Ancient Monuments Laboratory
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TREE-RING ANALYSIS OF TIMBERS FROM THE MASTER'S HOUSE, SALTISFORD, WARWICK

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Summary

Dendrochronological analysis of timbers from The Master's House, Saltisford, Warwick, resulted in the production of two site chronologies. The first of these could not be securely dated. The second gives a felling date in the range AD 1503-1528. This site chronology of 88 rings spans the period AD 1412-1499.

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Introduction

The Master's House, Warwick, (SP 277654) is the traditional name for a timber-framed house close to, and in the same curtilage as, the small medieval chapel of St Michael's. Both house and chapel are considered to be associated with the medieval leper hospital of St Michael's, known to have been in the suburb of Saltisford. The foundation was governed by a Warden or Master, who had to be a priest and live on the site. The present building, thought to be his accommodation, is traditionally dated to the late fifteenth- or early sixteenth-century. The site is a Grade II* Listed Building and a Scheduled Ancient Monument.

The building has three separate components, labelled A-B-C (Morriss 1996). Component A is the oldest surviving part of the complex. It is a close-studded timber-framed two-storey two-bay structure, occupying the eastern two-thirds of the main range. It is just over 10m long and 4.5m wide. Each bay is of the same length and each is, therefore, a little under 5m square. The form of the frames of this range are all different, each having their own individual pattern.

It is evident that component B was added to the west end of component A, as it lacks its own integral east frame. It is a close-studded timber-framed single-bay two-storey structure. The framing sits on a stone plinth 0.8m high. Component B is the same width and height as the earlier structure and just over 3.5m long.

Component C, the latest addition, is a long single-storey lean-to structure against the south side of the main range. Although it has undergone considerable alteration it too was originally a timber-framed structure.

The individual frames of the building have been assigned numbers, prefixed by the relevant component identification (Fig 3). The buildings are aligned roughly north-west to south-east, but in this report, for the sake of convenience, they are deemed to align west-east, following R K Morriss' report.

Tree-ring analysis was commissioned by English Heritage to establish the construction dates of components A and B to help determine whether they are correctly associated with the medieval leper hospital.

The Nottingham Tree-ring Dating Laboratory would like to thank the owner, Mr Ivor Jones, for allowing free and unlimited access to the site for sampling. We would also like to thank Frank Haywood and Associates who most helpfully arranged access and power.

Site analysis and results

A total of fourteen samples was obtained from this site. Each sample was given the code WAR-A (Warwick, site "A"). Nine samples (WAR-A01 - 09) were taken from component A, the eastern-most part of the site. None of the main structural timbers of component A had sufficient rings to be worth sampling. However, following discussions on site, it was decided to sample the joists and rafters, these being original and having acceptable ring-width sequences.

Five samples (WAR-A10 - 14) were obtained from component B. Full details of the samples are given in Table 1. The location of each sample was also recorded at the time of sampling on drawings provided (Figure 4a/b).

All fourteen samples were measured and compared with each other by the Litton/Zainodin grouping procedure (Appendix). At a level of t=4.5 two groups of samples formed. The four samples of the first group cross-matched with each other at the offsets shown in Figure 1. These samples all come from component A. At these offsets the positions of the last measured complete sapwood rings and the relative positions of the heartwood/sapwood transitions are all indicative of timbers with the same felling date. Because of this and the satisfactory cross-matching, the ring-widths from these four samples were averaged at these positions to form WARASQ01, a site chronology of 87 rings. Site chronology WARASQ01 was compared with a wide series of reference chronologies for oak, but there was no cross-matching and thus no date obtained.

The five samples of the second group cross-matched with each other at the offsets shown in Figure 2. Two of these samples come from component A and three from component B. At these offsets the relative positions of the heartwood/sapwood transitions are again indicative of timbers with the same felling date. Because of this and the satisfactory cross-matching, the ring-widths from these five samples were averaged at these positions to form WARASQ02, a site chronology of 88 rings. Site chronology WARASQ02 was successfully cross-matched with a wide series of reference chronologies for oak, indicating a first ring date of AD 1412 and a last ring date of AD 1499. Evidence for this date is given by the t-values of Table 2. Site chronology WARASQ02 has an average last heartwood ring date of AD 1488. This gives an estimated felling date in the range AD 1503 - 1528.

If site chronologies WARASQ01 and WARASQ02 are compared with each other, there is a cross-match between them with a low, but maximum, value of t=3.9. This is found when the first ring of site chronology WARASQ01 is at minus 19 years relative to the first ring of WARASQ02. A cross-match at this relative position, if correct, would give site chronology WARASQ01 a last measured complete sapwood ring date, and thus a felling date, of AD 1479. Although such a date would be in agreement with the accepted construction sequence for the building, WARASQ01 has no cross-match with any national or local reference chronology at this date and so this sequence remains undated.

The remaining ungrouped samples with 55 or more rings, WAR-A12 and 14, were each compared separately with the full series of reference chronologies, but there was no satisfactory cross-matching. There appears to be no problem with these samples in that they do not have narrow or stressed growth-rings, nor are they particularly wide ringed. They do, however, appear to have complacent growth patterns which would tend to make them difficult to date.

Conclusion

Analysis of the timbers from the Master's House, Warwick, resulted in the production of a single dated site chronology, WARASQ02, spanning the period AD 1412 - 1499. The timber, mostly from component B, but including two samples (rafters) from component A, has a felling date in the range AD 1503 - 1528. However, if this is the case, it is perhaps surprising that John Leland, writing in the early 1540s, describes the house as "sore decayed" (Smith 1964).

The cross-match between site chronologies WARASQ01 and WARASQ02 is weak, but if correct would show that the floor joists of component A were felled earlier than the timbers of component B. Further sampling of timbers from component A would be worthwhile in order to create a stronger site chronology, with greater prospects for cross-matching and dating against the reference chronologies.

Table 1: Details of tree-ring samples from The Master's House, Saltisford, Warwick

Sample no	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
WAR-A01	East bay first floor joist 1 component A	87	35C	------	------	------
WAR-A02	East bay first floor joist 3 (E part) component A	47	h/s	------	------	------
WAR-A03	East bay first floor joist 3 (W part) component A	49	23C	------	------	------
WAR-A04	East bay first floor joist 6 component A	69	30C	------	------	------
WAR-A05	East bay first floor joist 5 component A	57	02	------	------	------
WAR-A06	East bay first floor joist 7 component A	74	17+12-15UM	------	------	------
WAR-A07	North rafter A30	56	h/s	AD 1420	1475	1475
WAR-A08	North rafter A28	48	03c	------	------	------
WAR-A09	North rafter A24	59	h/sc	AD 1422	1480	1480
WAR-A10	Central post frame B3	81	h/s	AD 1419	1499	1499
WAR-A11	Brace from north post to tie beam frame B2	75	h/s	AD 1412	1486	1486
WAR-A12	Central stud post, above tiebeam, frame B2	55	h/s	------	------	------
WAR-A13	Central post frame B1	77	h/s	AD 1423	1499	1499
WAR-A14	South-west corner post frames B1/B2	70	h/s	------	------	------

*h/s = heartwood/sapwood boundary on sample
UM = unmeasurable rings (due to compaction, decay etc)
c = complete sapwood on timber but all or part lost from core in sampling
C = complete sapwood on sample; last measured ring date is felling date of timber

Figure 1: Bar diagram of samples in site chronology WARASQ01

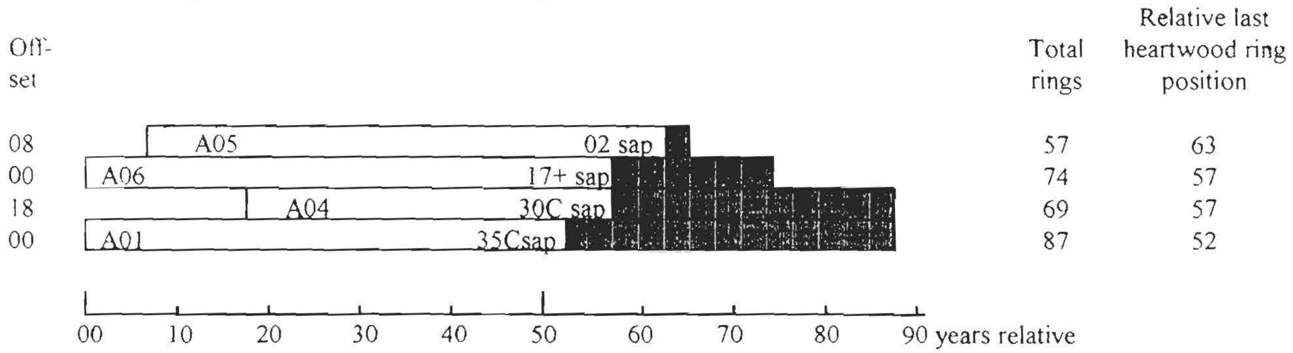
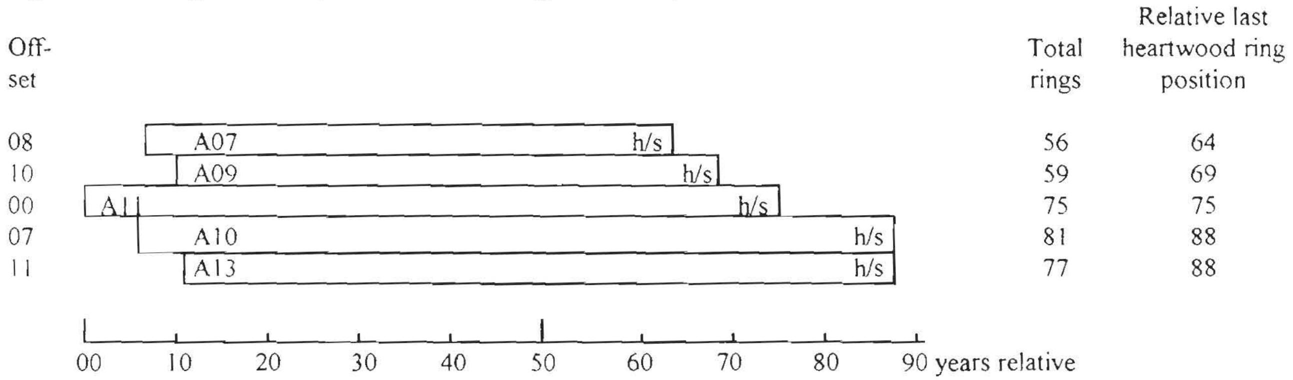


Figure 2: Bar diagram of samples in site chronology WARASQ02



White bars = heartwood rings, shaded area = sapwood rings

h/s = heartwood/sapwood boundary on sample

C = complete sapwood on sample; last measured ring date is felling date of timber

Table 2: Results of the cross-matching of site chronology WARASQ02 against relevant reference chronologies when first ring date is AD 1412 and last ring date is AD 1499

Reference chronology	span of chronology	t-value	
East Midlands	AD 882 - 1981	5.0	(Laxton and Litton 1988)
England	AD 401 - 1981	4.6	(Baillie and Pilcher unpubl)
Wales & West Midlands	AD 1341 - 1636	5.0	(Siebenlist-Kerner 1978)
MC10	AD 1386 - 1585	7.4	(Fletcher pers comm)
26 Manor Rd, Didcot, Oxon	AD 1415 - 1509	5.5	(Alcock *et al* 1989)
Folly House, Steventon, Oxon	AD 1437 - 1542	4.8	(Alcock *et al* 1989)
Dell Cottage, Harwell, Oxon	AD 1420 - 1509	5.3	(Alcock *et al* 1991)
Thatched Cottage, Radley, Oxon	AD 1436 - 1522	4.6	(Alcock *et al* 1991)

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Siebenlist-Kerner, V, 1978 Chronology, 1341-1636, for hillside oaks from Western England and Wales, in *Dendrochronology in Europe* (ed. J.M.Fletcher) BAR Int. Ser **51**, 156-60

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Figure 3: Frame identification

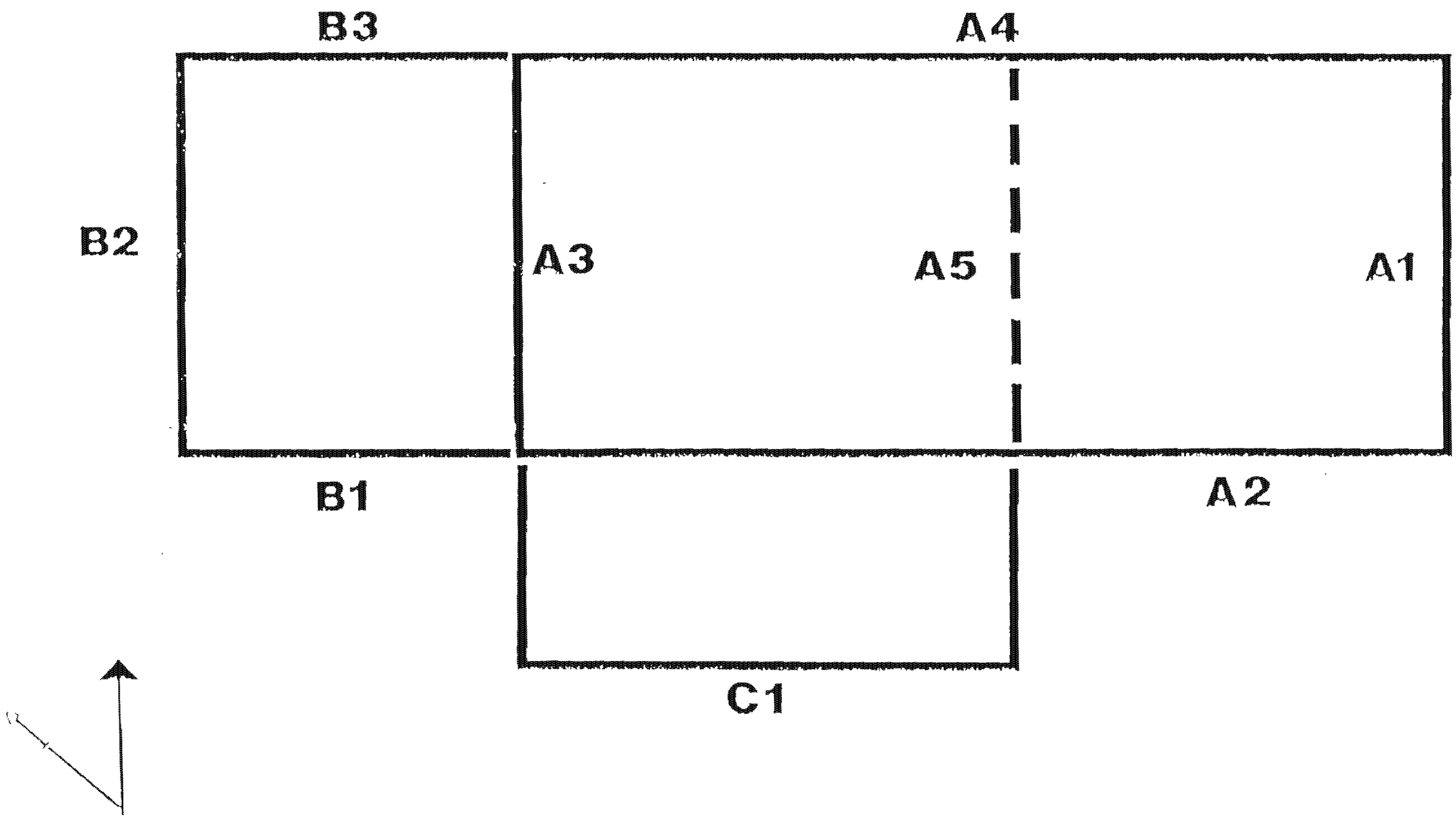
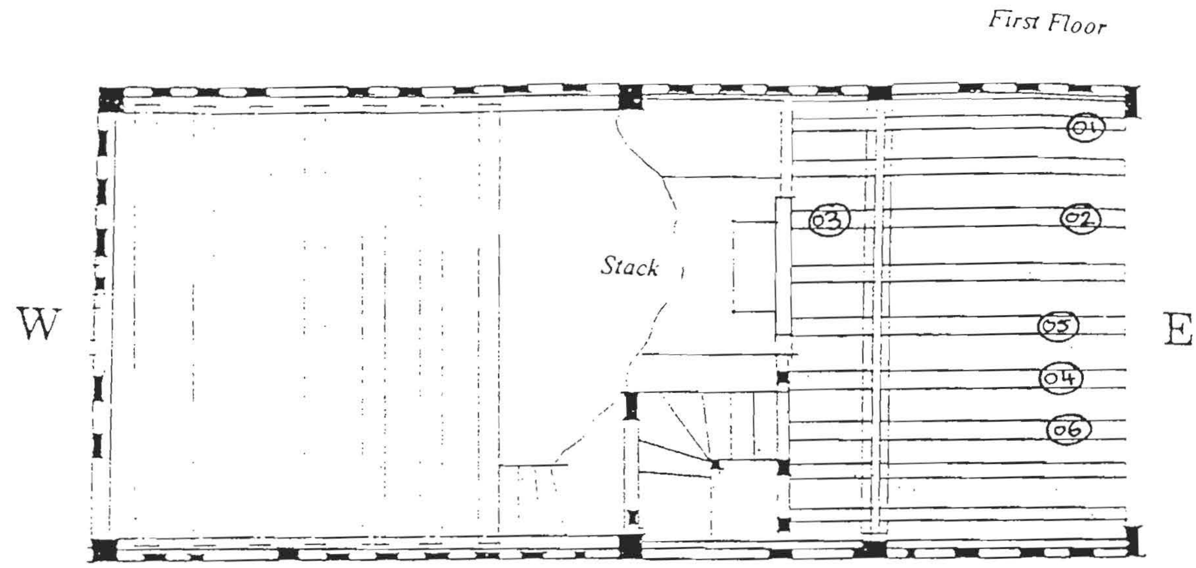
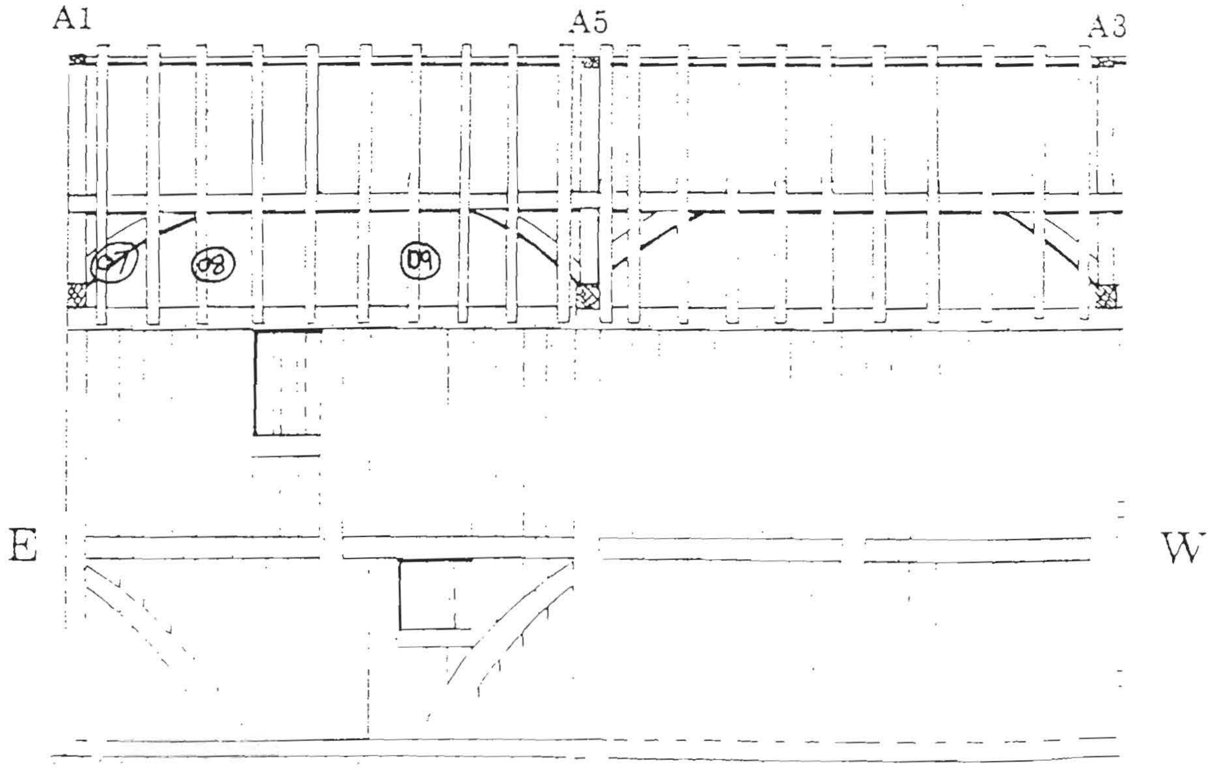


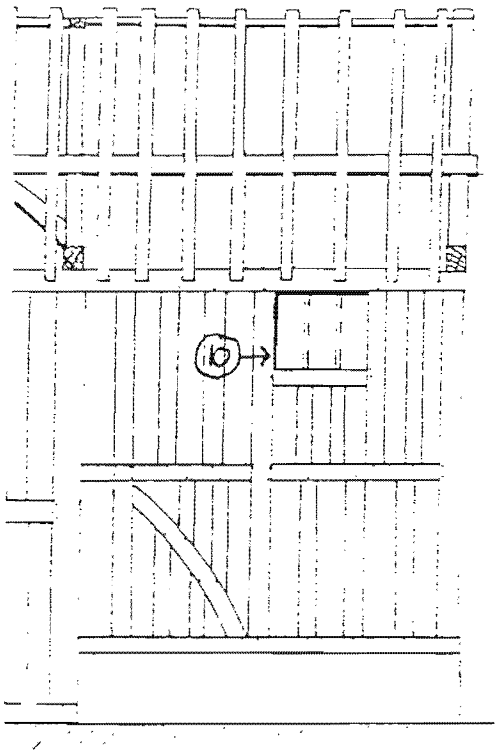
Figure 4a: Plan of sample locations (component A)





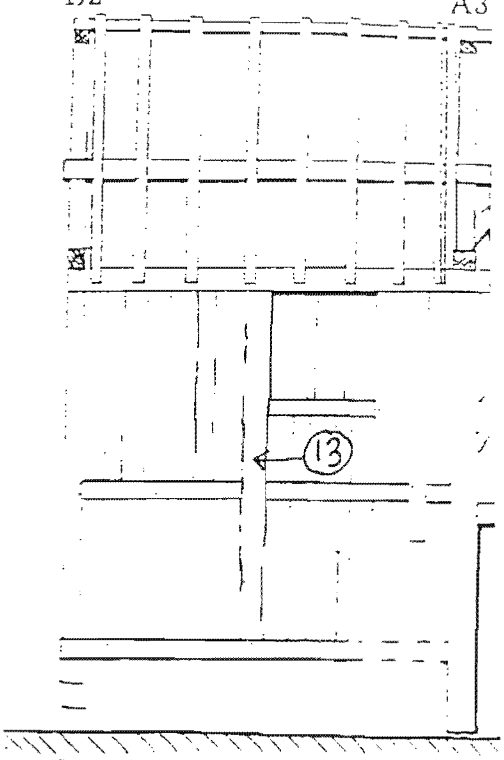
North Frame (Frame 3-4)

Figure 4b. Plan of sample locations (component B)

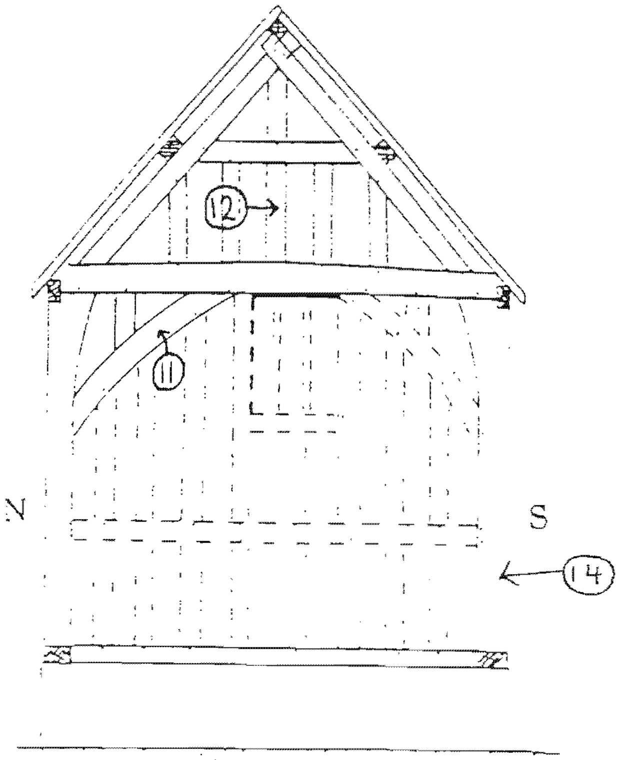


North Frame (Frame B3)

W



South Frame (Frame B1)



West Frame (Frame B2)

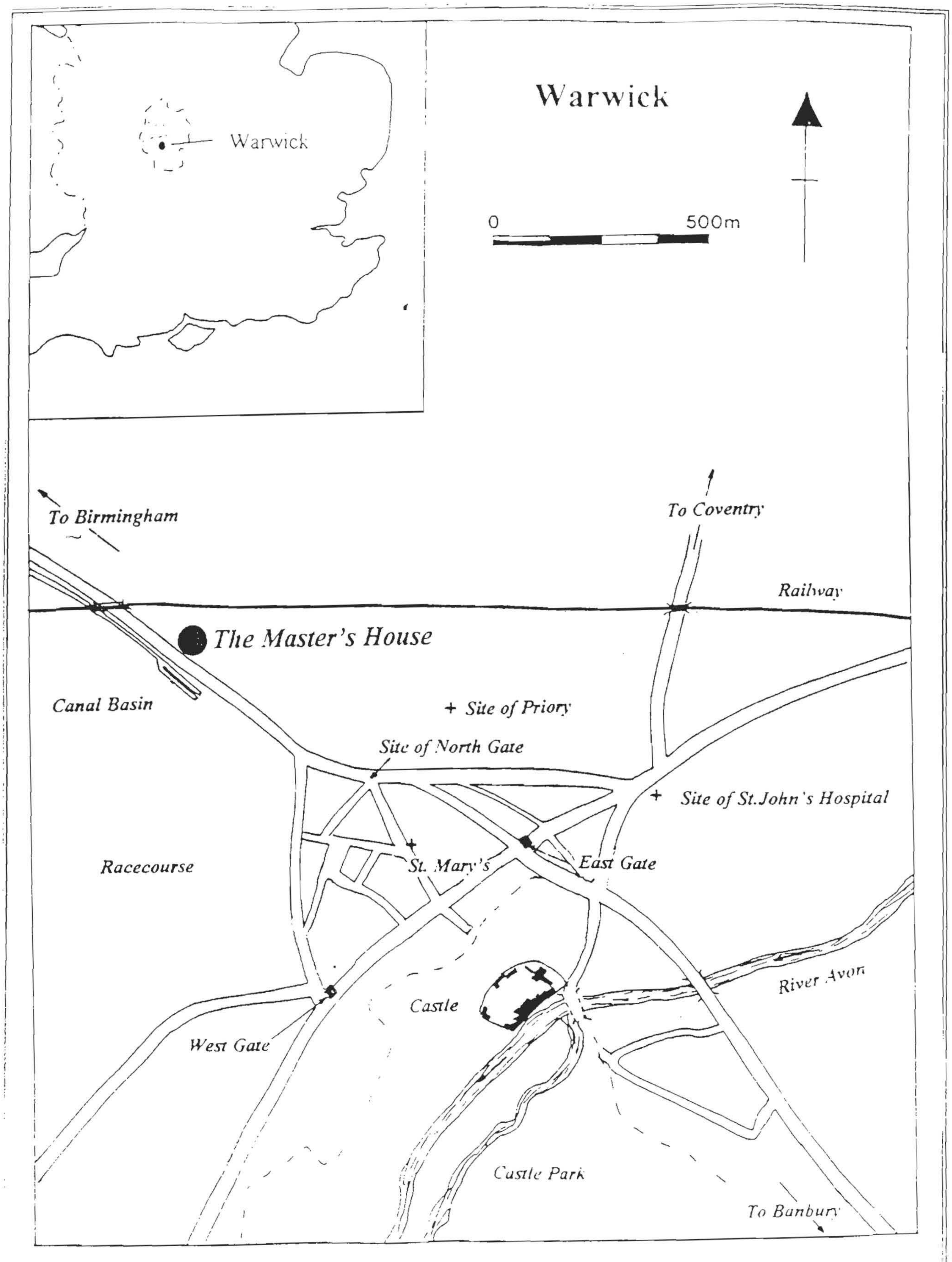


Figure 5:

The Location of the Master's House

Table 3: Data of fourteen measured samples (Samples measured in 0.0001 cm units)

[illegible]AR-A01A	87																		
[illegible]	219	255	184	206	208	241	261	275	334	380	270	214	269	285	225	205	118	201	281
[illegible]	213	44	50	36	89	89	125	69	89	37	56	74	88	68	65	82	42	134	144
[illegible]	128	81	124	85	50	33	50	56	38	41	41	110	120	126	98	94	70	79	80
[illegible]	88	86	48	42	27	22	24	28	24	29	50	42	59	28	33	28	23	24	28
	21	14	16	18	16	24													
[illegible]AR-A01B	87																		
[illegible]	218	273	193	210	229	251	257	297	362	352	249	194	260	259	240	231	119	186	275
320	224	47	51	48	82	92	133	69	91	49	54	76	88	64	71	80	42	132	146
[illegible]	120	91	102	80	47	35	49	53	43	38	48	107	119	127	97	93	69	79	82
[illegible]	96	80	58	41	25	23	25	27	29	34	39	50	58	28	32	28	17	29	33
[illegible]	27	20	23	15	20	26													
[illegible]AR-A02A	47																		
[illegible]	263	266	290	292	237	202	379	291	342	289	291	306	299	210	239	144	279	267	184
[illegible]	157	130	55	82	88	85	83	55	52	56	47	61	69	94	51	117	103	50	37
[illegible]	79	67	63	55	45	51													
[illegible]AR-A02B	47																		
[illegible]	267	277	298	309	241	183	368	339	359	289	297	305	297	209	215	182	226	271	189
[illegible]	147	127	60	82	86	73	76	57	54	55	47	68	67	86	48	117	106	43	44
[illegible]	73	66	66	66	36	40													
[illegible]AR-A03A	49																		
[illegible]	540	575	427	278	335	368	370	404	323	201	153	150	176	222	196	161	173	152	205
[illegible]	[illegible]	230	239	319	255	202	110	66	70	54	64	89	51	63	91	110	98	76	50
[illegible]	[illegible]	95	115	44	31	36	33	57											
[illegible]AR-A03B	49																		
[illegible]	549	567	438	279	310	397	360	402	303	216	151	149	193	222	205	163	188	183	221
[illegible]	161	230	242	313	256	202	113	68	78	53	69	81	55	62	93	108	105	75	46

36 111 104 109 39 32 37 33 55
WAR-A04A 69
[illegible] 470 498 357 83 81 104 129 232 203 193 168 62 102 109 107 90 110 108 56
84 69 62 118 106 92 62 61 49 65 65 118 102 73 69 64 80 68 103 91
[illegible] 125 101 116 110 84 91 81 71 61 43 65 53 59 62 53 75 73 75 41
[illegible] 76 83 77 47 49 49 44 60
WAR-A04B 69
358 483 500 360 84 77 104 133 232 209 182 165 58 90 108 109 88 98 93 65
75 75 56 123 98 99 63 58 57 56 65 117 97 74 73 67 74 79 90 99
108 124 96 120 112 87 93 81 66 62 55 51 60 52 58 61 69 70 81 45
99 76 80 77 48 45 49 46 59
WAR-A05A 57
[illegible] 208 167 329 379 233 287 304 273 431 387 368 487 354 55 73 79 132 254 262
156 116 127 375 320 343 266 326 314 127 75 54 59 69 46 90 123 108 39 75
66 36 46 31 38 45 40 33 30 44 39 30 26 29 26 34 26
WAR-A05B 57
146 203 171 327 377 243 267 275 271 433 397 364 486 359 53 73 73 138 252 267
151 119 128 372 327 357 272 321 309 130 67 60 65 67 51 83 110 102 42 65
77 38 46 26 39 47 40 41 34 33 40 26 26 24 30 30 24
WAR-A06A 74
[illegible] 150 251 226 275 260 233 301 271 400 406 356 399 463 410 362 335 174 195 219
280 243 60 54 44 53 74 68 54 39 57 111 102 110 100 66 97 62 171 191
177 223 137 129 140 141 67 110 94 84 77 113 279 248 260 187 113 152 86 89
[illegible] 88 79 100 68 45 31 41 32 59 50 60 58 63
WAR-A06B 74
134 142 248 231 250 290 244 307 278 418 387 358 406 429 398 356 345 167 201 213
279 229 63 55 32 55 69 72 60 39 52 110 109 106 102 69 103 62 164 199
181 217 140 129 153 137 60 97 115 76 80 110 272 245 259 185 126 135 96 82
70 85 87 98 66 36 39 32 37 61 50 55 50 72
WAR-A07A 56
119 262 108 179 131 207 164 251 269 113 188 128 184 91 129 114 85 70 59 66
74 114 71 94 84 51 61 62 55 46 60 77 46 58 58 83 73 81 65 58
[illegible] 42 65 80 46 54 47 44 56 41 29 38 21 38 45 76

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WAR-A07B 56
 116 245  66 149 141 228 185 288 288 110 177 127 188  88 134 106  86  75  62  59
  87 120  75  94  83  50  62  52  56  59  51  90  42  63  63  85  72  73  83  50
  71  36  75  81  38  65  46  53  56  38  28  30  30  36  45  69
WAR-A08A 48
 215 113 101 166 226 159 201 157 103 114  99 109  83 104  97  71  90 121 101 118
  83 100  85  93  65  67  95  63  65  66  69  92  90  57  55  43  59  79 102  42
  33  37  54 100  91  79  60  86
WAR-A08B 48
 186 117 132 188 223 142 212 161 108 113 102 113  82 104 104  68 103  90 109 114
  85 108  83  97  63  68  92  53  67  61  73  94  95  55  59  42  58  64 103  45
  27  40  61  95  95  70  62  84
WAR-A09A 59
 100 210 180 341 120 200 258 169 172 160 186  73 116 107 135 111  59  55  84 148
  88 141 128 105 104  85  91  82  93 119  66 108  80 121 134 117 126  98 130  73
  82  97  56  62  65  83 104 112  77  57  48  56  82 110  64  67  54  96 103
WAR-A09B 59
  98 216 196 319 134 195 282 174 161 155 198  81 111 122 122 105  71  55  85 153
  83 142 138 100 110  87  86  85  88 122  69 105  86 125 119 122 119  98 139  75
  91  97  50  62  69  82  96 103  79  62  42  64  76 114  66  62  51 102 103
WAR-A10A 81
 323 291 154 181 165 143 173 172 183 166 191 212 231 364 255 362 393 300 278 190
 215 287 333 285 314 476 318 253 311 242 239 244 288 228 169 184 228 235 246 222
 174 246 241 204 235 163 237 275 230 215 178 124 180 217 301 243 349 242 278 185
 203 211 289 241 257 252 289 264 248 208 218 243 188 201 202 198 191 229 208 163
 197
WAR-A10B 81
 341 291 156 188 162 148 188 170 199 154 223 202 227 379 268 363 396 287 266 180
 207 287 331 260 323 480 307 268 297 246 236 247 276 218 201 182 230 236 220 247
 174 252 233 204 225 162 240 275 219 220 168 128 188 213 306 233 360 249 273 201
 214 220 280 245 251 260 284 248 259 196 218 242 201 182 209 191 197 223 203 182
 218
WAR-A11A 75
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 168 124 125  42  45  80 107 110 123 107 111 171 132 189 217 164 170 149 160 197
 167 129 142 109  77  58  62  57  76 114 129 180 186 137 128 127 143 134 142 165
 185 141 142 132 161 164 139 118 162 143 132 137 113 128 150 151 183 109 124 101
 129 130 125 199 134 114 108 132 116 135 104 112 100 122 103
WAR-A11B 75
 165 122 115  45  45  77 103 101 127 107 109 176 134 185 215 169 169 155 160 200
 170 129 146 132  76  63  59  57  79 112 126 184 186 136 126 131 137 143 145 172
 184 136 147 142 159 170 154 119 150 142 144 140 110 131 150 149 184 109 131  97
 127 130 125 202 121 117 116 117 120 133 108 117  97 128 110
WAR-A12A 55
 417 308 250 320 332 223 242 281 288 228 267 189 227 223 212 200 146 158 221 192
 257 190 141 114 170 206 162 247 178 188 160 174 152 171 168 168 234 185 233 301
 210 199 195 226 138 141 179 175 151 155 158 126 171 141 141
WAR-A12B 55
 355 312 246 330 318 227 258 262 288 236 274 175 219 214 204 199 149 165 213 192
 259 188 144 110 163 215 160 250 184 180 177 186 168 182 180 181 231 183 242 294
 214 196 207 217 147 121 200 149 170 163 150 118 177 141 141
WAR-A13A 77
 396 346 431 321 278 267 284 274 335 425 321 316 315 231 221 191 185 272 286 224
 303 374 289 248 267 251 223 249 307 240 239 167 177 216 235 245 193 309 238 246
 258 194 236 243 227 271 218 218 209 191 206 264 307 220 141 174 200 178 273 207
 185 182 236 217 198 178 181 209 180 134 154 144 162 202 176 156 235
WAR-A13B 77
 404 351 432 296 278 267 275 281 320 393 320 342 314 220 272 181 199 303 307 224
 308 388 282 247 245 232 210 250 308 253 224 166 183 214 228 249 192 319 238 236
 270 192 234 237 226 278 218 212 196 196 211 256 306 209 161 161 201 178 303 209
 183 197 230 210 204 185 182 214 169 138 150 148 157 215 186 163 234
WAR-A14A 70
 224 189 129 125 179  76  50  57  80 102 159 252 178 303 203 184 114 172 181 197
 248 261 157 205 200 199 243 250 336 249 305 215 269 300 166 315 263 345 300 260
 164 146 186 157 246 267 217 227 157 285 192 195 229 201 208 205 253 261 247 230
 262 237 141 232 195 206 295 254 219 181
WAR-A14B 70
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230	177	121	128	162	67	57	49	71	89	166	244	174	294	211	199	128	164	195	190
240	258	155	190	211	199	231	255	298	269	320	226	296	269	164	311	274	328	314	252
141	151	190	149	259	270	211	240	158	286	187	202	227	202	211	203	258	266	248	237
244	241	146	233	184	203	301	250	227	205										

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.

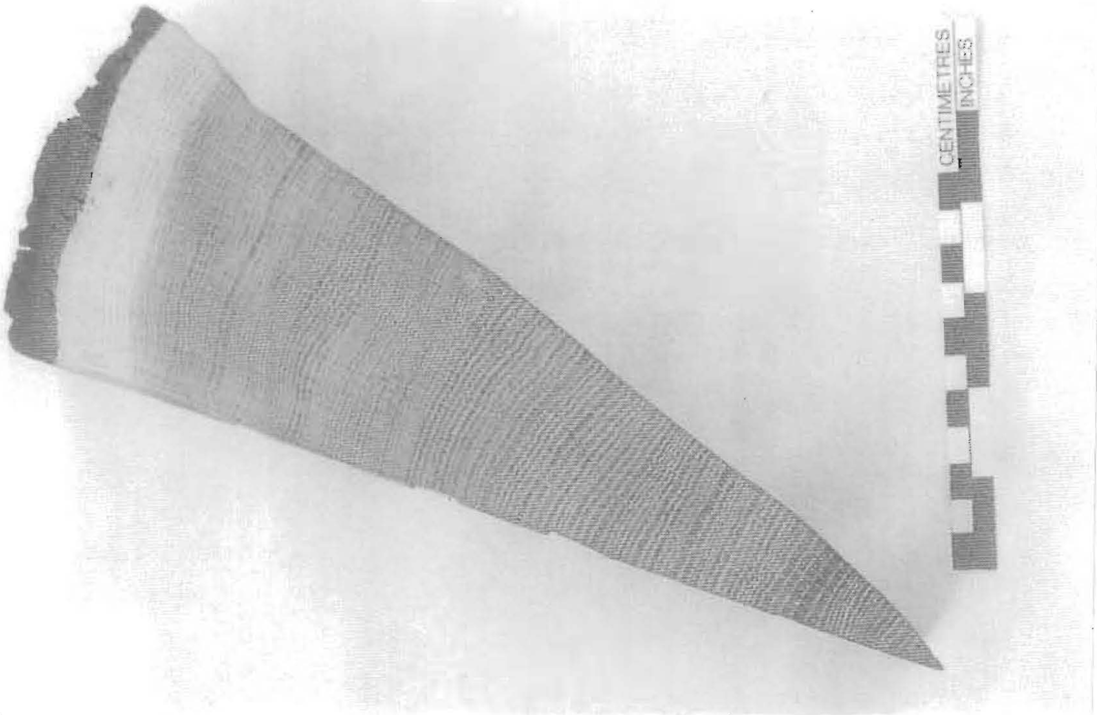

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

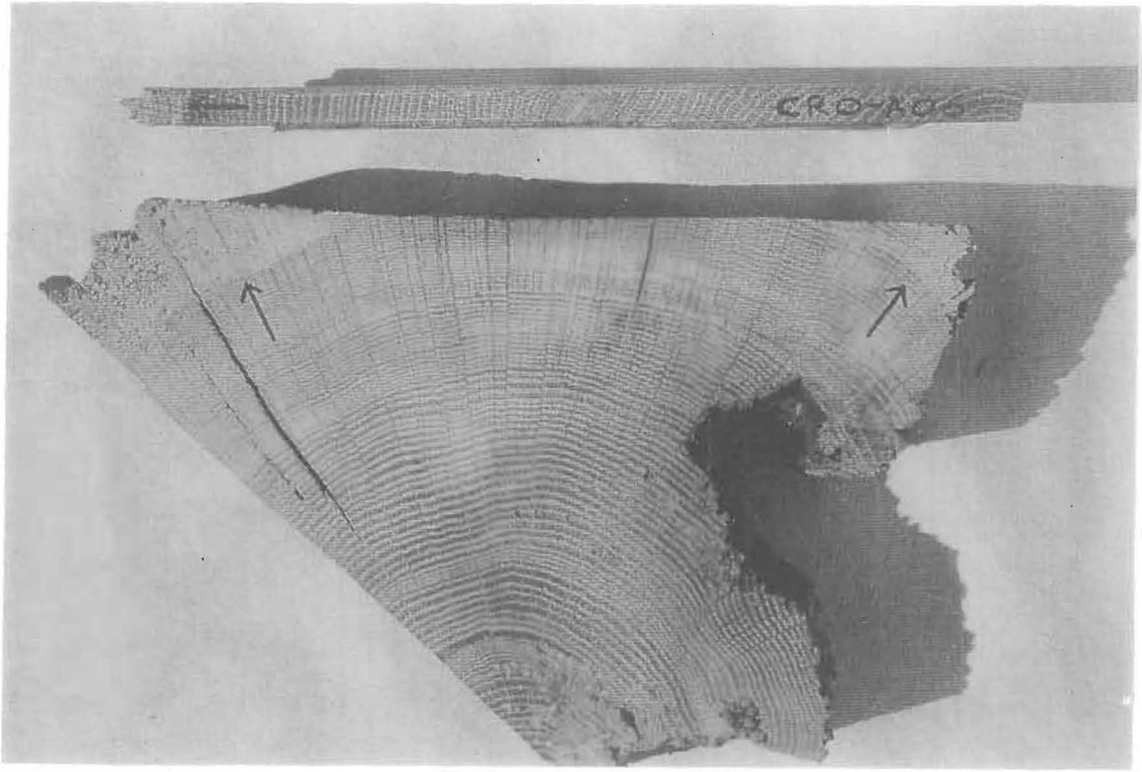

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners; the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

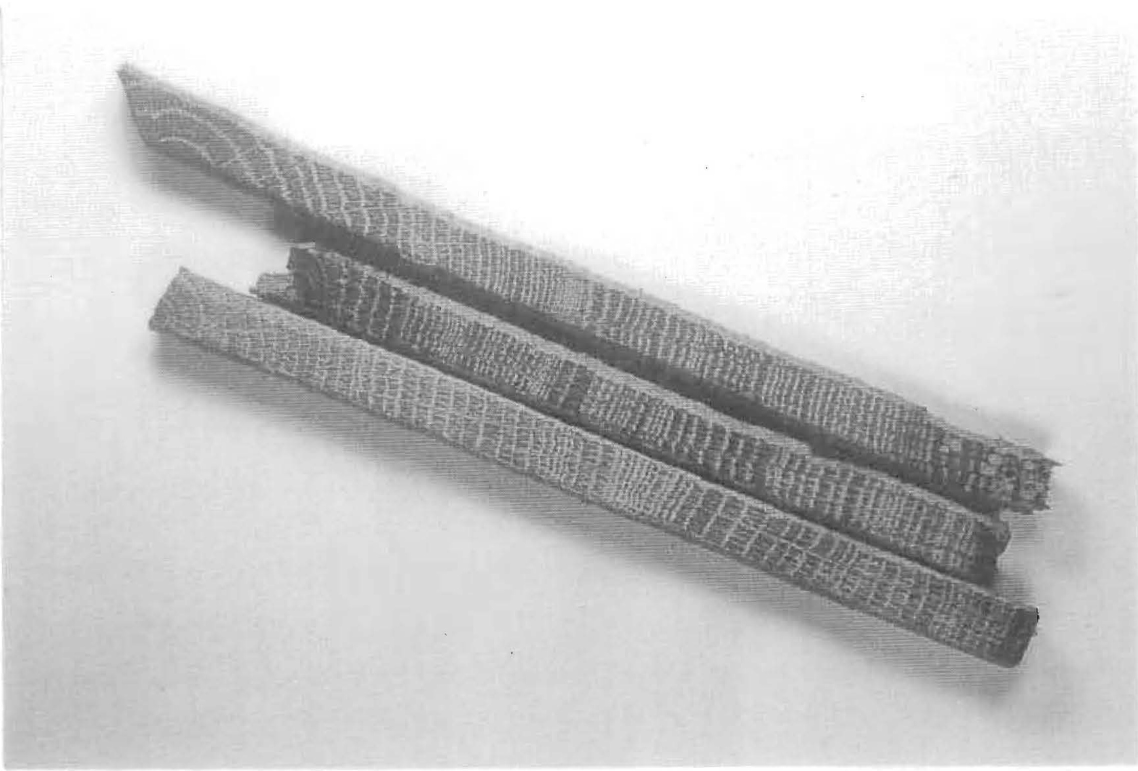

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

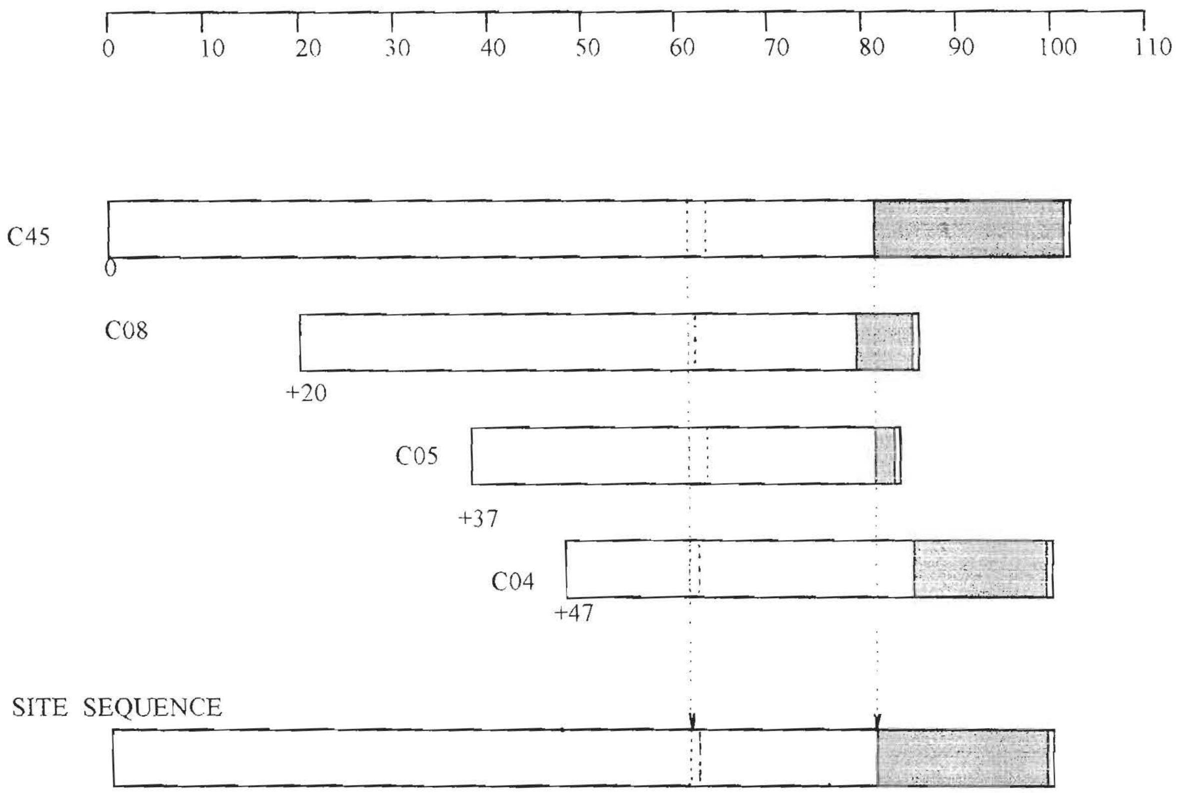

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

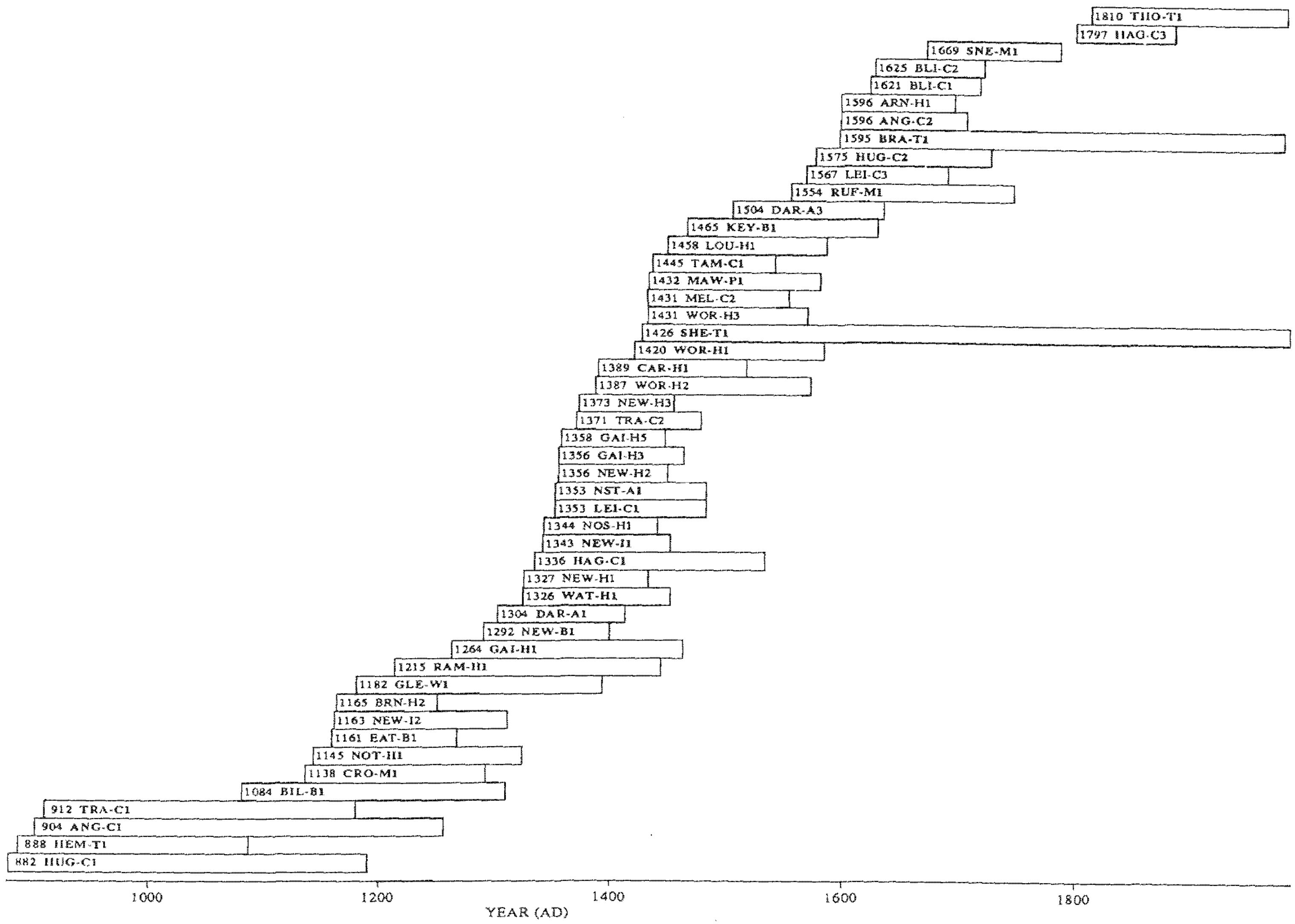

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

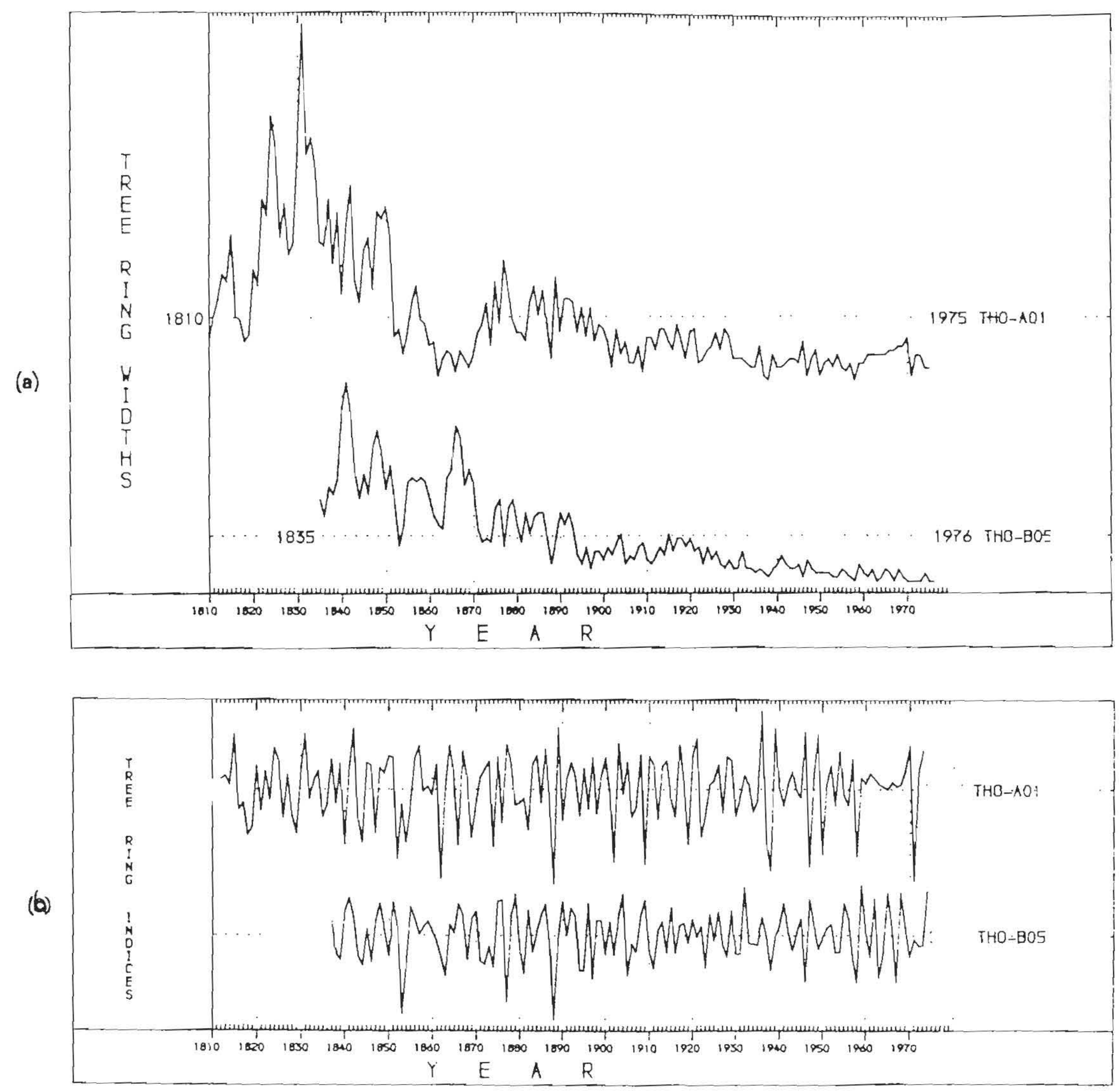

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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