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TREE-RING ANALYSIS OF TIMBERS FROM EXETER, GUILDHALL, HIGH STREET, EXETER, DEVON

C D Litton
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Summary

Twenty-six samples from the roof of Exeter Guildhall were analysed by tree-ring dating. This analysis produced three site chronologies. The first, consisting of eight samples, has 143 rings spanning the period AD 1314 - 1456. Interpretation of the sapwood on the dated samples would indicate a felling date for the timbers represented in the range Ad 1463 to AD 1498.

Authors' addresses :-

R E Howard
UNIVERSITY OF NOTTINGHAM
University Park
Nottingham
NG7 2RD

Dr R R Laxton
UNIVERSITY OF NOTTINGHAM
University Park
Nottingham
NG7 2RD

Dr C D Litton
UNIVERSITY OF NOTTINGHAM
University Park
Nottingham
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Introduction

Exeter Guildhall is set in a prominent position in the High Street of the City (SX 919924; Figs 1 and 2). It was the main administrative and ceremonial centre of the town in the Middle Ages, probably from as early as the twelfth century. There is little or nothing of this date surviving. Most of the visible fabric is mainly of the late-fifteenth century, probably of the AD 1480s, and of the late-sixteenth century. This latter phase is well documented to AD 1592-4 and has also been dated by dendrochronology (Bridge 1988). Repairs and alteration to the Guildhall took place in the eighteenth and nineteenth centuries, with later repairs being undertaken in AD 1900 and AD 1970. The most recent work was completed in AD 1986. The building now comprises an open hall with a two storied porticoed front and cells of Elizabethan date, with Magistrates rooms to rear. A plan of the building is provided in Figure 3.

On documentary evidence the masonry shell of the hall is believed to date to the late AD 1460s. The stylistic evidence of the stonework and other architectural details are quite consistent with this date. The evidence for the roof, however, is equivocal, and it is believed that it could be later.

The roof is of seven bays with main trusses of principal rafters, collars, and curved arch-braces on corbels with bosses. Between the main trusses are intermediate frames with pendant bosses, but without collars. These frames carry double purlins and wind braces. An illustrative example of a main and an intermediate truss is given in Figure 4. All timbers are highly decorated, being deeply moulded and carved.

Sampling and analysis by tree-ring dating was commissioned by English Heritage. The purpose of this was to establish an absolute date for the roof and to place it for comparative purposes within a group of similar roofs in Exeter. These include other buildings that the Nottingham Laboratory has analysed by dendrochronology, the Archdeacon of Exeter's House, the Deanery, and the Law Library (Howard *et al* forthcoming). The research into the group of roofs in Exeter is being undertaken in connection with a major programme of recording and repair at Bowhill in Devon (Blaylock forthcoming), which is being funded by English Heritage (Groves forthcoming).

A further purpose of sampling was to obtain additional tree-ring data for this region. Exeter, and the southwest in general, have relatively few dated reference chronologies. This is in part due to the slightly short growth-ring sequences found on samples in this area caused by the wide rings found on many trees and timber, and in part due to the complacency of the growth-ring patterns. It was believed that Exeter Guildhall would provide a substantial amount of timber with longer growth-ring sequences capable of providing a well-replicated site chronology with a distinctive regional climatic signature.

The Laboratory would like to take this opportunity to thank all those who assisted with the sampling of the timbers. In particular thanks are due to the Mr William Olive, Mace Sergeant of the Guildhall and the Guildhall cleaners who cooperated wholeheartedly with the sampling and uncomplainingly put up with the disruption caused. The Laboratory would also like to thank Stuart Blaylock. Not only did Stuart Blaylock assist with the sampling, the interpretation of the building, provide assistance with the site description given above and in liasing with the various bodies concerned, but also most usefully assisted with the erection and disassembly of the scaffolding tower. The Laboratory would finally like to thank John Allan of the Royal Albert Museum, Exeter, for his valuable help in this matter.

Sampling

A total of twenty-six different oak timbers was sampled by coring. Each sample was given the code EXT-E (for Exeter, site "E") and numbered 01–26. The positions of the samples were recorded on plans adapted from those provided by Stuart Blaylock, reproduced here as Figures 5a/b. For the sake of clarity in identifying sample locations the trusses have been numbered from west to east, that is from the rear of the building to the street frontage. In reality this is north-west to south-east.. Details of the samples are given in Table 1. Sampling of the timbers was undertaken after discussion with Stuart Blaylock of Exeter Archaeology. The carpentry within the roof strongly suggests that it is a single-phase construction and sampling was conducted under this interpretation.

Sampling was made difficult by the height of the roof, the lowest available timbers being some seven metres from the floor, and many of the others being nine to ten metres above floor level. Access to these timbers was gained from a mobile scaffolding tower, although the curved nature of the arch-braces and the height of the upper protective rails of the tower caused difficulties in safely reaching some members.

It will be seen from Table 1 that relatively few of the samples have sapwood or the heartwood/sapwood boundary. This is due to the highly moulded, carved, and curved nature of many of the timbers, in that there were few places where sapwood, or the heartwood/sapwood boundary, was present. Given that one of the purposes of sampling was to obtain tree-rings with local data, many of the timbers were sampled to obtain maximum number of rings, even if they had no sapwood or the heartwood/sapwood boundary.

Analysis

Each sample was prepared by sanding and polishing and the growth-ring widths of all samples measured. The data of these measurements are given at the end of the report. The growth-ring widths of all twenty-six samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum t-value of 4.5 three groups of samples formed.

The eight samples of the first group cross-matched with each other at relative positions as shown in the bar diagram Figure 6. The growth-ring widths of the nine samples were combined at these relative off-set positions to form EXTESQ01, a site chronology of 143 rings. Site chronology EXTESQ01 was compared with a series of relevant reference chronologies for oak, giving it a first ring date of AD 1314 and a last measured ring date of AD 1456. Evidence for this dating is given in the t-values of Table 2.

The average last heartwood ring date on site chronology EXTESQ01 is AD 1448. The usual 95% confidence limits for the amount of sapwood on mature oaks from this part of England is taken to be in the range 15-50 rings. This would give the timbers represented by these samples an estimated felling date in the range AD 1463-1498.

The two samples of the second group to be formed at t=4.5 by the Litton/Zainodin grouping procedure, cross-matched with each other at relative positions as shown in the bar diagram Figure 7. The growth-ring widths of these two samples were combined at these relative off-set positions to form EXTESQ02, a site chronology of 77 rings. Site chronology EXTESQ02 was compared with a series of relevant reference chronologies for oak, but there was no satisfactory cross-matching.

The two samples of the third and final group cross-matched with each other at relative positions as shown in the bar diagram Figure 8. The growth-ring widths of these two samples were combined at these relative off-set positions to form EXTESQ03, a site chronology of 77 rings. Site chronology EXTESQ03 was also compared with a series of relevant reference chronologies for oak, but again there was no satisfactory cross-matching.

The three site chronologies thus created, EXTESQ01, EXTESQ02, and EXTESQ03 were compared with each other, but there was, however, no further cross-matching. Each of the three site chronologies was then compared with all the remaining ungrouped samples. Again, there was no satisfactory cross-matching

Each of the fourteen remaining ungrouped samples was compared with a full series of relevant reference chronologies. While this indicated some tentative cross-matches for some individual samples the t-values were rather low and tended to be with non-relevant chronologies, those in Staffordshire, Nottinghamshire and Leicestershire, for example. There appeared to be no consistency to this individual tentative dating and as these samples cannot, therefore, be quoted with confidence, they must remain undated.

Conclusion

It would appear that, as expected, the roof of Exeter Guildhall is of a single phase of construction with the majority of the timbers have an estimated felling date in the range AD 1463-1498. Thus dating by dendrochronology supports the date expected on stylistic grounds.

Judging by the high t-value cross-matching between some samples it appears likely that a number of timbers are taken from the same tree. This is seen with samples EXT-E21 and E22, cross-matching with a t-value of 20.4, and samples EXT-E24 and E25, cross-matching with a t-value of 17.2, for example. The undated samples EXT-E18 and E19 probably also represent timbers taken from the same tree

Eighteen samples remain undated, E01-E04, E06, E07, E09, E11, E12, E13-19, E23, and E26. Most of these have less than 60 rings and show slightly complacent growth-ring patterns. The longest of the other undated samples has 77 rings. It is probably the lack of growth-rings on these undated samples, their complacency and the continuing lack of relevant reference data for the Southwest that makes these samples difficult to date.

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Table 1: Details of samples from Exeter Guildhall, High Street, Exeter

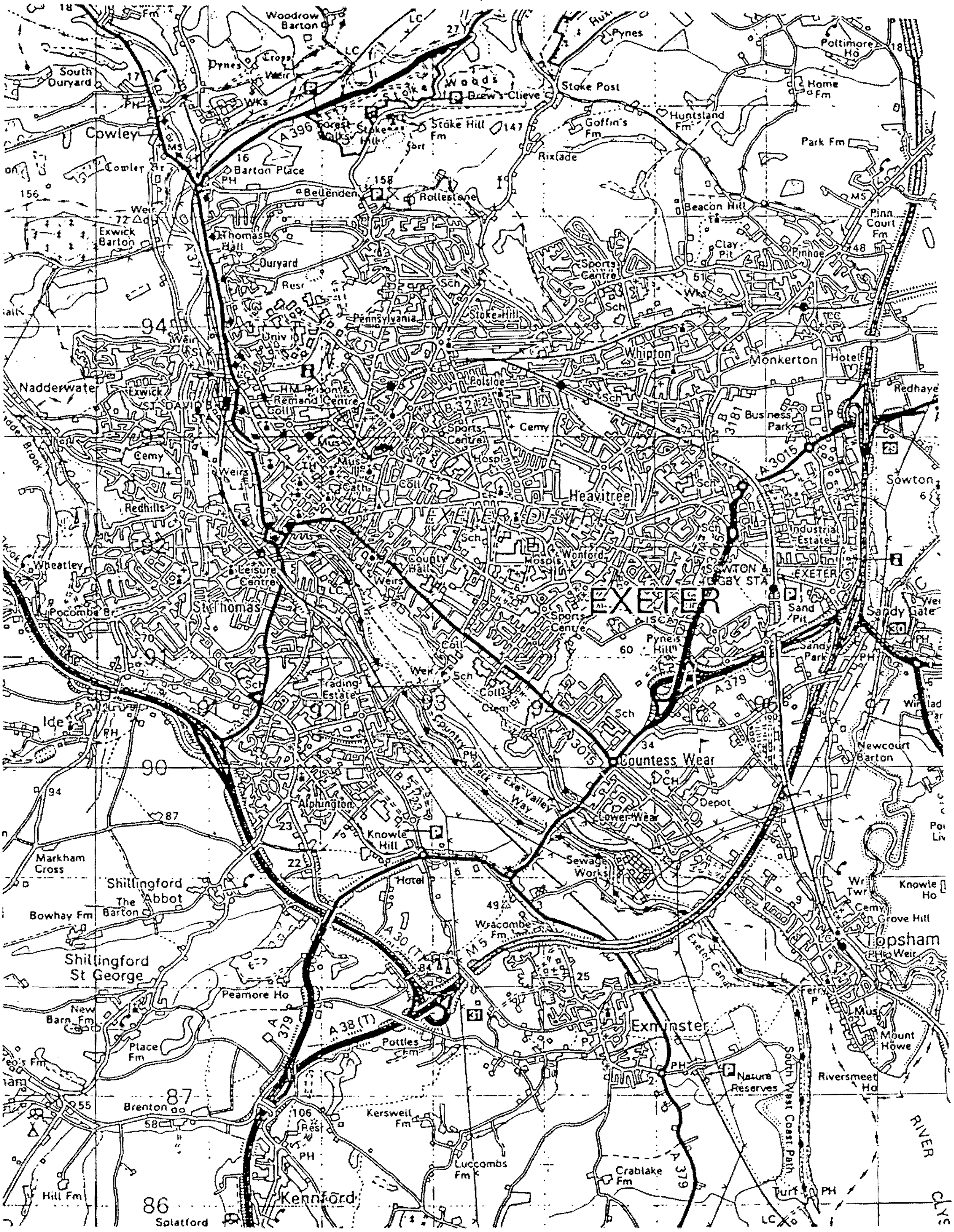
Sample no.	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
EXT-E01	South lower purlin, bay 1	54	20C	------	------	------
EXT-E02	South lower purlin, bay 2	75	no h/s	------	------	------
EXT-E03	East upper windbrace, south side, bay 2	75	no h/s	------	------	------
EXT-E04	South principal rafter, truss 2	55	no h/s	------	------	------
EXT-E05	South lower purlin, bay 3	106	no h/s	AD 1314	------	1419
EXT-E06	West upper windbrace, south bay 3	54	no h/s	------	------	------
EXT-E07	South upper arch-brace, truss 3	66	no h/s	------	------	------
EXT-E08	South intermediate rafter, bay 3	94	no h/s	AD 1343	------	1436
EXT-E09	South principal rafter, truss 5	77	no h/s	------	------	------
EXT-E10	South lower arch-brace, truss 5	87	no h/s	AD 1339	------	1425
EXT-E11	North lower purlin, bay 4	65	h/s	------	------	------
EXT-E12	East lower windbrace, south bay 4	54	no h/s	------	------	------
EXT-E13	West lower windbrace, south bay 4	54	no h/s	------	------	------
EXT-E14	East upper windbrace, north bay 5	71	h/s	------	------	------
EXT-E15	Collar, truss 6	52	no h/s	------	------	------
EXT-E16	Collar truss 5	72	no h/s	------	------	------
EXT-E17	North upper arch-brace, truss 5	54	no h/s	------	------	------
EXT-E18	North intermediate rafter, bay 5	59	10	------	------	------
EXT-E19	South principal rafter, truss 7	77	no h/s	------	------	------
EXT-E20	North principal rafter, truss 6	72	12	AD 1385	1444	1456
EXT-E21	North principal rafter, truss 7	102	h/s	AD 1348	1449	1449
EXT-E22	South principal rafter, truss 4	106	h/s	AD 1344	1449	1449
EXT-E23	West upper windbrace, north bay 6	58	no h/s	------	------	------
EXT-E24	South principal rafter, truss 6	125	no h/s	AD 1315	------	1439
EXT-E25	North principal rafter, truss 4	101	no h/s	AD 1339	------	1439
EXT-E26	North upper arch-brace, truss 6	56	no h/s	------	------	-----

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on sample

Table 2: Results of the cross-matching of site chronology EXTESQ01 and relevant reference chronologies when first ring date is AD 1314 and last ring date is AD 1456

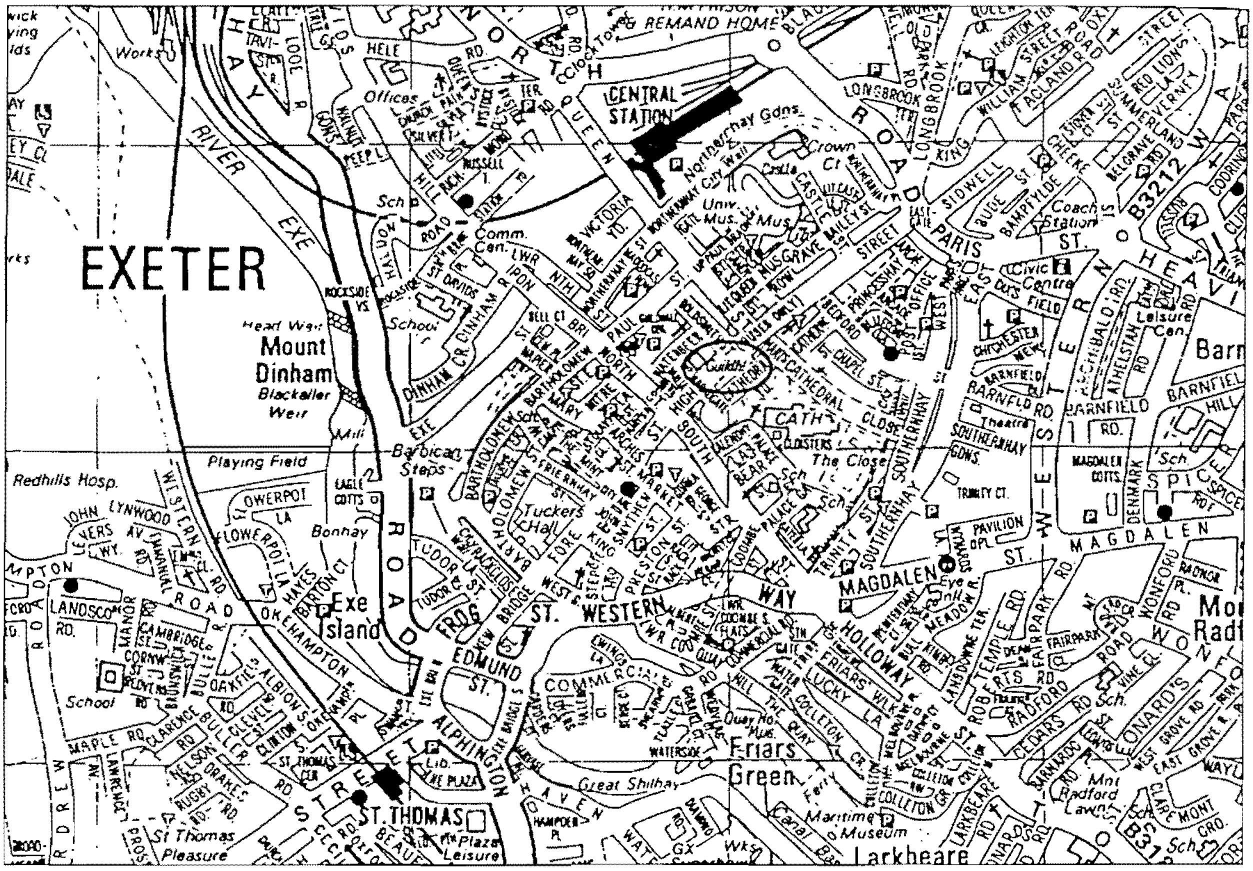
Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	7.0	(Laxton and Litton 1988)
England	AD 401 – 1981	6.4	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	6.3	(Bridge 1988)
Reading Waterfront, Berks	AD 1160 – 1407	4.4	(Groves *et al* 1997)
Lodge Park, Aldsworth, Glos	AD 1324 – 1587	4.6	(Howard *et al* 1995)
Lacock Abbey, Wilts	AD 1314 – 1448	5.1	(Esling *et al* 1990)

Figure 1: Map to show general location of Exeter



(based upon the Ordnance Survey 1:50000 map with permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright).

Figure 2: Map to show location of Exeter Guildhall in the High Street



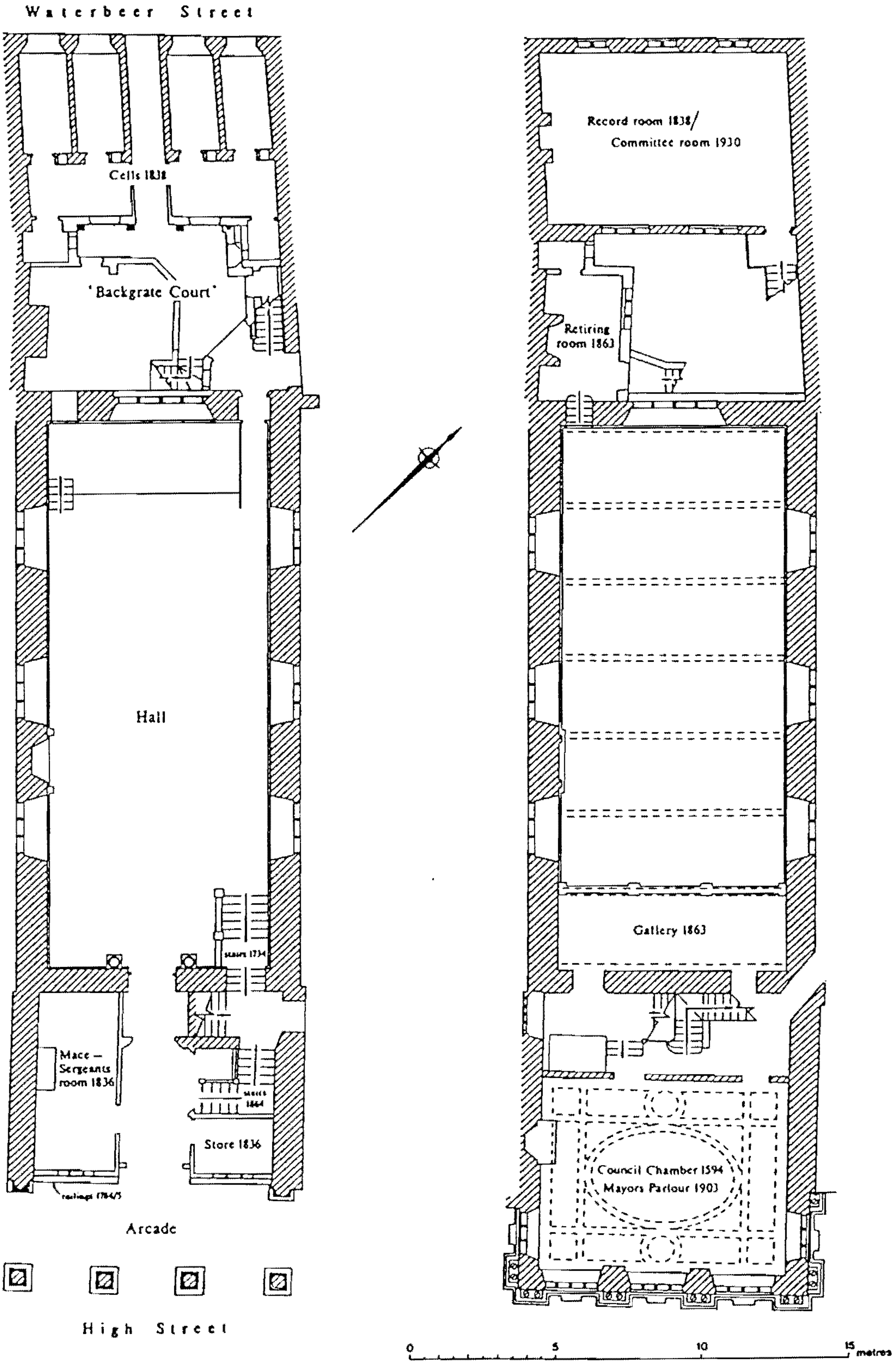
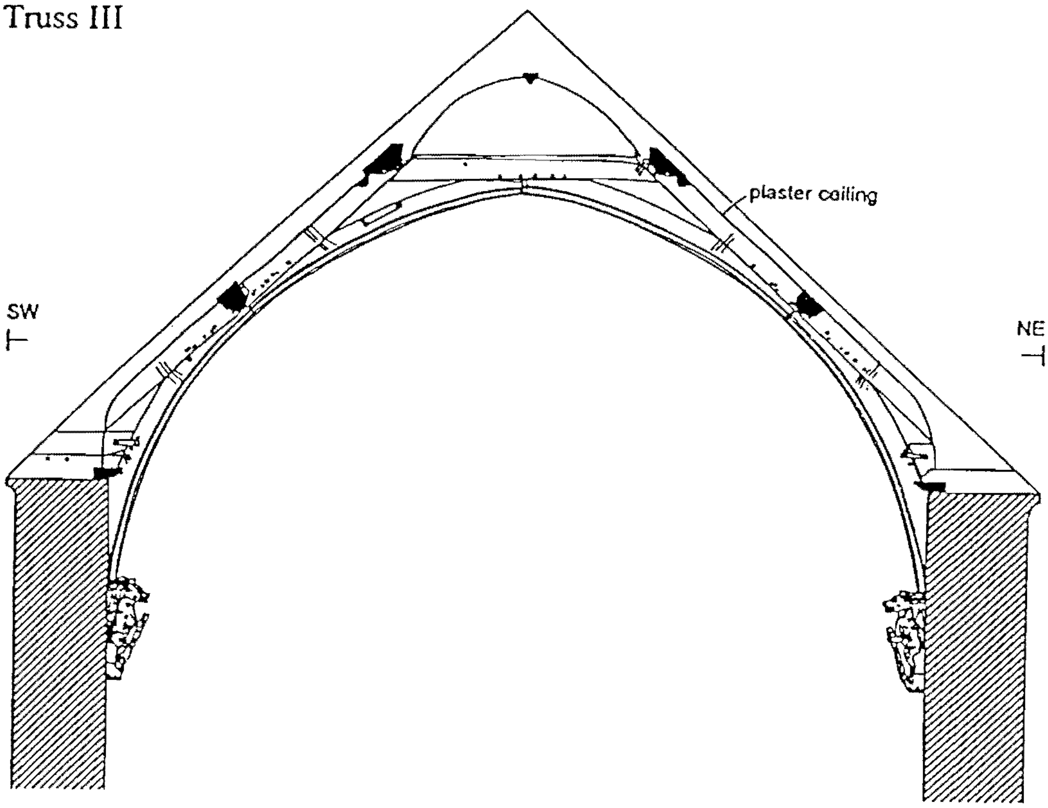


Figure 3: General plan of ground and first floors of Exeter Guildhall

Figure 4: Illustrative examples of a main and an intermediate truss

Truss III



Intermediate Truss III

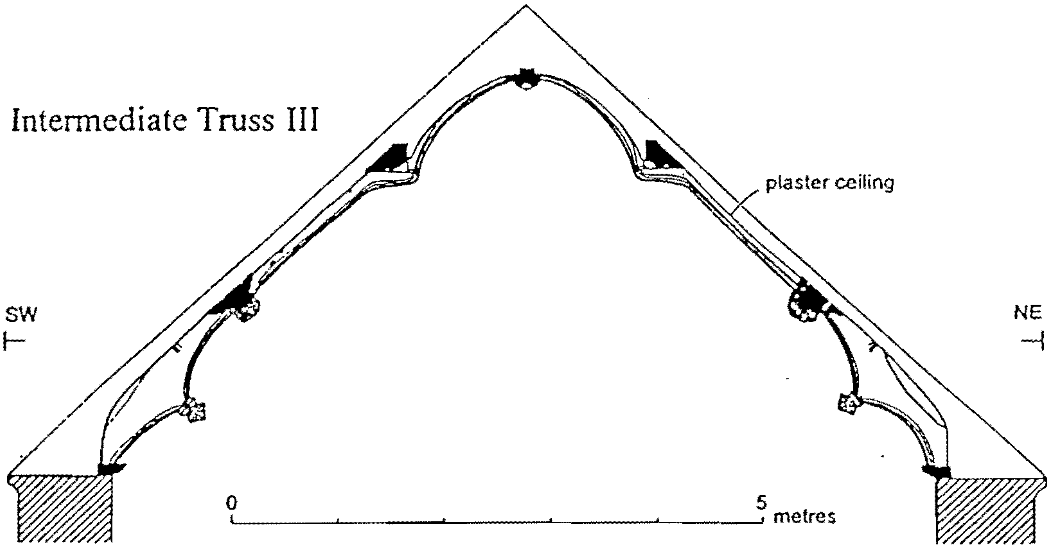


Figure 5a: Section looking north to show position of samples

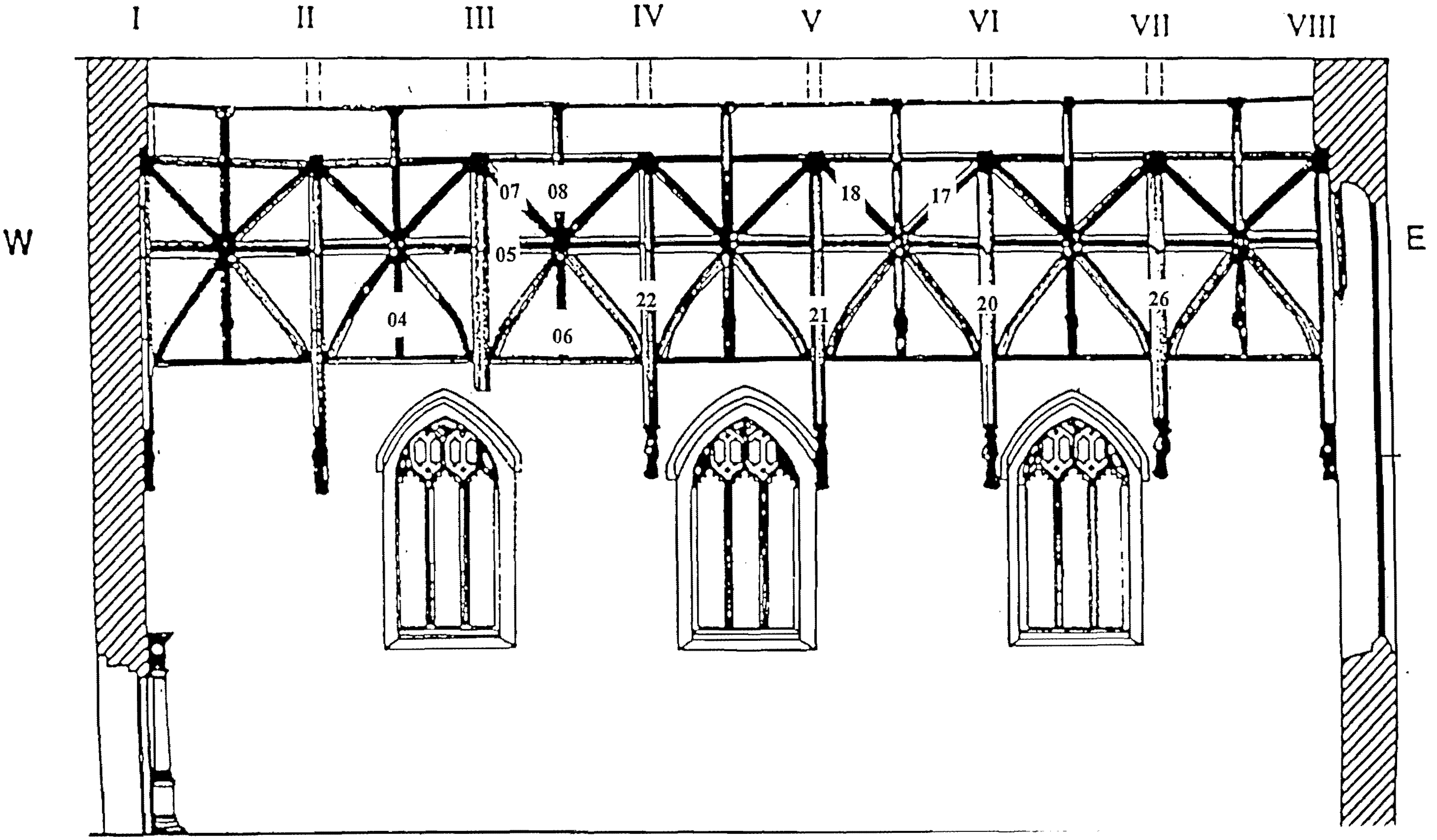


Figure 5b: Section looking south to show position of samples

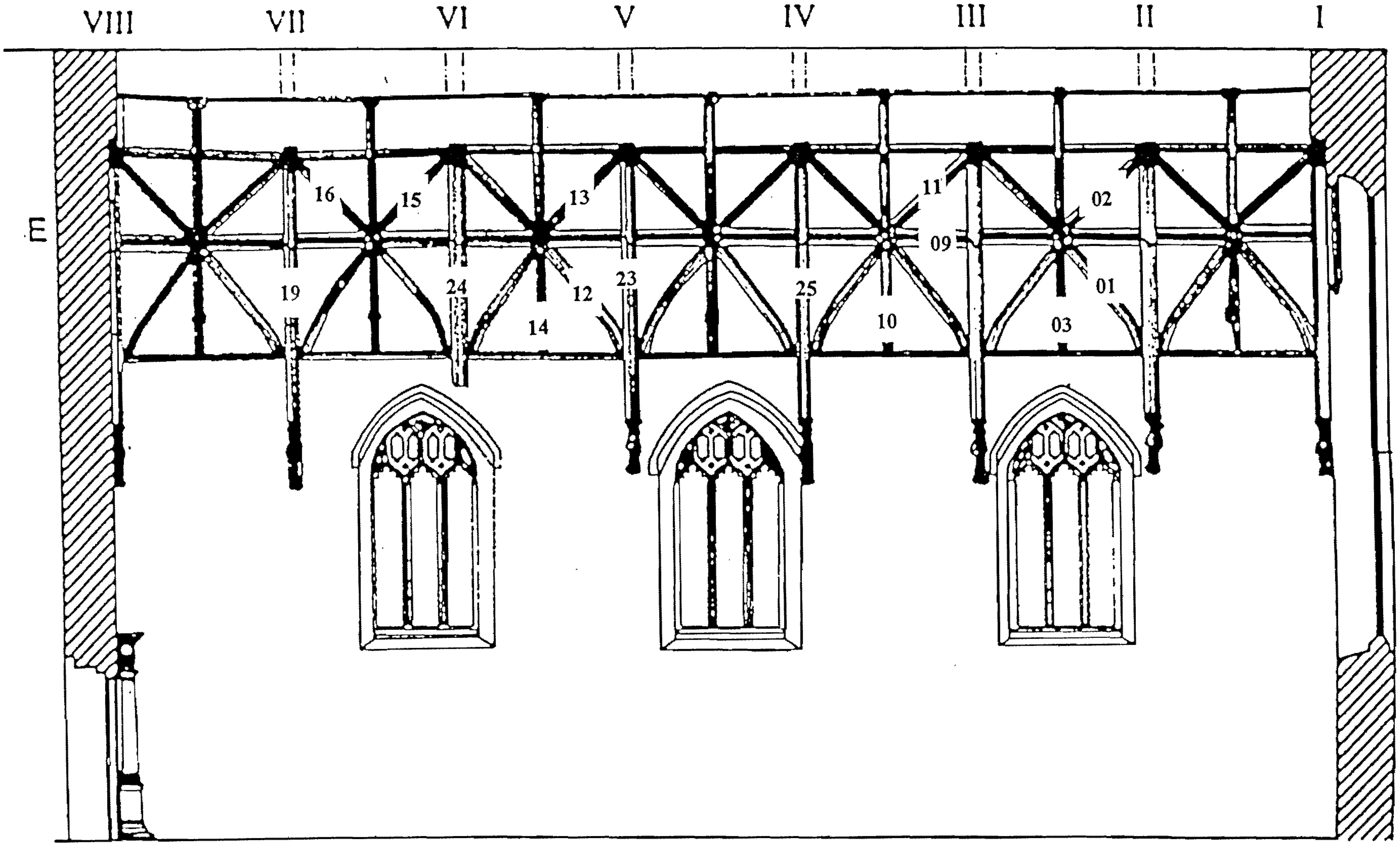


Figure 6: Bar diagram of samples in site chronology EXTESQ01

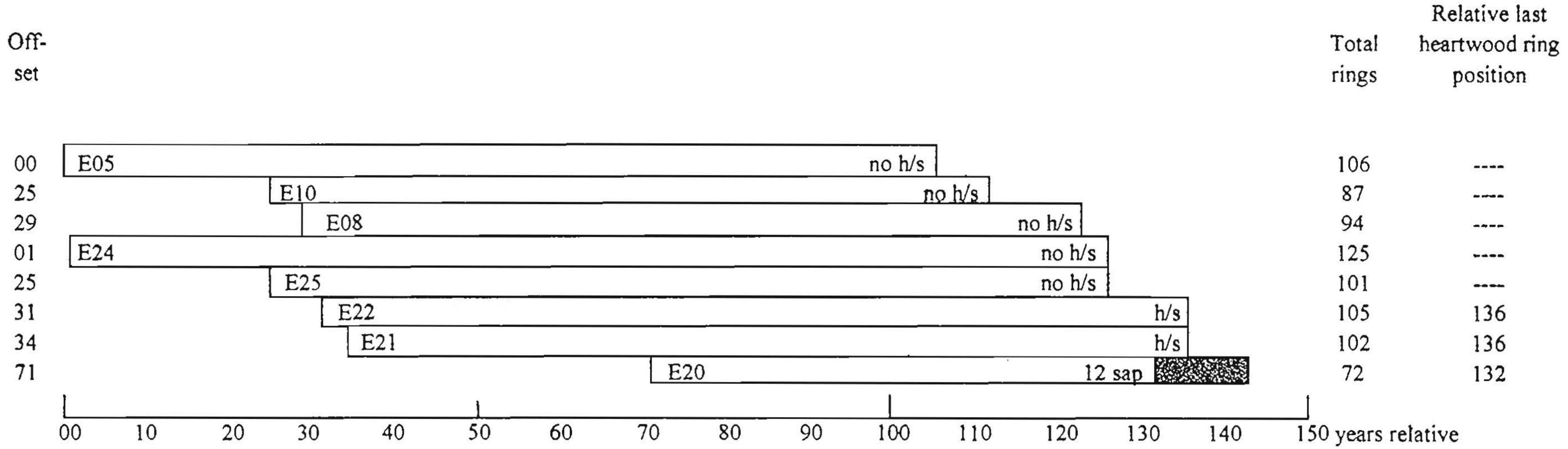
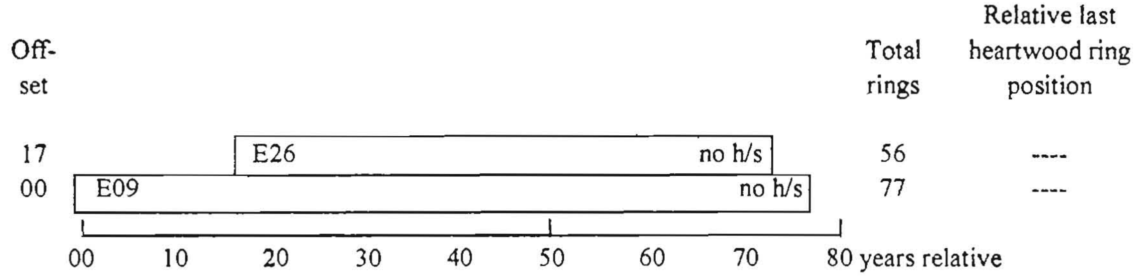
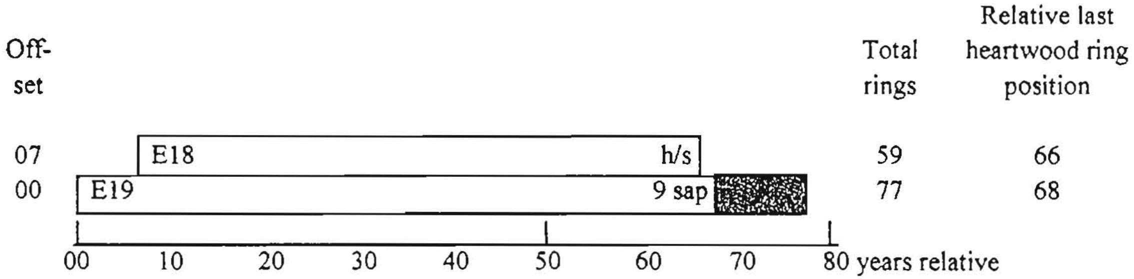


Figure 7: Bar diagram of samples in site chronology EXTESQ02



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 8: Bar diagram of samples in site chronology EXTESQ03



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Data of measured samples – measurements in 0.01mm units

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EXT-E01A 54
 286 321 366 274 311 315 395 242 339 426 320 340 279 179 259 188 172 244 276 172
 172 252 187 218 169 172 167 130 140 138  77 141 120 158 145 118 131 148 100  60
  94  99  79  82  97  92  81  64  94  90  91  96  71 119
EXT-E01B 54
 325 304 374 286 281 315 395 243 332 389 305 336 285 198 257 173 154 229 296 174
 186 232 199 204 154 166 156 130 142 138  94 126 133 153 151 120 124 149 101  58
  93 100  77  80  95  92  91  62  84  96  80  98  91 100
EXT-E02A 75
 452 155 161 129 137 292 207 248 221 180 236 181 206 146 110  72  81 159 132 143
 139 162 105 156  83 125  83 122  91 146 101 122 144 147 134 110 127 132  77  96
  74  76 235 196 236 136 146 196 150  84  98  99 132 148 216 139 103  99 239 199
 162 228 190 207 361 462 406 332 122 100  67 161 145 163 265
EXT-E02B 75
 444 158 153 133 133 295 204 257 235 184 236 174 209 146 113  75  73 164 143 139
 137 167  88 151  92 107  88  97 116 164 104 109 151 124 140 106 120 108  76 101
  77  76 218 193 227 128 143 203 147  90 108  95 139 145 213 130 104 109 252 196
 153 248 190 208 385 447 397 315 120  93  71 159 148 155 266
EXT-E03A 75
 256 302 355 329 207 278 173 256 279 229 210 255 299 350 225 125 174 118 153 226
 216 134 126  92  98 115 126 146 194 266 300 323 370 259 202 221 129 183 163 138
 203 132 142 104 106 105 125 204 215 250 354 349 171 183 129 124 135 219 199 213
 150 172 207 191 228 318 363 299 330 322 262 159 139 189 232
EXT-E03B 75
 261 281 348 325 223 283 167 264 302 258 210 241 283 321 204 144 155 132 181 224
 228 147 122 103  93 114 128 169 208 282 296 325 349 269 208 255 127 191 138 150
 208 139 138 106 105  95 122 207 212 253 350 353 188 165 122 135 137 209 201 206
 157 175 206 192 220 317 344 317 342 302 257 162 141 182 189
EXT-E04A 55
  70 109 118 150 115  83  83  99 116  98 158 201 168 196 254 228 146 162 100 117
 136 178 189 158 162 164 175 262 219 215 214 187 226 140 244 255 220 246 249 260
 241 167 187 143 167 177 188 275 212 218 203 254 245 270 190
EXT-E04B 55
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 142 176 195 161 152 173 165 254 229 213 204 178 228 146 247 249 226 258 239 287
 264 162 207 149 160 171 196 270 249 209 197 261 264 274 193
EXT-E05A 106
 336 393 421 316 202 241 249 216 194 182 177 192 120 169 208 305 190 172 161 148
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 183 203 174 209 223 205 171 165 167 208 222 184 201 221 235 204 196 175 209 226
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122 119 160 151 142 174 169 210 276 206 216 206 167 168 153 160 171 210 144 212
164 206 188 219 236 211 161 163 172 204 212 198 199 225 225 196 206 181 210 229
283 279 220 201 247 254 247 205 245 189 189 214 174 221 209 162 127  94  88 125
118 134 142 110 116 126 150 145 121 147  73 116 209 210 243 281 247 253 221 223
240 224 141 134 102 123
EXT-E06A 54
317 525 359 421 399 308 481 311 345 399 617 360 339 326 286 265 316 350 356 339
565 511 542 276 336 298 213 218 277 394 334 225 277 274 397 329 190 277 214 211
190 181 293 500 343 440 309 499 379 404 630 351 333 287
EXT-E06B 54
291 531 344 454 419 310 478 289 348 415 615 364 341 327 298 235 322 304 352 323
486 514 502 320 334 298 217 215 260 408 331 224 279 287 376 313 182 255 215 222
177 174 299 529 343 439 294 486 336 409 631 347 333 285
EXT-E07A 66
372 190 150 148 125 351 214 204 177 141 125 107 193 189 184 137 102 244 179 254
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378 309 230 208 154  89  73  99  44  36  70 102 170 150  99 179 326 193 124 184
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200 195 167 145 114  93  82  75  94  80  79  87  65  46  51  46  50  62  55  43
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148 138 119 121 130 171 112 140 164 264 186 246 292 296
EXT-E09A 77
462 491 437 416 373 368 360 406 311 303 326 250 214 300 304 233 183 138 172 216
162 204 213 200 207 192 191 189 233 194 227 229 179 134 147 150 139  96  53  80
 79 122 184 254 282 275 175 208 196 270 295 239 342 400 440 220 212 121 142  84
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EXT-E09B 77
400 503 468 440 359 372 364 404 314 279 324 236 210 286 305 270 181 133 179 217
175 208 206 201 186 200 191 195 255 194 228 230 183 139 137 159 140  91  60  69
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EXT-E10A 87
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EXT-E10B 87
236 352 356 460 299 366 329 272 287 285 295 236 307 215 286 329 229 280 282 268
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91 107 130 113 128 141 130
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568 491 434 392 353 273 218 268 209 259 363 266 299 364 289 364 314 237 183 270
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129 118 89 69 55 49 39 55 51 81 98
EXT-E14B 71
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137 105 111 80 72 52 53 46 79 68 75 45 53 57 50 68 58 64 114 100
141 125 86 75 48 47 47 61 59 77 89
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EXT-E15A 52
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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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring..

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. ***Inspecting the Building and Sampling the Timbers.*** Together with a building historian we inspect the timbers in a building to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings. Similarly the core has just over 100 rings.

   To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8 to 10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time

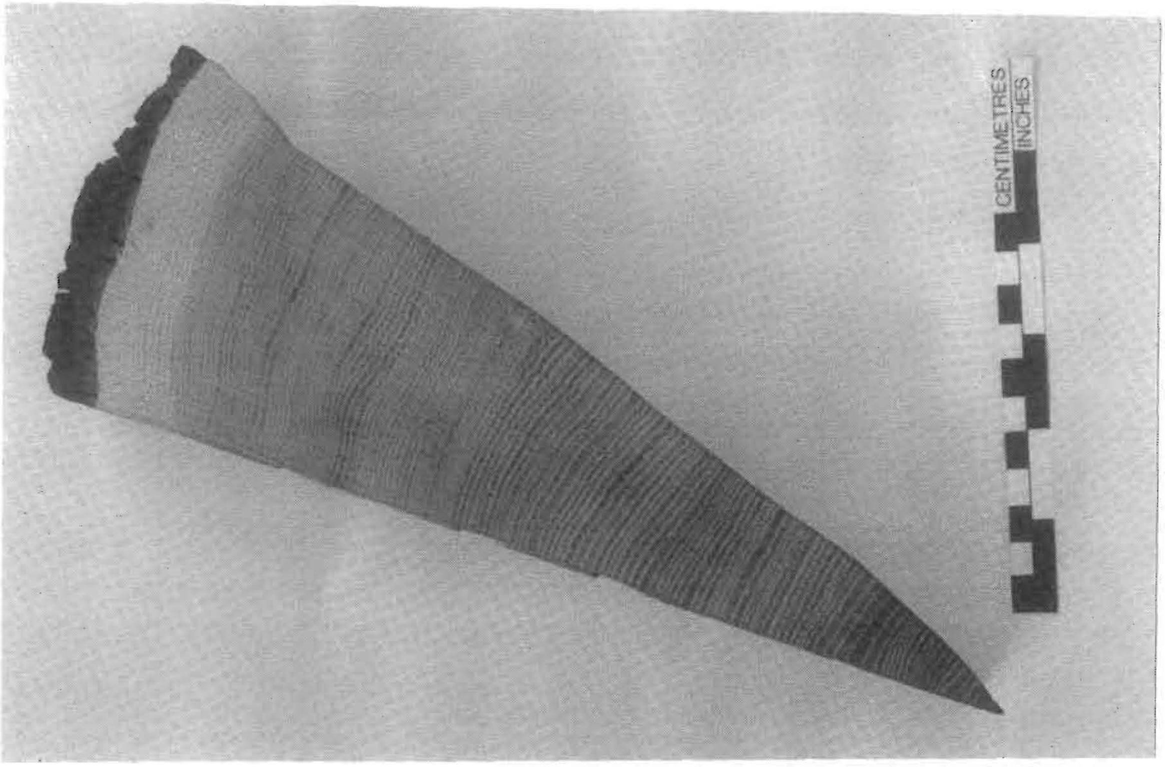

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

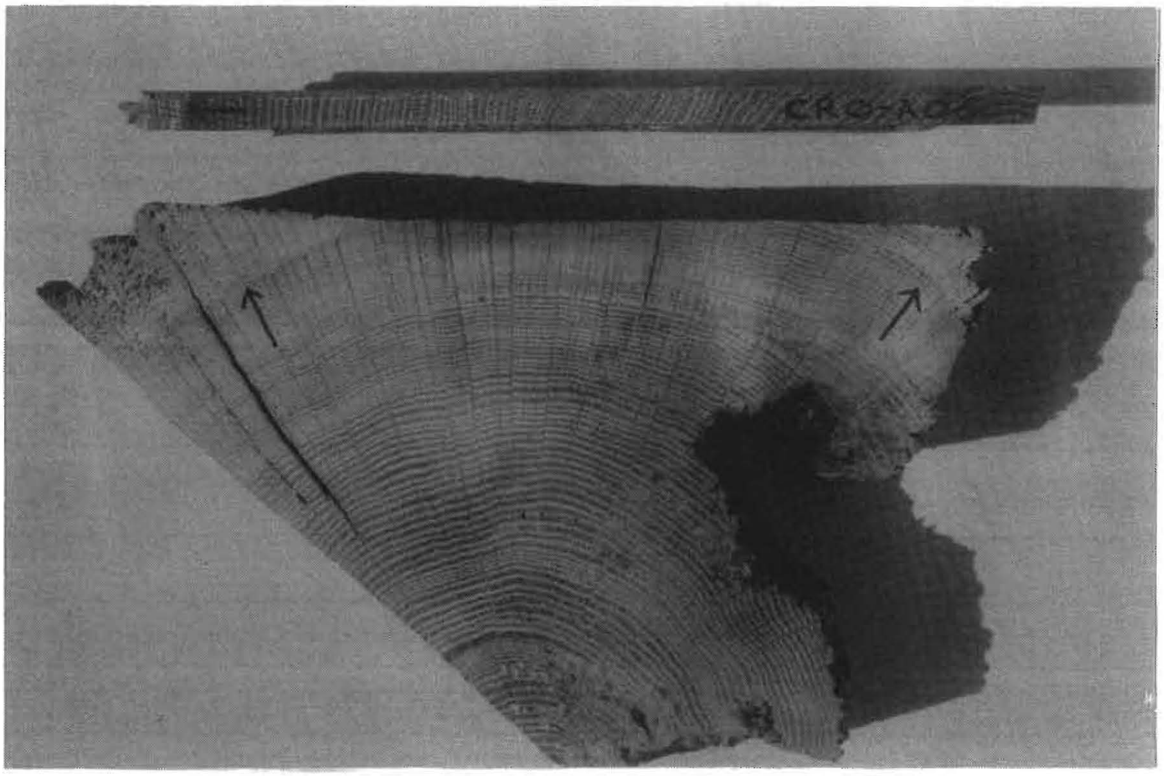

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners; the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

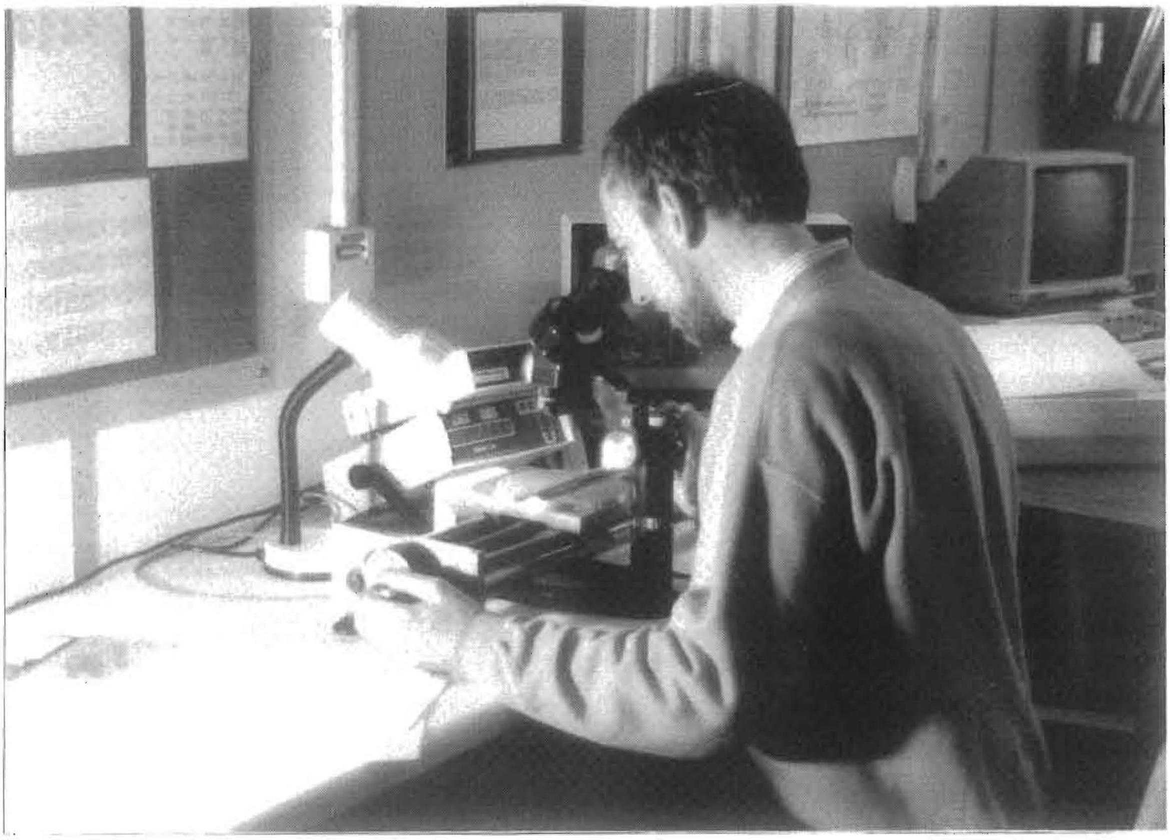

Fig 3. Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

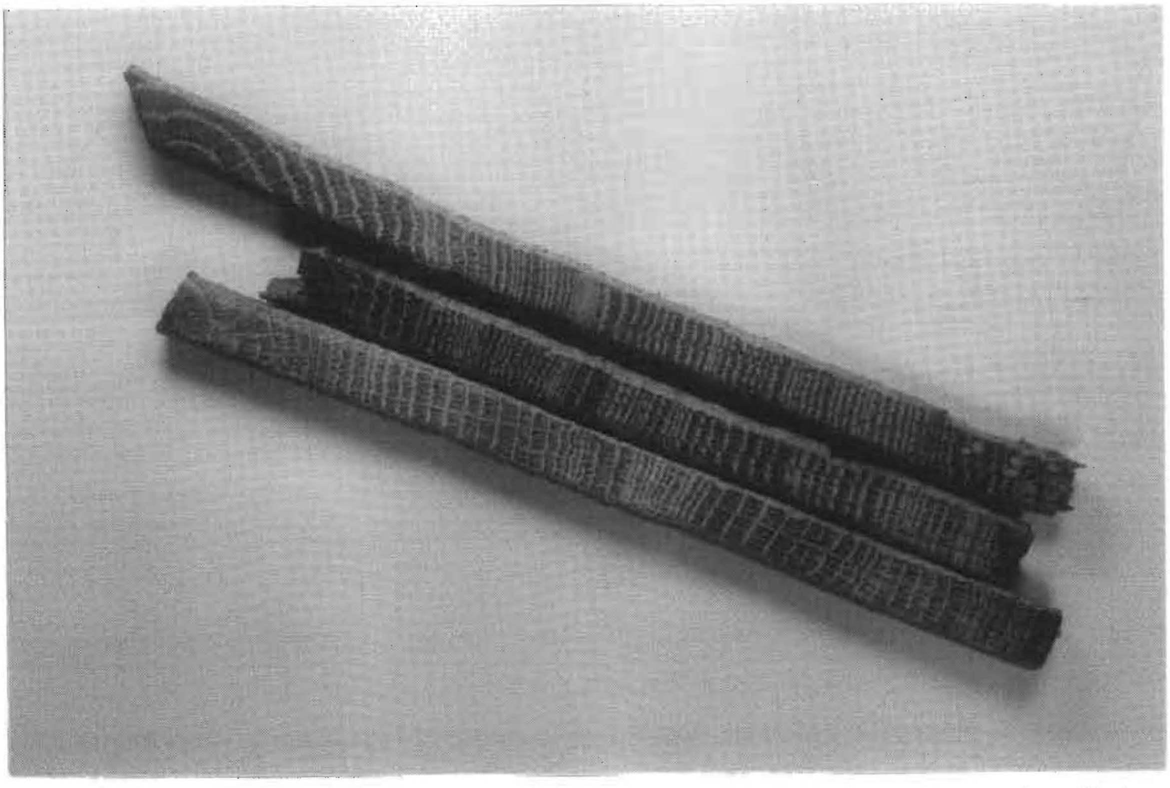

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

All sampling by the Laboratory is undertaken according to current Health and Safety Standards.
The Laboratory is insured with the CBA.

2. ***Measuring Ring Widths.*** Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples.*** Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum t-value among the t-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a t-value of at least 4.5, and preferably 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

   This is illustrated in Fig 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN- C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the t-value between C45 and C08 is 5.6 and is the maximum between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately

This straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal t-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

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

   Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely for these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

   Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

   Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

   More precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 40 years later we would have estimated without this observation

T-value/Offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

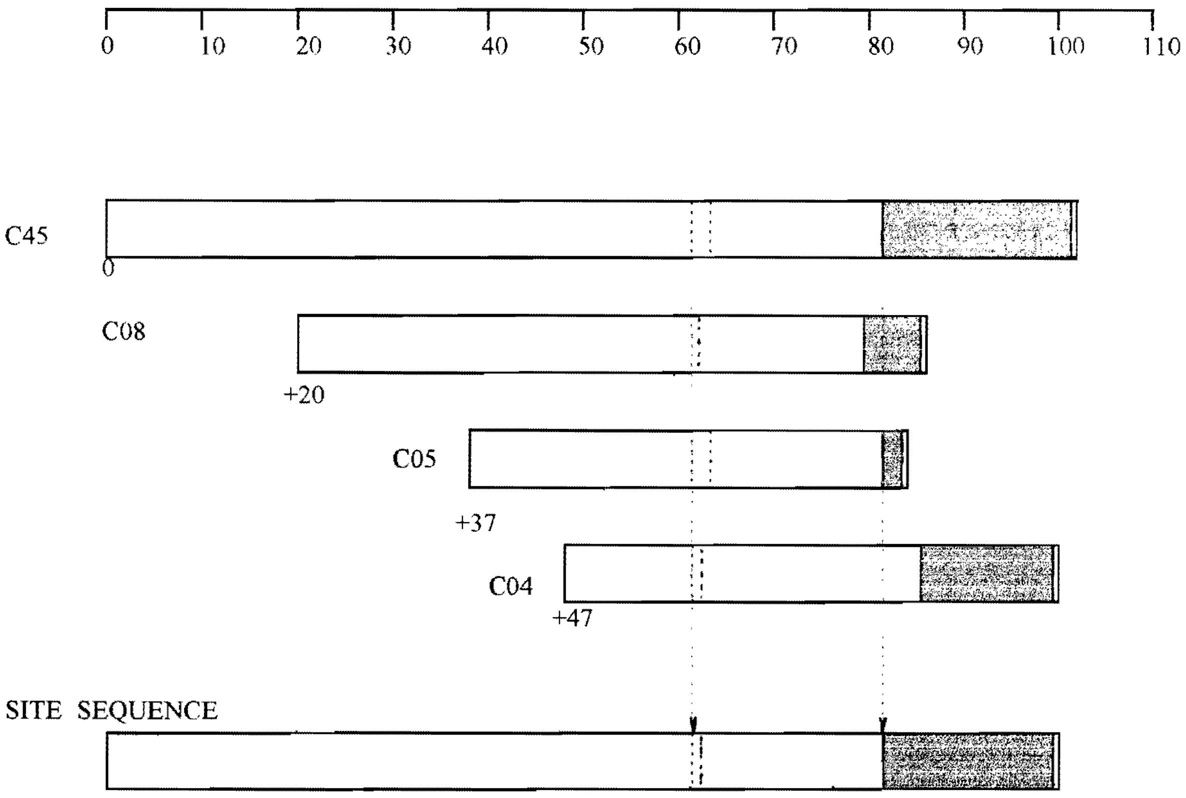

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t-values*.
The *t-value/offset* matrix contains the maximum t-values below the diagonal and the offsets above it.
Thus, the maximum t-value between C08 and C45 occurs at the offset of +20 rings and the t-value is then 5.6.
The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ,* and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed for this.

6. ***Master Chronological Sequences.*** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton 1988b, but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988a). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

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

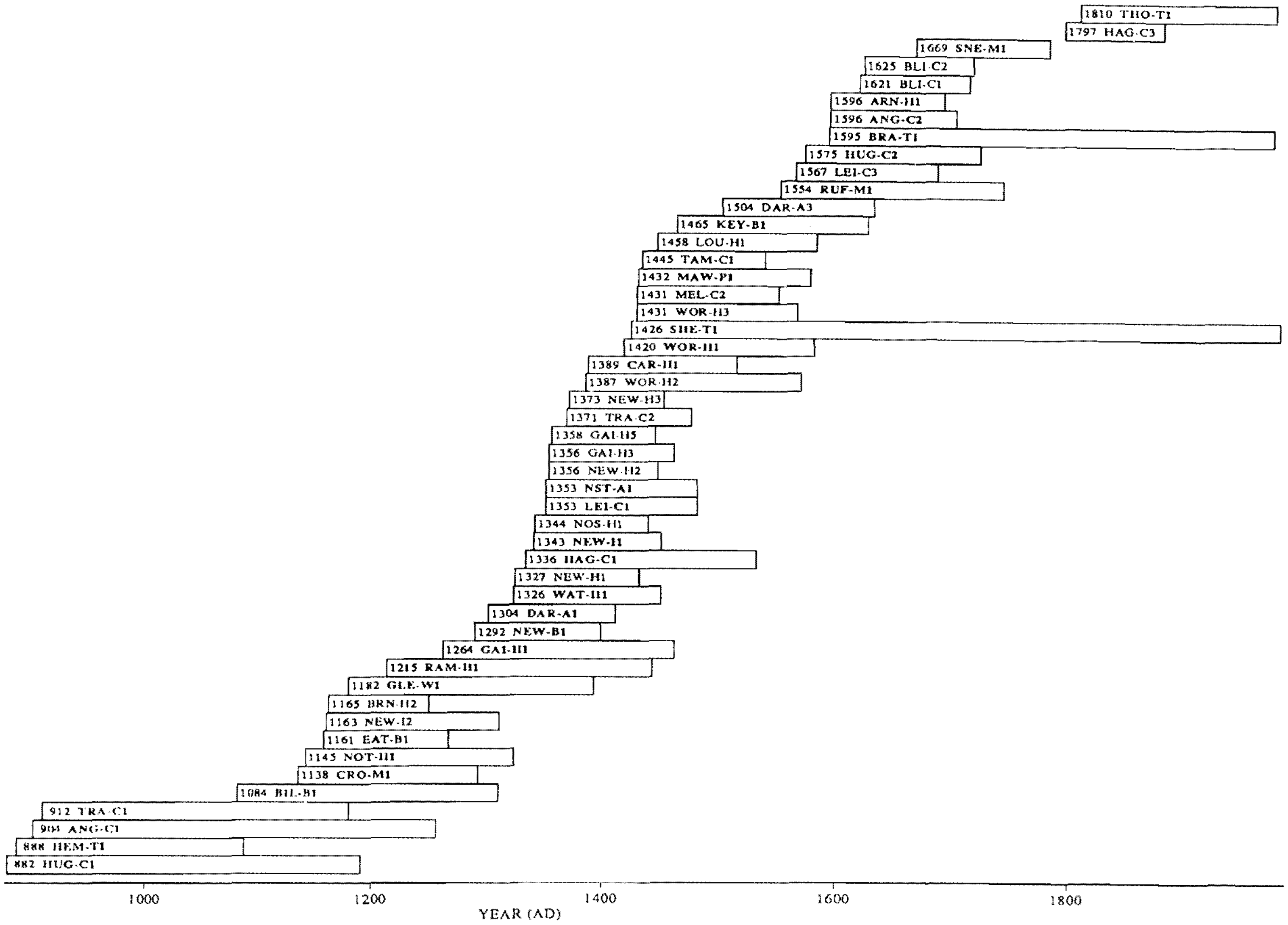

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

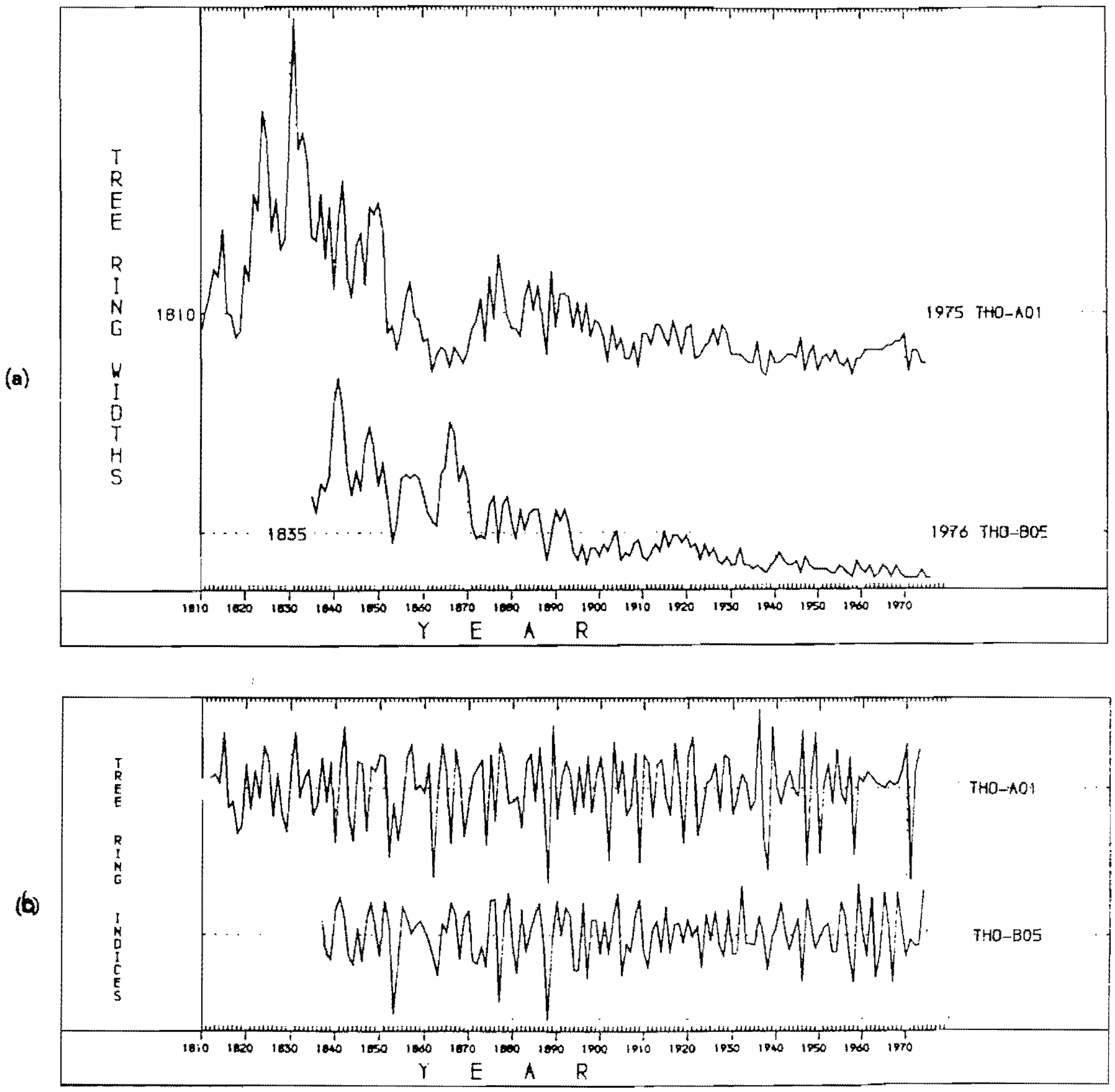

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

(b) The *Baillie-Pilcher indices* of the above widths. The growth-trends have been removed completely.

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