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ICKENHAM MANOR, LONG LANE, ICKENHAM, HILLINGDON, LONDON
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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Alison Arnold and Robert Howard

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SUMMARY

Analysis of material from the oak timbers of the cross-wing at Ickenham Manor Farm has resulted in the production of a single site chronology comprising 10 of the 13 samples obtained. This site chronology has an overall length of 110 rings, these being dated as spanning the years AD 1374 to AD 1483. Interpretation of the sapwood indicates that all the dated timbers were probably cut in a single phase of felling in AD 1483. As such this date is slightly earlier than the sixteenth century date ascribed to the cross-wing on the basis of stylistic and comparative evidence.

CONTRIBUTORS

Alison Arnold and Robert Howard

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Greater London Historic Environment Record
English Heritage
1 Waterhouse Square
138-142 Holborn Place
London EC1N 2ST

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

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INTRODUCTION

Ickenham Manor lies on the eastern edge of Ickenham, just north of the A40 and west of Ickenham Marsh (TQ 0829 8533, Figs 1 and 2). It is a two-storeyed grade 1 listed timber-framed house surrounded by the remains of a moat. The following information is summarised from Clarke (1991).

The origins of Ickenham Manor can be traced back to three Saxon holdings amalgamated under Earl Roger of Shrewsbury by the time of Domesday Book. In the second quarter of the fourteenth century the Manor was acquired, through marriage, by Nicholas Shorediche, the Shorediche family then holding the estate until it was sold to George Robinson in AD 1812. The estate was then sold to Thomas Clarke, owner of the adjoining Swakeleys Manor, in AD 1859, it being held by the Clarke family from then until AD 1961. At that time the Manor House and a few acres of land were purchased by Sir Peter Tizard, a descendent of the Shorediche family. It has now passed to Sir Peter's son, Humphrey Tizard.

There are several phases of building detectable within the extant building (Fig 3). The earliest phase is believed to have been a four-bay open hall running east–west. The service rooms are thought to have been at the west, or lower, end of the hall, the high end, with solar over, being at the east end. On the basis of stylistic evidence and features of the carpentry, it is believed that the hall can be dated to the middle or later part of the fourteenth century and it is possible that its construction is related to the acquisition of the site by Nicholas Shorediche at about this time.

In the second major phase of construction a two-storeyed, north–south, cross-wing was added to the east end of the hall. This is also of four bays and is jettied at its north end. On the basis of stylistic evidence again, as seen in door and window mouldings, the cross-wing has been dated to the first half of the sixteenth century.

It is believed, again on stylistic evidence, that in the seventeenth century a three-storey staircase wing was built in the angle between hall and cross-wing. It is likely that there was accommodation on the ground and top floors of this wing, with a large landing at first floor level giving access to each of the other wings. It is believed that this staircase wing replaced an existing structure here, probably a simple outshut, but possibly an earlier stairs.

Brick-built additions were made in the eighteenth century to both the south-east and north-east corners of the cross-wing, that to the south-east being used as a parlour, with that to the north-east being used as services. In addition to these major periods of building there were other, minor, alterations including the insertion, and later blocking, of fireplaces, and the construction of porches and small extensions.

The roof of the open hall is of crown-post construction, the crown posts being plain and un-moulded, with straight braces to the collar purlin. The timbers of the extant roof are heavily sooted indicating the existence of an open fire in the hall below. The original walling was probably of large panels with upward braces and studding, the cross-frame probably being of heavy wall-posts, held by slightly cambered tiebeams with arch braces. Only the roof timbers and some of the larger members of this framing, including the main wall posts, now survive.

The roof of the cross-wing is of clasped purlin type, with paired common rafters between three main trusses divided by two intermediate trusses. The main trusses to the north and south gable ends, trusses 1 and 5 respectively, comprise principal rafters, tiebeams, collars and queen posts (through truss 5 is a modern, twentieth-century, oak replacement). Main truss 3, the central truss, is closed above its mid-rails by vertical studs and plaster, and by plaster on wattle below. It is also pierced by a doorway. Between the main trusses are found intermediate trusses 2 and 4, which have lighter principal rafters and collars, and are without tiebeams.

The roof of the staircase wing consists of a single bay of common rafter frames between two larger frames at the east and west gables, these being of tiebeam, queen post, and collar form. Below this the walls are constructed of close studding with diagonal braces to the west wall, and rails to the north wall.

SAMPLING

Sampling and analysis by tree-ring dating of the roof timbers within Ickenham Manor was commissioned by English Heritage. The purpose of this was to elucidate the chronological development of the site and hence inform a programme of repairs. In particular tree-ring sampling was requested of timbers from three main areas, the remains of the former open hall, the cross-wing, and the staircase wing.

It was decided, however, after a thorough examination of the building was undertaken with Richard Bond, then of English Heritage's Historical Analysis and Research Team, and in conjunction with the sampling brief, that only the roof timbers of the cross-wing should be sampled, all the timbers of the open hall and the staircase wing being either derived from fast grown trees or too small. As such, it was felt that they were very unlikely to provide samples with at least the minimum of 54 rings necessary for reliable analysis. It was seen during this examination that, although they were of more substantial size, the timbers of the lower floors of the cross-wing were also unsuitable for dating.

Thus, from the timbers available a total of 10 core samples was obtained, each sample being given the code ICK-A (for Ickenham, site "A") and numbered 01–10. All the timbers sampled appeared to be primary and integral with each other, all being jointed and pegged. In addition to the 10 core samples obtained from the cross-wing by the Nottingham Tree-ring Dating Laboratory, three cross-sectional slices, previously analysed by Ian Tyers, then of the Museum of London, were also re-analysed as part of this programme of research. These three slices, designated in this report as ICK-A11–A13, had been cut from discarded timbers removed during repairs to the cross-wing and sent to Ian Tyers in 1990. This work was not published and hence it was agreed to incorporate the results into this extended study.

The positions of the trusses of the cross-wing, and the 10 cores obtained from them, were marked on sketch drawings made at the time of sampling (Figs 4 and 5). Details of the samples are given in Table 1. In this Table, all bays, trusses, and other timbers have been numbered from north to south, being further identified on an east–west basis as appropriate.

ANALYSIS

Each of the 10 core samples obtained was prepared by sanding and polishing and their annual growth-ring widths were measured. The growth-ring widths of these 10 samples, plus those of the three additional samples, by then held by the University of Sheffield Dendrochronology Laboratory, were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum value of t=4.5 a single group comprising 10 samples could be formed, the samples cross-matching with each other at relative off-set positions as shown in Figure 6. The samples were combined at these off-sets to form ICKASQ01, a site chronology of 110 rings. Site chronology ICKASQ01 was then satisfactorily dated by comparison to a number of relevant reference chronologies for oak as spanning the years AD 1374 to AD 1483. The evidence for this dating is given in Table 2.

Site chronology ICKASQ01 was then compared with the three remaining ungrouped samples, ICK-A05, A10, and A12. There was, however, no further satisfactory cross-matching. Each of the three ungrouped samples was than compared individually with the full range of reference chronologies. There was, again, no reliable cross-matching and the three samples must remain undated.

INTERPRETATION

Analysis by dendrochronology of material from this site has produced a single site chronology, ICKASQ01, comprising 10 of the 13 samples obtained, its 110 rings dated as spanning the years AD 1374 to AD 1483. Two samples in this site chronology, ICK-A02 and A04, retain complete sapwood. This means that they each have the last ring produced before the tree, or trees, they represent were felled. In both cases the last measured ring date, and thus the felling of the trees represented, is the same at AD 1483.

Some supporting evidence for all the dated timbers being cut as part of a single programme of felling may be found in the degree of cross-matching between some of the samples here analysed. This process produces a number of cross-matches with values in excess of t=6.0. Such t-values would suggest that the trees were growing very close to each other in the same woodland. Indeed, given that a value of t=10,0 is found between samples ICK-A03 and A04, the cross-rails to either side of the doorway in truss 3, it is likely that at least two timbers have been derived from the same tree. It would be relatively unexpected to find timbers in the same structure which had originally been growing close to each other, but which had been felled at very different times. The evidence of the tree-ring analysis therefore indicates a single felling programme.

On the basis of stylistic evidence a date in the first half of the sixteenth century had been proposed for the cross-wing. A date of AD 1483 for the felling of the timbers would suggest that the sampled timbers are a little older than had been previously believed. Although only the cross-wing has been dated, the accuracy of the result provides a fixed point around which the sequential development of the site, the relative date of the earlier hall and the later stair-wing, might now be more reliably fixed. Such a result thus reinforces the benefits of tree-ring dating even where only part of a larger building can be sampled and dated.

Three samples, ICK-A05, A10, and A12, remain undated. None of these samples show compacted or distorted rings that might make cross-matching and dating difficult. There appeared to be nothing unusual about the timbers such as evidence for the reuse of earlier, or later repair, timbers that might cause difficulties in dating.

The source woodland for the timbers dated here cannot be identified precisely by dendrochronology (eg Bridge 2000), but it seems probable that they are relatively local to London. As may be seen from Table 2, which lists a short selection of the reference chronologies used to date site sequence ICKASQ01, the highest *t*-values, and thus the greatest degree of similarity, are with the reference chronologies made up of material from other sites in London and the south–east.

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TABLES

Table 1: Details of tree-ring samples from Ickenham Manor, Ickenham

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
ICK-A01	West purlin, truss 1–3	69	h/s	AD 1393	AD 1461	AD 1461
ICK-A02	West purlin, truss 3–5	101	22C	AD 1383	AD 1461	AD 1483
ICK-A03	West cross rail, truss 3	74	h/s	AD 1395	AD 1468	AD 1468
ICK-A04	East cross rail, truss 3	77	16C	AD 1407	AD 1467	AD 1483
ICK-A05	East purlin, truss 3–5	80	h/s	------	------	------
ICK-A06	West principal rafter, truss 3	88	h/s	AD 1374	AD 1461	AD 1461
ICK-A07	East queen post, truss 1	80	no h/s	AD 1374	------	AD 1453
ICK-A08	West queen post, truss 1	92	22	AD 1385	AD 1454	AD 1476
ICK-A09	Collar, truss 1	70	h/s	AD 1399	AD 1468	AD 1468
ICK-A10	East purlin, truss 1–3	60	h/s	------	------	------
ICK-A11	Wall post 1 (exact location uncertain)	76	h/s	AD 1395	AD 1470	AD 1470
ICK-A12	Wall post 2 (exact location uncertain)	62	no h/s	------	------	------
ICK-A13	Wall post 3 (exact location uncertain)	76	h/s	AD 1395	AD 1470	AD 1470

*h/s = the heartwood/sapwood ring is the last ring on the sample

C = complete sapwood is retained from the sample

Table 2: Results of the cross-matching of site sequence ICKASQ01 and relevant reference chronologies when first ring date is AD 1374 and last ring date is AD 1483

Reference chronology	Span of chronology	*t*-value	Reference
Headstone Manor barn, Harrow, London	AD 1374–1505	10.3	(Howard *et al* 2000)
Hays Wharf, Southwark, London	AD 1248–1647	8.9	(Tyers 1996a; Tyers 1996b)
Walmer Castle, Kent	AD 1396–1523	8.7	(Howard *et al* 1997)
Fulham Palace, Hammersmith and Fulham, London	AD 1356–1494	8.4	(Bridge and Miles 2004)
Windsor Castle, Berkshire	AD 1192–1613	8.3	(Tyers *et al* 1997)
Mercer's Hall, Gloucester	AD 1289–1541	7.8	(Howard *et al* 1996)
Millennium Bridge, Southwark, London	AD 1403–1582	7.3	(Tyers 1999)
Mary Rose ship	AD 1334–1503	7.3	(Bridge and Dobbs 1994)

FIGURES

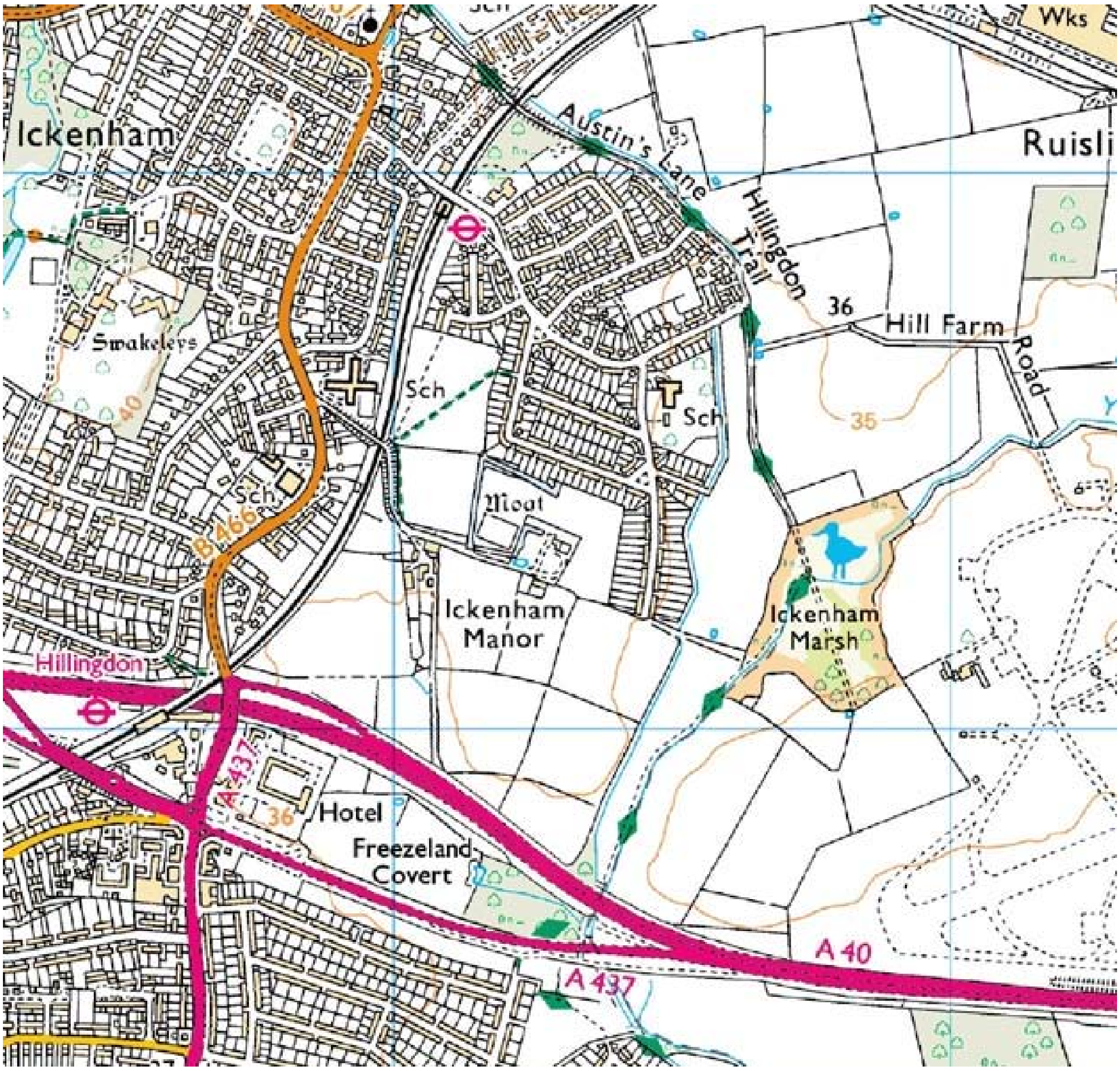


Figure 1: Location of Ickenham Manor (circled). © Crown Copyright. All rights reserved. English Heritage 100019088 2011

Figure 2: Detailed location of Ickenham Manor. © Crown Copyright. All rights reserved. English Heritage 100019088. 2011

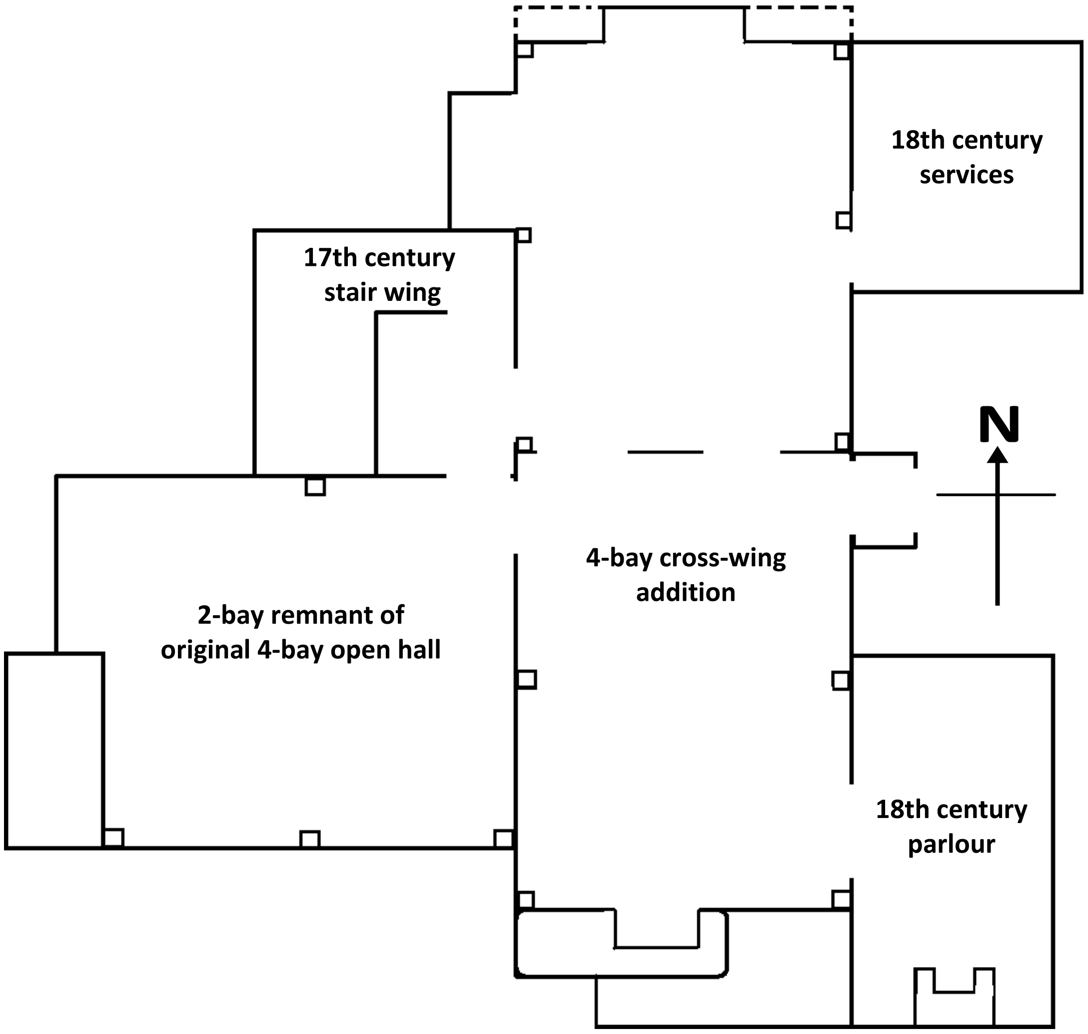


Figure 3: Basic plan of Ickenham Manor (after Clarke 1991)

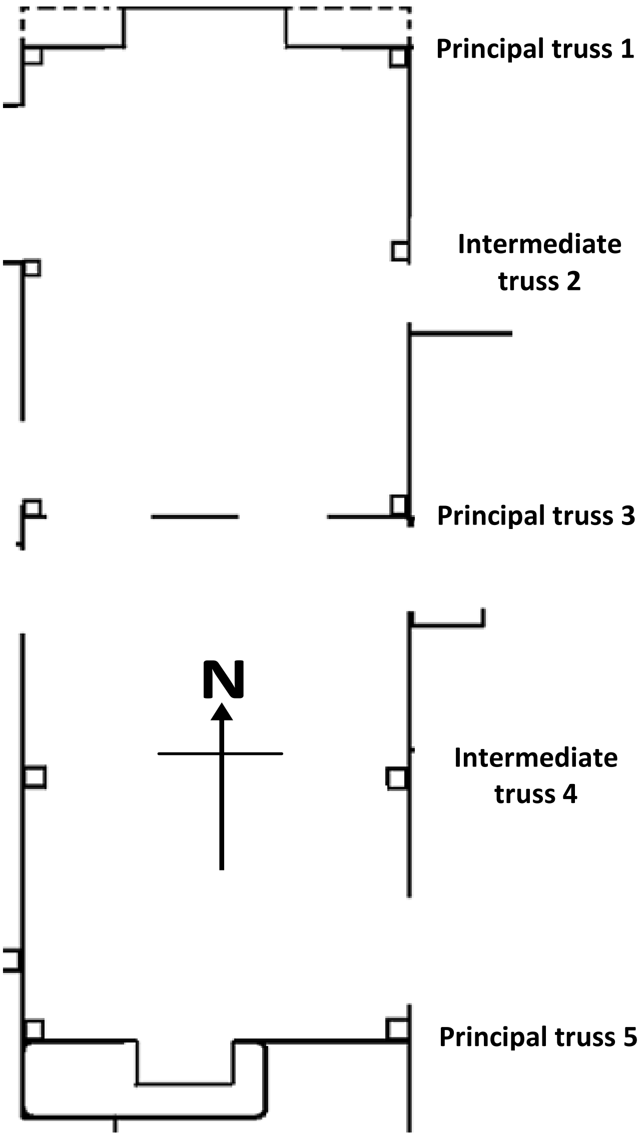


Figure 4: Simple plan of the cross-wing to show truss positions (after Clarke 1991)

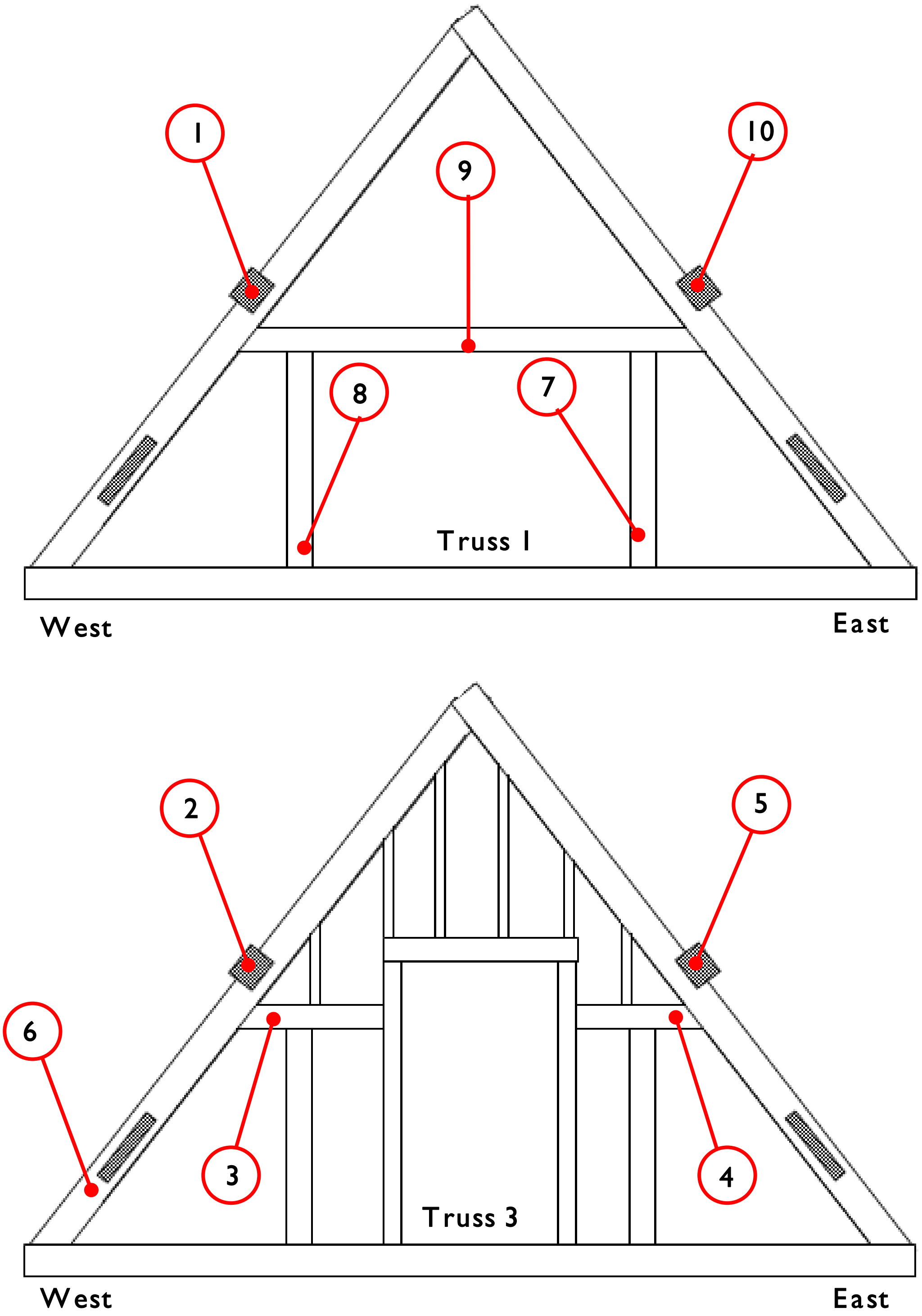
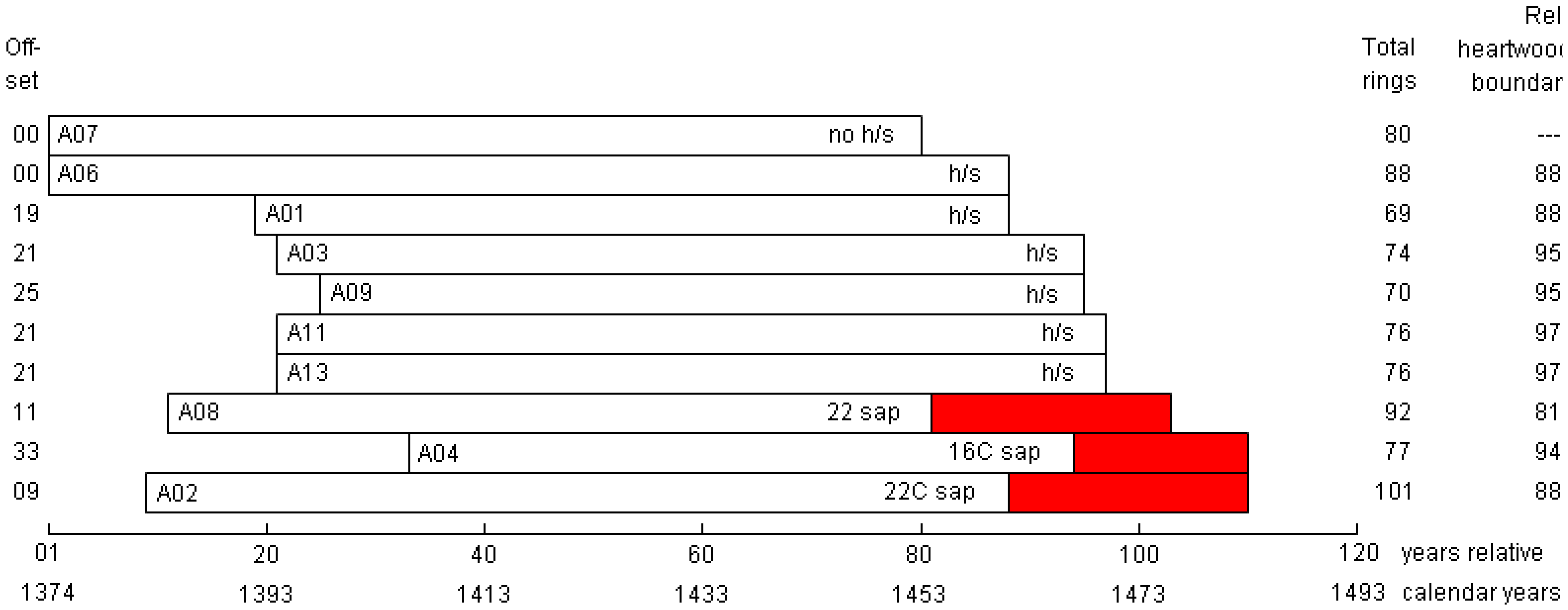


Figure 5: Sketch section of the cross-wing trusses to show sampled timbers



White bars = heartwood rings; Red bars = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing
C = complete sapwood is retained on the sample

Figure 6: Bar diagram of the samples in site chronology ICKASQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

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ICK-A01A 69
 156 177 213 161 144 182 118 219 201 125 110 179 179 249 242 364 276 286 203 143
  89  92 102  86  79 143 155 177 154 126 182 162 158  95 123 203 166 148 177 167
 132 129 147 101  79 100 115 107 104 145  94  86 101  89 141  93 129 119 113 113
  92 126  98 118 110 136 112  85 131
ICK-A01B 69
 159 192 197 173 136 188 107 229 186 112 137 170 201 248 245 362 270 284 202 155
  84  70  93  82  91 139 145 205 164 127 186 160 164  91 120 198 178 151 181 178
 119 125 136 112  82 101 109  93 115 151  87  93  89 104 134  85 133  99 116 108
  87 128  98 100 125 132 134  65 132
ICK-A02A 101
 240 380 171 291 476 417 291 304 311 125 123 232 200 199 195 191 183 161 155 155
 142 255 235 323 233 219 202 133 151 106  99  62  79  60  56 110  86 203 147 122
 197 129  94  43  49  94  78  88  81  77  58  46  88  83  75  54  60  65  60  73
  47  46  45  37  44  47  53  37  39  37  62  59  49  53  53  49  42  45  60  67
  63  48  64  91  65  62 106  94  76  91  59  85 100  44  45  60  49  99 116 100
  99
ICK-A02B 101
 209 364 214 317 500 375 281 295 307 121 130 200 197 202 184 190 184 169 157 151
 150 255 232 326 237 220 204 127 150 103  97  64  70  77  60 110  86 187 145 113
 185 136  98  52  38  97  75  86  80  78  60  46  91  82  80  65  56  72  58  50
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  64  47  78  64  69  68  91  87  84  79  69  83  92  53  42  50  58  81 106 101
  99
ICK-A03A 74
 270 249 226 311 350 275 254 175 252 369 368 439 299 291 268 164 221 215 164 153
 142 136 118 149 137 247 279 197 302 234 156 115  88 180 167 210 210 231 161 179
 223 190 214 168 166 161 180 197 135 166 143 166 215 179 166 163 223 148 143 178
 126 109 126 158 118 157 115 175 133  71 124 105 120 123
ICK-A03B 74
 246 256 223 300 347 269 246 175 240 386 375 426 267 304 232 183 244 227 169 166
 152 144 113 149 141 247 284 189 295 239 161 114  86 190 162 199 222 232 162 184
 223 193 210 164 171 156 186 200 138 161 163 161 215 179 161 169 212 155 144 171
 131 113 119 148 135 162 118 174 120  83 129  98 117 121
ICK-A04A 77
 258 351 269 213 290 163 174 151 138 151  96 141 117 233 237 214 257 244 139 106
 105 191 127 145 190 288 149 155 239 188 223 183 201 162 188 209 117 140 131 149
 182 172 195 193 242 181 184 243 149 144 144 125  95 111 115 124 110  64 116  85
  66  97 168 163 149 153 102 106 128 102  74  88 201 140 208 199 180
ICK-A04B 77
 282 370 246 237 268 278 156 154 147 152  94 151 119 213 245 214 261 241 162 118
 105 224 107 147 183 282 146 158 220 170 207 182 196 149 183 192 144 124 114 151
 169 172 193 205 220 193 176 230 159 152 149 124 107 104 119 133 101  65 108  92
  84  80 176 149 157 154  94 110 134  97  79  91 175 148 202 198 180
ICK-A05A 80
 490 483 471 466 444 657 482 319 244 236 162 207 191 236 203 149  86  74  65  52
  95  83  76  70  54  61  42  37  30  38  37  40  34  29  35  32  39  14  29  34
  30  22  70 115 105 101  74  88  66  67  66  48  58  71  55  64  54  51  52  46
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  33  25  20  26  38  29  64 215 191 200 152 158 172 185 185 207 164  88 139 162
ICK-A05B 80
 507 464 477 487 420 644 493 302 241 250 153 219 215 222 200 155  93  55  51  78
  91  94  63  63  63  59  35  45  38  28  28  30  26  43  29  23  24  22  41  34
  23  27  65 113 109  99  78  85  71  65  62  54  48  73  53  63  54  59  53  44
  37  30  22  15  34  32  63 218 193 204 136 158 175 184 187 206 172 129 146 164
ICK-A06A 88
 412 303 407 282 267 338 212 220 254 242 318 281 306 355 354 193 293 286 220 246
 191 199 184 165 252 199 212 146 134 151 188 169 208 170 128 163 132 146  92  98
  69 100  75  97  92  84  90 109  90 109  98  72  52  53  62  67  71  65  73  62
  64  70  72  64  85  81  95  98  88  87  88  76  66  75  80  80  81  83  77  80
  76  96  91  86  74  88 108 122
ICK-A06B 88
 343 295 414 277 257 339 212 216 254 239 315 288 295 367 347 199 296 288 215 232
 191 199 180 165 248 208 208 159 127 158 186 173 214 162 153 163 130 147  94  88
  70 109  78  81  95  81  93 112  83 106 110  54  49  63  60  64  76  64  75  62
  66  76  69  70  81  82  90  97  84  85  93  72  67  75  84  85  76  82  69  86
  85  94 101  77  76  80  98 126
ICK-A07A 80
 183 364 436 264 266 338 349 240 295 213 262 197 242 239 201 222 305 210 224 226
 223 198 210 152 245 280 308 208 128 164 196 170 176 158 195 182  97 118  88  85
  76  86  73  99 110  80 128 123  79 111  65  56  50  75 145 117  88 105 173  92
  88  98  84  57  57  67  76  67  79  59  74  48  44  41  47  48  44  64  46  37
ICK-A07B 80
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 228 180 210 154 240 281 297 207 130 147 217 162 170 145 181 175  98 117  86  75
  64  92  81  92 102  91 124 115  84  97  63  62  58  85 131 109 105 107 155  92
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ICK-A08A 92
 253 320 347 334 354 354 325 241 229 250 227 233 203 294 221 195 134  79  93  93
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ICK-A09A 70
 180 162 154 156 197 238 204 202 185 226 155 131 146 137 149 124 124 110  95 123
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 108 114 134 137 114  80  98 110 134 157
ICK-A09B 70
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 121 152 137 179 184 131 108  70  77 105 102  92  99  94  85  70  74  72  67  96
  70  73  62  95 105  94  76  77  73  91  69  72 103 113 121 140 141 147 127 135
 101 109 143 119 120  77  97 116 121 149
ICK-A10A 60
 262 288 293 339 422 378 359 410 356 373 387 460 407 449 396 403 389 260 294 354
 253 256 194 192 203 158 195 178 148 138 121 129 163 139 119  80 129 142 114 119
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 112  94 112  79  73  74 102  76 122 101  75  85  63  73  58  72  70  54  61  66
ICK-A10B 60
 223 301 354 319 457 369 354 421 350 355 338 445 409 452 431 397 376 264 283 353
 278 246 188 199 187 147 192 174 155 145 110 138 168 131 114  84 125 147 121 104
 112 102  94  89  71  82  86  81  93 101  77  95  58  75  61  54  71  53  66  75
ICK-A11A 76
 319 316 201 274 270 264 250 232 162 241 232 254 226 335 248 280 218 175 179 218
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 208 248 269 202 214 257 385 284 275 216 256 175 244 216 249 294 337 240 288 390
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 293 136 189 346 270 279 269 207 319 263 292 244 227 256 215 243 245 171 186 224
 193 148 230 175 200 300 228 230 167 155 207 258 175 238 230 181 148 175 140 239
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 239 264 210 265 254 183 296 221 228 330 193 271 287 371 307 262 291 247 270 289
 290 260 235 258 238 295 274 213 297 293 226 209 262 371 359 364 407 411 247 227
 318 280 315 224 248 226 312 255 252 245 246 194 258 199 237 238 335 191 242 316
 275 292 225 238 197 174 177 193 227 184 219 310 236 190 200 146
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building (Laxton and Litton 1988) and Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 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.

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 A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: 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

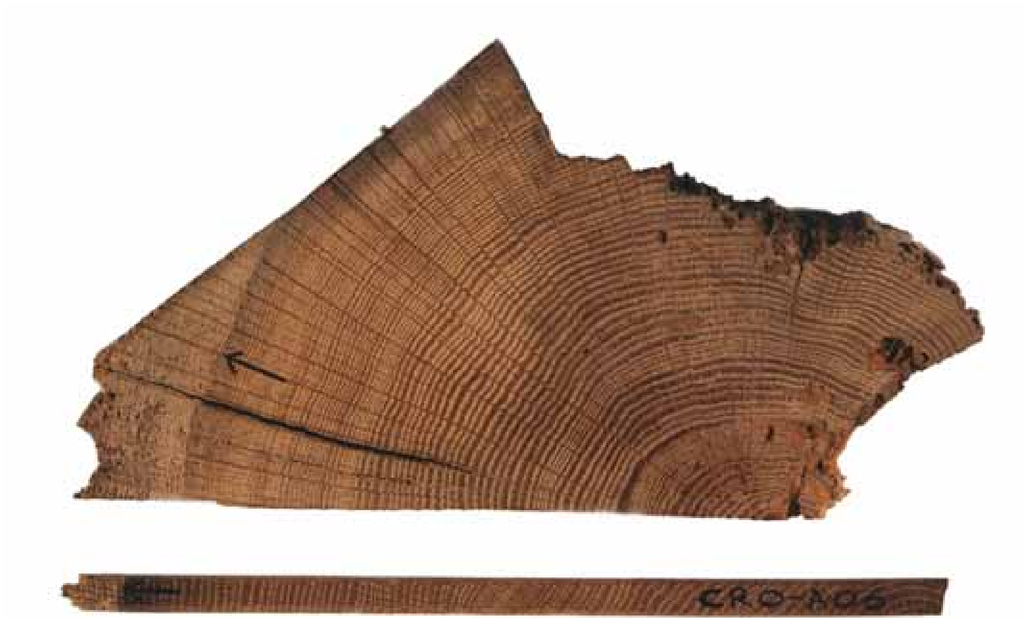


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: 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

Figure A4: 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

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 A2. 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 A3).

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 A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the t-value (defined in almost any introductory book on statistics). That offset with the maximum t-value among the t-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a t-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton et al 1988; Howard et al 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the t-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal t-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton et al 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton et al 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard et al 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a post quem date for felling is possible.

5. **Estimating the Date of Construction.** There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton et al 2001, fig 8; 34–5, where ‘associated groups of fellings’ are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. **Master Chronological Sequences.** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 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 Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton et al 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. **Ring-Width Indices.** Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

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	

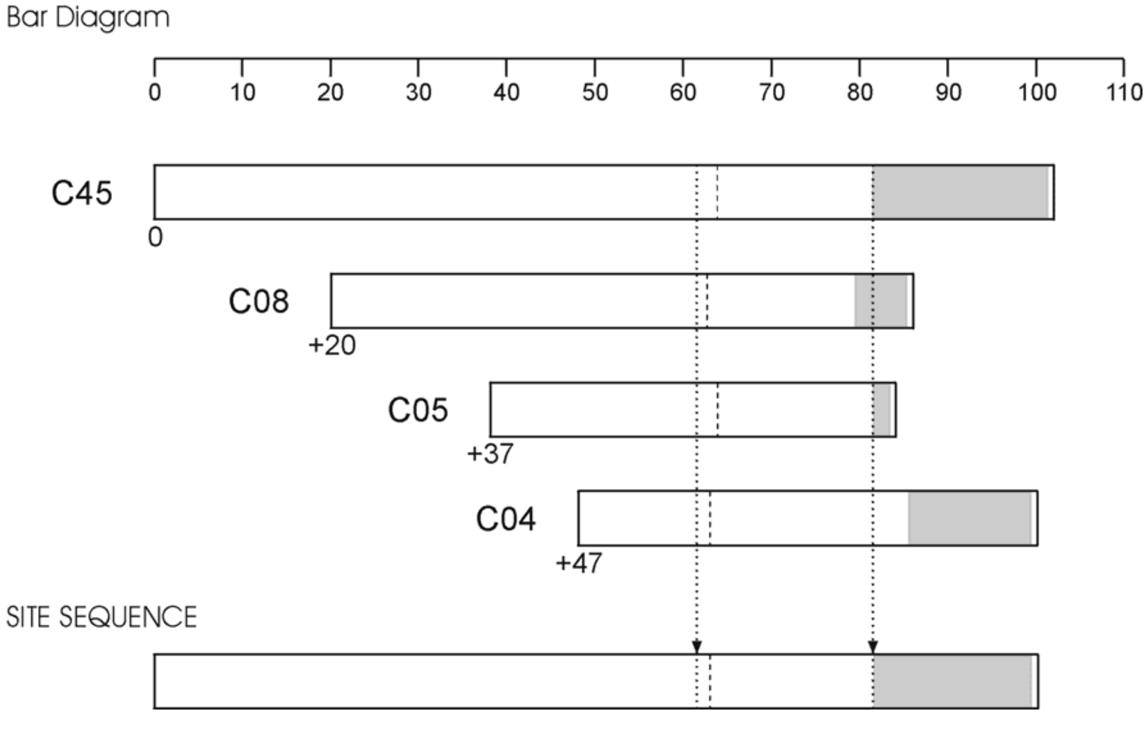


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

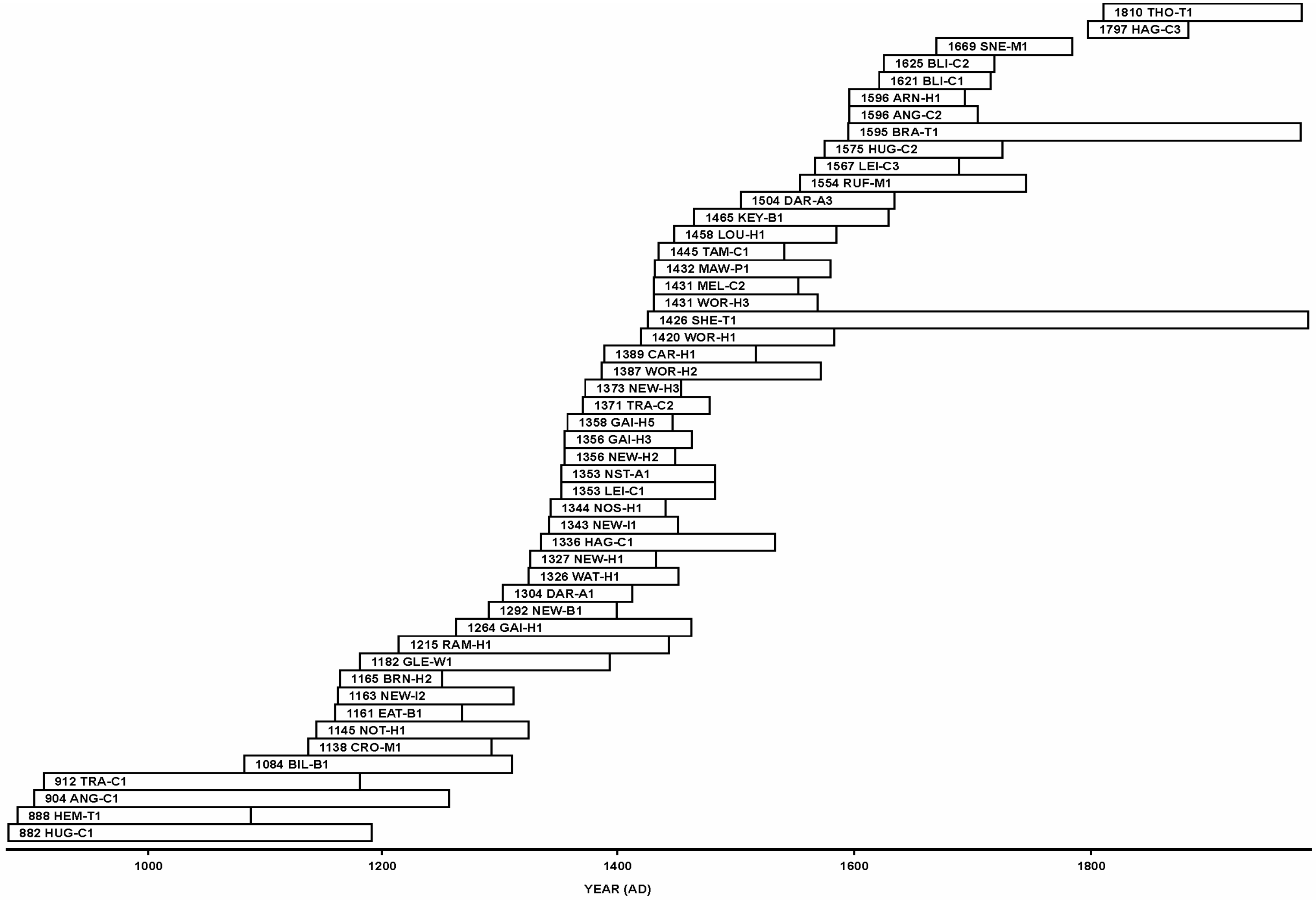
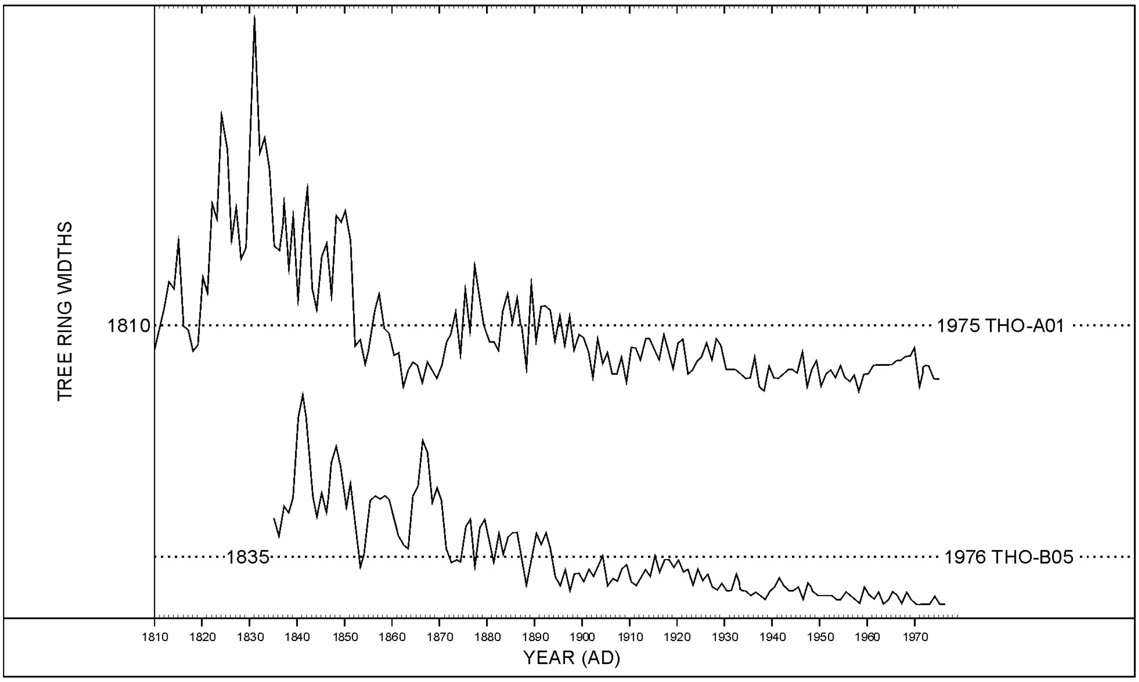


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

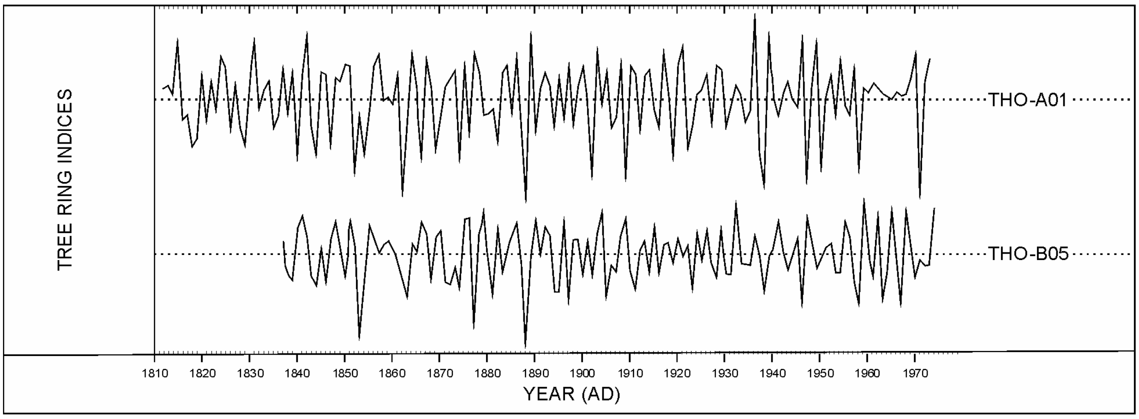


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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