD 1246 to AD 1271. The felling date of the other sample cannot be estimated because it has no sapwood. It has thus not been possible to produce any satisfactory dendrochronological interpretation of the building.

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Introduction

Place House, Ware (TL 351453, see Fig 1), is an aisled hall with a crown-post roof and is believed to date to the late-thirteenth or early-fourteenth centuries. Tree-ring analysis was commissioned by English Heritage to establish its construction date with greater reliability and to confirm its dating on architectural grounds.

The Laboratory is grateful to Adrian Gibson for providing the following description of the building. 'Place House comprises a two-and-a-half bayed aisled hall and service end cross-wing. Another cross-wing once existed at the 'high end'. Although considerably altered, the essential hall framing survives with arched bracing, a central fair-way braced crown-post, plus moulded tiebeams and cornices. Between the spere-posts a sixteenth-century parchemin decorated screen has been inserted.

The building, the manor house of Ware, has had some notable owners including Joan of Kent, Margaret Beaufort, Countess of Richmond, and Mary Tudor. In AD 1685 it was bought by Christ's Hospital when a floor was inserted into the hall and the south aisle raised to provide gabled lighting to the upper floor. Having first been privately bought with a view to preservation the building was extensively restored and brought back to its original form by the Hertfordshire Preservation Trust in 1977 for general use by the people of Ware'.

Sampling and analysis

A total of eight oak timbers was sampled by coring. Each sample was given the code WRE-B (Ware, site "B") and numbered 01 - 08. A detailed drawn survey of this building has not been undertaken and there were no drawings, plans or cross-sections of any sort available on which to record the sample positions. Recourse was therefore made to recording the sample locations on a sketch plan Figure 2, with a view to transferring these to a survey should one ever be carried out. The location of each sample is also given in Table 1.

All eight samples were prepared and measured, and those with more than fifty-four rings (the number considered minimum for reliable analysis) were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). There was, however, no grouping by this process. Each sample was therefore compared separately with the reference chronologies. This indicated a cross-match for two samples, WRE-B04 with a first ring date of AD 1185, and WRE-B08 with a first ring date of AD 1179. The t-values of these cross-matches are shown in Tables 2 and 3 respectively.

These two dates give a relative offset between the two samples of 6 years, as shown in the bar diagram Figure 3. At this relative position the cross-match between the two samples has a t-value of 3.8. Although this t-value is lower than we would like, it does support the individual dating of the two samples. As is customary when samples date but do not cross-match well with each other, the two samples were combined at these relative positions to form WREBSQ02, a site chronology of 75 rings. This was done despite the relative positions of the heartwood/sapwood boundaries not being consistent with timbers having the same felling date. Site chronology WREBSQ02 was then compared to a full range of relevant reference chronologies. This indicated a cross-match when the date of its first ring is AD 1179 and the date of its last ring is AD 1253. Evidence for this dating is given in the t-values of Table 4.

Site chronology WREBSQ02 was then compared with the remaining ungrouped samples. There was, however, no satisfactory cross-matching. Each of the remaining samples with more than 54 rings was then compared separately with the full range of reference chronologies. Again there was no satisfactory cross-matching.

Conclusion

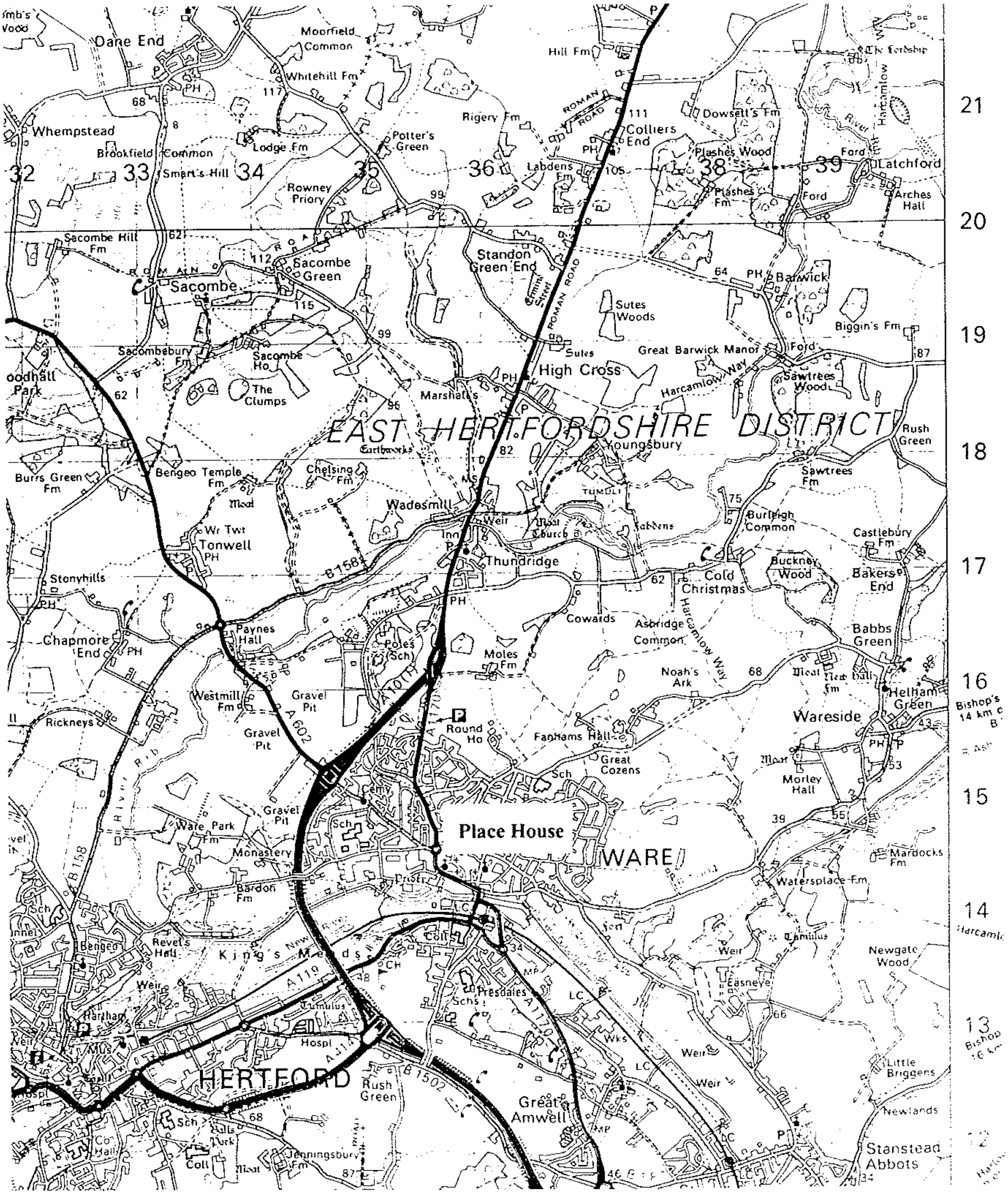
The analysis has dated only two samples with acceptable t-values. One sample, WRE-B04, has a last measured ring date of AD 1245, with twenty-four sapwood rings. Using 15 to 50 sapwood rings as the 95% confidence limits the timber represented is estimated to have a felling date in the range AD 1246 to AD 1271.

The other dated sample, WRE-B08, has a last ring date of AD 1253, but there is no evidence of sapwood on the sample, nor on the timber from which it was taken. It is thus not possible to estimate a felling date for this timber. It is quite possible that this timber has a completely different felling date to that represented by sample WRE-B04.

From the analysis it would appear that we are dealing with a building which has possibly undergone alterations, with some timbers being replaced. Many of the timbers now extant at the site therefore may have different felling dates. This lack of homogeneity makes the production of an acceptable site chronology and the dating of the site very difficult.

It will be seen from Table 1 that most of the samples have relatively few rings. Two samples have less than 50 rings, and only one has more than a hundred rings. Apart from this latter sample all show generally complacent growth rings which also makes cross-matching and dating difficult.

Figure 1: Map to show general location of Place House, Ware



(based upon the Ordnance Survey 1:50000 map with the permission of The Controller of Her

Table 1: Location of samples from Place House, Bluecoat Yard, Ware, Hertfordshire

	Sample Location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
WRE-B01	South post, truss 2 (central truss)	59	h/s	------	------	------
WRE-B02	North post, truss 2	66	none	------	------	------
WRE-B03	East arcade brace from north post, truss 3	30	none	------	------	------
WRE-B04	North brace to tiebeam from south post, truss 1 (spere truss)	61	24	AD 1185	1221	1245
WRE-B05	South aisle tie, truss 2	56	none	------	------	------
WRE-B06	South post, truss 1	110	07	------	------	------
WRE-B07	Spandrel strut from south post, truss 1	49	none	------	------	------
WRE-B08	North post, truss 1	75	none	AD 1179	------	1253

* h/s = heartwood/sapwood boundary on sample

Figure 2: Sketch diagram to show sample locations (provided by Adrian Gibson)

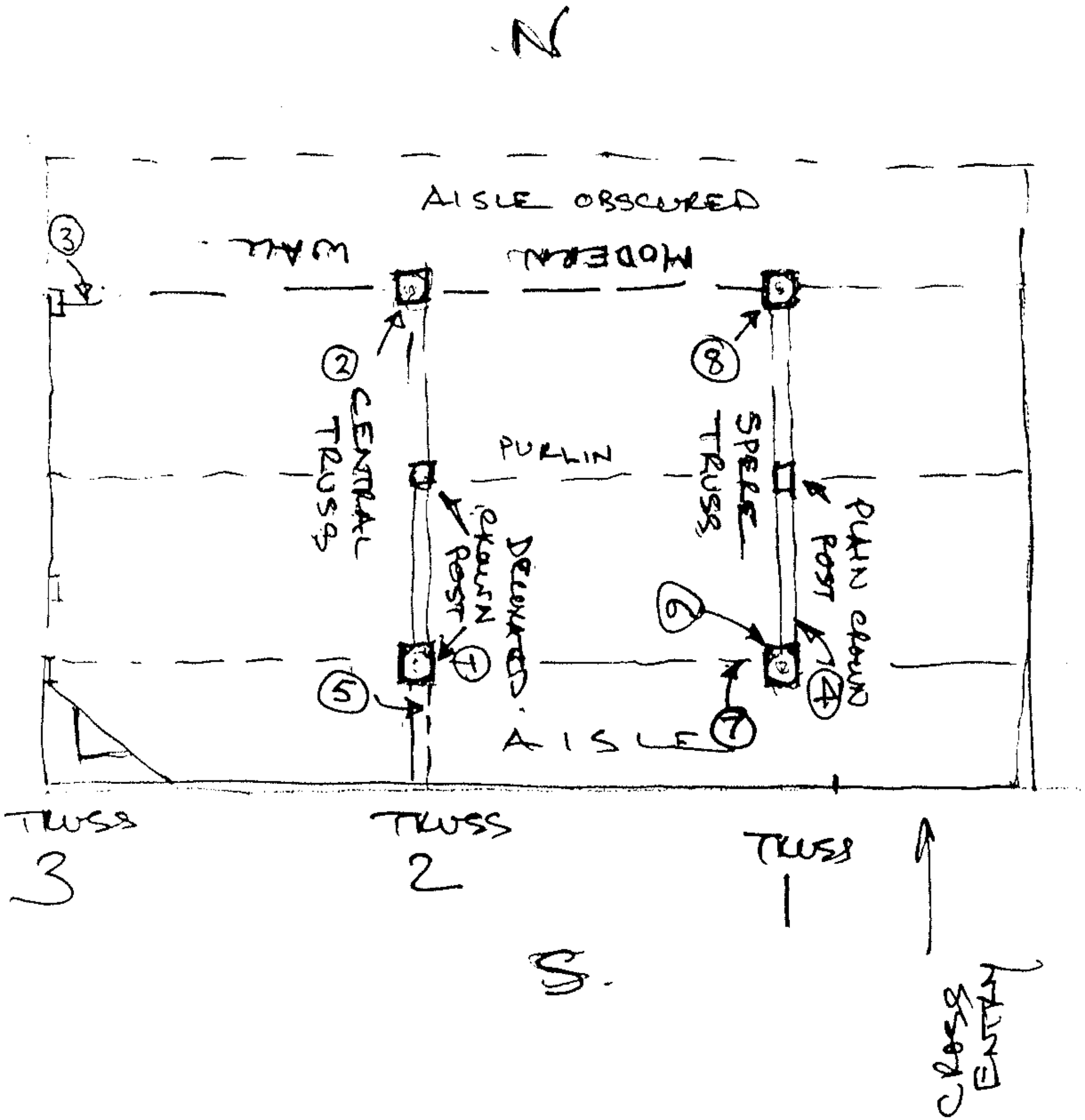


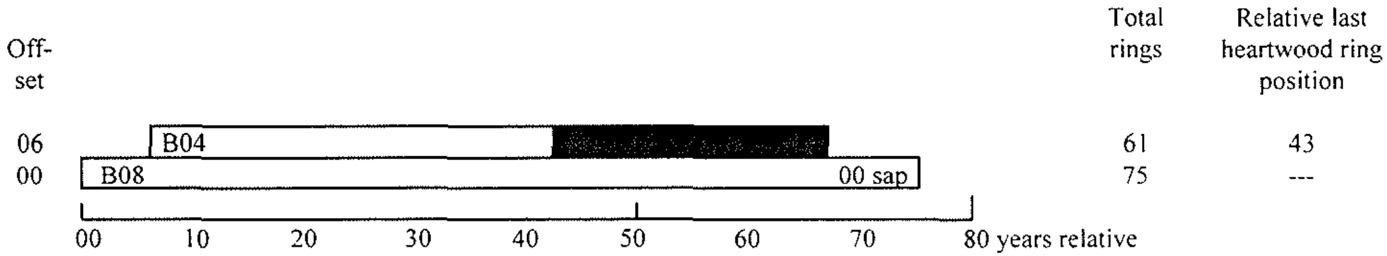
Table 2: Results of the cross-matching of sample WRE-B04 when first ring date is AD 1185 and last ring date is AD 1245

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	4.2	(Laxton and Litton 1988)
England	AD 401 - 1981	2.3	(Baillie and Pilcher 1982 unpubl)
SENGLAND	AD 1083 - 1589	5.3	(Bridge 1988)
Chichester Cathedral	AD 1173 - 1295	3.9	(Howard *et al* 1992)
Cross Keys Inn, Leicester	AD 1104 - 1309	5.5	(Howard *et al* 1988)
Upwich, Droitwich	AD 1178 - 1415	4.8	(Groves 1988)
Reading Abbey	AD 1160 - 1407	4.8	(Groves *et al* 1985)

Table 3: Results of the cross-matching of sample WRE-B08 when first ring date is AD 1179 and last ring date is AD 1253

East Midlands	AD 882 - 1981	6.5	(Laxton and Litton 1988)
England	AD 401 - 1981	6.2	(Baillie and Pilcher 1982 unpubl)
SENGLAND	AD 1083 - 1589	8.6	(Bridge 1988)
Chichester Cathedral	AD 1173 - 1295	8.6	(Howard *et al* 1992)
Cross Keys Inn, Leicester	AD 1104 - 1309	6.0	(Howard *et al* 1988)
Upwich, Droitwich	AD 1178 - 1415	9.0	(Groves 1988)
Reading Abbey	AD 1160 - 1407	6.6	(Groves *et al* 1985)

Figure 3: bar diagrams of samples in site chronology WREBSQ02



White bar = heartwood rings, shaded area = sapwood rings

Table 4: Results of the cross-matching of site chronology sample WREBSQ02 when first ring date is AD 1179 and last ring date is AD 1253

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	7.4	(Laxton and Litton 1988)
England	AD 401 - 1981	5.3	(Baillie and Pilcher 1982 unpubl)
SENGLAND	AD 1083 - 1589	9.9	(Bridge 1988)
Chichester Cathedral	AD 1173 - 1295	8.4	(Howard *et al* 1992)
Cross Keys Inn, Leicester	AD 1104 - 1309	8.0	(Howard *et al* 1988)
Upwich, Droitwich	AD 1178 - 1415	9.1	(Groves 1988)
Reading Abbey	AD 1160 - 1407	7.6	(Groves *et al* 1985)

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Data of measured samples - measurements in 0.01 mm units

WRE-B01A 70
314 359 333 516 389 416 351 388 378 340 413 568 422 314 136 165 171 222 244 231
193 276 226 238 228 224 119 168 177 174 233 213 235 212 171 210 223 178 93 124
204 168 218 263 264 244 208 185 146 118 135 143 134 137 137 126 136 142 147 179
202 176 205 173 169 198 138 186 152 155
WRE-B01B 70
314 353 331 503 429 394 382 390 361 344 457 513 412 303 136 169 185 225 224 248
183 284 223 243 227 218 129 172 193 158 239 216 221 219 168 208 225 178 94 129
200 181 203 261 265 233 213 184 155 117 137 137 130 138 140 117 131 139 147 191
201 176 195 172 166 193 131 183 156 151
WRE-B02A 66
340 182 296 336 278 221 321 207 298 279 434 269 295 364 299 259 293 284 229 301
119 257 220 199 210 185 264 232 223 208 291 359 241 158 250 214 231 356 356 353
306 264 121 182 127 111 203 340 303 400 309 499 281 304 212 211 239 273 324 359
210 159 189 189 228 337
WRE-B02B 66
323 192 282 325 331 206 339 231 301 277 455 265 291 348 274 258 275 282 225 306
139 274 215 210 211 169 266 221 213 181 346 339 253 168 260 206 237 392 345 350
306 270 123 178 124 106 212 341 309 394 321 484 298 295 217 221 237 268 309 356
205 152 210 203 237 341
WRE-B03A 30
406 570 409 364 346 229 177 188 187 222 113 154 150 127 144 266 250 144 138 139
101 131 187 222 205 170 183 249 296 212
WRE-B03B 30
378 567 440 369 373 219 221 202 187 220 115 141 139 129 172 290 251 166 141 144
108 124 174 240 223 183 178 255 285 216
WRE-B04A 61
445 576 407 93 105 177 261 347 529 231 331 409 337 201 247 296 294 332 292 343
309 220 230 209 149 252 303 268 254 187 222 198 140 106 150 158 133 127 102 108
169 140 151 167 183 89 77 91 88 170 111 100 131 214 180 174 101 80 111 149
180
WRE-B04B 61
598 529 417 102 122 179 247 341 530 246 320 407 328 198 259 288 293 323 299 359
289 219 220 210 137 287 302 291 239 172 192 206 133 100 152 163 122 107 117 122
157 160 148 144 179 91 82 73 94 150 114 102 128 225 190 168 108 74 110 154
224
WRE-B05A 56
122 140 104 93 58 54 90 113 212 319 331 335 429 384 384 387 332 318 403 387
539 585 484 381 351 461 600 483 590 615 498 442 418 265 222 187 309 390 251 292
278 215 295 387 241 267 266 371 282 307 343 381 287 253 266 285
WRE-B05B 56
128 138 107 93 62 60 96 124 210 271 337 353 442 393 372 386 307 304 390 367
494 555 462 380 365 456 630 508 599 617 503 438 421 265 214 195 313 391 266 303
271 212 303 389 243 245 271 380 257 296 352 371 290 244 310 311
WRE-B06A 110
308 358 320 418 372 313 393 308 305 456 483 277 408 461 410 192 202 150 110 283
156 151 163 102 100 94 137 172 146 125 158 128 177 114 88 53 106 87 129 104
146 88 101 66 118 143 142 112 139 103 82 55 60 103 64 70 86 148 175 81
101 188 113 143 152 137 262 178 89 118 172 177 204 128 108 145 83 127 173 136
92 70 103 133 187 246 244 147 141 129 117 148 171 158 134 116 114 104 117 154
126 219 313 162 144 92 141 112 105 136
WRE-B06B 110
314 353 329 427 383 302 394 262 312 475 507 290 388 450 411 190 219 156 100 273
141 151 159 108 113 96 130 162 161 132 139 120 175 125 75 62 83 87 145 110
134 88 97 67 122 140 146 100 147 92 83 51 52 103 72 73 87 141 176 88
105 183 110 152 138 146 270 173 86 116 184 176 193 137 113 128 100 112 170 144
94 57 105 133 178 237 244 155 136 134 110 160 159 163 128 136 114 101 98 168
117 218 318 159 121 119 152 137 87 98

WRE-B07A 49
135 154 235 236 398 289 318 264 283 392 396 230 237 348 441 308 181 261 198 164
293 372 422 354 240 278 253 216 161 260 317 278 386 440 250 262 277 273 201 245
242 186 175 113 161 122 143 156 165
WRE-B07B 49
161 173 278 236 401 311 306 261 278 400 378 261 243 336 466 309 187 247 197 166
308 377 401 374 202 297 280 235 158 249 300 282 391 421 281 263 277 272 212 243
242 191 166 111 153 124 133 151 189
WRE-B08A 75
177 107 159 239 258 168 246 308 320 146 203 200 235 269 370 320 436 346 157 140
261 229 397 253 236 150 190 198 134 194 146 207 264 166 198 190 144 133 160 107
184 184 170 124 134 101 128 213 154 214 222 143 108 83 140 161 168 118 244 159
162 93 81 76 65 98 111 165 171 101 161 156 173 171 177
WRE-B08B 75
179 106 160 243 252 159 262 308 320 147 207 254 223 256 378 322 406 351 139 134
251 240 400 263 247 141 178 182 123 222 156 202 269 178 205 194 154 141 150 120
169 181 181 135 137 108 118 223 161 205 218 143 102 77 148 151 176 109 240 151
172 86 82 75 73 98 91 159 187 94 151 148 178 167 198

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.

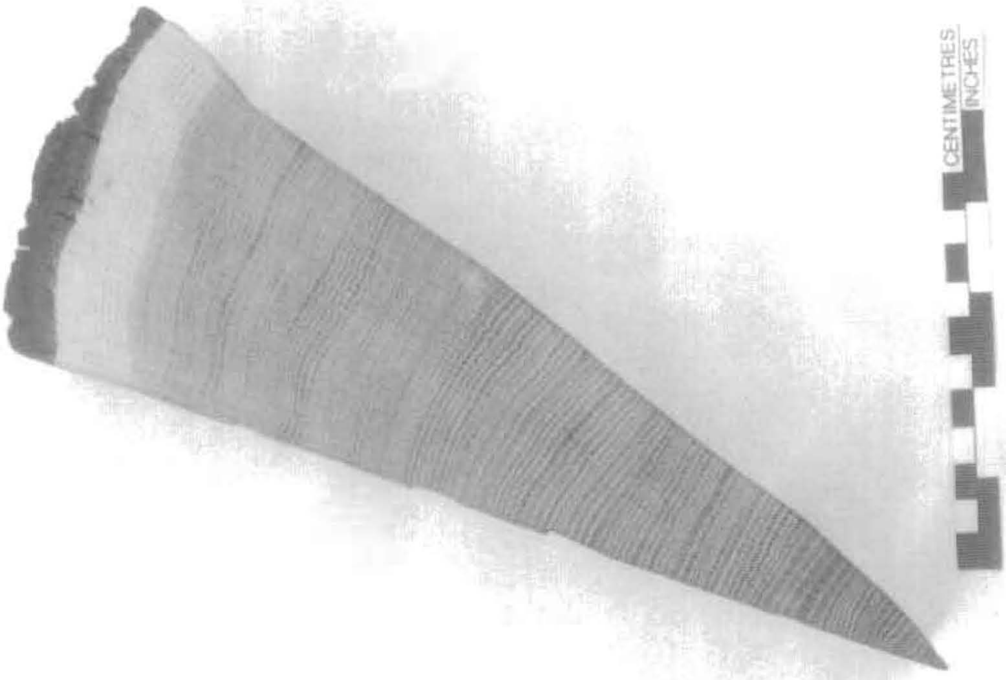

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

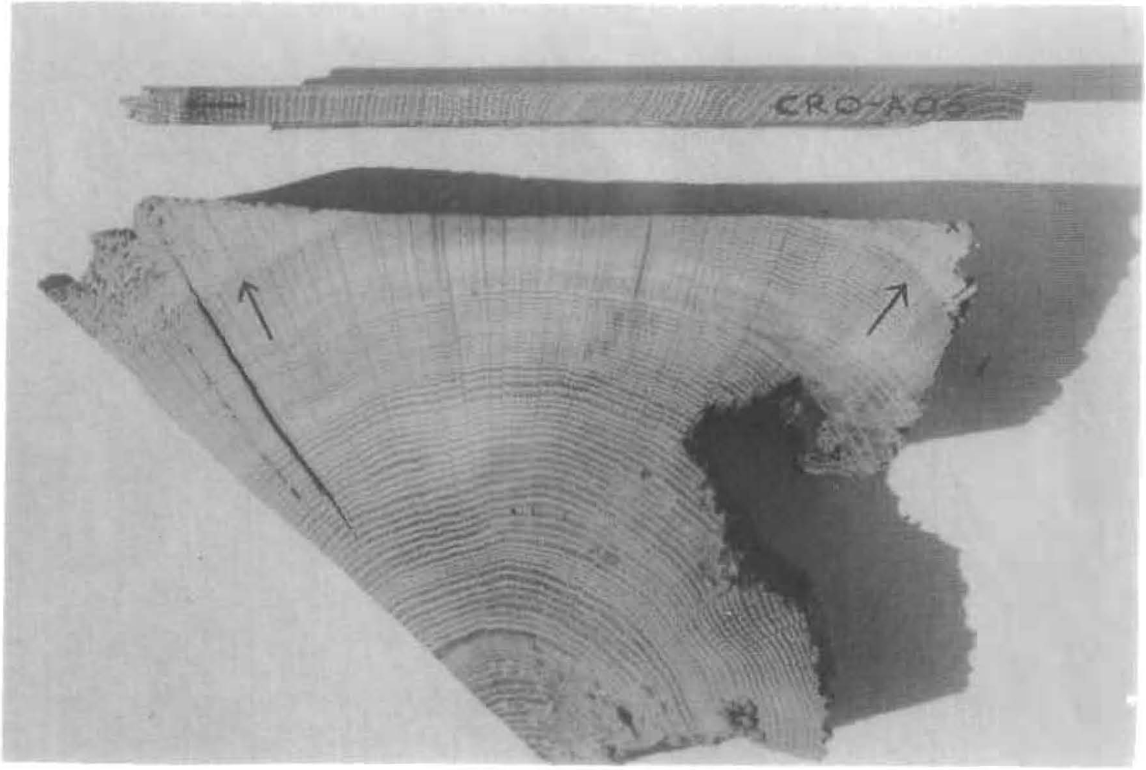

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

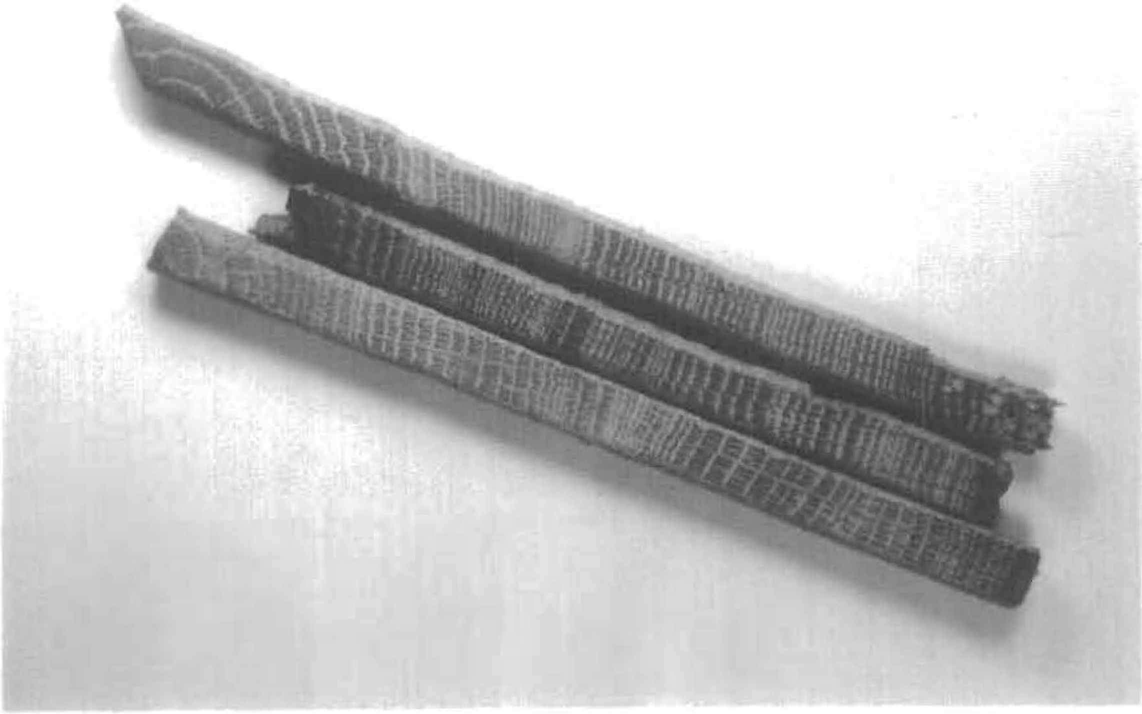

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

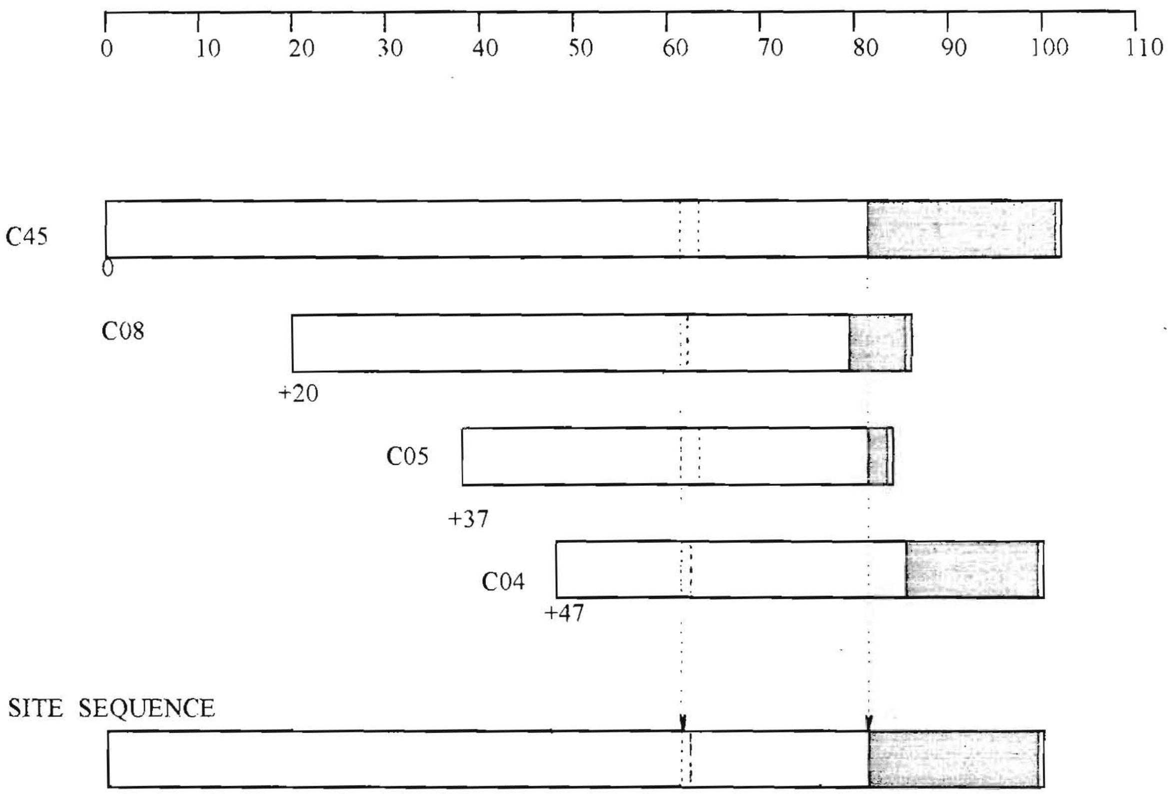

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

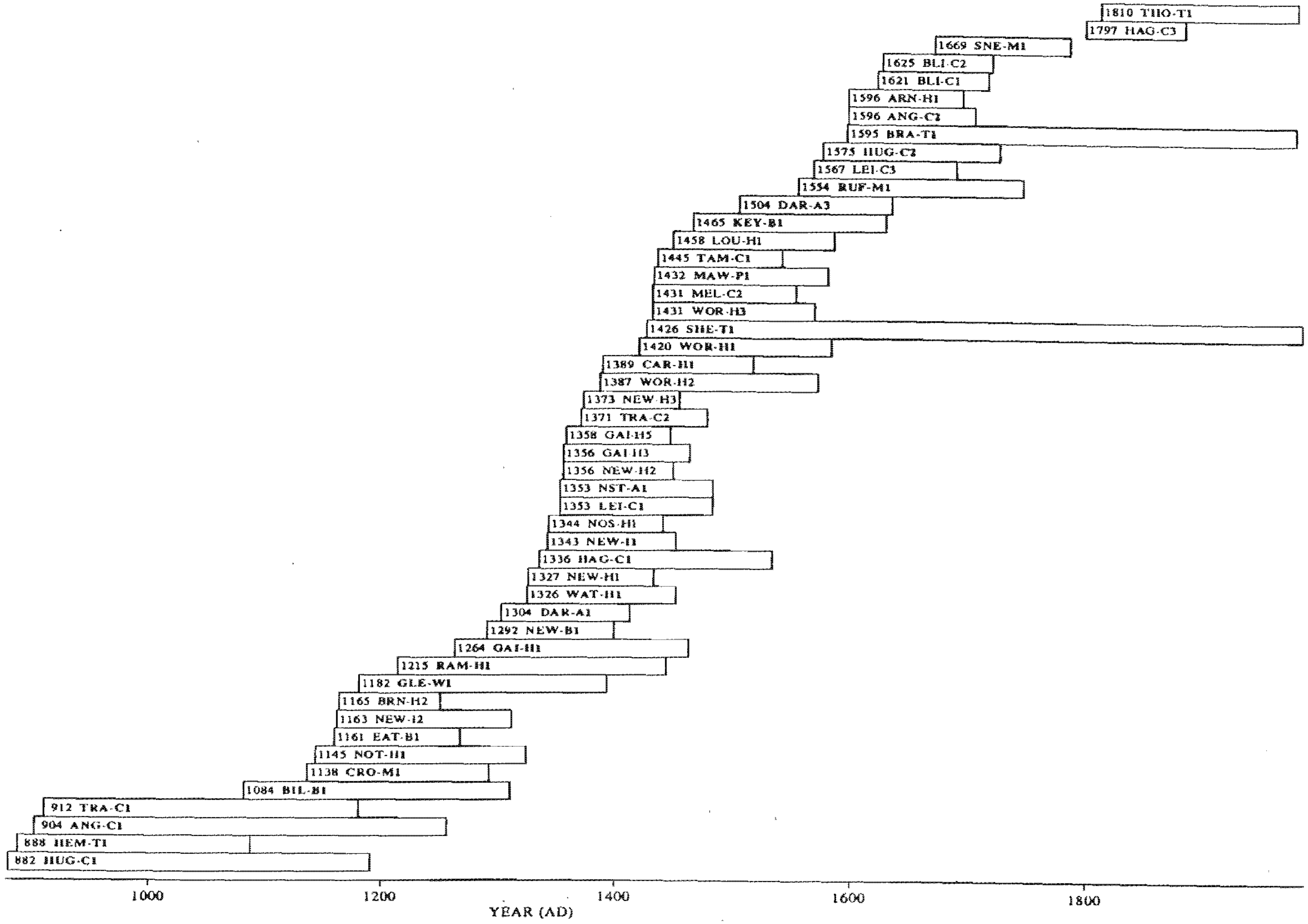

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

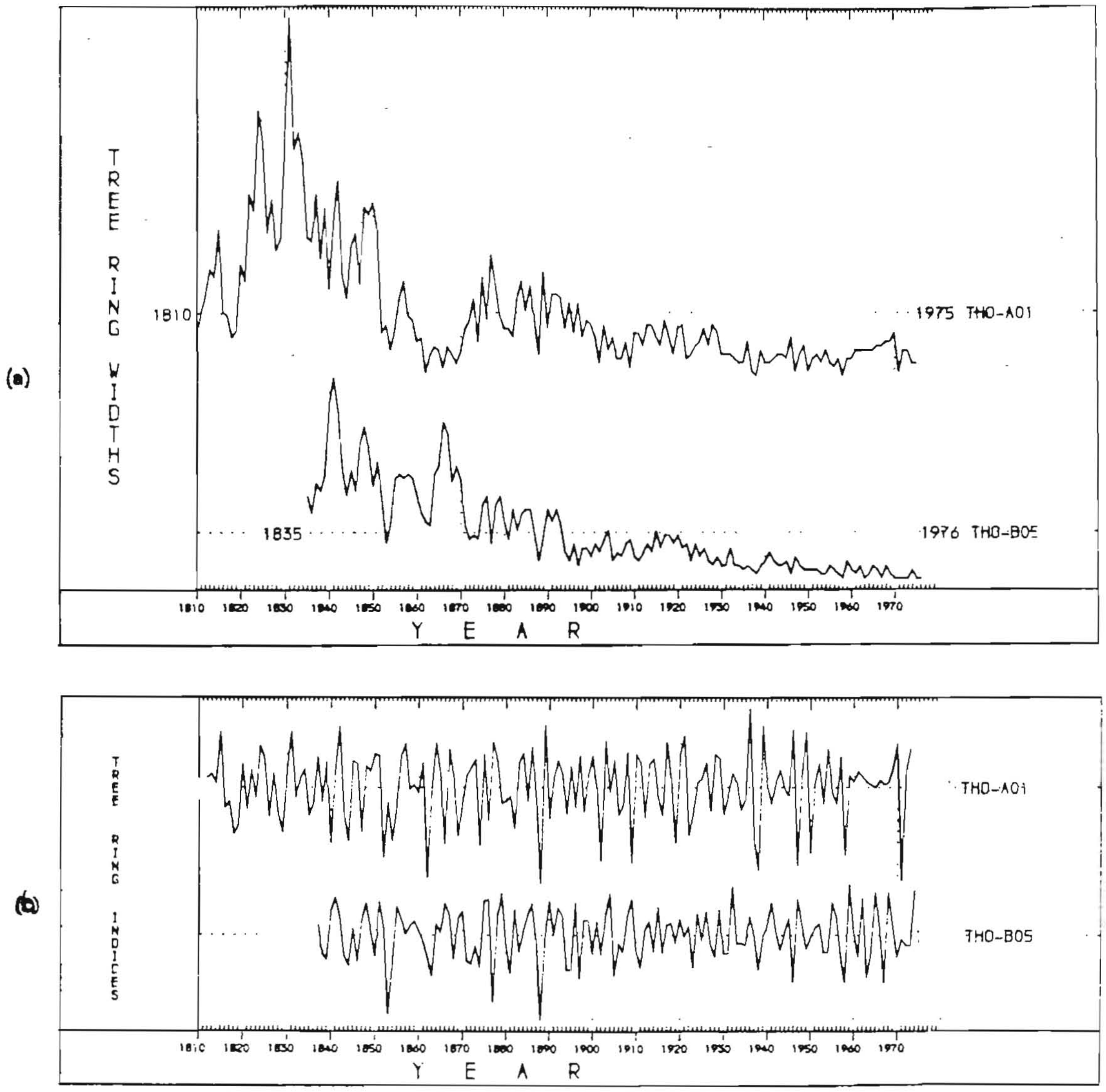

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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