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Summary

A total of twelve samples was obtained from the roof of the nave of St Peter's Church, Claybrooke Parva. The analysis of these samples produced a single site chronology consisting of eight samples, being 146 rings long. This site chronology was dated as spanning the years AD 1271 to AD 1416.

Interpretation of the meagre heartwood/sapwood boundaries on the dated samples indicates that all of them represent timbers with a felling date estimated to be in the range AD 1425 - 50

Keywords

Dendrochronology
Standing Building

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Introduction

St Peter's in Claybrooke Parva, Leicestershire (SP 496879; Figs 1 and 2) is a large parish church with possible twelfth-century remains. On the basis of architectural features it is believed that parts of the church, particularly the chancel, were rebuilt in the early to mid fourteenth century with the nave being rebuilt towards the end of the same century. The tower was remodeled in the early seventeenth century, and the whole church was restored in the period AD 1876 - 8. The church is a grade I listed building.

The nave roof consists of five very fine brattished, or heavily decorated and moulded, tiebeam trusses, arcaded in the spandrels of the trusses and to either side of the king-posts. The trusses are supported on carved and moulded wall posts, some with carved figures at their bases, which rise from stone corbels. The trusses carry heavily moulded single purlins and a ridge beam. A number of finely carved bosses, some of leaves and foliage, others of figures, including grotesques, are also present. An illustrative example of a truss is provided in Figure 3. It is believed that much of this roof was replaced during the nineteenth-century repair, though some of the earlier timbers, thought on stylistic grounds to date from the fourteenth-century rebuilding, were retained.

Sampling

Sampling and analysis by tree-ring dating of timbers from the nave roof were commissioned by English Heritage. The purpose of this was to provide a more precise date for the construction of this feature to inform a programme of grant-aided repairs.

Thus, from those timbers which appeared to be original, a total of twelve samples was obtained. Each sample was given the code CBP-A (for Claybrooke Parva, site "A"), and numbered 01 – 12. Timbers were selected for sampling on the basis of their appearing to have sufficient rings for satisfactory analysis by tree-ring dating, and for having at least the heartwood/sapwood boundary. Given the highly moulded and deeply carved nature of the decoration of the timbers, and that they had undergone nineteenth-century restoration such timbers were difficult to find, and only four cores with the heartwood/sapwood boundary were obtained.

The positions of the timbers sampled are shown on drawings made by Parkinson, Dodson, and Associates, Architects, and provided by English Heritage. These are reproduced here as Figure 4a-e. Details of the samples are given in Table 1. In this report the roof trusses have been numbered from east to west with individual timbers described on a north or south basis as appropriate.

The Laboratory would like to take this opportunity of thanking John Dodson for his help in accessing the site and for his discussions on likely timbers for dating.

Analysis

Each of twelve samples was prepared by sanding and polishing and their annual growth-ring widths were measured. The data of these measurements are given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a minimum t-value of 4.5 a single site chronology, CBPASQ01, consisting of eight samples of combined overall length 146 rings was formed. A bar diagram showing the relative positions of the samples in this site chronology is given in Figure 5. Site chronology CBPASQ01 was then compared with a large number of relevant reference chronologies for oak. This indicated a consistent cross-match with a number of these when the date of its first ring is AD 1271 and the date of its last measured ring is AD 1416. The t-values for this cross-matching are given in Table 2.

Site chronology CBPASQ01 was then compared with the four remaining ungrouped samples but there was no further satisfactory cross-matching. Each of the four remaining ungrouped samples was then compared individually with the reference chronologies, but again there was no satisfactory cross-matching, and these samples must remain undated.

Interpretation

Analysis by dendrochronology has produced a single site chronology made up of material obtained from a wide spread of locations within the nave roof. This site chronology consists of eight samples and is 146 rings long, these being dated as spanning the period AD 1271 to AD 1416.

Only three of the samples in site chronology CBPASQ01 retain the heartwood/sapwood boundary. The average last heartwood ring date of these three is AD 1410. The usual 95% confidence limit for the amount of sapwood on mature oaks from this part of England is 15 - 40 rings and such a limit would give the timbers represented an estimated felling date in the range AD 1425 - 50.

Conclusion

Analysis by dendrochronology has produced a single site chronology of eight samples, 146 rings long, and dated as spanning the period AD 1271 to AD 1416. It is highly likely that the great majority of dated timbers are of a single phase of felling, this having taken place, it is estimated, in the period AD 1425 - 50.

Such a felling date would thus not appear to be consistent with the supposed fourteenth-century date ascribed to the roof on the basis of stylistic interpretation, but would indicate the roof is later by at least a generation and possibly more. Analysis, and close observation of the timbers during sampling, has perhaps shown, however, that more early timber has been retained during the nineteenth-century restoration than might have been thought. The results obtained here thus reinforce the benefits of applying tree-ring analysis even to buildings which are thought to be reliably tightly dated on the basis of architectural features.

Four samples remain undated. Three of these do have low, though not insufficient, numbers of rings for analysis and all, including the sample with the higher number of rings, show very slight signs of compaction and distress. It is this feature that might make cross-matching and dating difficult.

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Table 1: Details of samples from the nave roof, St Peter's Church, Claybrooke Parva, Leicestershire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
CBP-A01	Tiebeam, truss 1	121	h/s	AD 1296	AD 1416	AD 1416
CBP-A02	Ridge figurine boss, truss 1	93	no h/s	AD 1303	------	AD 1395
CBP-A03	North principal rafter, truss 2	119	h/s	AD 1292	AD 1410	AD 1410
CBP-A04	Ridge figurine boss, truss 2	102	no h/s	AD 1298	------	AD 1399
CBP-A05	Tiebeam, truss 3	110	h/s	AD 1296	AD 1405	AD 1405
CBP-A06	North arch brace, truss 3	69	no h/s	AD 1313	------	AD 1381
CBP-A07	Ridge beam, truss 3 – 4	65	h/s	------	------	------
CBP-A08	Ridge beam, truss 4 – 5	81	h/s	------	------	------
CBP-A09	King post, truss 4	58	h/s	------	------	------
CBP-A10	Ridge figurine boss, truss 4	62	no h/s	AD 1327	------	AD 1388
CBP-A11	Tiebeam, truss 5	125	no h/s	AD 1271	------	AD 1395
CBP-A12	South principal rafter, truss 5	61	no h/s	------	------	------

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

Table 2: Results of the cross-matching of site chronology CBPASQ01 and relevant reference chronologies when first ring date is AD 1271 and last ring date is AD 1416

Reference chronology	Span of chronology	*t*-value	
East Midlands	AD 882 – 1981	9.3	(Laxton and Litton 1988)
England London	AD 413 – 1728	8.6	(Tyers and Groves 1999 unpubl)
Green Farm, Ansty, Leics	AD 1254 – 1449	7.8	(Alcock *et al* 1990)
Welesbourne, Warwicks	AD 1287 – 1429	7.2	(Alcock *et al* 1989)
April Cottage, Rothley, Leics	AD 1343 – 1443	7.0	(Alcock *et al* 1990)
Rooftree Cottage, Hoby, Leics	AD 1348 – 1441	6.8	(Alcock *et al* 1990)
Leicester Castle, Great Hall	AD 1337 – 1486	5.9	(Howard *et al* 1986)
Chicksands Priory, Beds	AD 1200 – 1541	5.5	(Howard *et al* 1998)

Figure 1: Map to show general location of Claybrooke Parva

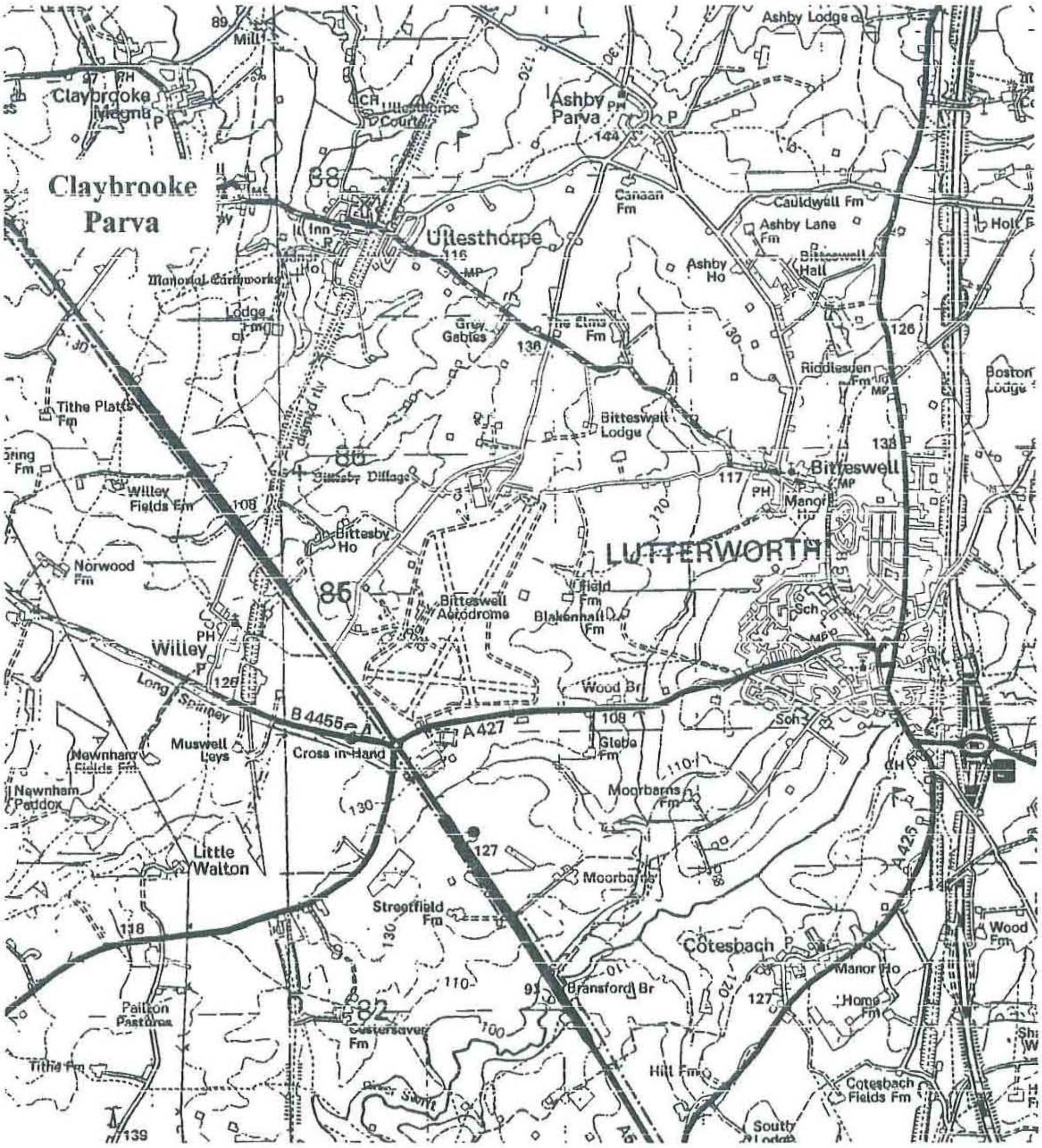


Figure 2: Map to show location of St Peter's Church

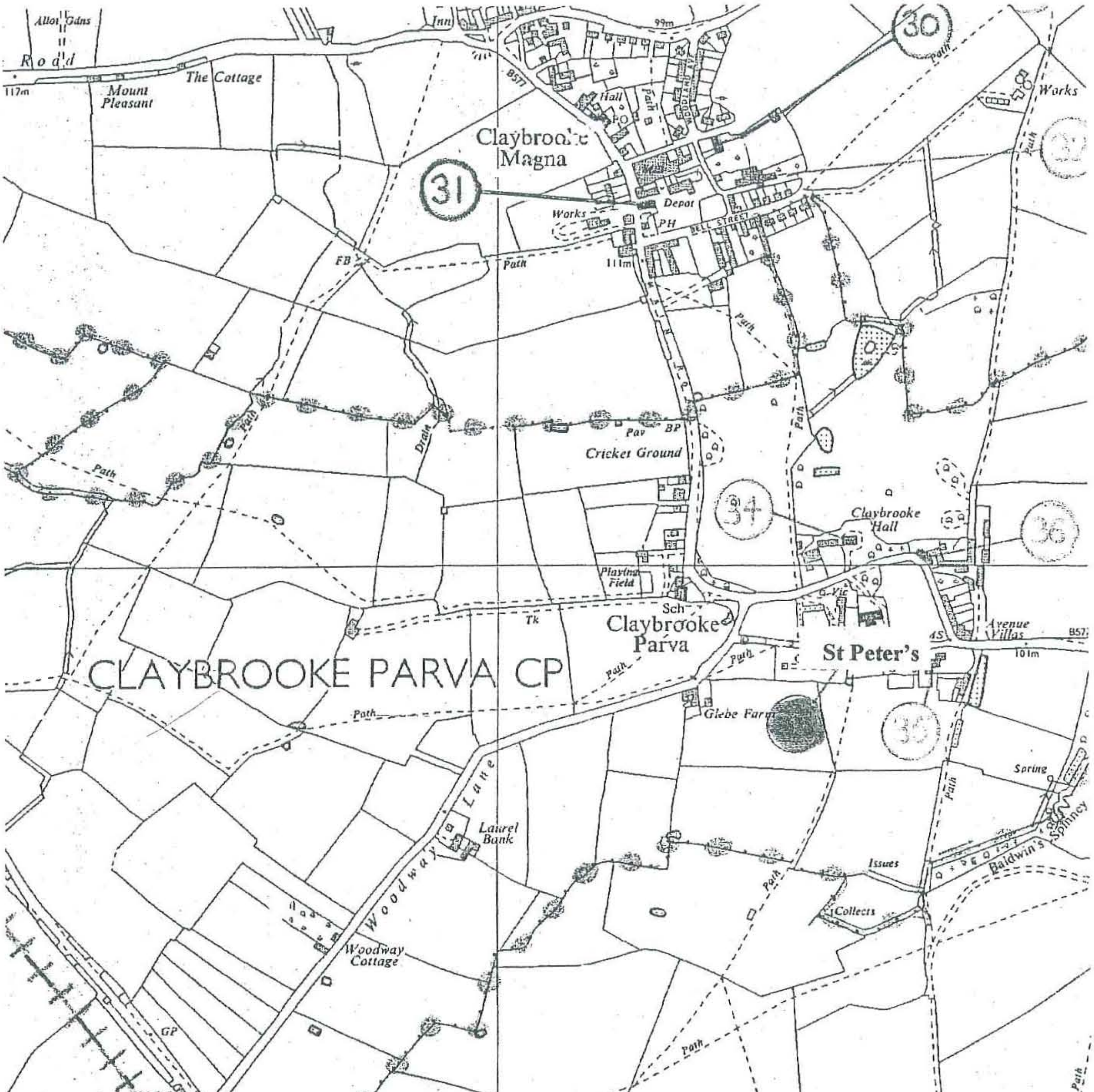


Figure 3: Illustrative example of a roof truss

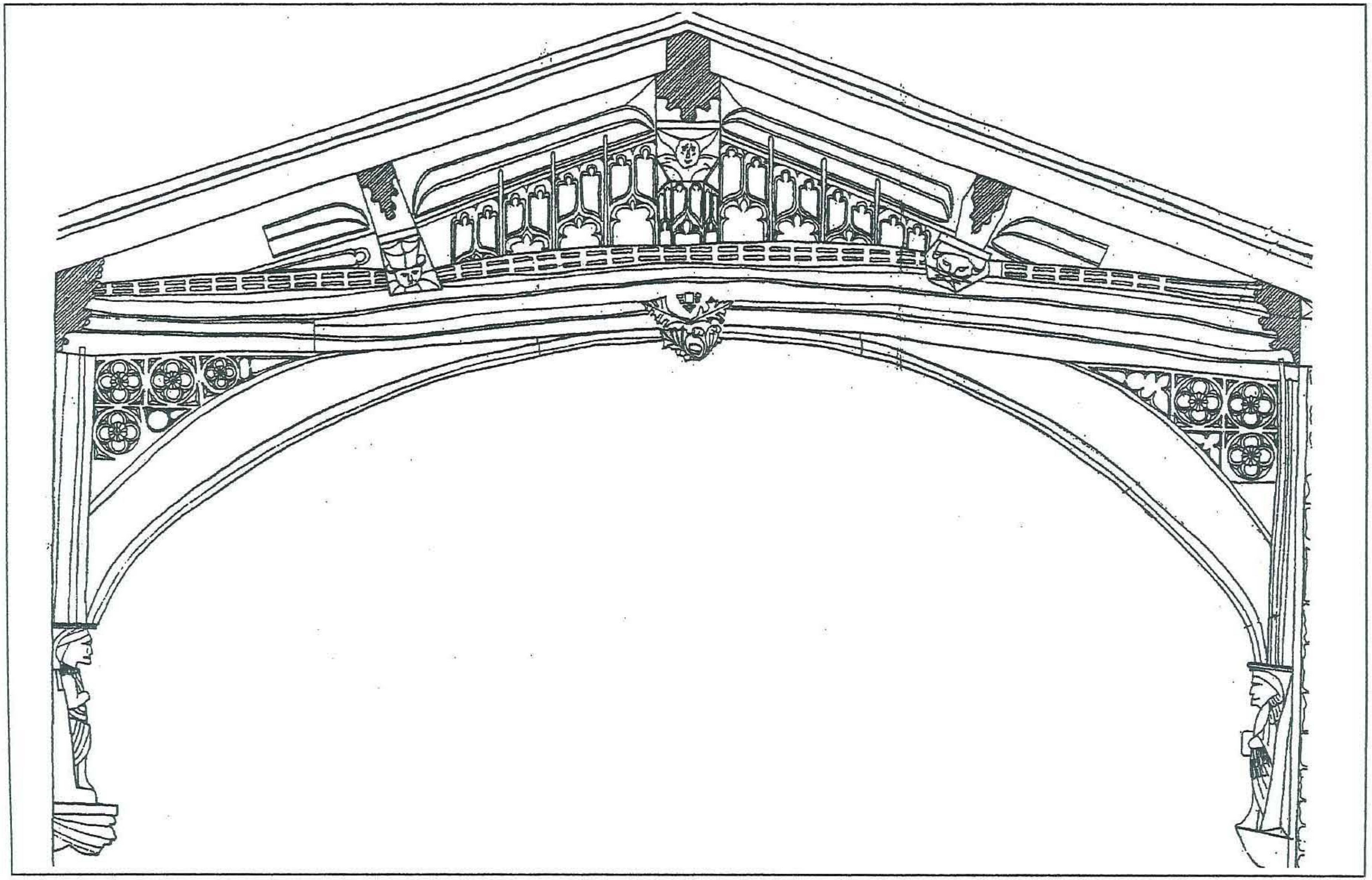


Figure 4a: Drawing of truss 1 to show timbers sampled (viewed from the west looking east)

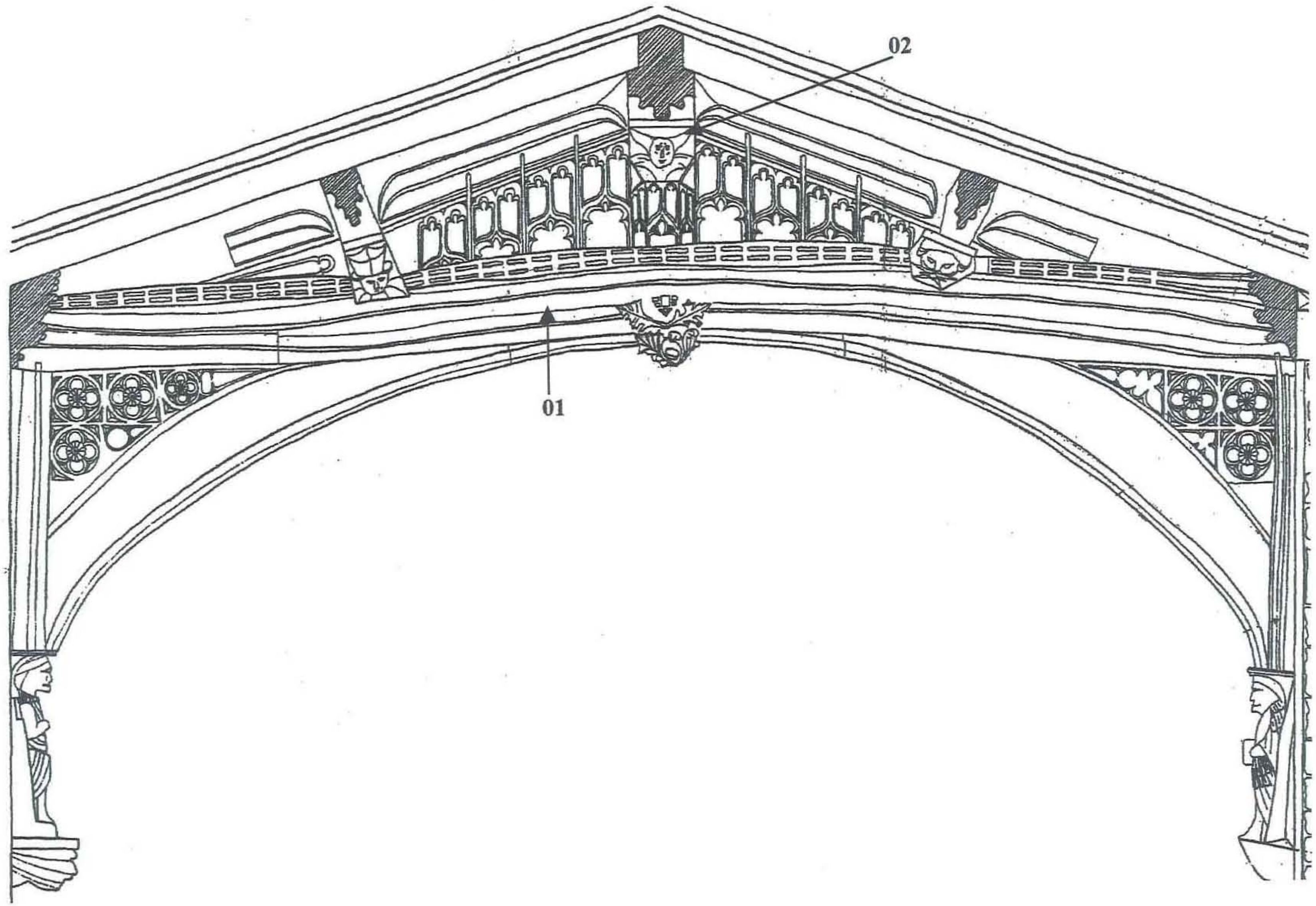


Figure 4b: Drawing of truss 2 to show timbers sampled (viewed from the west looking east)

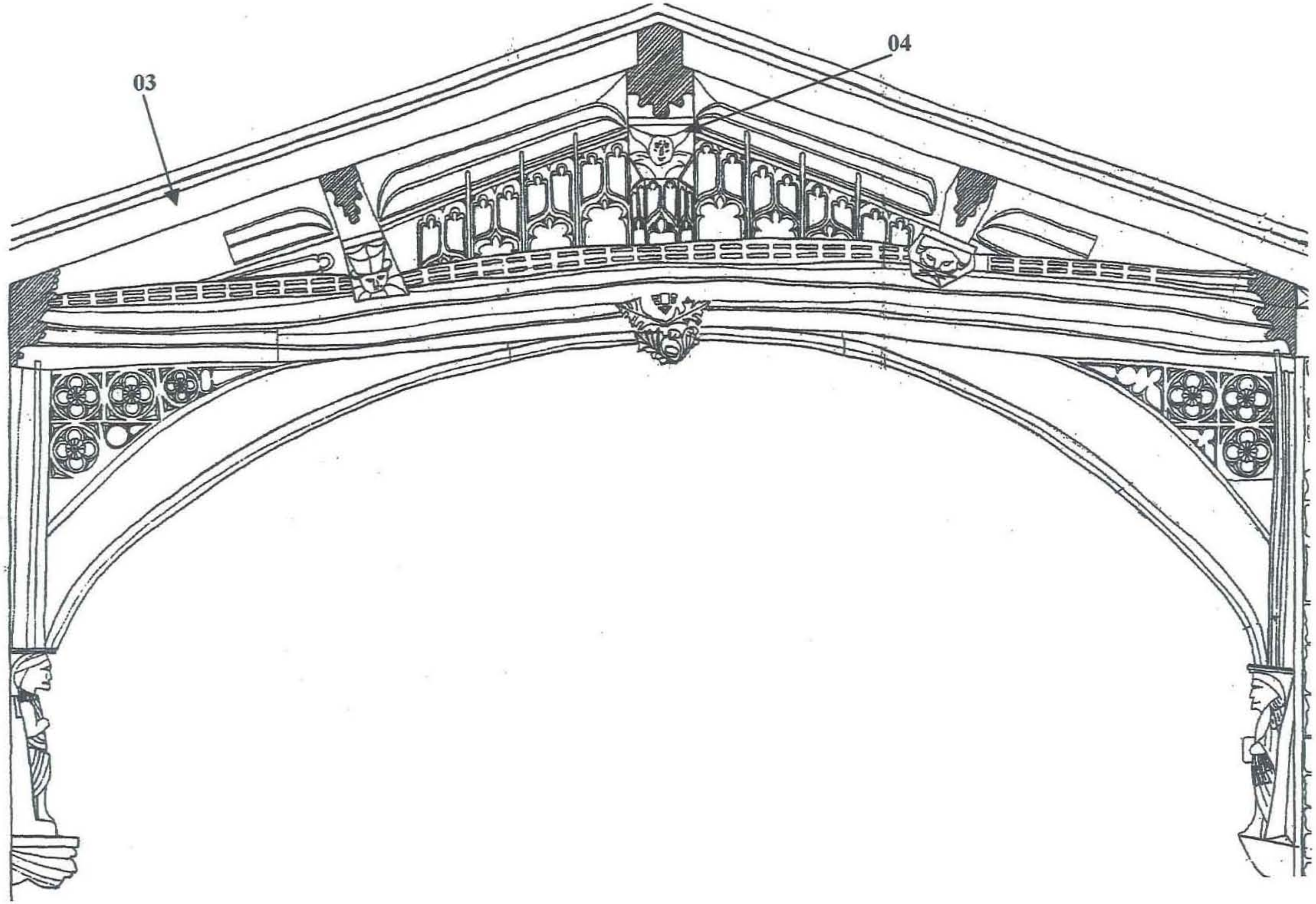


Figure 4c: Drawing of truss 3 to show timbers sampled (viewed from the west looking east)

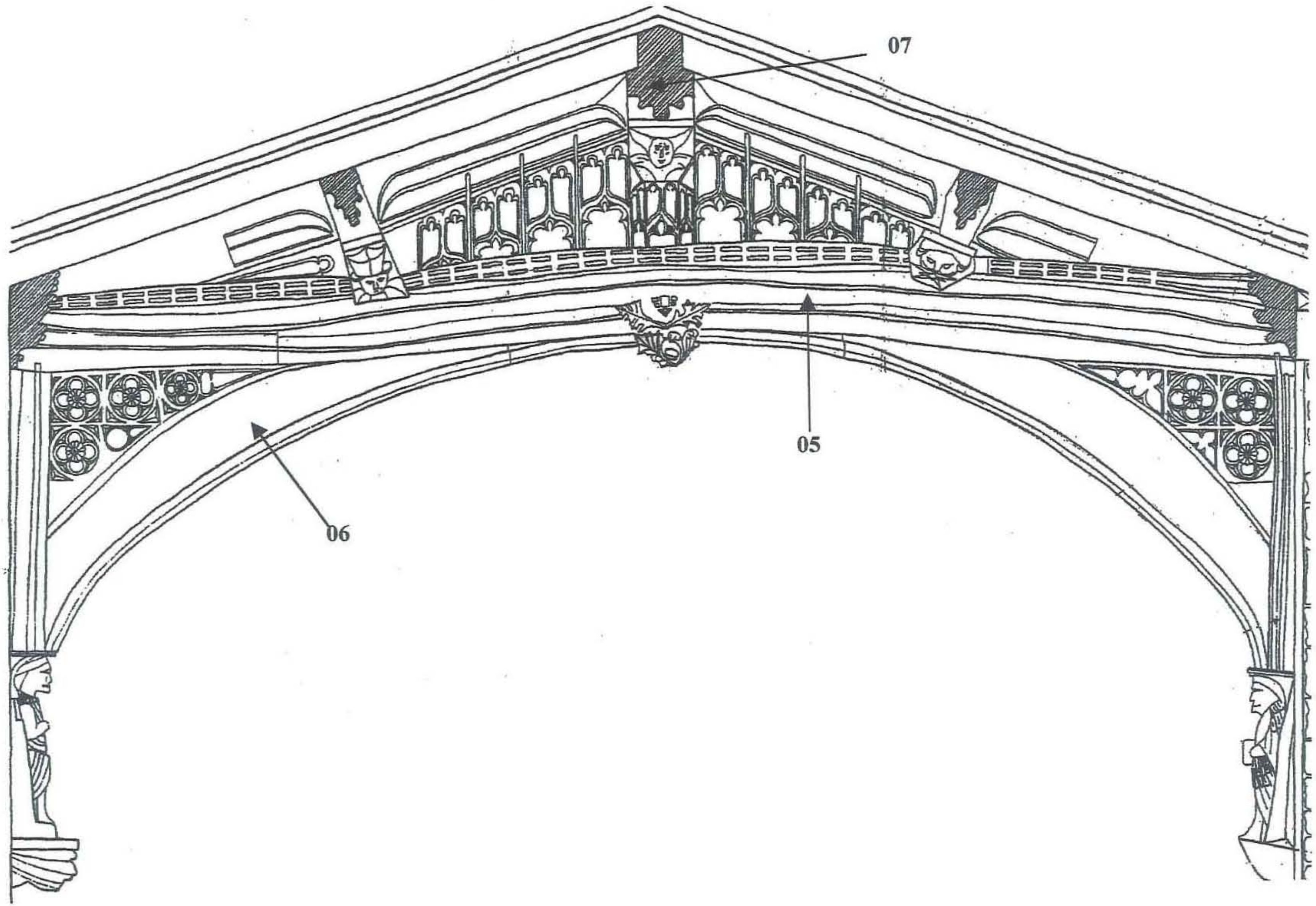


Figure 4d: Drawing of truss 4 to show timbers sampled (viewed from the west looking east)

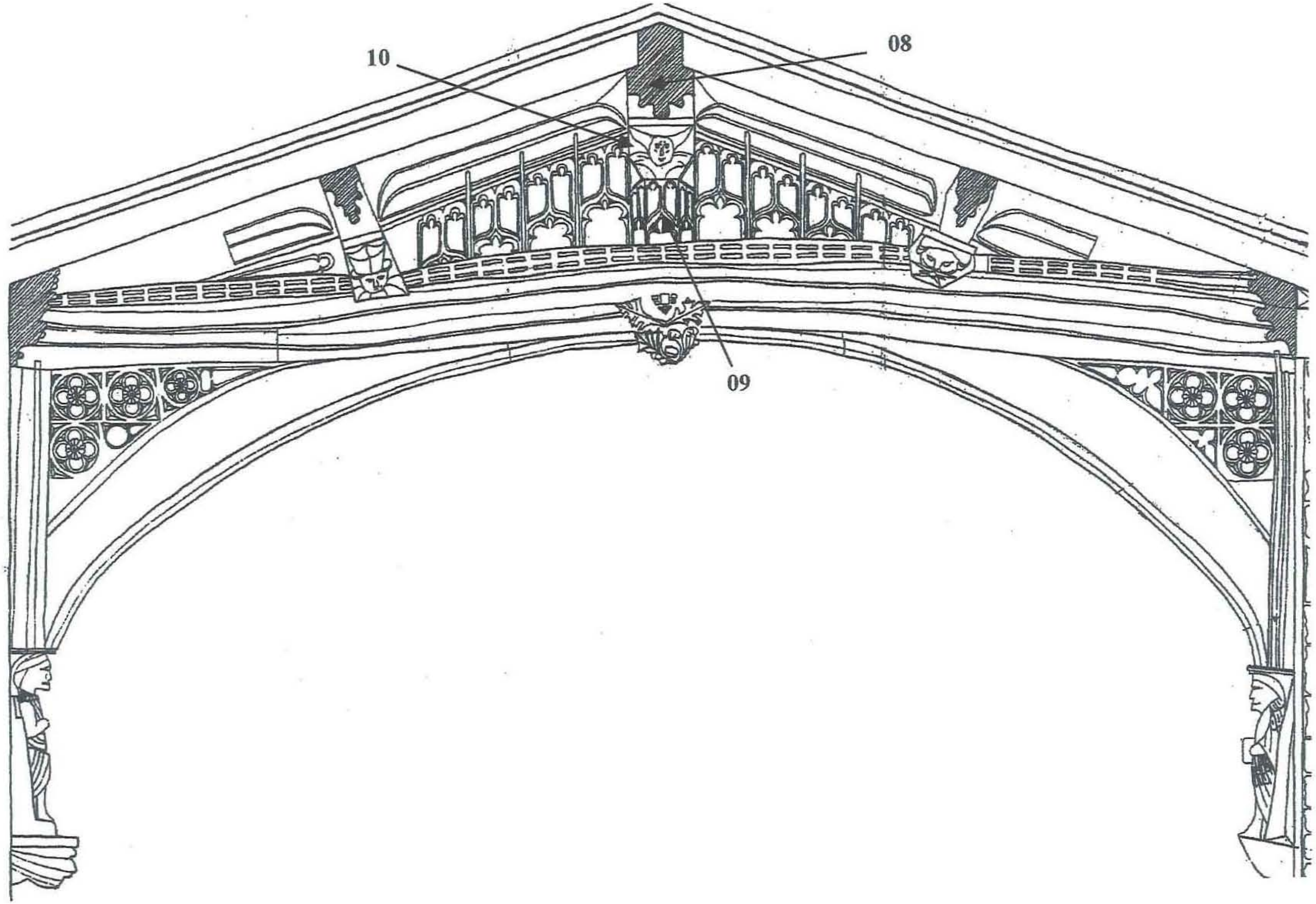


Figure 4e: Drawing of truss 5 to show timbers sampled (viewed from the east looking west)

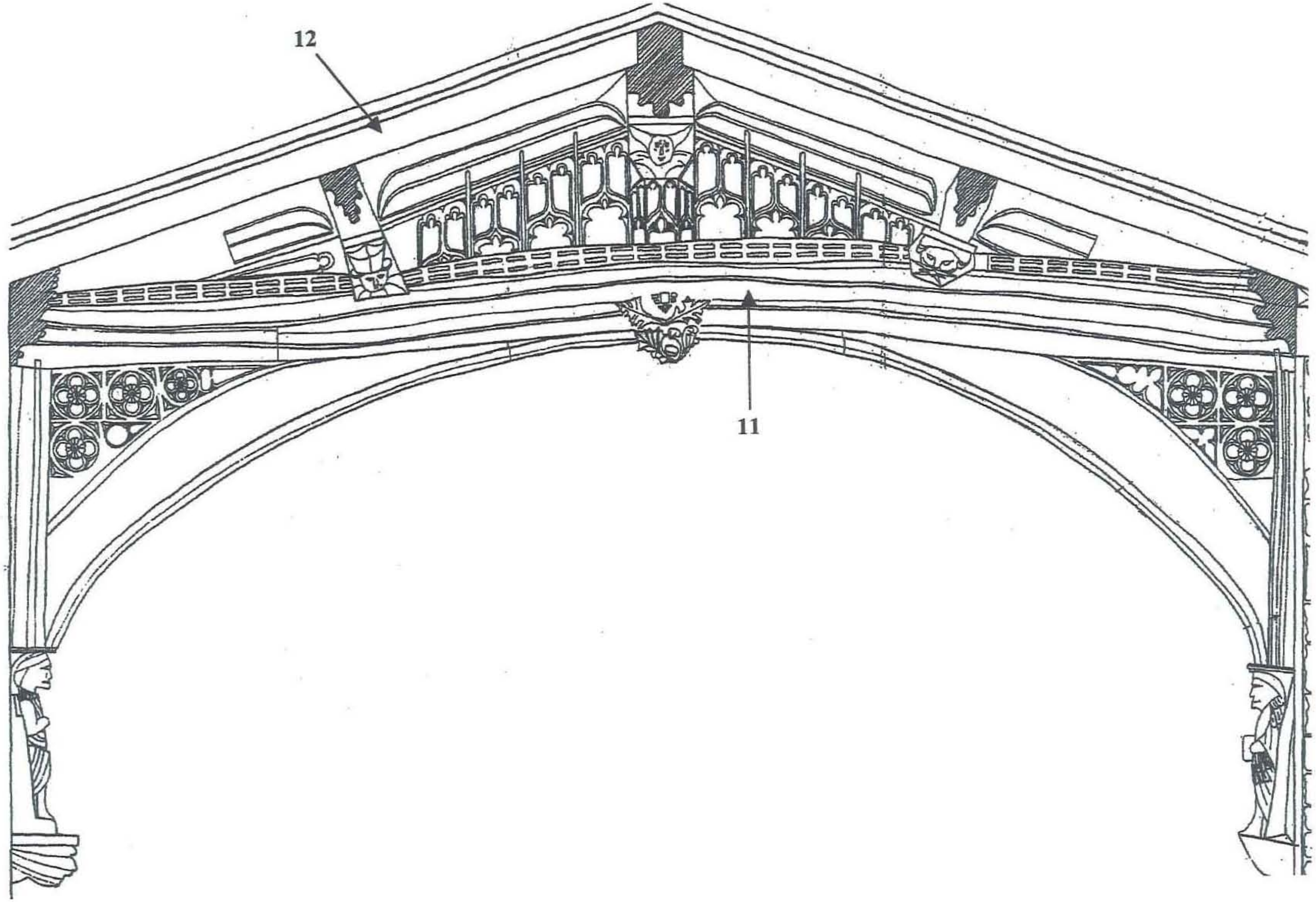
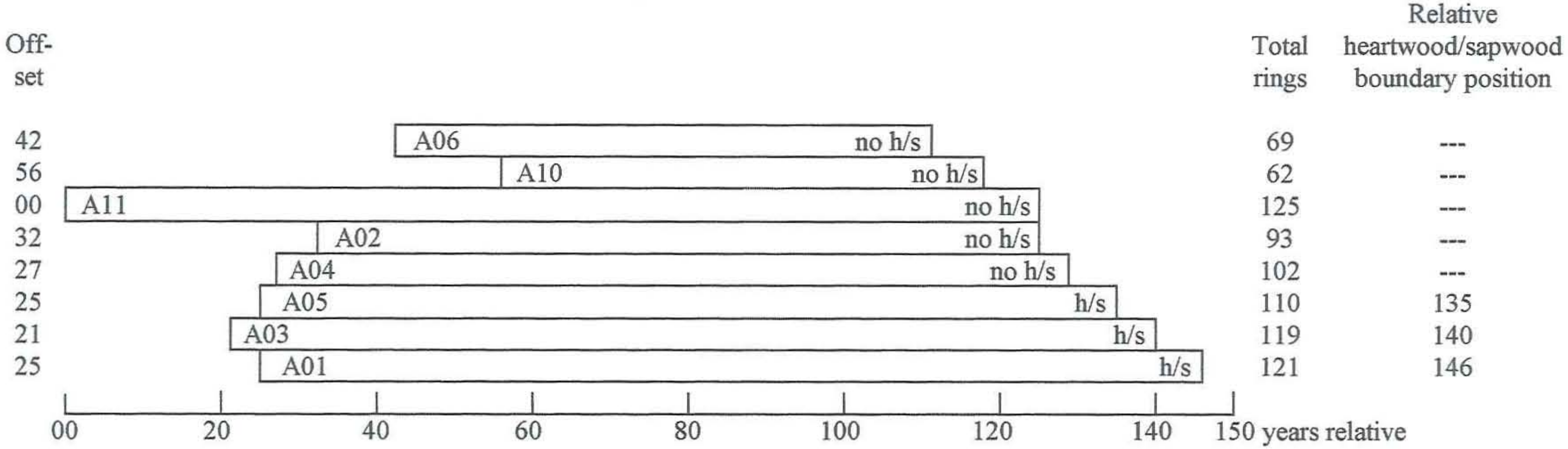


Figure 5: Bar diagram of the samples in site chronology CBPASQ01



white bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Data of measured samples – measurements in 0.01 mm units

CBP-A01A 121
315 333 225 298 150 218 188 194 210 186 221 280 270 278 222 252 249 212 190 224
189 216 227 305 306 330 334 313 215 191 122 216 210 171 217 132 124 169 136 148
117 148 185 168 156 188 185 175 106 184 164 185 238 275 214 244 203 305 290 217
155 185 126 166 196 194 292 247 223 142 141 152 115 161 162 147 174 186 143 141
158 171 181 212 171 161 134 111 98 120 146 154 167 137 144 126 129 144 149 116
132 107 125 141 168 187 141 172 184 148 137 115 130 161 135 174 139 141 135 134
107
CBP-A01B 121
316 324 237 247 189 230 179 196 212 181 230 271 272 275 218 254 259 218 186 221
193 246 214 288 320 321 336 299 233 191 125 199 216 188 219 134 116 153 139 126
130 156 168 178 159 177 186 181 103 183 167 184 243 262 218 246 200 309 293 211
163 141 127 170 189 186 284 248 201 160 130 154 107 158 170 147 168 196 134 131
151 172 188 202 178 152 136 115 97 124 139 155 170 143 135 126 142 136 153 97
126 109 116 151 161 200 130 174 179 149 143 115 130 153 149 162 146 137 123 132
131
CBP-A02A 93
312 249 348 291 553 376 298 208 331 401 276 355 370 446 317 356 337 303 324 290
252 223 236 120 173 157 188 145 137 186 139 156 190 180 177 220 229 215 190 192
133 158 214 129 138 227 99 117 108 121 124 91 73 91 123 89 86 76 65 69
66 50 35 63 45 65 64 59 54 59 87 42 42 82 97 100 83 72 93 97
59 65 109 103 109 74 63 92 61 63 82 72 90
CBP-A02B 93
257 235 354 288 533 375 314 209 340 401 271 347 383 418 323 363 331 306 345 265
256 231 253 119 152 169 181 134 137 175 136 154 181 174 171 229 257 219 190 181
153 175 228 105 139 206 99 117 125 121 121 92 81 82 117 80 90 78 61 65
48 52 45 59 38 63 70 55 49 56 89 52 41 73 96 101 83 69 94 103
57 64 108 111 95 73 81 85 54 65 68 71 90
CBP-A03A 119
305 602 558 372 222 267 212 206 296 298 318 152 199 285 187 347 264 174 192 193
248 141 204 230 253 216 208 176 190 248 164 204 167 166 116 100 199 184 119 179
146 136 183 118 128 179 213 193 167 128 179 111 79 160 101 109 160 95 72 86
117 144 98 72 109 86 70 118 138 127 181 184 134 126 68 58 123 119 125 105
143 133 169 171 191 171 138 157 129 141 146 146 92 115 197 193 194 151 110 116
84 162 133 99 142 142 162 163 185 132 126 189 128 89 101 93 96 98 127
CBP-A03B 119
321 627 566 383 214 278 217 214 298 310 300 156 203 277 187 374 240 173 207 188
208 154 194 242 248 211 218 166 185 270 151 191 173 187 121 117 184 190 124 181
131 143 176 114 135 178 217 183 172 129 174 111 83 154 107 101 166 96 74 83
108 159 90 76 111 87 66 118 134 133 185 182 139 121 65 63 122 133 130 111
154 122 168 179 190 157 143 156 124 142 157 151 88 107 203 188 202 169 115 97
84 162 154 92 140 138 181 153 189 156 99 178 128 105 95 97 94 110 115
CBP-A04A 102
305 341 385 320 304 135 152 192 152 309 185 164 130 189 299 158 228 281 322 297
267 290 231 299 213 204 157 184 135 133 180 199 119 155 147 141 144 115 58 81
119 118 161 153 141 137 128 211 122 118 220 122 107 100 107 120 114 80 89 88
95 71 52 59 58 71 47 42 41 66 60 53 52 60 57 54 57 47 64 112
120 82 70 78 90 59 44 82 107 111 93 74 76 69 90 118 81 104 93 110
111 131

CBP-A04B 102
301 336 393 328 306 129 165 196 153 331 198 163 136 200 268 157 219 285 324 301
271 288 232 304 212 207 152 184 140 159 165 186 121 144 175 139 135 118 67 90
125 118 165 157 151 129 135 198 122 168 229 104 72 29 103 125 105 90 93 113
92 50 53 54 59 63 49 47 48 54 62 60 49 57 63 63 41 46 66 100
112 84 78 84 88 54 48 73 110 119 71 74 87 64 95 120 92 103 94 100
109 126
CBP-A05A 110
205 204 141 138 153 186 192 183 137 185 232 216 215 214 215 320 197 222 208 308
264 258 171 202 160 197 275 277 228 209 163 209 174 245 264 230 210 194 194 202
198 259 371 363 351 256 314 245 219 273 207 265 362 392 202 220 179 240 101 132
166 180 110 149 154 127 194 220 189 164 144 159 148 211 192 171 163 180 153 165
184 166 218 232 210 190 243 199 141 151 229 191 214 134 130 115 124 100 116 83
122 141 150 195 151 148 125 122 139 200
CBP-A05B 110
150 199 142 148 134 200 187 183 138 186 229 196 221 207 219 330 211 218 205 313
259 243 183 213 156 189 263 277 242 238 168 206 176 242 263 241 191 206 186 212
196 232 364 363 368 229 300 111 192 277 213 292 363 365 225 228 171 270 309 191
181 193 111 145 143 156 183 221 228 179 151 157 155 204 195 169 164 187 163 176
178 179 211 222 210 186 248 209 140 148 214 191 204 148 131 121 117 100 122 73
137 141 152 187 166 147 119 121 162 190
CBP-A06A 68
401 406 351 319 286 231 153 129 135 188 135 133 131 117 186 268 221 350 366 260
183 189 156 93 110 185 187 128 162 147 118 94 131 120 121 180 158 118 129 118
179 168 145 170 112 186 274 249 214 243 177 167 136 135 201 220 161 144 123 143
187 136 91 124 157 200 154 136
CBP-A06B 69
362 410 375 330 308 210 164 110 138 181 140 133 118 120 194 268 212 338 350 272
177 184 156 102 123 190 187 132 136 128 129 86 142 118 116 192 148 111 125 118
174 172 137 172 107 179 267 254 204 220 191 166 128 149 212 212 185 185 130 141
178 157 122 166 161 200 157 144 128
CBP-A07A 65
409 411 383 258 242 301 510 404 324 257 312 340 253 240 319 386 424 386 314 323
301 246 184 196 265 325 442 295 347 379 327 233 311 297 258 258 168 232 229 372
355 307 220 156 156 175 152 154 153 184 163 130 182 172 153 129 166 130 140 153
139 108 131 178 208
CBP-A07B 65
412 419 414 242 242 306 507 397 339 255 315 336 250 245 304 396 428 385 314 343
294 240 195 209 268 321 443 310 365 346 328 249 315 295 247 236 174 224 237 361
346 307 222 148 162 171 161 140 174 207 181 140 167 179 150 135 161 129 140 153
123 109 141 169 241
CBP-A08A 81
408 245 242 184 101 103 101 172 332 373 411 281 270 154 139 133 142 160 169 215
275 269 192 173 174 162 156 150 208 199 186 208 232 192 210 166 184 213 134 142
191 192 295 393 395 191 187 152 161 173 227 376 296 178 190 215 227 167 328 259
191 190 192 216 253 210 203 171 187 204 256 160 139 97 97 137 112 159 159 119
230
CBP-A08B 81
428 241 244 184 117 87 89 181 351 376 432 295 262 153 130 130 142 155 166 206
276 257 197 171 164 177 153 146 195 187 199 167 236 188 204 167 187 205 138 142
186 210 281 397 410 208 200 160 162 189 221 338 319 176 197 240 246 160 320 271
193 204 185 214 274 205 205 170 186 188 249 171 138 93 102 144 118 143 156 152
172

CBP-A09A 58
320 244 180 161 74 133 137 100 77 62 64 57 50 47 65 100 93 58 77 79
75 67 78 91 103 93 76 91 104 79 100 85 92 104 103 122 139 124 121 119
136 116 95 116 75 83 82 117 94 108 83 89 111 108 88 87 89 100
CBP-A09B 58
290 249 203 125 76 114 163 89 66 69 65 54 42 45 64 89 72 69 77 93
76 67 77 98 100 91 86 78 94 88 75 79 97 97 105 135 133 114 117 110
154 130 99 102 85 101 69 108 97 112 88 85 100 108 91 85 96 136
CBP-A10A 62
252 220 283 259 283 212 244 315 320 205 352 373 454 471 383 380 290 173 332 221
284 467 377 178 239 230 315 386 244 359 291 224 274 256 221 241 219 205 199 197
86 143 139 151 116 106 122 141 131 108 133 191 158 140 118 146 133 70 96 94
101 79
CBP-A10B 62
239 224 287 254 267 221 243 308 330 215 354 363 452 477 370 383 297 183 313 218
308 450 385 164 230 232 328 388 239 352 290 236 281 243 225 242 226 218 189 197
103 150 136 150 113 107 126 138 137 103 136 195 154 140 116 147 141 74 91 95
86 83
CBP-A11A 125
508 626 568 310 232 207 152 163 210 235 208 185 149 141 189 191 68 76 140 173
125 162 162 153 123 117 119 86 115 105 141 120 115 95 119 150 154 129 135 84
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CBP-A11B 125
500 611 587 307 221 195 183 161 204 238 244 189 143 142 164 184 102 80 148 186
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147 90 143 104 132
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149 163 155 198 201 162 78 105 160 196 145 161 134 149 199 134 100 189 182 199
234
CBP-A12B 61
152 248 196 212 245 152 57 117 79 105 197 194 148 230 125 117 111 143 183 211
247 322 229 202 255 128 155 119 188 93 64 96 93 61 61 77 83 69 86 110
150 187 173 201 198 170 72 113 163 193 146 164 128 169 181 134 112 155 167 198
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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.

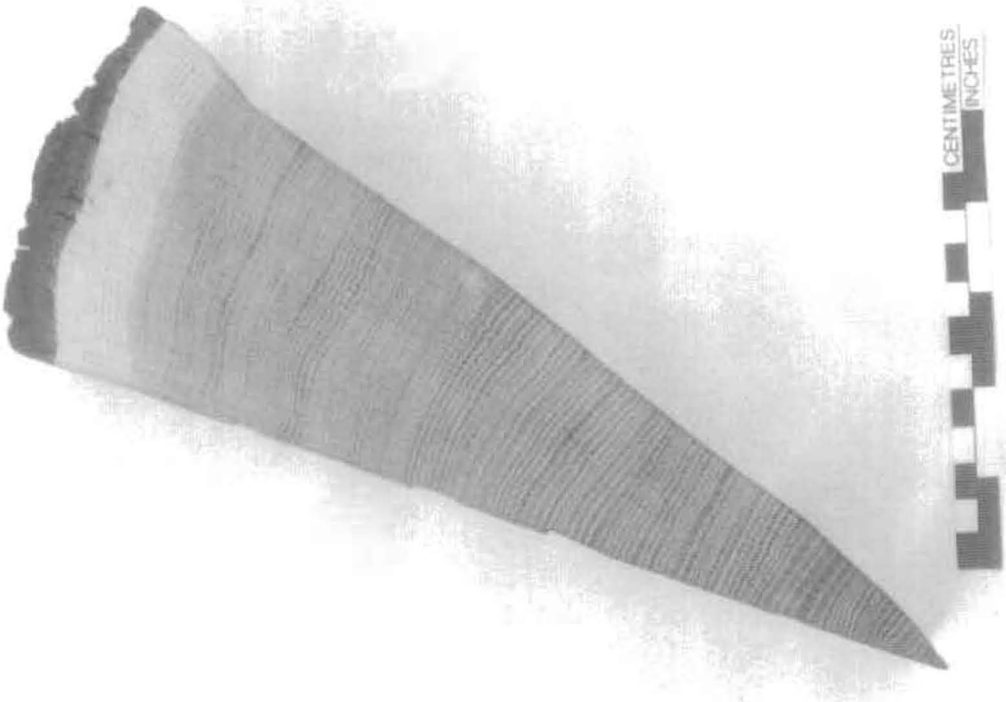

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

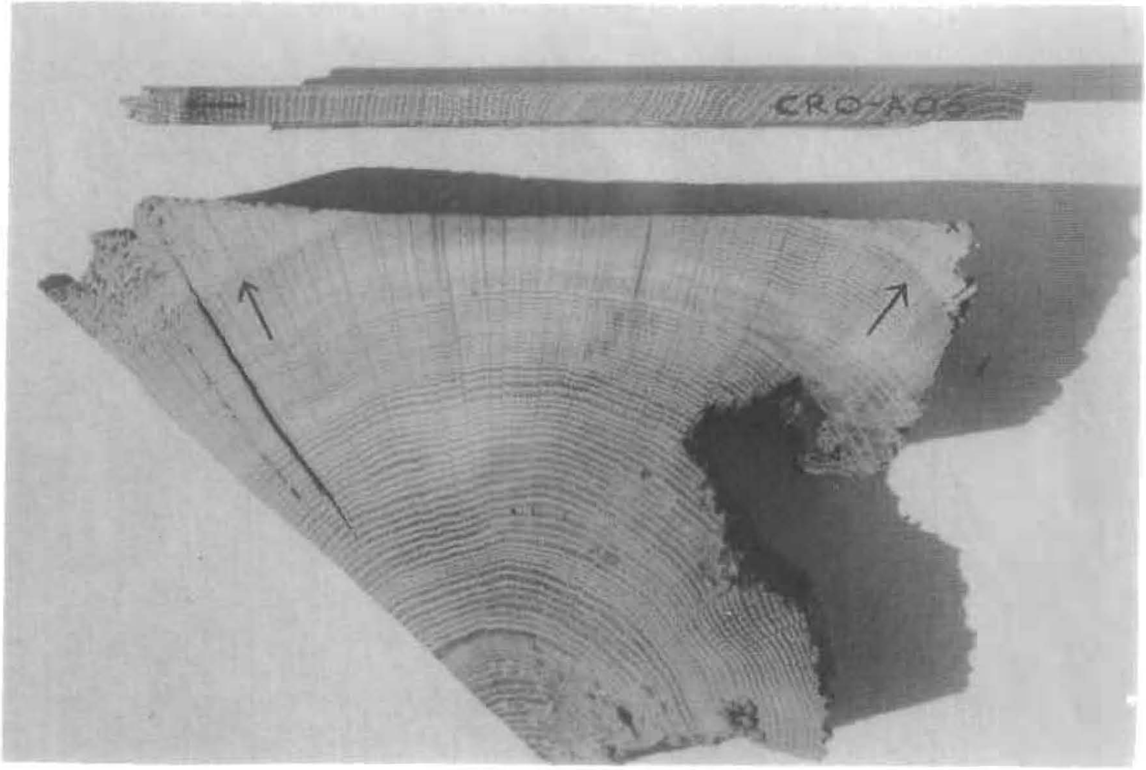

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

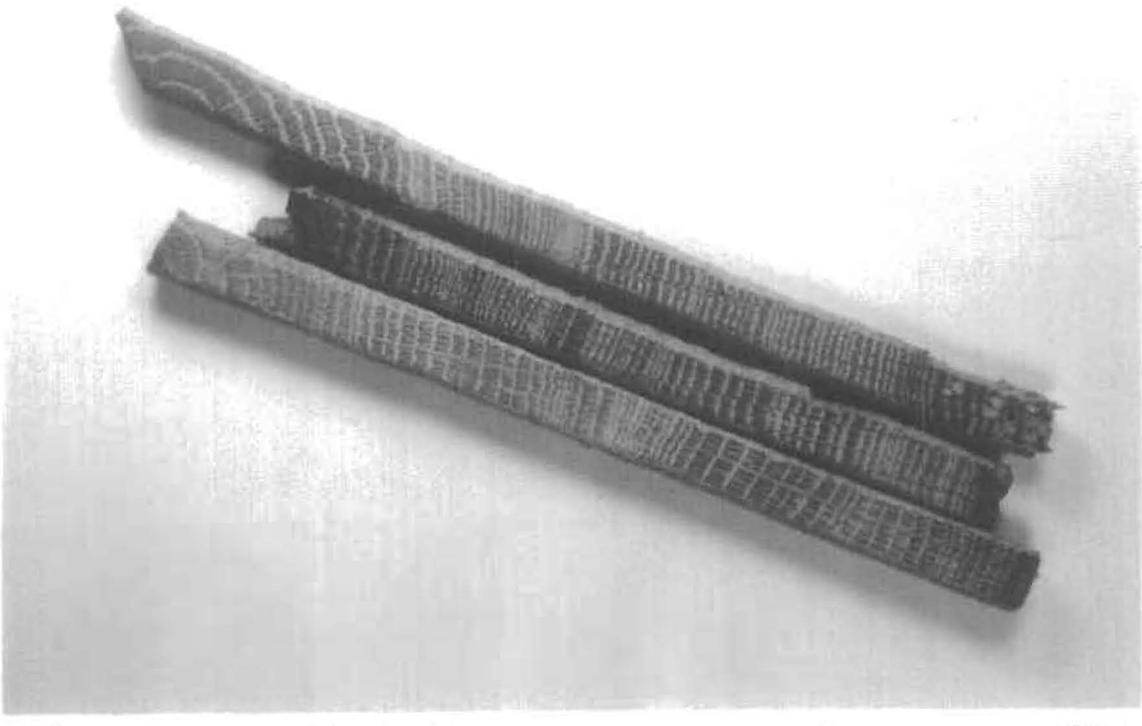

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

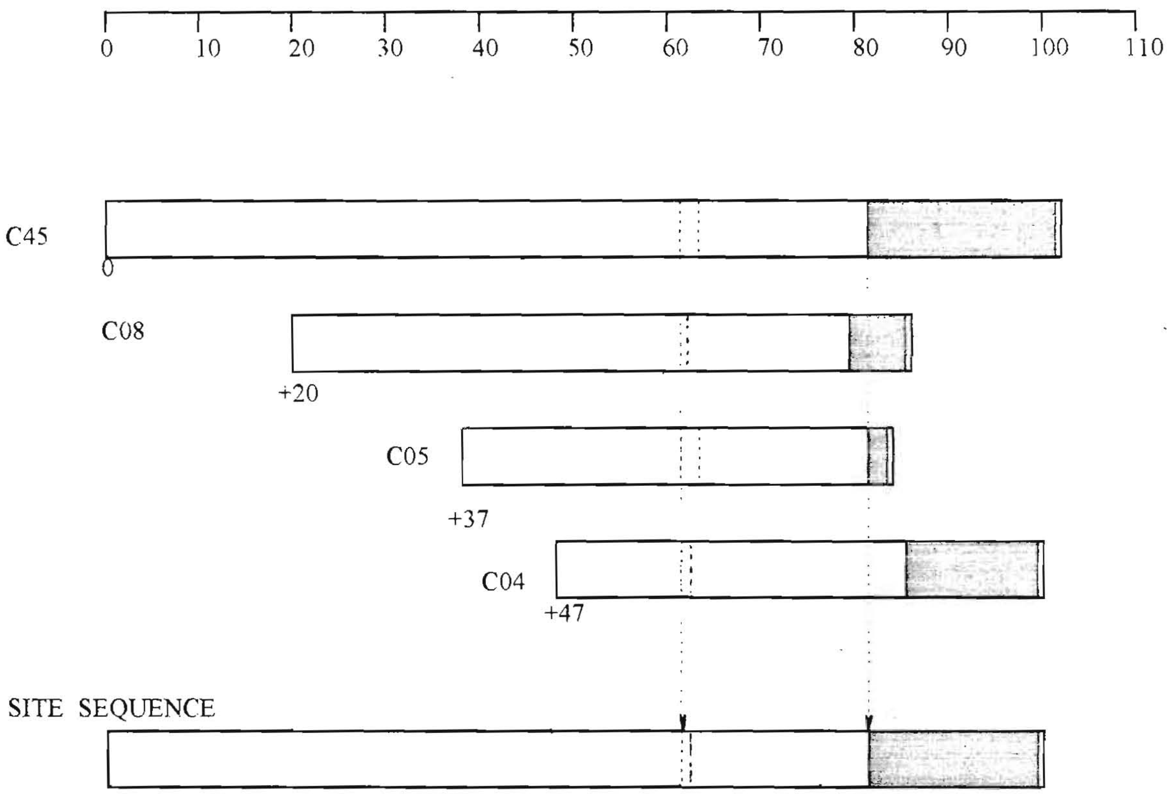

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

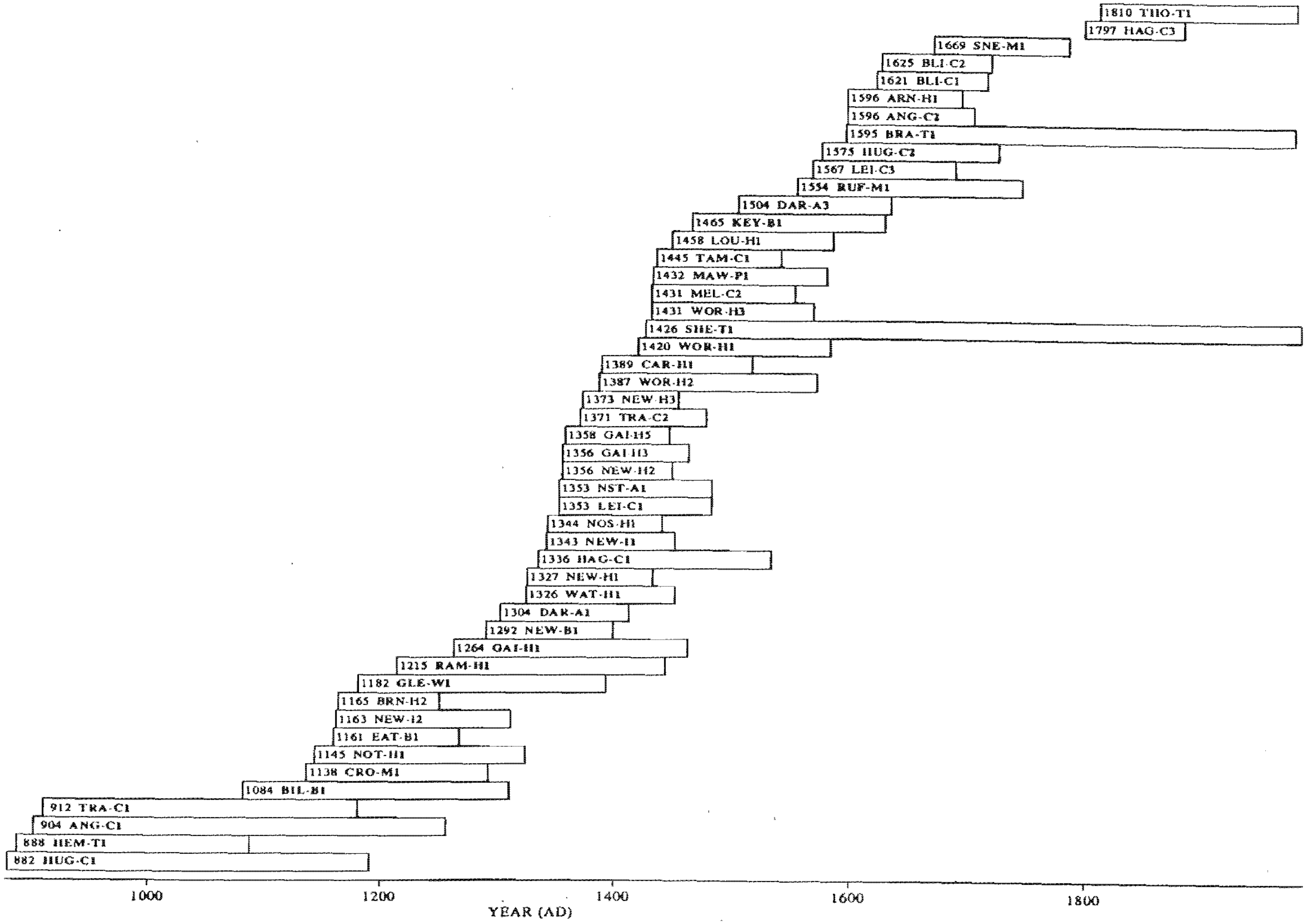

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

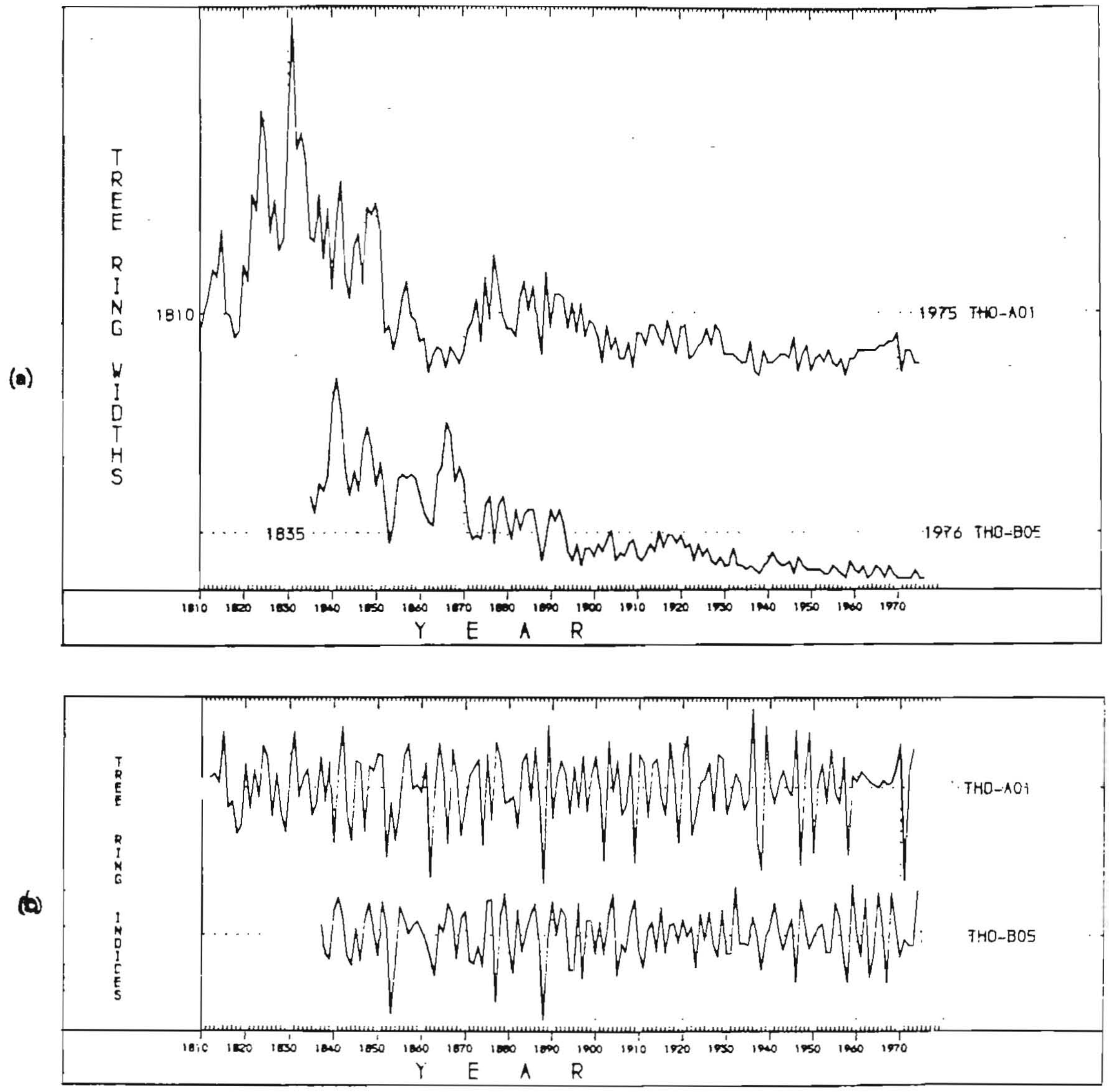

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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