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TREE-RING ANALYSIS OF TIMBERS FROM THE NORTH AISLE OF ST NICHOLAS' CHURCH, STANFORD-ON-AVON, NORTHAMPTONSHIRE

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Summary

Dendrochronological analysis of samples from timbers of the North aisle of St Nicholas' resulted in the production of a felling date in the range 1488 to 1513. While they all have a similar felling date, it appears likely that the timbers come from different sources. A site chronology spanning the period AD 1349 - 1479 was created.

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Introduction

When built originally, *c* AD 1300 - 50, St Nicholas' church (SP 589789) was covered by a single roof spanning the nave and both aisles. Some time later, *c* AD 1500 on stylistic grounds, the present roofs were constructed, one covering the nave and one each for the north and south aisles. The roof of the south aisle was recently restored but its historic fabric was not recorded. The roof of the north aisle is of five bays, formed by six trusses. The tiebeams of the trusses are extensively decorated, with continuous mouldings at either side of a central boss. The central boss of each is integral to the beam and is deeply carved in relief depicting flowers or foliage. The tiebeams at either end of this roof are only moulded on the inner, visible, faces. The bosses of these two are left as rough unfinished lumps where they fit against the walls of the gables. The frames have been labelled A - F from east to west. The common rafters have been numbered 1 - 7 from east to west within each bay, being further identified as coming from the north or south pitch of the aisle roof.

The extensive repairs to the north aisle roof revealed large portions of the fabric to be badly affected by wood-boring beetle infestation and widespread dry-rot. This was particularly the case with the ends of the tiebeams where they entered the side walls. Repairs and renovations necessitated the complete dismantling of the roof.

The dismemberment of the roof allowed for very close inspection and accurate recording of the timberwork. This has revealed differences between the three eastern trusses, A - C, and the three western trusses, D - F. For example the mouldings of the tiebeams of trusses A - C are consistent with each other but differ markedly from the moulding of the tiebeams of trusses D - F, which are equally consistent with each other. Differences between the mouldings of the wall posts of trusses A - C and D - F were also observed. The manner in which the ridge-beams were joined to the tiebeams similarly varied between the two halves of the roof. In trusses A - C the ridge-beams merely lapped on top of the tiebeams, in trusses D - F they were housed or tenoned into the upper arris of the beam. The purlins also exhibit differences in moulding forms and other traits between the two halves of the roof.

It has been suggested that the stylistic differences between trusses A - C and D - F indicate the work of two separate carpenters. Tree-ring analysis was commissioned to determine the felling date of the timbers in an attempt to establish whether they were working concurrently or consecutively.

A particular problem at this site from a tree-ring dating point of view was the lack of complete sapwood, or indeed any sapwood, that was not completely decayed. This was not only because the timbers were extensively moulded and highly decorated but also because they were extensively worm eaten and rotten, especially at the beam ends.

Site analysis and results

Sampling was accomplished at this site by slicing up offcuts taken from the rotted ends of tiebeams and rafters. These offcuts had been taken by the conservation carpenters who recorded the location of each as they were removed from the roof. Each sample was given the code SOA-C for Stanford-on-Avon Church, and numbered 1 - 12. Full details of the samples are given in Table 1. The location of each sample is also recorded on the drawings provided at the time of sampling (Fig 3).

Two of the samples, SOA-C09 and 10, had too few rings and were not measured. All ten usable samples were measured and compared with each other by the Litton/Zainodin grouping procedure (Appendix). Three samples cross-matched with each other at the offsets shown in Figure 1. The ring widths from these three samples were averaged at these positions to form SOACSQ14, a site chronology of 80 rings. Site chronology SOACSQ14 was successfully cross-matched with a series of reference chronologies for oak, giving a first ring date of AD 1400 and a last measured ring date of AD 1479. Evidence for this dating is given by the t-values of Table 2.

Each of the remaining nine samples was cross-matched with a series of reference chronologies, five of these being dated: samples C01, 02, 03, 08, and 12 (Table 3 - 7). The dates of C02 and 03 could be confirmed by cross-matching with site chronology SOACSQ14. These two samples were combined with the three samples in the site chronology, at their suggested relative positions, to form site chronology SOACSQ20 (Fig 2). This site chronology was likewise successfully cross-matched with the reference chronologies, having a first ring date of AD 1349 and a last measured ring date of AD 1479. Evidence for this dating is given by the t-values of Table 9. This site chronology did not cross-match with any of the remaining ungrouped samples.

Two of the measured samples remain undated. One, sample SOA-C11, has only 41 rings and is too short to provide reliable data. The other, sample SOA-C04, has 77 rings. There appears to be no particular problem with this sample but, although it was compared with the full range of reference chronologies, there was no suggestion of a possible date.

Taking the last heartwood of all dated samples, grouped and ungrouped, we obtain an average last heartwood ring date of AD 1473. This gives a felling date in the range AD 1488 to 1513.

Conclusion

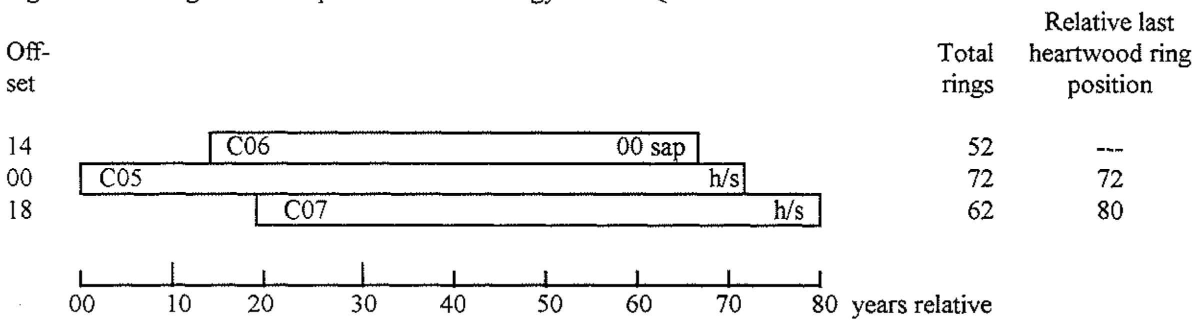
Analysis of the timbers from St Nicholas' resulted in the production of a single dated site chronology, SOACSQ20, spanning the period AD 1349 - 1479. It would appear that all the timbers used here were probably felled within the period AD 1488 to 1513. There is no appreciable difference, perhaps only a few years, in the likely felling dates of the trees used for trusses A - C or trusses D - F. However, the lack of cross-matching between samples from the different trusses means it may be possible that the trees used do come from quite different sources. This might suggest the use of different workshops and carpenters which may account for the different styles of decoration.

Table 1: Details of tree-ring samples from St Nicholas' Church, Stanford-on-Avon, Northamptonshire.

Sample no.	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
SOA-C01	Tiebeam truss B	98	h/s	AD 1373	1470	1470
SOA-C02	Tiebeam truss D	111	none	AD 1349	------	1459
SOA-C03	Tiebeam truss E	112	h/s	AD 1357	1468	1468
SOA-C04	Tiebeam truss F	77	h/s	------	------	------
SOA-C05	North common rafter 5 bay C/D	72	h/s	AD 1400	1471	1471
SOA-C06	North common rafter 6 bay C/D	52	none	AD 1414	------	1465
SOA-C07	North common rafter 7 bay C/D	62	h/s	AD 1418	1479	1479
SOA-C08	North common rafter 4 bay D/E	60	h/s	AD 1423	1482	1482
SOA-C09	North common rafter 1 bay D/E	NM	----	------	------	------
SOA-C10	North common rafter 3 bay C/D	NM	----	------	------	------
SOA-C11	Tiebeam truss A	41	h/s	------	------	------
SOA-C12	Tiebeam truss C	76	h/s	AD 1394	1469	1469

* NM = not measured
h/s = heartwood/sapwood boundary on sample

Figure 1: Bar diagram of samples in site chronology SOACSQ14



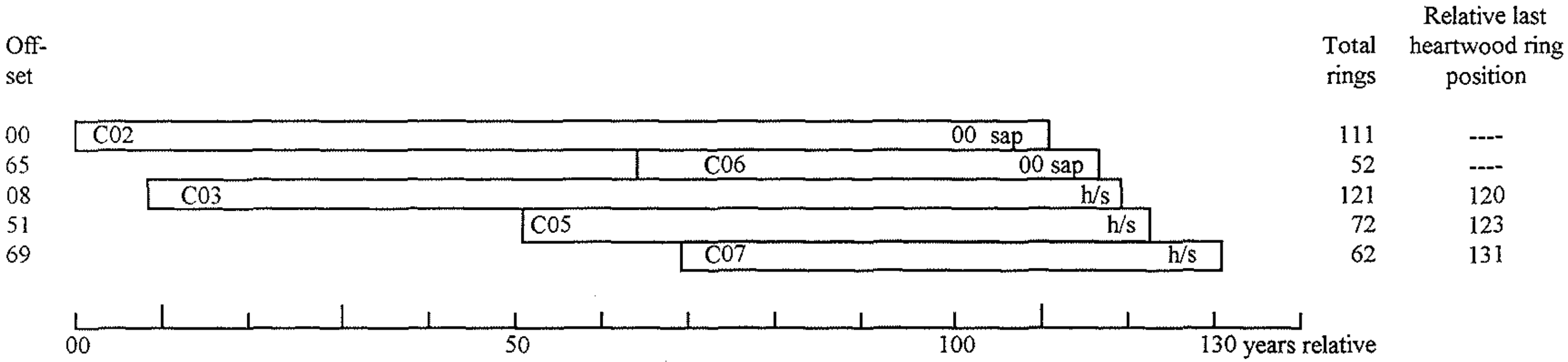
White bar = heartwood rings, h/s = heartwood/sapwood boundary on sample

00 sap = only heartwood on sample, no heartwood/sapwood boundary
h/s = heartwood/sapwood boundary on sample

Table 2: Results of the cross-matching of site chronology SOACSQ14 and relevant reference chronologies when last ring date is AD 1479

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	6.7	(Laxton and Litton 1988)
England	AD 401 - 1981	4.7	(Baillie and Pilcher unpubl)
MC10	AD 1386 - 1585	4.7	(Fletcher pers comm)
Southern England	AD 1083 - 1589	4.7	(Bridge 1983)
Wales & West Midlands	AD 1341 - 1636	4.6	(Siebenlist-Kerner 1978)
The Gables, Little Carlton, Notts	AD 1389 - 1516	6.1	(Howard *et al* 1986)
Thatched Cottage, Hill Wootton, Warwicks	AD 1392 - 1469	7.0	(Alcock *et al* 1989)
Newstead Abbey, Notts	AD 1353 - 1482	5.5	(Laxton and Litton 1984)
The Governors House, Newark, Notts	AD 1356 - 1448	5.5	(Howard *et al* 1986)

Fig 2: Bar diagram of samples in site chronology SOACSQ20



White bar = heartwood rings, h/s = heartwood/sapwood boundary on sample

00 sap = only heartwood on sample, no heartwood/sapwood boundary
h/s = heartwood/sapwood boundary on sample

Table 8: Results of the cross-matching of site chronology SOACSQ20 and relevant reference chronologies when last ring date is 1479

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	6.0	(Laxton and Litton 1988)
England	AD 401 - 1981	4.9	(Baillie and Pilcher unpubl)
Wales & West Midlands	AD 1341 - 1636	6.0	(Siebenlist-Kerner 1978)
Southern England	AD 1083 - 1589	4.6	(Bridge 1983)
MC10	AD 1386 - 1585	4.3	(Fletcher pers comm)
Newstead Abbey, Notts	AD 1353 - 1482	5.6	(Laxton and Litton 1984)
Dog & Duck, Shardlow, Derbys	AD 1380 - 1455	5.1	(Howard *et al* 1993)
Hagworthingham church, Lincs	AD 1336 - 1451	5.5	(Laxton and Litton 1984)

Table 3: Results of the cross-matching of sample SOA-C01 and relevant reference chronologies when last ring date is AD 1470

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	7.2	(Laxton and Litton 1988)
Southern England	AD 1083 -1589	4.5	(Baillie and Pilcher unpubl)
Northant	AD 1350 -1494	4.8	(Pilcher pers com)
Hagworthingham church, Lincs	AD 1336 - 1533	6.0	(Laxton and Litton 1984)
Lacock Abbey, Wilts	AD 1314 - 1448	6.0	(Esling *et al* 1990)
Lincoln Cathedral Transept	AD 1371 - 1477	5.9	(Laxton and Litton unpubl)
Dog & Duck, Shardlow, Derbys	AD 1380 - 1455	5.7	(Howard *et al* 1993)
Holm Pierrpont, Notts	AD 1373 - 1469	5.6	(Esling *et al* 1990)

Table 4: Results of the cross-matching of sample SOA-C02 and relevant reference chronologies when last ring date is AD 1459

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	3.5	(Laxton and Litton 1988)
England	AD 401 - 1981	3.7	(Baillie and Pilcher unpubl)
Wales & West Midlands	AD 1341 - 1636	4.4	(Siebenlist-Kerner 1978)
Southern England	AD 1083 - 1589	3.5	(Bridge 1983)
Woolpack Inn, Newark, Notts	AD 1393 - 1451	4.1	(Howard *et al* 1994)
Thatched Cottage, Hill Wootton, Warwicks	AD 1392 - 1469	4.0	(Alcock *et al* 1989)
Dog & Duck, Shardlow, Derbys	AD 1380- 1455	5.7	(Howard *et al* 1993)
White House, South Leverton, Notts	AD 1344 - 1496	4.3	(Howard *et al* 1994)
21 Birmingham Rd, Stonleigh, Warwicks	AD 1399 - 1487	3.8	(Alcock *et al* 1989)

Table 5: Results of the cross-matching of sample SOA-C03 and relevant reference chronologies when last ring date is AD 1468

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	4.4	(Laxton and Litton 1988)
England	AD 401 - 1981	3.2	(Baillie and Pilcher unpubl)
Wales & West Midlands	AD 1158 - 1540	3.8	(Siebenlist-Kerner 1978)
Hagworthingham church, Lincs	AD 1336 - 1533	4.3	(Laxton and Litton 1984)
Leicester castle	AD 1353 - 1482	4.0	(Howard *et al* 1986)
The Chestnuts, Water Orton, Warwicks	AD 1339 - 1398	5.3	(Alcock *et al* 1991)
Anne Hathaways Cottage, Warwicks	AD 1319 - 1462	4.4	(Alcock *et al* 1991)

Table 6: Results of the cross-matching of sample SOA-C08 and relevant reference chronologies when last ring date is AD 1482

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	5.6	(Laxton and Litton 1988)
England	AD 401 - 1981	3.9	(Baillie and Pilcher unpubl)
Wales & West Midlands	AD 1158 - 1540	5.6	(Siebenlist-Kerner 1978)
MC10	AD 1386 - 1585	7.3	(Fletcher pers comm)
Southern England	AD 1083 - 1589	5.9	(Bridge 1983)
Coates' Barn, Cosby, Leics	AD 1426 - 1562	4.9	(Alcock *et al* 1991)
Sherwood Forest, Notts	AD 1426 - 1981	4.8	(Laxton and Litton 1988)

Table 7: Results of the cross-matching of sample SOA-C12 and relevant reference chronologies when last ring date is AD 1469

Reference Chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	4.1	(Laxton and Litton 1988)
England	AD 401 - 1981	3.6	(Baillie and Pilcher unpubl)
Southern England	AD 1083 - 1589	5.9	(Bridge 1983)
Hagworthingham church, Lincs	AD 1336 - 1533	4.3	(Laxton and Litton 1984)
Leicester Castle	AD 1353 - 1482	4.0	(Howard *et al* 1986)
Dog & Duck, Shardlow, Derbys	AD 1380 - 1455	4.0	(Howard *et al* 1993)
Gotham Manor, Gotham, Notts	AD 1391 - 1590	3.7	(Howard *et al* 1991)
The Old Forge, Stretton-under-Fosse, Warwicks	AD 1410 - 1467	4.0	(Alcock *et al* 1989)

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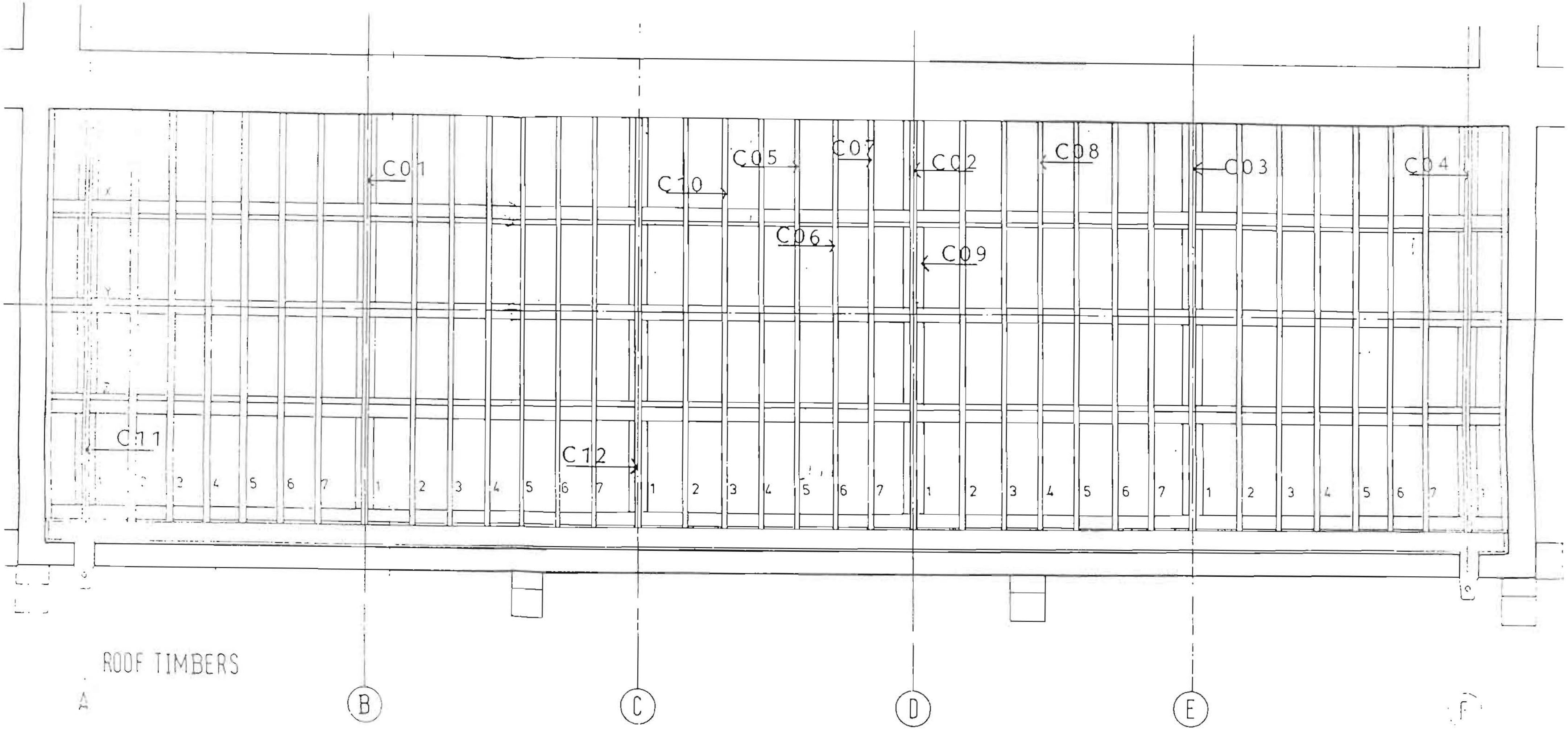
Figure 3: Plan of North Aisle showing the location of tree-ring samples



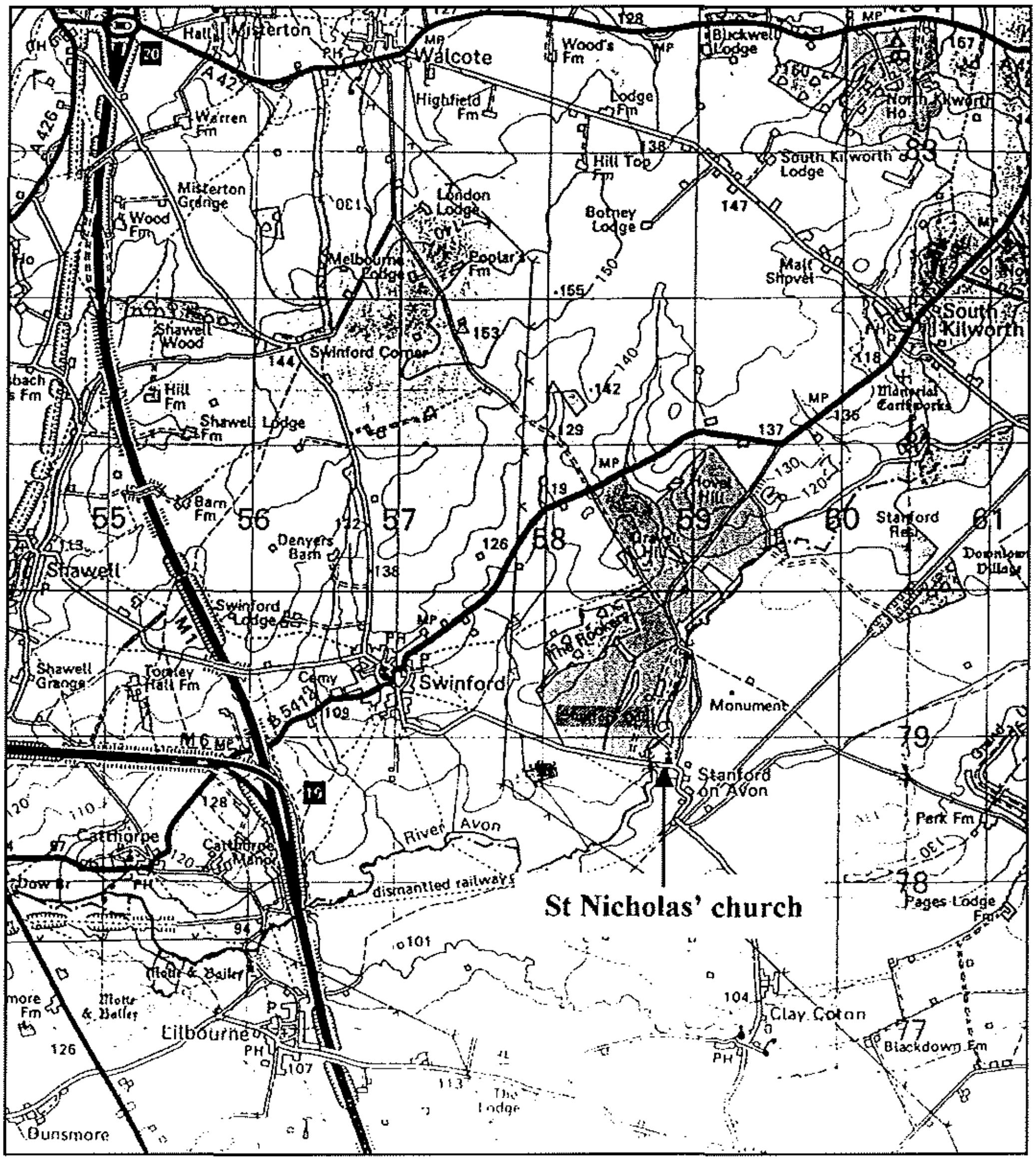


Figure 4: The location of St Nicholas' church, Stanford-on-Avon (based upon the Ordnance Survey 1:50000 map with the permission of The Controller of Her Majesty's Stationery Office, © Crown Copyright)

Table 9: Data of ten measured samples (Ring-widths measured in 0.0001 cm units)

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SOA-C01A 98
 154 357 136 138 283 301 359 387 254 310 248 156 209 237 364 226 175 151 215 161
 179 156 168 177 165 201 177 154 197 173 313 197 217 201 184 173 170 142 119  98
 155 129 134 126 126 210 141 168 168 182 194 216 122  97 113 136 146 137 145 193
 173 211 175 143 176 186 129 188 237 230 242 230 191 158 161 242 211 175 186 157
 133 157 151 186 178 121 129 109 169 119 173 141 128  96 112 111 136 132
SOA-C01B 98
 171 330 153 139 298 335 405 361 246 294 269 157 211 259 360 240 175 164 208 166
 185 149 180 191 137 202 166 153 189 184 316 207 210 194 187 180 172 140 109  92
 153 132 132 136 128 201 140 170 168 191 191 217 122  95 112 139 164 135 159 205
 169 208 164 149 167 182 124 204 227 230 242 227 187 163 164 231 221 173 182 163
 142 157 148 197 178 123 124 104 157 134 138 118 124 150 123 100 147 136
SOA-C02A 111
  95  64 108  94 214 298 263 211 120 188 232 155 116 275 273 304 261 302 264 230
 204 209 218 272 199 207 253 272 232 270 338 479 614 550 377 377 403 572 522 468
 429 389 393 330 302 235 274 305 367 299 353 426 330 304 273 324 277 283 231 260
 293 254 197 157 152 106 190 141 158 156 127 141 177 179 194 260 232 212 142 164
 176 176 209 230 109 160 172 115  97  78  87 102 132 122 128 140  93  65  82  65
  94 141 145 120 104 138 110 118  98  66  70
SOA-C02B 111
 107  66 106 109 198 280 278 220 130 189 230 159  98 274 253 295 234 311 267 229
 209 198 214 275 197 210 251 251 237 272 328 495 609 541 377 372 403 559 557 461
 418 400 397 336 302 221 280 298 360 300 350 423 333 307 267 327 282 282 236 255
 288 252 192 159 150 110 186 132 158 152 132 142 178 177 206 246 224 216 145 168
 179 187 205 245 123 167 178 116 105  83  91  95 130 116 148 140 101  63  66  90
  94 138 163 136 124 143 118 138  87  54  68
SOA-C03A 66
 243 313 292 228 241 440 594 429 394 385 411 331 447 281 225 254 235 222 308 252
 239 279 377 255 274 259 311 222 250 199 284 245 295 228 281 293 322 211 174 268
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232 258 236 272 267 260 278 233 240 177 173 234 226 206 204 213 213 173 168 133
149 129 164 141 213 184
SOA-C03B 98
154 164 208 213 272 288 222 265 226 315 209 206 265 169 213 183 187 248 319 260
266 320 310 215 244 164 242 201 217 214 264 218 258 310 209 206 174 166 220 190
143 132 209 208 189 221 181 165 147 153 99 193 160 201 201 234 198 153 178 172
134 147 149 145 187 227 214 131 108 95 132 95 120 103 103 79 63 64 77 72
64 91 64 79 84 71 67 61 53 75 65 75 79 74 59 67 61 113
SOA-C04A 67
282 302 326 361 345 324 402 323 306 87 54 102 182 274 214 258 216 315 402 373
353 333 264 228 179 203 249 196 232 318 198 211 196 209 192 212 300 270 291 271
154 151 172 98 99 90 145 149 117 170 129 150 141 109 120 126 150 210 140 154
204 141 161 181 222 233 183
SOA-C04B 59
826 742 693 616 376 385 239 246 265 242 221 380 321 260 286 157 232 270 364 307
238 245 201 218 282 196 236 160 222 235 180 172 135 200 181 147 156 200 233 313
226 413 464 281 253 230 321 275 166 141 160 159 179 214 133 108 183 143 220
SOA-C05A 72
285 240 228 287 389 411 361 375 292 290 210 175 166 150 111 88 68 104 175 174
225 207 172 232 157 133 103 76 104 106 54 85 109 115 167 161 119 132 81 93
128 211 157 244 241 184 147 130 170 256 319 263 189 94 96 84 101 98 88 53
104 75 73 116 85 93 111 83 127 132 136 167
SOA-C05B 72
274 246 218 296 387 406 366 375 300 285 192 172 197 194 136 109 108 177 176 200
218 215 182 223 149 154 93 77 104 91 67 94 107 118 162 163 123 135 70 82
123 211 163 236 238 180 135 137 172 238 329 277 190 98 97 75 102 92 87 82
83 79 84 106 82 97 114 81 122 139 104 189
SOA-C06A 52
231 217 222 236 199 184 278 236 177 195 162 169 136 146 168 126 117 115 151 101
174 166 142 168 158 129 139 176 128 200 233 138 137 161 160 145 215 261 261 198
235 260 238 254 266 275 319 206 227 254 198 216
SOA-C06B 52
193 268 200 233 201 192 242 235 186 187 191 161 134 175 187 149 120 112 143 120

173 163 153 176 138 133 140 166 139 197 234 135 147 154 164 153 217 275 233 223
270 285 278 260 263 239 305 232 193 261 198 191
SOA-C07A 62
127 124 232 226 201 210 226 181 141 205 191 289 171 201 237 160 231 216 210 119
62 73 131 161 107 225 299 229 139 170 213 257 290 355 356 225 164 189 202 225
173 116 140 153 153 165 160 183 211 300 311 250 177 242 299 291 291 326 351 165
133 179
SOA-C07B 62
121 158 200 219 177 202 189 184 140 184 176 257 124 178 194 162 247 241 237 171
109 137 162 142 111 212 307 188 157 149 218 246 258 352 329 218 188 195 216 196
157 125 127 123 139 156 158 201 224 316 335 240 180 235 308 243 298 335 354 172
159 254
SOA-C08A 60
231 176 200 185 328 392 332 392 429 421 355 381 323 352 301 312 259 389 371 359
540 503 353 336 303 289 307 272 285 260 237 300 246 288 241 263 239 261 238 164
166 134 135 108 140 135 144 131 87 104 77 174 334 237 156 149 187 198 249 173
SOA-C08B 60
202 186 202 210 306 407 341 382 419 441 344 366 315 357 288 326 261 395 383 366
523 504 342 339 303 291 311 269 276 269 251 305 253 271 260 265 223 246 235 152
163 122 124 124 112 115 110 132 73 112 115 215 315 245 142 164 184 185 277 244
SOA-C11A 41
497 544 608 636 584 500 526 578 639 591 656 561 628 505 296 256 407 357 272 301
425 404 529 501 854 536 385 486 589 501 329 355 310 334 413 348 313 253 221 221
354
SOA-C11B 41
503 564 607 720 635 502 520 587 632 563 643 562 642 473 295 250 372 379 262 288
439 402 553 518 931 494 354 511 601 504 340 354 301 346 431 359 345 240 215 199
362
SOA-C12A 76
159 197 247 231 239 179 204 331 304 412 357 223 378 230 185 171 168 143 180 187
121 157 266 292 300 211 317 204 207 164 200 134 148 259 291 264 240 231 213 204
254 273 378 276 299 249 225 286 247 536 321 245 235 268 297 319 223 258 315 284
303 257 305 224 240 209 229 218 153 181 177 216 243 234 205 250

SOA-C12B 76
179 194 233 188 222 175 266 225 292 288 376 276 346 216 159 151 138 114 198 188
136 134 257 298 246 189 308 213 195 169 207 136 168 252 311 289 234 234 210 224
258 266 363 280 305 244 221 255 259 517 351 230 216 263 308 316 215 273 301 278
297 273 282 239 223 208 222 220 164 189 170 224 226 235 228 224

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.

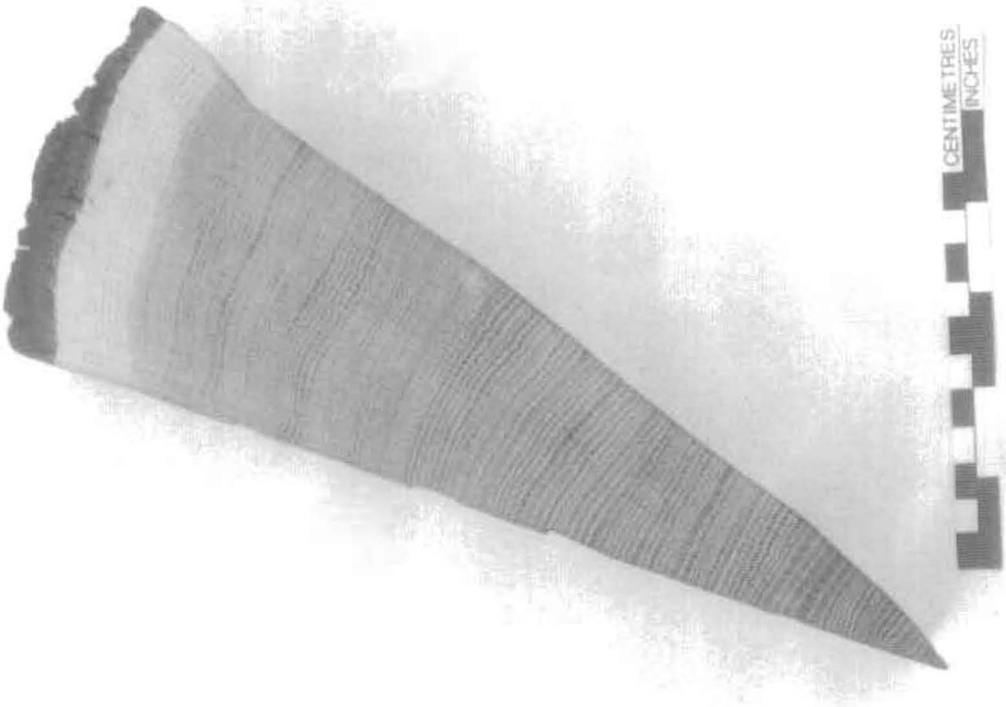

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

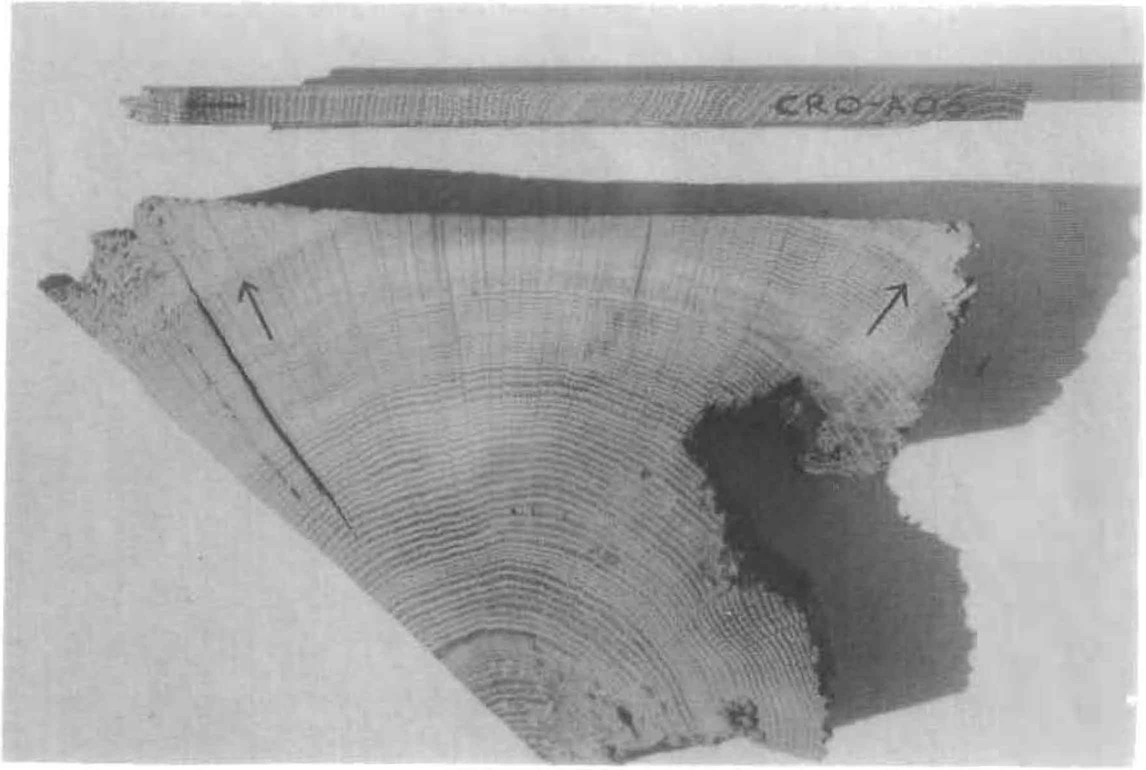

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

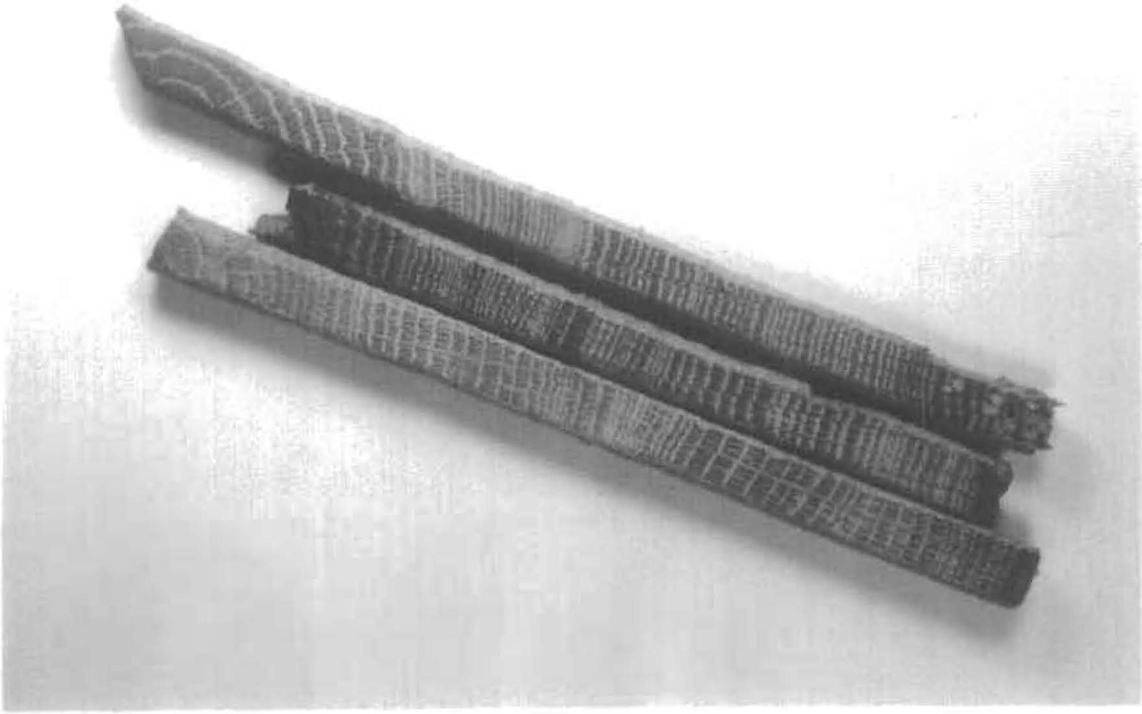

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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.

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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

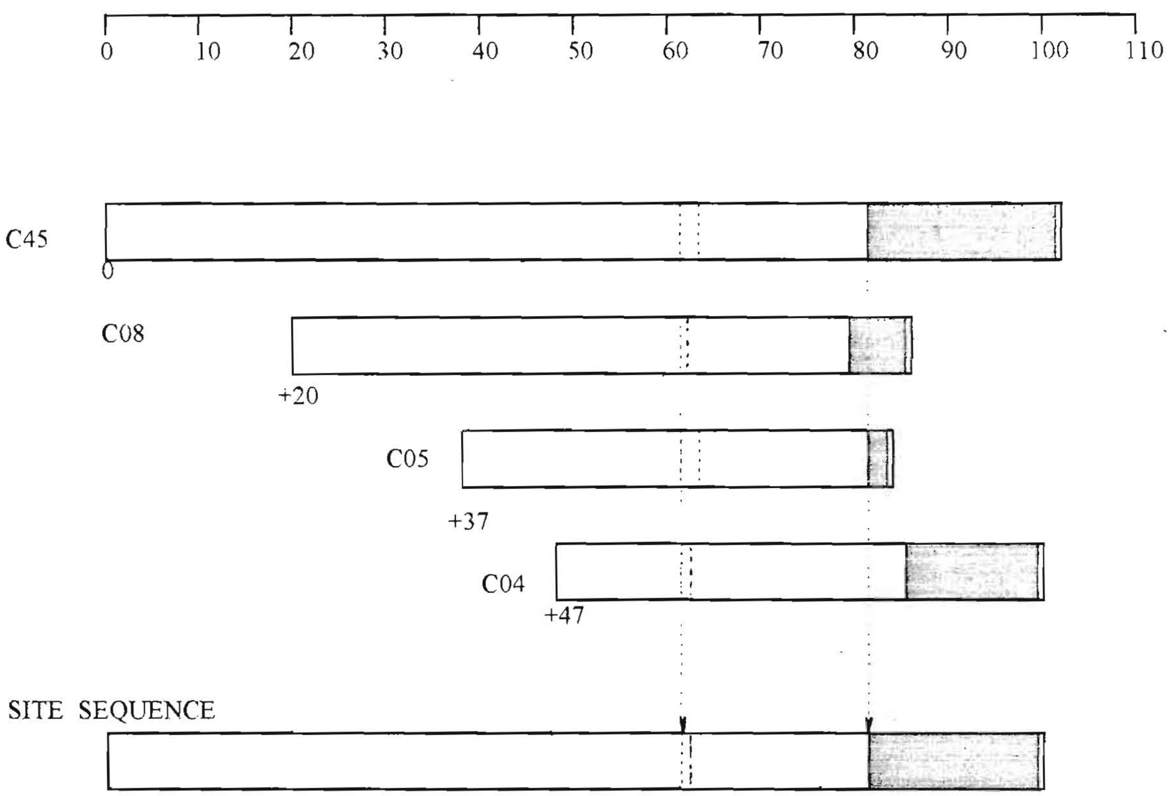

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

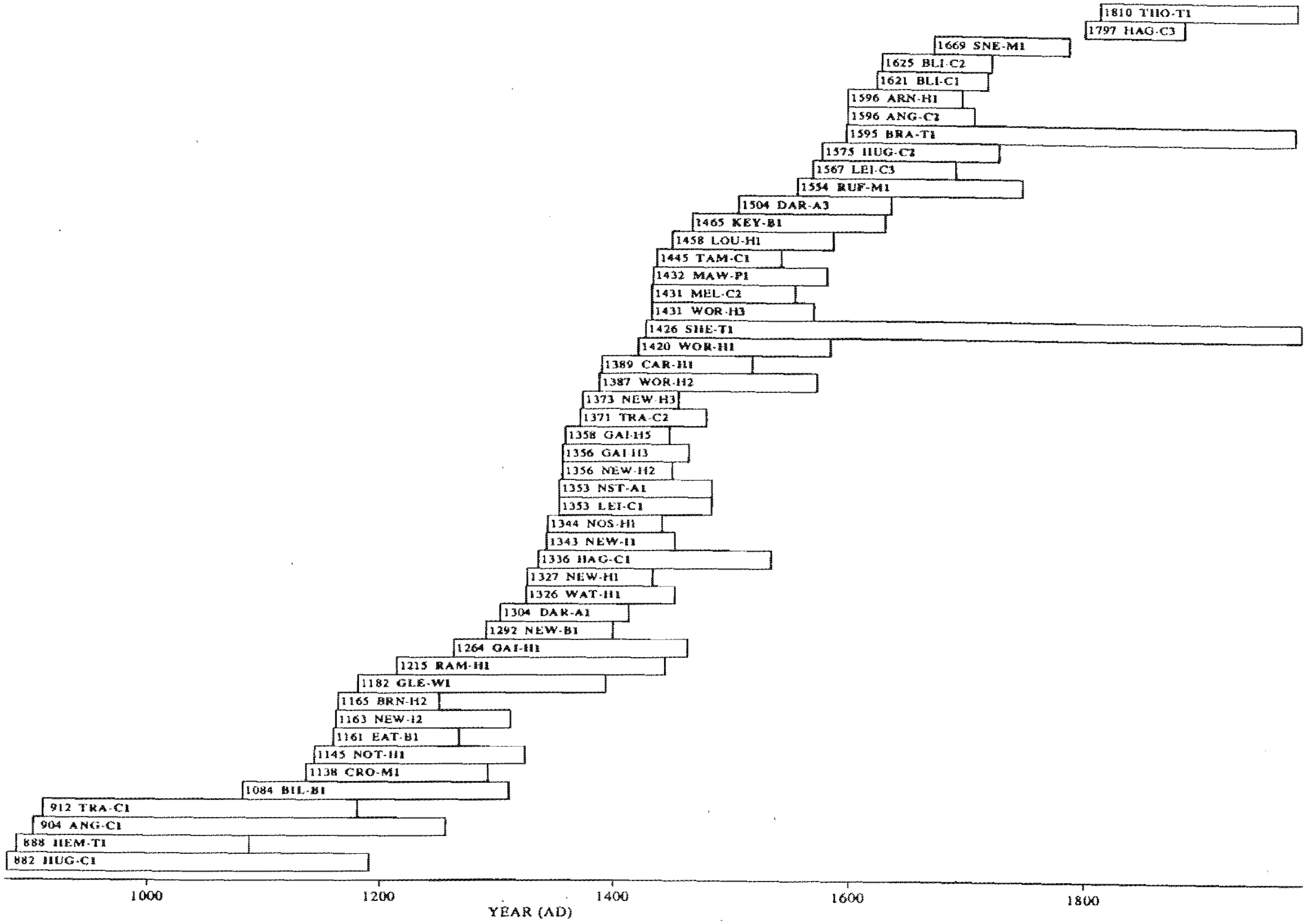

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)

(b)

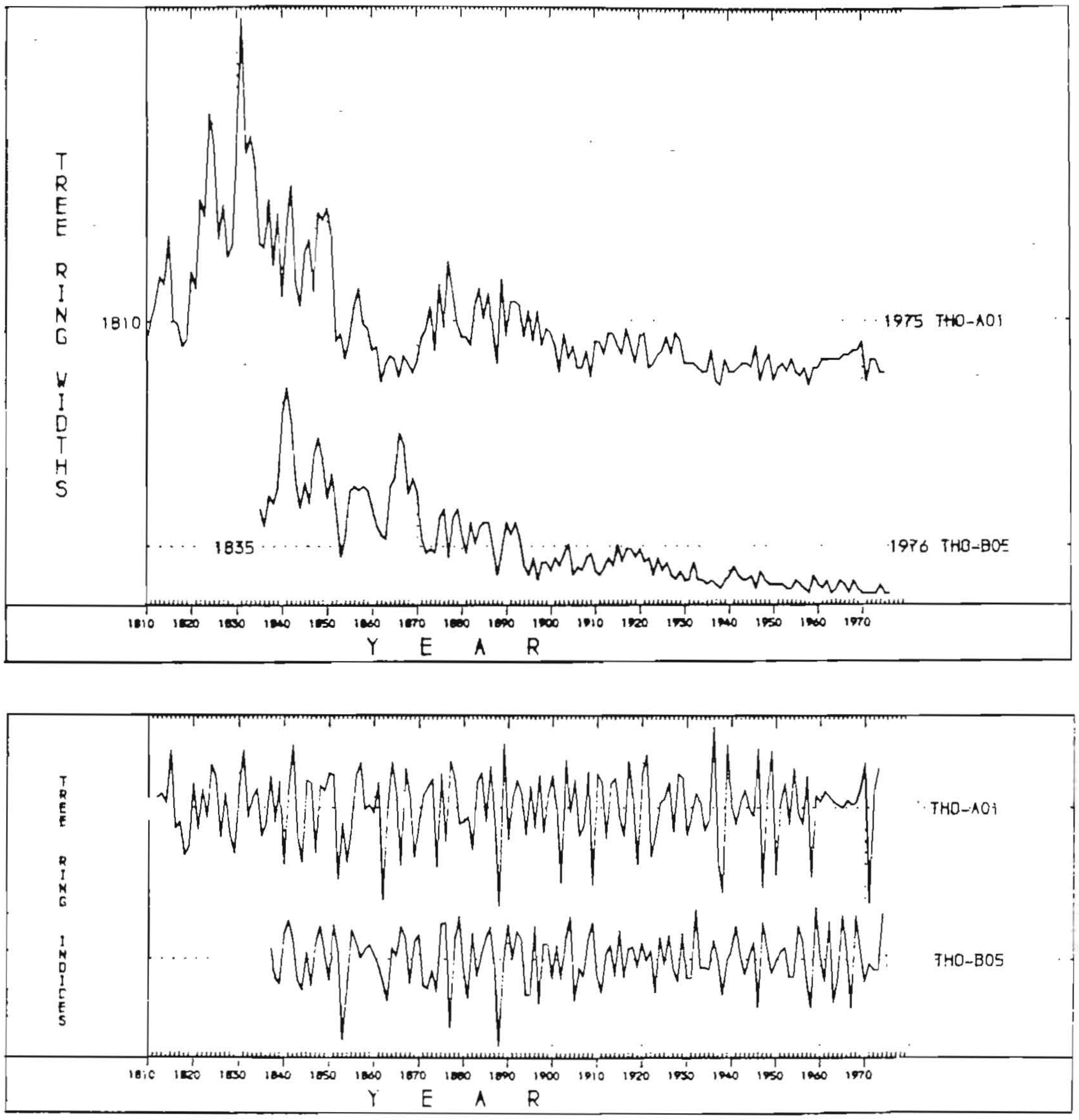

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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