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Tree-Ring Analysis of Timbers from 1 Vicars' Close, Lichfield, Staffordshire

A J Arnold[1], Dr R R Laxton[2] and Dr C D Litton[2]

Summary

Thirteen samples were taken from this building, two from first-floor timbers with the rest being from roof timbers. Four of these were not analysed because of their short ring sequences. The analysis carried out on the remaining nine samples resulted in the construction of three site chronologies.

The first of these, LVCASQ01, was of 88 rings and contained four samples. This site chronology was matched at a first-ring date of AD 1359 and a last-ring date of AD 1446. One of the four samples, LVC-A04 was from a timber which had complete sapwood, some of which was lost in coring. By estimating how many rings had been lost it was possible to calculate a felling date for the timber represented of *c* AD 1451. The average heartwood/sapwood boundary ring date for the other three samples is AD 1428, giving an estimated felling date range of AD 1443-68 for the three timbers represented.

The second site chronology, LVCASQ02, of 76 rings was found to span the period AD 1356 to AD 1431. The average heartwood/sapwood boundary ring date of the two samples which make up this site chronology is AD 1427, which gives an estimated felling date range for the two timbers represented of AD 1442-67.

The third chronology, LVCASQ03, again of 76 rings, could not be matched and the two samples which go to make up this chronology are undated.

Sample LVC-A09 was individually matched at a first-ring date of AD 1396 and a last-ring date of AD 1449. This sample was again from a timber which had complete sapwood. However, a couple of rings are estimated to have been lost in sampling which would in fact give the timber this sample represents a felling date of *c* AD 1451.

The analysis has resulted in seven samples being successfully dated. Two of these are from timbers felled in *c* AD 1451 with felling date ranges for the other five timbers making it likely that they were also felled at this time. This indicates a construction date for the house in the middle of the fifteenth century, about 50 years earlier than the date of *c* AD 1500, suggested on typological grounds.

Keywords
Dendrochronology
Standing Building

Author's address
[1] Department of Archaeology, University of Nottingham, University Park, Nottingham, NG7 2RD
[2] Department of Mathematics, University of Nottingham, University Park, Nottingham, NG7 2RD

Introduction

This grade II* listed building forms part of the central range of buildings, located to the north west of the Cathedral (approximately SK118097; Figs 1 and 2), which separated two courtyards; the former communal hall of the Vicars' Choral was at the west end of this central range. The front elevation of the building (Fig 3) faces north into the south-east corner of the Upper Vicars' Court, but part of this elevation is overlapped by the end of the east range (Fig 4). This arrangement implies that the east range was built later than 1 Vicars' Close.

The primary outside walls of the property were both of storey-high close studding. However, in the angle between 1 Vicars' Close and the east range, the original south wall framing has been removed to make way for a shallow timber-framed extension. The latter has, at first-floor level, a close-studded frame with a midrail, broken by a large aperture that might once have contained an oriel window (Fig 3). Curiously, the extension is framed storey-by-storey, suggesting that it might have been jettied in its original form, and altered later. The early reconstruction of number 1 may have been made in tandem with the building of the east range.

In 1 Vicars' Close, the partition walls that define each side of this single-bay dwelling are comprised of large rectangular panels, with long curved arch-braces up to the tiebeams. Both roof trusses have single collars (Fig. 5). At the eastern truss the single side purlins are tenoned into the principal rafters. In the western truss they are clasped between the collar and the principals, and scarfed to continue into the next bay. The roof also has curved wind-braces, trenched across the backs of the purlins and double-pegged. The common rafters are halved and pegged at the apex.

When inspected by Bob Meeson, a construction date of *c* AD 1500 was suggested was suggested for this building, on typological grounds.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage, as part of their training programme in dendrochronology. Additionally, it was hoped that by undertaking this analysis it would be possible to secure a date for the original frame of the building and in doing so assist in the understanding of the general development of buildings in the Vicars' Closes.

The Laboratory would like to take this opportunity to thank Mr David Wallington of the Dean and Chapter Office for allowing us access to the property and Bob Meeson for his help in interpreting the building, producing a roof plan on which the location of samples could be marked, and providing further drawings to illustrate this report (Figs 3-6). Bob Meeson also provided the description of the building used in the Introduction.

Sampling

After on-site discussion with Bob Meeson about the provenance of the timbers and an assessment of their suitability for tree-ring analysis, thirteen core samples was obtained with sampling being concentrated upon elements of the primary frame within the attic. . Each sample was given the code LVC-A (for Lichfield, Vicars' Close, site "A") and numbered 01-13.

These thirteen samples were obtained from a post and a rail on the first floor, and principal, and common rafters from the roof. The position of the timbers in the house from which these samples came are marked on Figures 5 and 6. Details of the samples are given in Table 1.

Analysis

At this stage four of the samples, LVC-A01, LVC-A02, LVC-A05, and LVC-A07, were rejected as they were deemed to have too few rings for secure dating. The remaining nine samples were prepared by sanding and polishing and their growth-ring widths were measured; the data of these measurements are given at the end of the report. The growth-ring widths of these nine samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a minimum value of t=4.5 eight of the samples had formed into three groups. Four of the samples had matched each other at the relative positions shown in Figure 7. The growth-ring widths of these four samples were combined at these relative offset positions to form LVCASQ01, a site chronology of 88 rings. Site chronology LVCASQ01 was successfully compared with a series of relevant reference chronologies giving it a first-ring date of AD 1359 and a last measured ring date of AD 1446. Evidence for this dating is given in the t-values of Table 2.

Two samples matched each other at the relative positions shown in Figure 8. The growth-ring widths of these two samples were combined at these relative offset positions to form LVCASQ02, a site chronology of 76 rings. Site chronology LVCASQ02 was successfully compared with a series of relevant reference chronologies giving it a first-ring date of AD 1356 and a last measured ring date of AD 1431. Evidence for this dating is given by the t-values in Table 3.

The third site chronology was again made up of two samples which matched at the relative positions shown in Figure 9. The growth-ring widths of these two samples were combined at these relative offset positions to form LVCASQ03, a site chronology of 76 rings. Attempts to match this site chronology against the reference chronologies were unsuccessful and this site chronology and the samples which go into it must remain undated.

Attempts were then made to date the remaining sample, LVC-A09, individually by comparing it with the reference chronologies. This resulted in the sample being successfully matched at a first-ring date of AD 1396 and a last-ring date of AD 1449. The evidence for this dating is given by the t-values in Table 4.

Interpretation

The analysis of samples from Number 1 Vicars Close produced three site chronologies and one individually dated sample. Site chronology LVCASQ01 spans the period AD 1359-AD 1446 and contains four samples. One of these, LVC-A04, was from a timber that had complete sapwood. Unfortunately, during sampling *c* 5mm of sapwood was lost. By noting how many rings this 5mm represents on the sample it was possible to estimate, although not say definitely, that *c* 6 sapwood rings were missing. This sample has a last ring date of AD 1445, which with the additional 6 rings would calculate to a felling date for the timber represented of *c* AD 1451. The average heartwood/sapwood boundary ring date for the other three samples which go to make up this site chronology is AD 1428, which allows an estimated felling date range for the timbers represented to be calculated to AD 1443-68, therefore, also consistent with a felling date of *c* AD 1451.

The second site chronology, LVCASQ02, spanned the period AD 1356-AD 1431 and contained two samples, both of which had the heartwood/sapwood boundary ring as their last rings. The average of these two dates is AD 1427, which calculates to an estimated felling date range for the two timbers represented of AD 1442-67, again consistent with a felling date of *c* 1451.

The third site chronology, LVCASQ03, also contained two samples, but unfortunately could not be matched and, therefore, remains undated at this point.

Sample LVC-A09 was dated to a first-ring date of AD 1396 and a last-ring date of AD 1449. The timber from which this sample was taken had complete sapwood. However, as in the case of LVC-A04, some of this was lost in sampling, *c* 2mm, which relates to *c* 1 or 2 rings. This sample has a last-ring date of AD 1449, which, with the additional 2 rings, would calculate, to a felling date for the timber represented of *c* AD 1451 again. All estimated felling dates and date ranges have been based on the estimate that mature oaks growing in this area have between 15-40 sapwood rings.

Conclusion

Following analysis by tree-ring dating it has been possible to obtain dates for seven of the timbers in this building. Two of the timbers are now known to have been felled in *c* AD 1451 with the other five timbers having felling date ranges entirely consistent with them also being felled at the same time. These results suggest construction of the building at or soon after the felling of these timbers, therefore, in the middle of the fifteenth century, nearly 50 years earlier than the date of *c* AD 1500, previously assigned to the building on typological grounds.

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Figure 1: Map showing the general location of Vicars' Close, Lichfield Cathedral (based upon the Ordnance Survey map

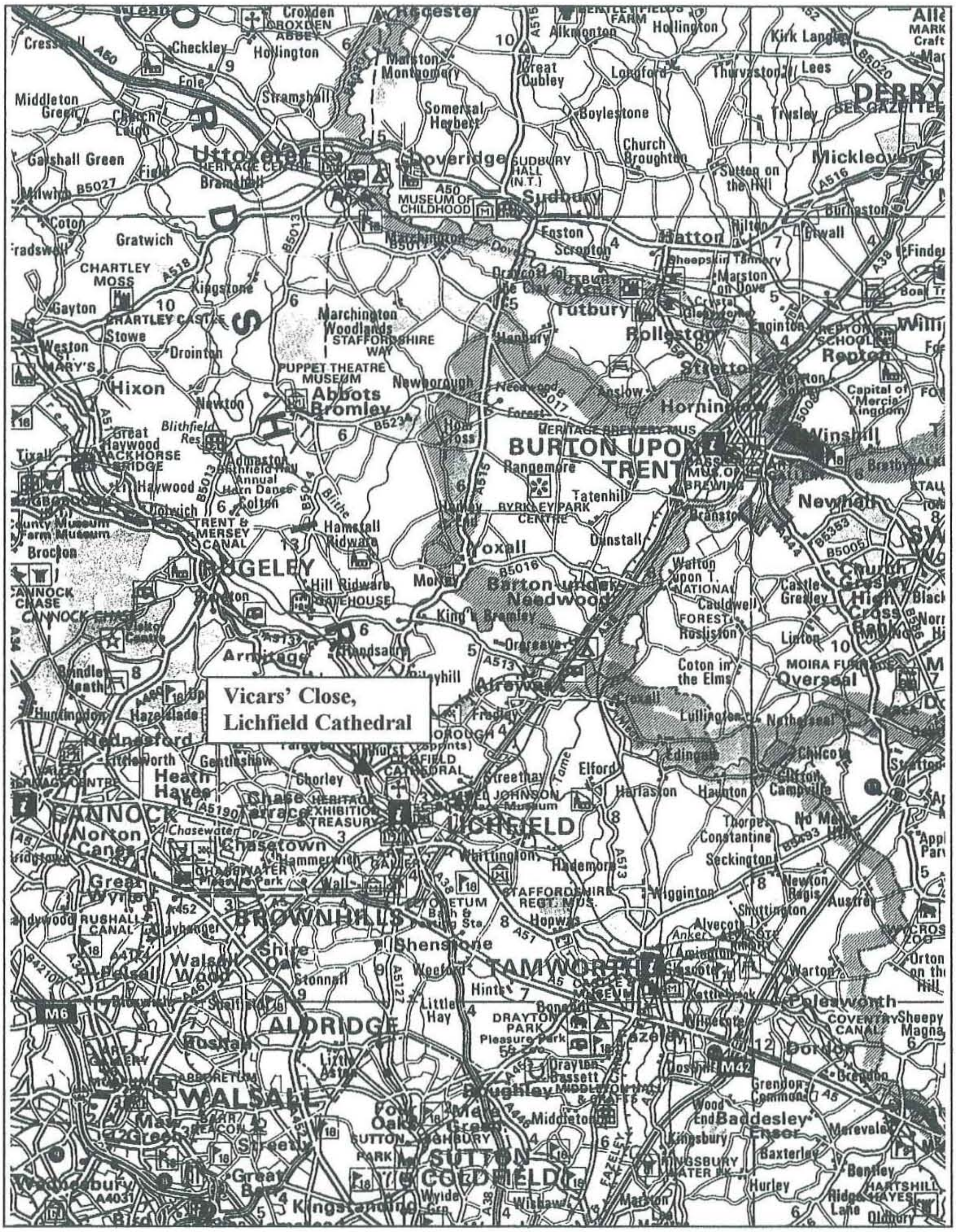


Figure 2: Sketch plan of the Vicars' Close, with Number 1 hashed

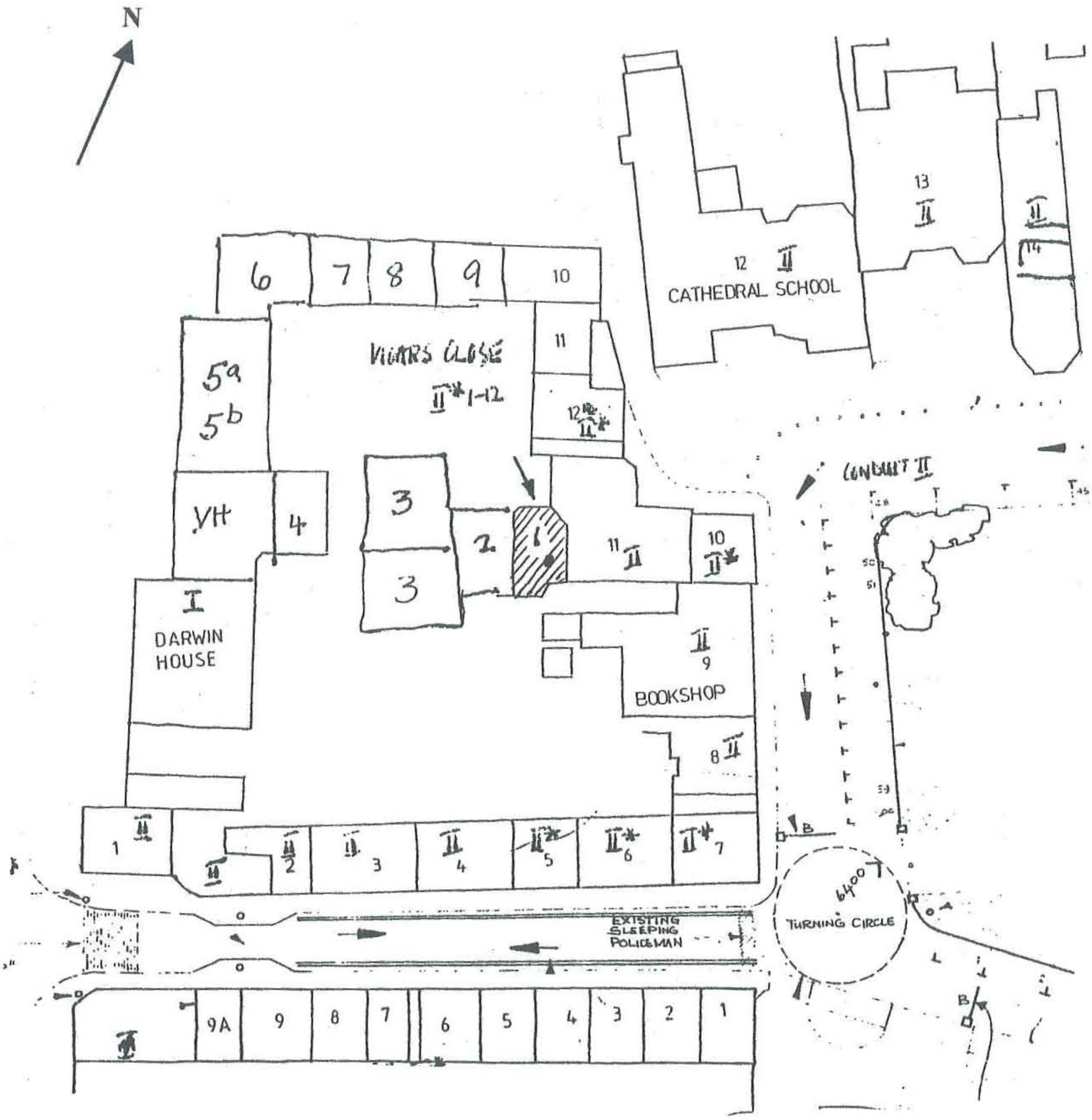


Figure 3: Number 1 Vicars' Close, Lichfield - Front Elevation (supplied by Staffordshire SMR)

Figure 4: Number 1 Vicars' Close, Lichfield - Ground Plan (supplied by Staffordshire SMR)

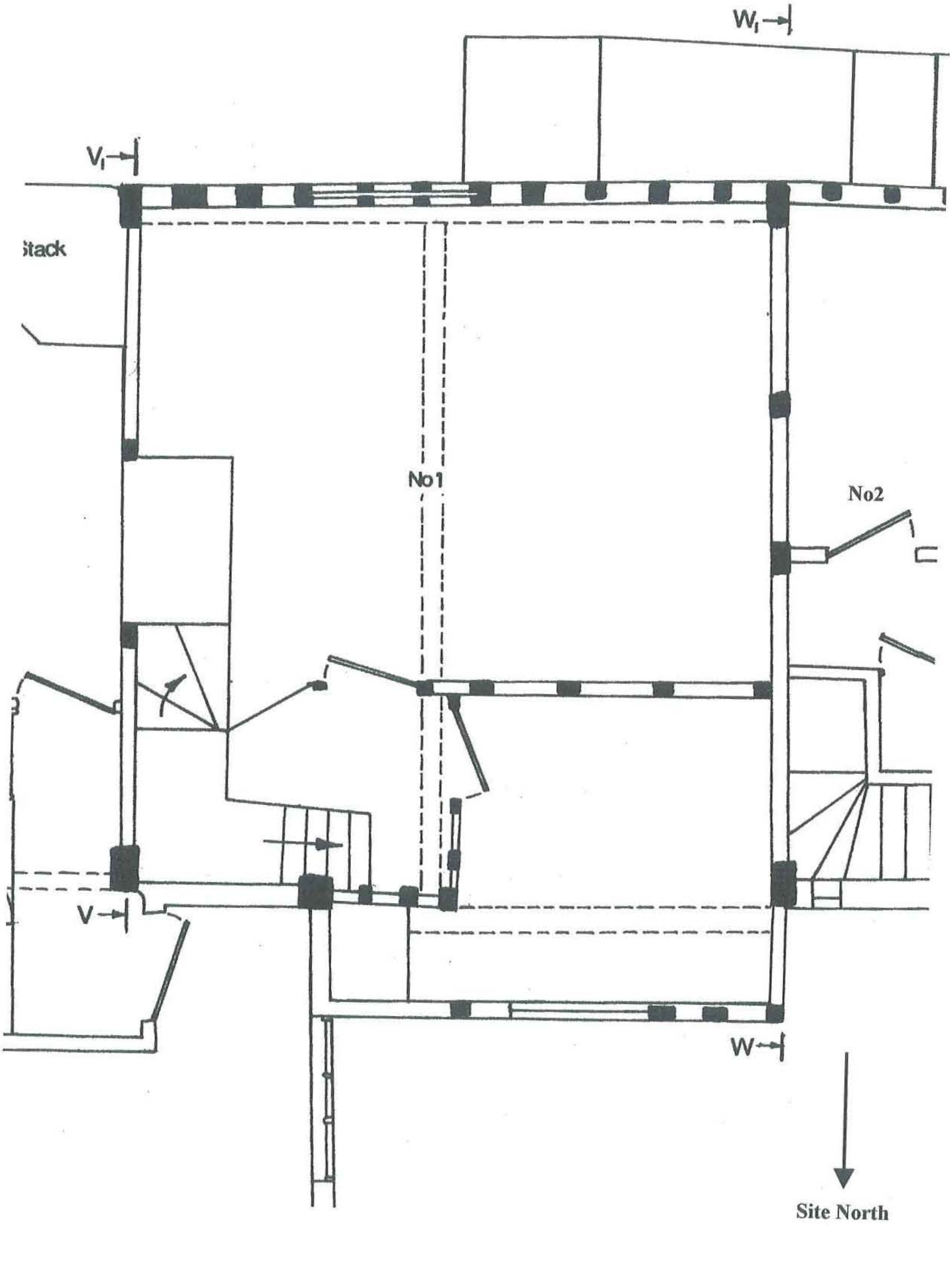


Figure 5: Number 1 Vicars' Close, Lichfield - Section V-V1, showing the location of samples LVC-A01 and LVC-A02 (supplied by Staffordshire SMR)

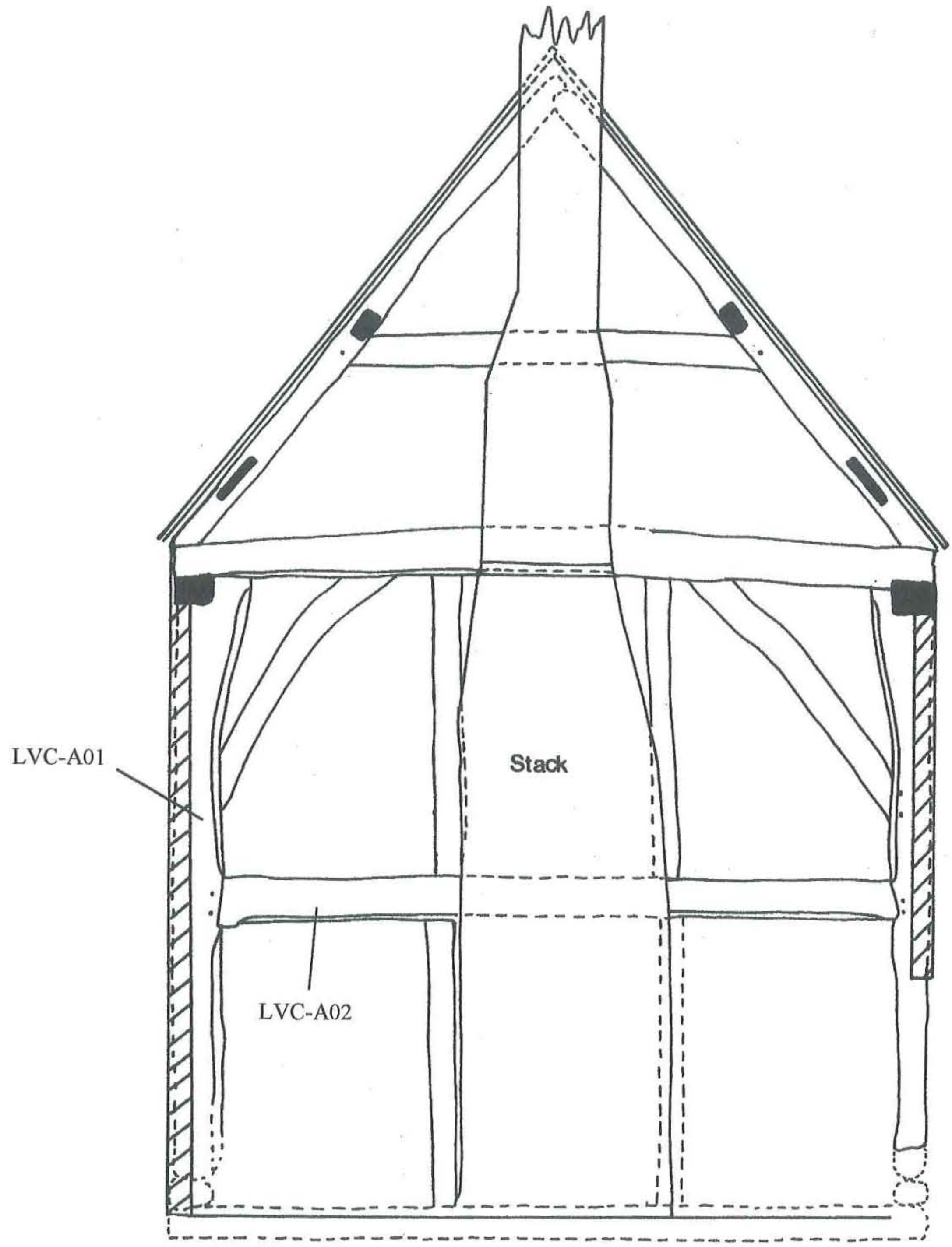


Figure 6: Number 1 Vicars' Close, Lichfield - Sketch plan of roof timbers, showing the location of samples LVC-A03-13 (drawn by Bob Meeson)

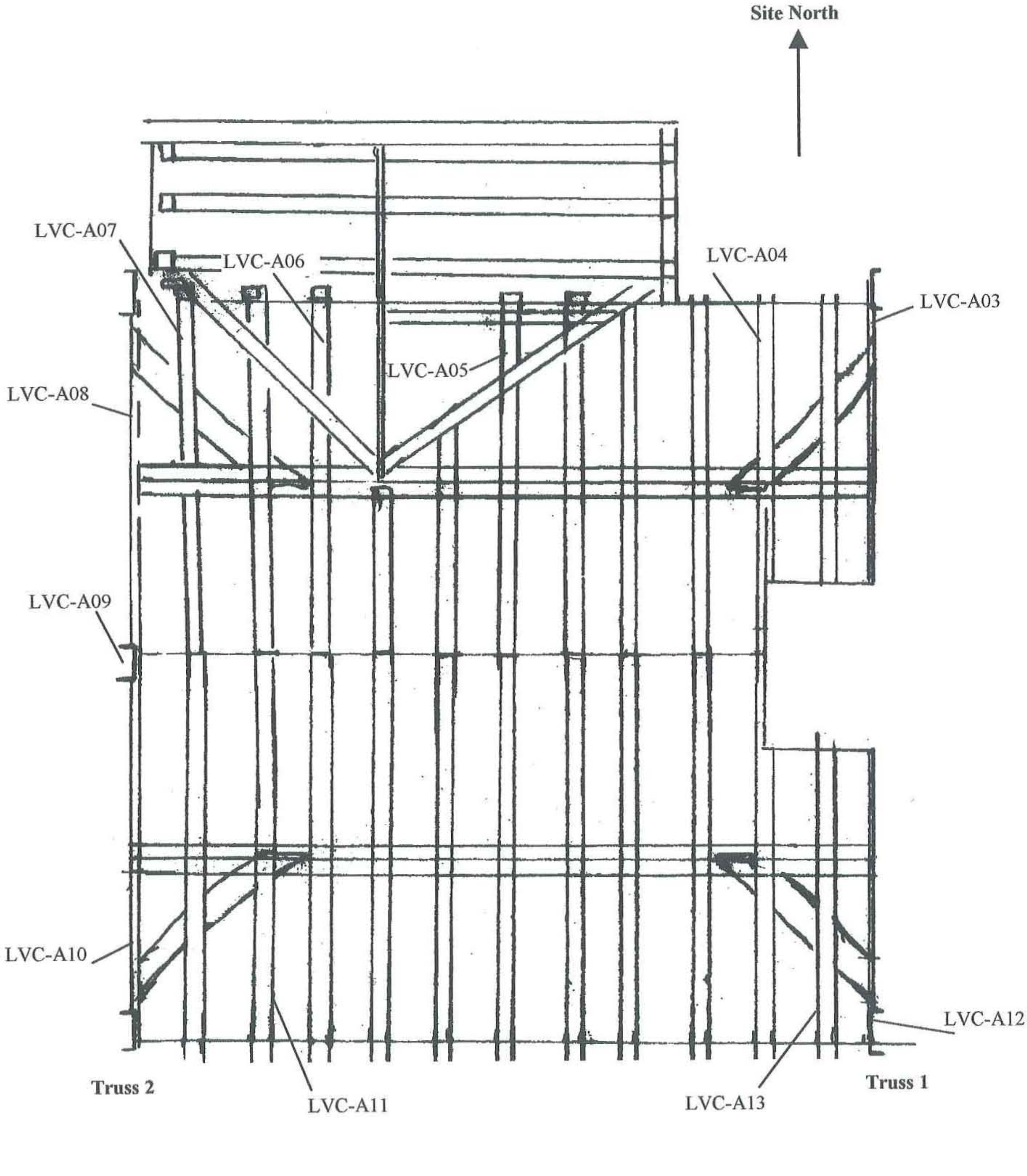


Figure 7: Bar diagram of samples in site chronology LVCASQ01

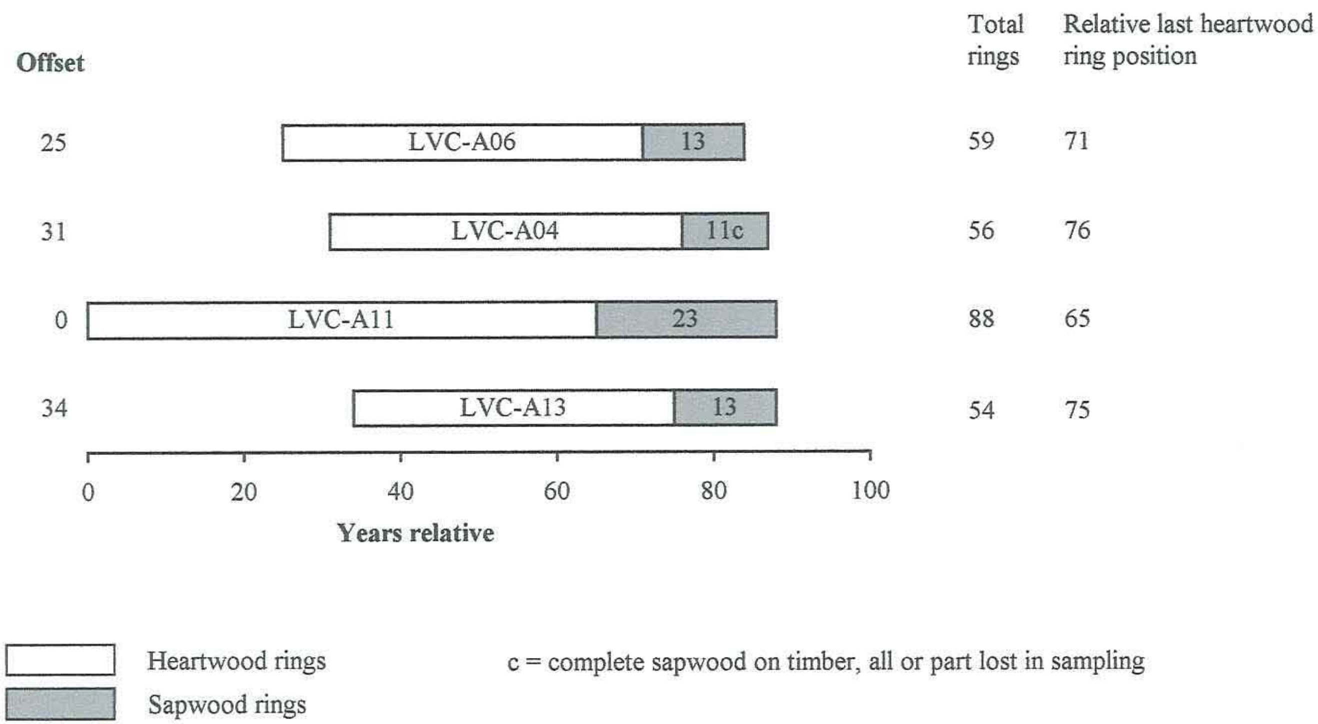


Figure 8: Bar diagram of samples in site chronology LVCASQ02

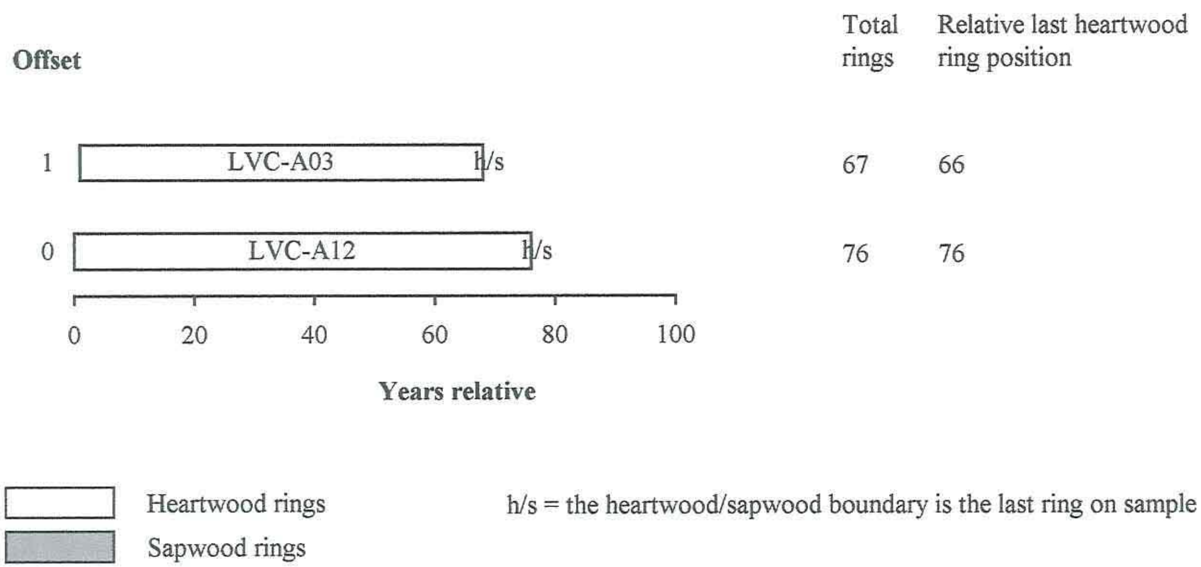


Figure 9: Bar diagram of samples in site chronology LVCASQ03

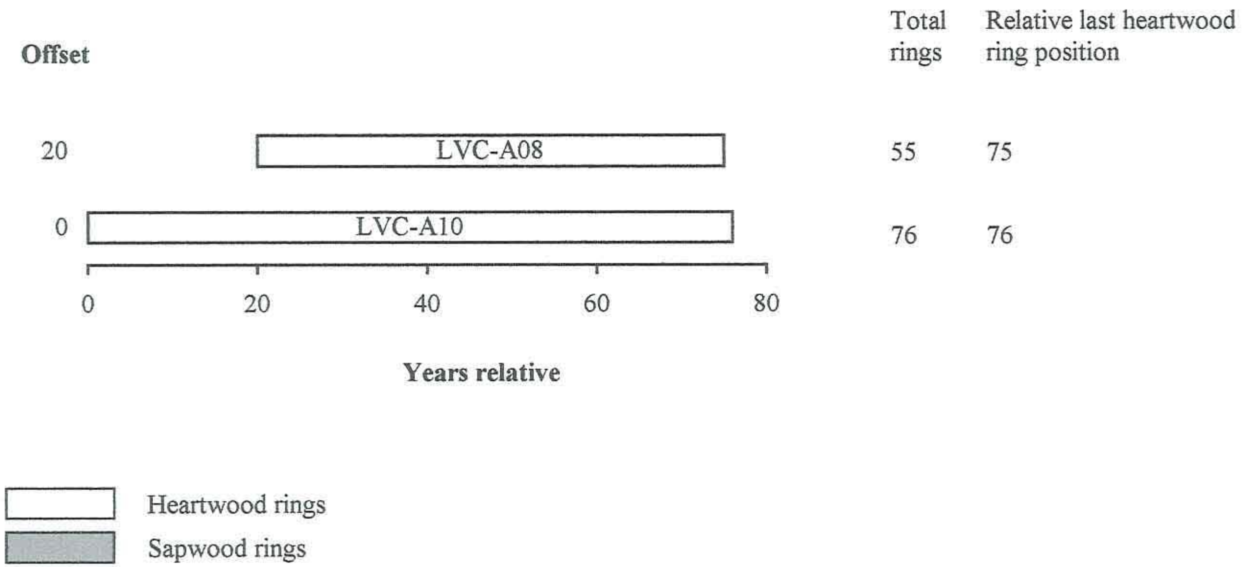


Table 1: Details of samples from 1 Vicars' Close, Lichfield

Sample number	Sample location	*Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
LVC-A01	Post, truss 1	NM	--	------	------	------
LVC-A02	Rail, truss 1	NM	--	------	------	------
LVC-A03	North principal rafter, truss 1	67	h/s	AD 1357	AD 1423	AD 1423
LVC-A04	North common rafter, frame 2	56	11c(+6NM)	AD 1390	AD 1434	AD 1445
LVC-A05	North common rafter, frame 6	NM	--	------	------	------
LVC-A06	North common rafter, frame 9	59	13	AD 1384	AD 1429	AD 1442
LVC-A07	North common rafter, frame 11	NM	--	------	------	------
LVC-A08	North principal rafter, truss 2	55	--	------	------	------
LVC-A09	Central strut, truss 2	54	13c(+2NM)	AD 1396	AD 1436	AD 1449
LVC-A10	South principal rafter, truss 2	76	--	------	------	------
LVC-A11	South common rafter, frame 10	88	23	AD 1359	AD 1423	AD 1446
LVC-A12	South principal rafter, truss 1	76	h/s	AD 1356	AD 1431	AD 1431
LVC-A13	South common rafter, frame 1	54	13	AD 1393	AD 1433	AD 1446

*h/s = the heartwood/sapwood boundary is the last ring on the sample
NM = not measured
c = complete sapwood on timber, all or part lost in sampling

Table 2: Results of the cross-matching of site chronology LVCASQ01 with relevant reference chronologies when the first ring date is AD 1359 and last ring date is AD 1446

Reference chronology	Span of chronology	*t*-value	Reference
Southern England and Wales	AD 1386-1585	5.4	Fletcher 1980
Western England and Wales	AD 1341-1636	5.0	Siebenlist-Kerner 1978
107/8 High Street, Stourbridge, W Mids	AD 1389-1462	8.4	Esling *et al* 1989
Mercers Hall, Gloucester, Glos	AD 1289-1541	6.0	Howard *et al* 1997
Ordsall Hall, Taylorson Street, Salford, Cheshire	AD 1385-1512	5.6	Howard *et al* 1994
Morleys Hall, Manchester (*MANBSQ03*)	AD 1386-1463	5.6	Howard *et al* 1993a
Speke Hall, The Walk, Speke, Merseyside	AD 1387-1574	5.0	Howard *et al* 1992
St Cuthbert's Church, Wick	AD 1255-1496	5.0	Bridge 1983

Table 3: Results of the cross-matching of site chronology LVCASQ02 with relevant reference chronologies when the first-ring date is AD 1356 and last-ring date is AD 1431

Reference chronology	Span of chronology	*t*-value	Reference
East Midlands	AD 882-1981	5.4	Laxton and Litton 1988
Redroofs Farmhouse, Sawbridge, Warwicks	AD 1355-1448	5.9	Howard *et al* 1995
Dog & Duck Inn, Shardlow, Derbys	AD 1380-1455	5.9	Howard *et al* 1993b
Old Hall, Church Broughton (hall), Derbys	AD 1368-1467	5.7	Howard *et al* 1993b
Holme Pierrepont Hall, Notts	AD 1373-1469	5.5	Esling *et al* 1990
11 Bridlesmith Gate, Nottingham, Notts	AD 1353-1443	5.4	Howard *et al* 1996
Cad Beeston, Temple Crescent, Leeds, W Yorks (*CADBSQ10*)	AD 1333-1419	5.3	Esling *et al* 1991
Leicester Castle (Great Hall), Leics	AD 1353-1482	5.2	Howard *et al* 1986
Sinai Park, Staffs	AD 1227-1747	5.1	Tyers 1997

Table 4: Results of the cross-matching of sample LVC-A09 with relevant reference chronologies when the first-ring date is AD 1396 and last-ring date is AD 1449

Reference chronology	Span of chronology	*t*-value	Reference
East Midlands	AD 882-1981	4.8	Laxton and Litton 1988
The Hallgarth, HM Prison, Durham, Tyne and Wear	AD 1349-1464	6.5	Howard *et al* 1992
Dog & Duck Inn, Shardlow, Derbys	AD 1380-1455	5.9	Howard *et al* 1993b
Redroofs Farmhouse, Sawbridge, Warwicks	AD 1355-1448	5.8	Howard *et al* 1995
Old Hall, Church Boughton (hall), Derbys	AD 1368-1467	5.7	Howard *et al* 1993b
Thatched Cottage, The Green, Collingham, Notts	AD 1374-1509	5.5	Howard *et al* 1991
Manor House, West Bromwich, W Mids	AD 1371-1578	5.4	Esling *et al* 1989
Hagworthingham Church (bell-frame), Lincs	AD 1336-1533	5.4	Laxton and Litton 1988
Leicester Castle (Great Hall), Leics	AD 1353-1482	4.9	Howard *et al* 1986

Data of measured samples – measurements in 0.01mm units

LVC-A03A 67
269 308 235 199 190 182 213 311 250 295 193 222 153 146 108 162 187 271 213 197
265 213 302 208 238 341 246 138 182 270 324 249 253 198 273 170 112 143 101 160
157 165 212 293 223 211 199 174 158 167 114 190 242 156 186 175 160 119 216 112
120 131 135 142 187 176 98
LVC-A03B 67
268 304 249 219 187 173 218 308 255 275 186 219 162 142 118 158 185 266 214 186
269 218 295 199 240 339 229 121 178 266 309 256 248 187 275 193 92 156 101 175
147 167 210 295 212 211 193 175 160 168 124 201 212 180 149 152 142 119 224 124
109 143 126 139 191 172 87
LVC-A04A 56
153 137 172 169 151 193 219 174 184 202 194 224 165 230 194 169 206 183 166 184
145 137 131 107 110 118 114 109 97 80 123 161 129 164 145 156 160 170 131 141
128 126 160 127 140 157 158 130 81 60 65 99 91 94 136 100
LVC-A04B 56
167 130 176 166 156 198 222 160 189 201 194 222 156 227 189 176 210 180 166 181
143 145 126 114 113 117 114 105 89 83 121 158 133 161 159 152 162 168 131 142
127 130 160 127 145 156 159 127 86 58 78 92 81 88 140 105
LVC-A06A 53
328 274 379 387 236 290 197 274 180 224 190 179 221 216 210 198 218 155 109 152
133 162 185 152 176 212 188 141 140 123 111 152 136 121 122 78 110 119 90 130
114 124 113 95 96 121 139 143 158 101 122 132 105
LVC-A06B 41
90 123 163 165 154 137 149 184 169 140 159 112 132 140 146 122 123 78 115 92
82 130 102 115 91 73 91 95 112 114 135 93 109 123 88 61 55 26 38 77
72
LVC-A08A 55
74 116 126 194 180 188 228 146 190 344 289 307 263 331 388 252 300 199 188 237
228 205 192 217 189 146 188 171 145 131 160 167 115 129 114 159 132 114 111 154
107 105 102 84 67 106 80 105 145 208 391 324 321 166 168
LVC-A08B 55
72 122 118 194 178 184 231 149 201 314 293 306 261 327 396 249 305 209 183 236
215 204 195 238 187 150 197 189 130 145 146 174 116 142 123 154 149 117 119 145
110 99 105 86 77 103 80 105 158 227 385 306 261 184 165
LVC-A09A 54
335 335 388 355 337 267 313 397 333 244 332 270 331 293 202 197 231 239 191 253
179 192 187 207 300 302 328 259 332 200 171 185 268 298 233 261 305 258 215 204
214 180 182 137 212 288 185 219 193 134 160 172 176 176
LVC-A09B 54
357 357 319 347 345 267 307 410 342 253 330 272 348 285 210 193 236 246 198 245
176 183 186 212 305 298 324 250 319 201 172 189 261 295 230 266 314 253 225 205
215 188 174 130 248 298 194 226 205 145 149 168 173 173

LVC-A10A 76
48 77 123 206 114 75 152 206 119 168 216 302 204 268 205 193 166 190 129 177
137 119 149 354 304 268 387 324 282 485 329 339 279 417 470 316 344 219 219 231
214 236 236 236 187 167 183 181 200 189 157 165 140 139 154 167 161 119 120 118
131 113 127 81 69 75 76 107 152 189 234 198 195 184 107 115
LVC-A10B 76
102 85 164 195 114 67 168 188 116 156 216 287 222 274 212 173 191 177 128 188
132 118 153 350 301 266 390 323 298 454 325 335 287 408 464 299 336 221 211 237
214 243 225 258 180 167 159 190 197 181 163 185 100 148 162 167 157 124 110 105
121 115 113 70 73 75 57 110 147 189 248 192 192 172 128 101
LVC-A11A 70
152 103 94 146 128 92 64 54 43 39 61 35 36 40 31 61 210 302 174 180
211 208 198 235 238 333 259 391 313 236 276 190 281 220 242 237 192 210 191 154
161 144 92 59 79 56 68 56 62 50 55 52 45 55 54 58 68 46 60 47
47 57 53 44 79 78 64 58 52 53
LVC-A11B 88
155 76 94 143 127 93 72 65 38 39 57 35 39 40 31 61 219 295 173 181
201 218 213 252 228 324 270 401 322 241 274 184 255 230 257 233 189 188 156 148
164 132 92 48 79 61 63 63 59 49 54 57 43 58 53 55 62 50 55 59
47 53 50 53 82 72 67 53 61 54 63 72 91 102 69 62 44 55 51 42
32 53 40 39 49 47 46 50
LVC-A12A 76
315 313 319 392 366 288 333 229 248 208 223 125 131 102 70 86 90 98 151 122
139 246 250 236 159 169 192 153 136 120 165 214 153 158 143 169 166 119 171 134
161 171 159 131 146 118 100 93 91 99 85 78 70 85 58 68 87 78 79 136
72 71 51 64 117 84 163 201 184 97 91 102 137 122 78 78
LVC-A12B 75
241 318 280 375 365 290 325 227 242 202 227 110 121 109 76 87 98 113 129 139
136 232 233 212 155 171 189 150 111 130 174 221 170 128 147 163 186 125 167 104
181 155 152 142 127 115 95 104 104 72 112 83 76 75 71 60 83 81 88 140
60 72 53 69 96 105 146 215 181 104 84 109 113 111 71
LVC-A13A 54
147 124 193 160 207 220 219 295 317 182 209 193 182 160 151 146 123 117 102 119
89 106 113 107 126 99 86 115 155 113 159 141 168 137 122 145 119 143 138 141
130 132 147 116 122 88 75 66 85 79 100 118 139 95
LVC-A13B 54
169 145 221 174 200 204 215 292 305 182 210 202 187 177 153 143 127 112 108 116
89 100 112 110 125 92 82 112 141 115 158 139 166 136 132 136 125 147 132 145
135 124 138 124 125 88 67 74 88 80 95 117 145 91

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.

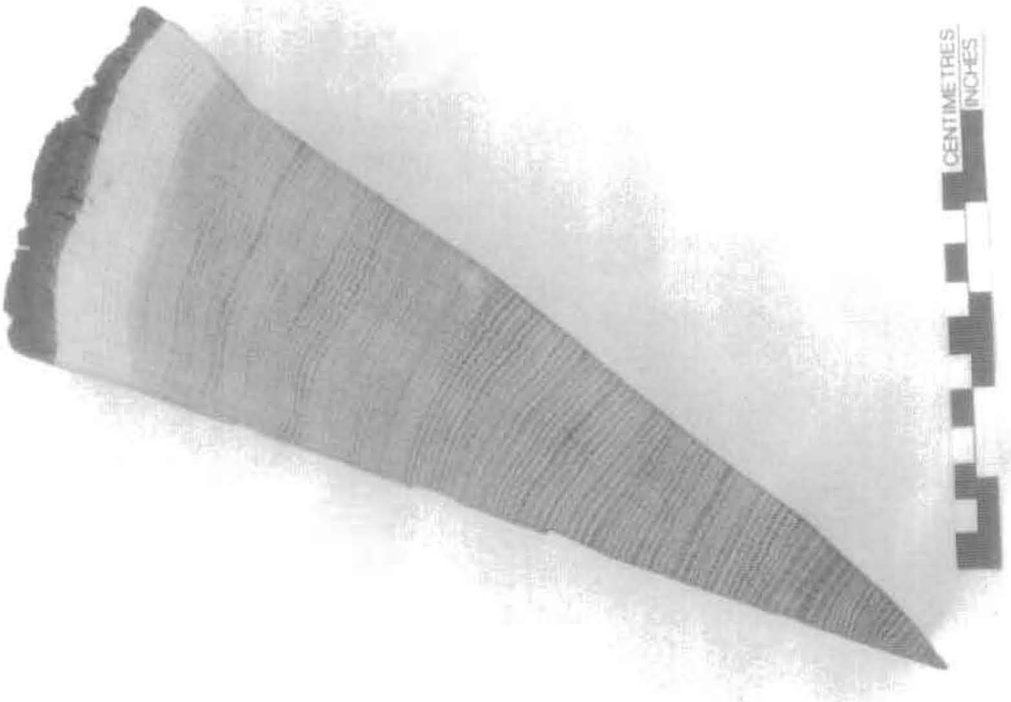


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

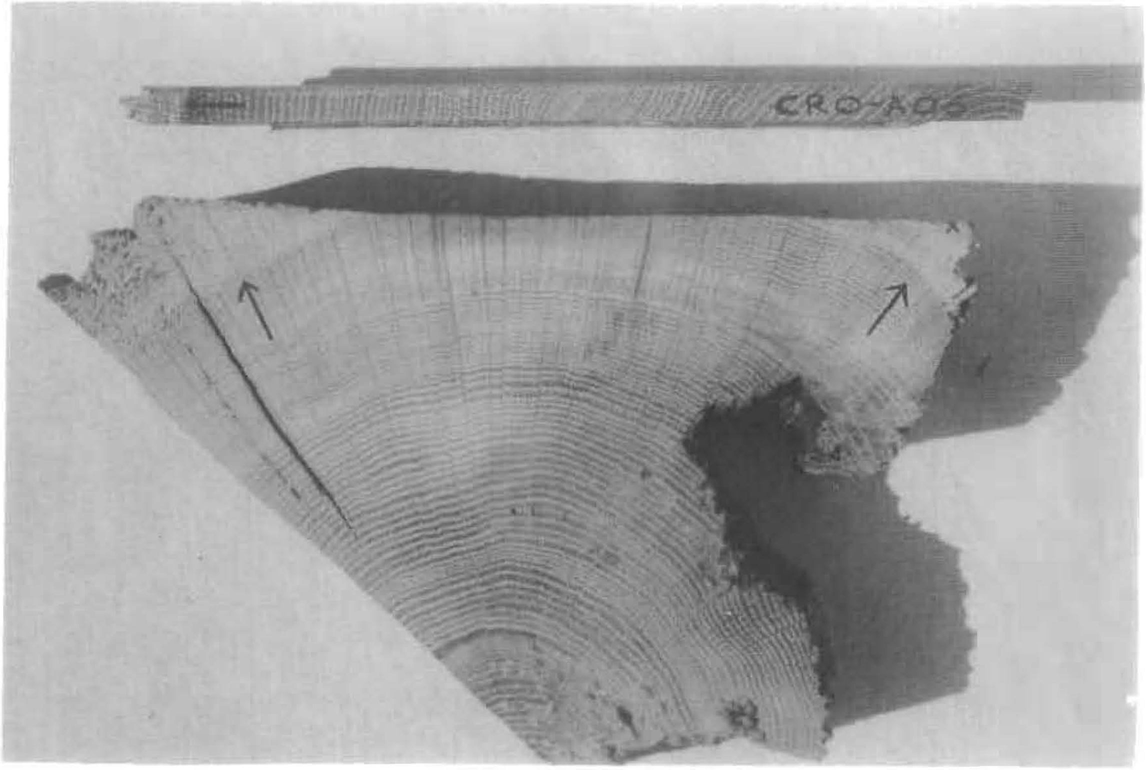


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

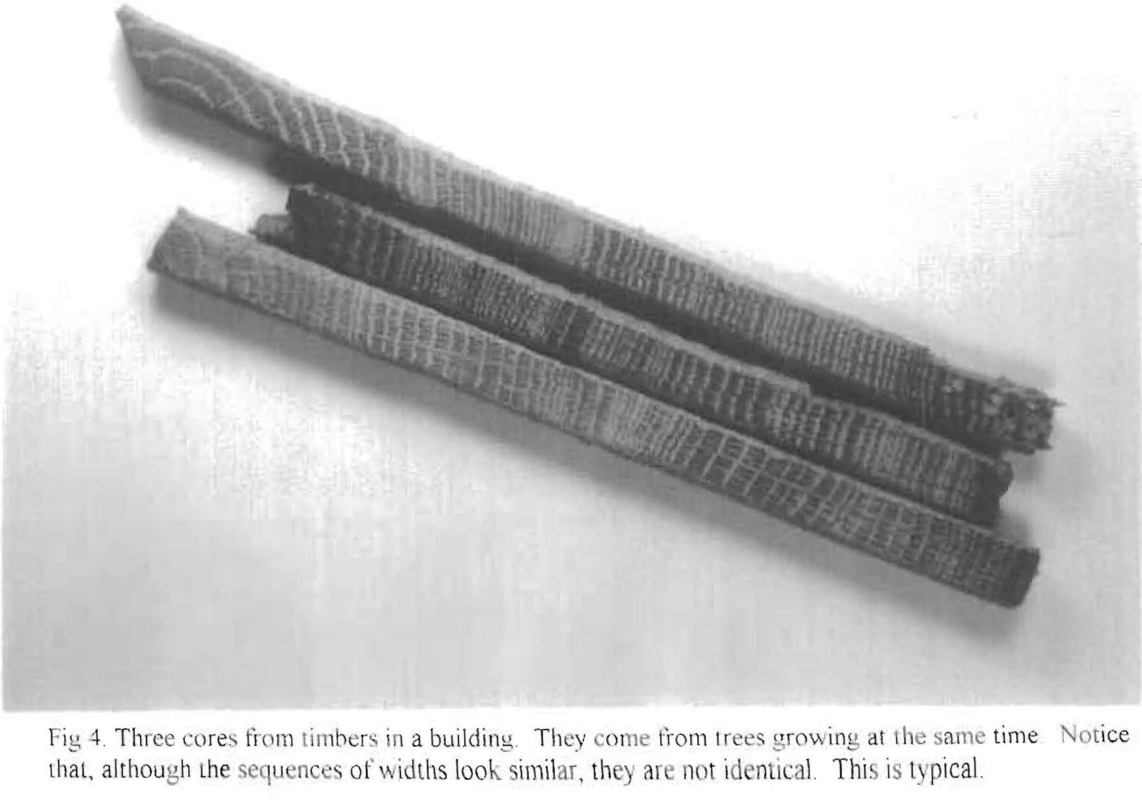


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

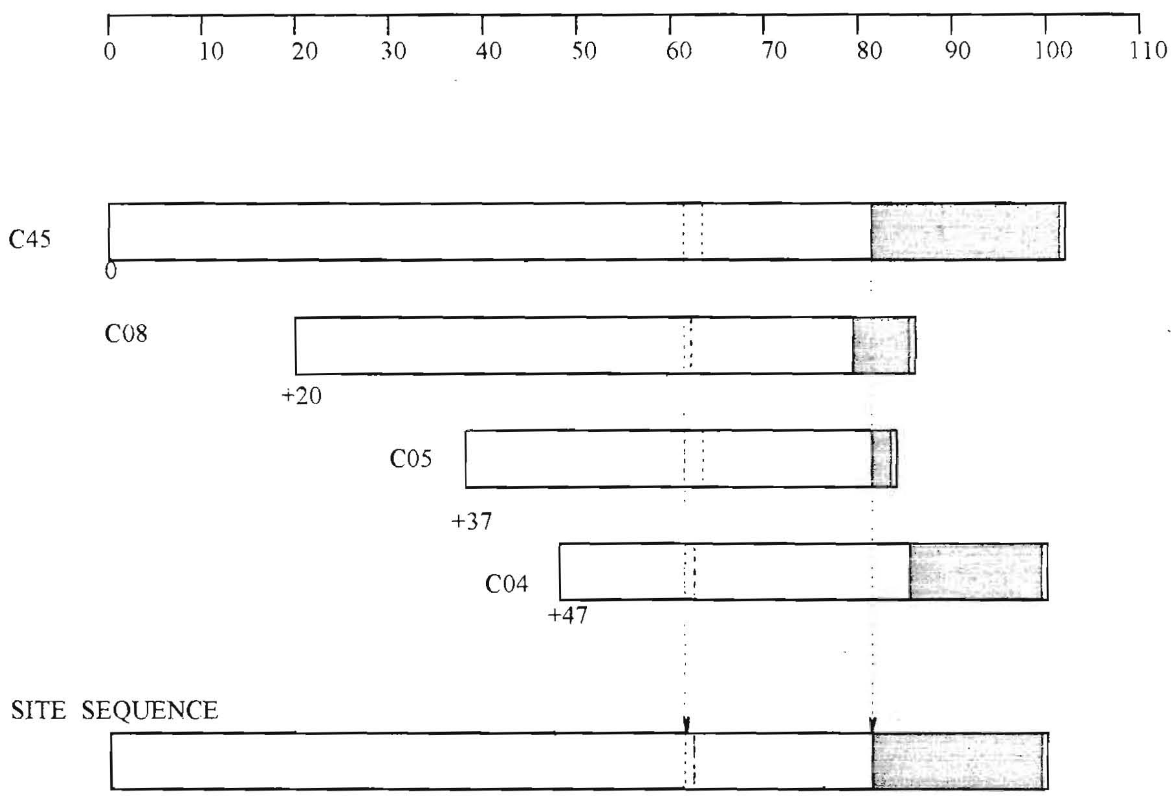


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

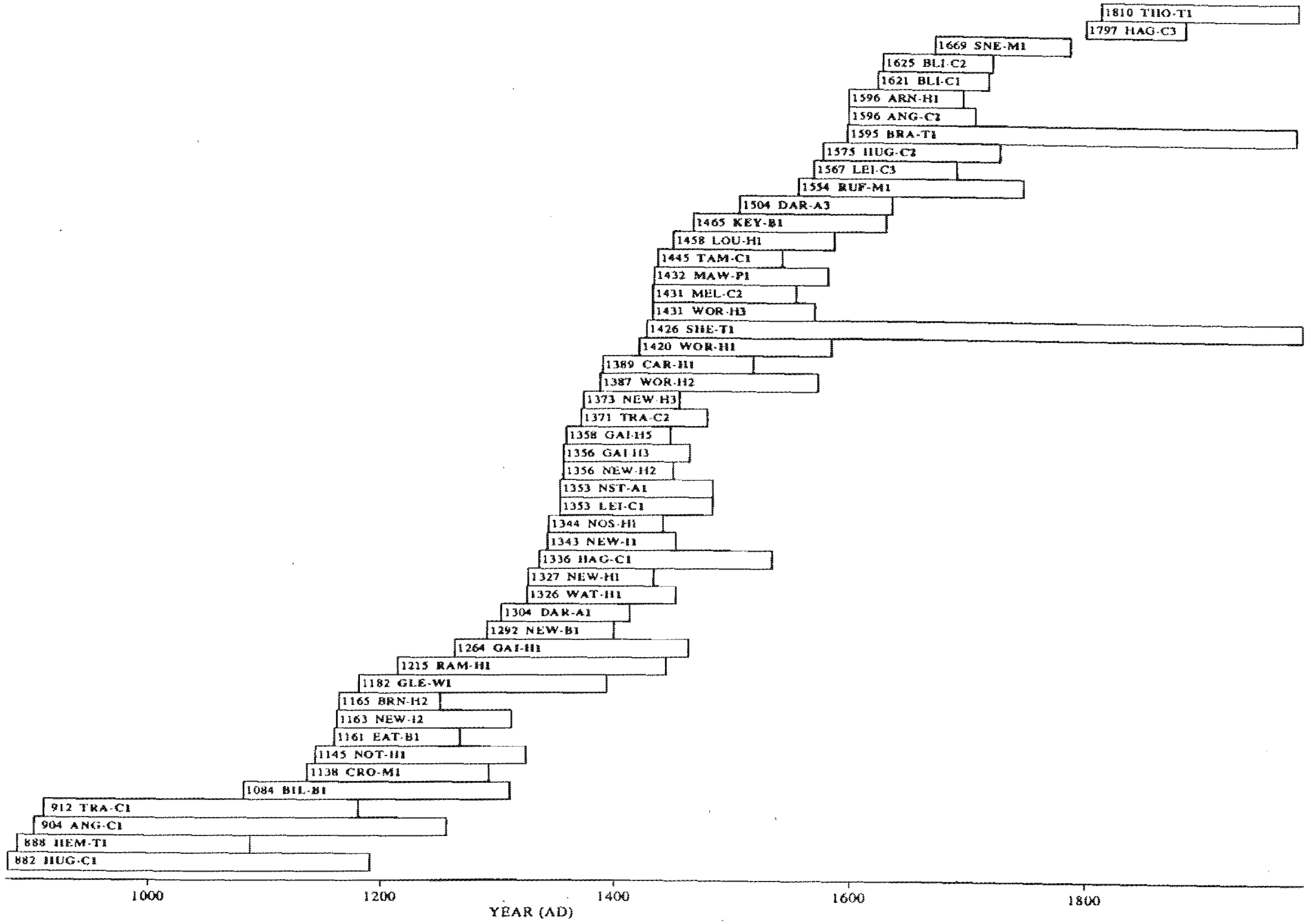
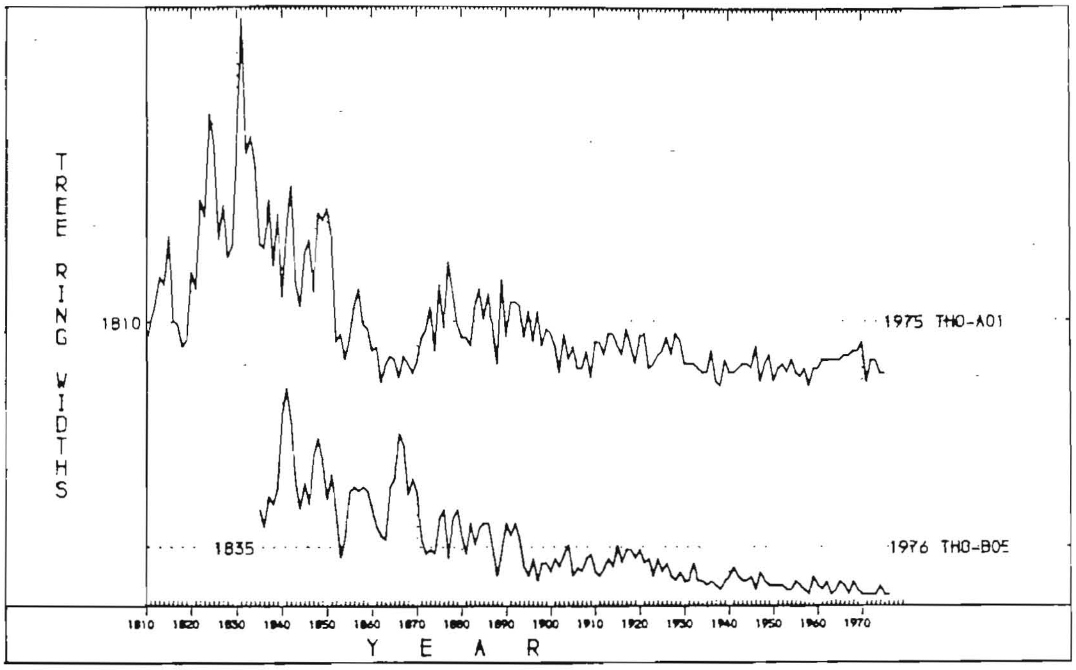


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)



(b)

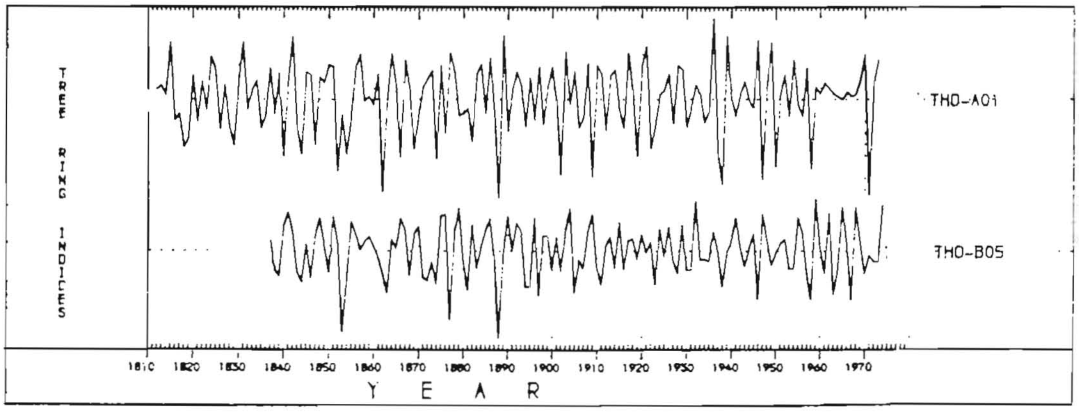


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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