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EXTENDED TREE-RING ANALYSIS OF TIMBERS FROM BROCKWORTH COURT BARN, BROCKWORTH, GLOUCESTERSHIRE

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Summary

Analysis was undertaken of twenty-nine samples from oak timbers at Brockworth Court barn, Brockworth, Gloucestershire. The analysis of these samples resulted in the production of two site chronologies. The first site chronology consists of twenty-one samples of length 185 rings spanning the period AD 1122 - AD 1306. Interpretation of the sapwood on the dated samples indicates that the timbers represented have an estimated felling date in the range AD 1307 - 15. The second site chronology consists of only four samples. This site chronology has 190 rings spanning the period AD 1352 - AD 1541. Only one sample in this site chronology has a heartwood/sapwood boundary. If it is accepted that the timbers represented are of a single phase, it is estimated that the felling took place in the range AD 1556 - 81.

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Introduction

This grade II* barn is a complex eight-bay structure of more than one period standing adjacent to the medieval and later house of Brockworth Court (SO891170; Figs 1 and 2), a major house of Llanthony Abbey. The core of the barn is a four-bay cruck structure which was believed to be of medieval date and which has later been extended at each end. An elevation and long-section of the barn is reproduced here from a report by the Oxford Archaeological Unit as Figure 3. The medieval bays contain base-crucks, a type in which the curved principals do not meet together at the top but are joined by a collar beam. The trusses have inner and outer blades; an illustrative example of the type is given in Figure 4. The east extension has an open two-bay section while the west extension has a two-bay section with a floored area. The timber-work of the later extensions consists of wall-posts with tie-beams and principal rafters.

The listing description of AD 1987 suggestes that the barn may be of late fifteenth or early sixteenth-century date, though it is believed that the general date range for this style of roof in England lies between the thirteenth and fifteenth centuries. A recent authority (Brady 1996) has dated the medieval portion of the barn on stylistic grounds to the fifteenth century. Brockworth would thus appear to be one of the comparatively few barns recognised to have this type of roof structure.

The barn was subject to a severe fire in December AD 1996. This appears to have started at the east end where the roof and other timbers have been almost totally destroyed. The central part, containing the medieval cruck trusses, was badly damaged and large parts of the roof fell in, though three of the four trusses remain standing to collar level. The west end of the barn was comparatively undamaged, having lost only the apex of the roof. Part of the east gable and other portions of the roof were demolished after the fire on safety grounds.

The Nottingham University Tree-ring Dating Laboratory was commissioned to make an initial sampling of the building in December AD 1997. Due to the unsafe condition of the barn at that time it was not possible to sample the standing timbers remaining *in situ*. The only timbers available at that time were those that had been removed from the structure and placed in stacked piles; fourteen such timbers were sampled. The timber members and the original location of the beams within the barn analysed in this first programme was not known. The first programme of analysis of these removed timbers produced a felling date in the range AD 1285 – AD 1310 (Howard *et al* 1998a)

Given the early date obtained for the timbers in this initial analysis and the lack of samples from the main body of the structure, extended additional sampling and analysis by tree-ring dating were commissioned by English Heritage. The purpose of this was to analyse the remaining *in situ* timbers to establish whether or not the major portion of the barn dates to the early fourteenth century or is a later rebuild. This additional sampling was undertaken as the remaining timbers were removed from the building in October AD 1998 prior to rebuilding. The timber members and their locations having been noted.

The Laboratory would like to take this opportunity to thank the owners of the barn, Mr and Mrs Wiltshire for their hospitality and their enthusiasm with the programme of analysis. We would also like to thank the builders for their help in sampling.

Sampling

In addition to the fourteen samples obtained in December AD 1997 a further fifteen sliced oak samples were obtained from the timbers in AD 1998, thus giving twenty-nine samples in total. All samples were given the code BRK-A (for Brockworth, site "A") and numbered 01 – 29. While timbers from the later extensions to the barn were examined, where these remained, they were found to have too few rings for satisfactory analysis and consequently most samples were obtained from the timbers of the central range

The positions of the samples obtained in this analysis from timbers of known location were recorded at the time of sampling on drawings taken from the Oxford Archaeological Unit's report, reproduced here as Figures 5a - d. In these drawings the trusses have been numbered from east to west. Details of the samples are given in Table 1.

Analysis and dating

All twenty-nine samples were prepared by sanding and polishing. The ring widths of all samples were then measured, the data of the measurements of the samples being given at the end of the report. The samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a value of t=4.5 two groups of samples were formed.

The twenty-one samples of the first group cross-match with each other as shown in the bar diagram, Figure 6. The ring widths from these twenty-one samples were combined at their suggested relative offsets to form BRKASQ01, a site chronology of 185 rings. Site chronology BRKASQ01 was successfully cross-matched with a series of relevant reference chronologies for oak, giving it a first ring date of AD 1122 and a last measured ring date of AD 1306. Evidence for this date is given in the t-values of Table 2. It is probable that the timbers represented by samples BRK-A04, A08, and A09 are from the same tree, the samples cross-matching as they do with t-values in excess of 11.0.

The four samples of second group to form cross-match with each other as shown in the bar diagram Figure 7. The ring widths from these four samples were combined at their suggested relative offsets to form BRKASQ02, a site chronology of 190 rings. Site chronology BRKASQ02 was cross-matched with a series of relevant reference chronologies for oak, giving it a first ring date of AD 1352 and a last measured ring date of AD 1541. Evidence for this date is given in the t-values of Table 3.

The high t-values of the cross matching seen between some samples in this group (in excess of t=15.0) suggest that it is very likely that the timbers represented by samples BRK-A11, A12 and A25 are from the same tree.

The two site chronologies were compared with each other and with the remaining ungrouped samples. There was, however, no further satisfactory cross-matching. Each of the remaining four ungrouped samples was compared individually with the reference chronologies, but again there was no further satisfactory cross-matching.

Interpretation

The average last heartwood ring date on the samples of site chronology BRKASQ01 is AD 1275. The usual 95% confidence limits for sapwood on mature oaks from this part of England is in the range 15 to 40 rings. Using this figure would give the timbers represented by these samples an estimated felling date in the range AD 1307 – 15, allowing that the last measured ring on the site chronology is AD 1306.

The average last heartwood ring date on the samples of site chronology BRKASQ02 is AD 1541 (based on that of a single sample only, BRK-A16). Using the same sapwood estimate as above would give the timbers represented by these samples a felling date in the range AD 1556 – 81.

Conclusion

From the tree-ring dating, both in this analysis in which the main *in situ* structural timbers were sampled and in the previous analysis, in which timbers of unknown location were dated, it would appear that the bulk of the barn dates from the early fourteenth century. Most of the timber is estimated to have been felled in AD 1307 – 15.

A very small amount of later timber is represented in the barn, this dating from the mid-to late-sixteenth century.

Four samples, BRK-A13, A14, A18, and A28 remain undated, despite all of them having sufficient rings for satisfactory cross-matching. Samples BRK-A13 and A14 both show a sudden change to much narrower growth-rings in their later years, see Figure 8. This may indicate a period of stressed growth of non-climatic origin that might account for their lack of cross-matching and dating. There is nothing particularly unusual about the growth-ring pattern on either of the other two ungrouped and undated samples that might cause difficulties in cross-matching.

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Table 1: Details of tree-ring samples from Brockworth Court Barn, Brockworth, Gloucestershire

Sample no.	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
BRK-A01	Unknown	96	no h/s	AD 1141	------	AD 1236
BRK-A02	Unknown	125	h/s	AD 1151	AD 1275	AD 1275
BRK-A03	Unknown	108	h/s	AD 1160	AD 1267	AD 1267
BRK-A04	Unknown	113	h/s	AD 1155	AD 1267	AD 1267
BRK-A05	Unknown	89	h/s	AD 1178	AD 1266	AD 1266
BRK-A06	Unknown	93	h/s	AD 1180	AD 1272	AD 1272
BRK-A07	Unknown	102	h/s	AD 1176	AD 1277	AD 1277
BRK-A08	Unknown	91	no h/s	AD 1156	------	AD 1246
BRK-A09	Unknown	80	no h/s	AD 1158	------	AD 1237
BRK-A10	Unknown	80	h/s	AD 1186	AD 1265	AD 1265
BRK-A11	Unknown	101	no h/s	AD 1352	------	AD 1452
BRK-A12	Unknown	95	no h/s	AD 1362	------	AD 1456
BRK-A13	Unknown	65	h/s	------	------	------
BRK-A14	Unknown	65	h/s	------	------	------
BRK-A15	South outer blade, truss 3	114	12	AD 1193	AD 1294	AD 1306
BRK-A16	North inner blade, truss 3	144	h/s	AD 1398	AD 1541	AD 1541
BRK-A17	North outer blade, truss 3	135	no h/s	AD 1137	------	AD 1271
BRK-A18	South inner blade, truss 3	109	no h/s	------	------	------
BRK-A19	Brace from south blade to collar, truss 3	79	no h/s	AD 1122	------	AD 1200
BRK-A20	Collar, truss 4	113	h/s	AD 1166	AD 1278	AD 1278
BRK-A21	North outer blade, truss 4	119	6	AD 1171	AD 1283	AD 1289
BRK-A22	Collar, truss 3	112	h/s	AD 1164	AD 1275	AD 1275
BRK-A23	South outer blade, truss 4	135	h/s	AD 1141	AD 1275	AD 1275
BRK-A24	Windbrace, truss 3 – 4	61	no h/s	AD 1195	------	AD 1255
BRK-A25	South outer blade, truss 2	119	no h/s	AD 1369	------	AD 1487
BRK-A26	Foot-pad, south outer blade, truss 3	122	no h/s	AD 1145	------	AD 1266
BRK-A27	North outer blade, truss 5	79	no h/s	AD 1171	------	AD 1249
BRK-A28	Collar, truss 5	80	h/s	------	------	------
BRK-A29	South post, truss 5	130	h/s	AD 1148	AD 1277	AD 1277

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

Table 2: Results of the cross-matching of site chronology BRKASQ01 and relevant reference chronologies when first ring date is AD 1122 and last measured ring date is AD 1306

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	4.6	(Laxton and Litton 1988)
England	AD 401 – 1981	7.5	(Baillie and Pilcher 1982 unpubl)
England London	AD 413 – 1728	5.5	(Tyers and Groves 1999 unpubl)
Southern England	AD 1083 – 1589	7.3	(Bridge 1988)
Worcester Cathedral, Worcester, Worcs	AD 1181 – 1291	7.7	(Howard *et al* 1995)
Salisbury Cathedral, Salisbury, Wilts	AD 1119 – 1241	6.5	(Howard *et al* 1992)
Horninglow St, Burton upon Trent, Staffs	AD 1101 – 1325	7.2	(Howard *et al* 1995)

Table 3: Results of the cross-matching of site chronology BRKASQ02 and relevant reference chronologies when first ring date is AD 1352 and last measured ring date is AD 1541

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1984	4.1	(Laxton and Litton 1988)
England London	AD 413 – 1728	3.9	(Tyers and Groves 1999 unpubl)
Southern England	AD 1083 – 1589	6.1	(Bridge 1988)
Sawbridge, Warwicks	AD 1355 – 1448	4.4	(Howard *et al* 1995)
Aldsworth, Glos	AD 1324 – 1587	4.8	(Howard *et al* 1995)
Shardlow, Derbys	AD 1434 – 1614	4.7	(Alcock *et al* 1990)
Sinai, Staffs	AD 1227 – 1750	3.6	(Tyers 1997)
Chicksands, Beds	AD 1200 – 1541	4.2	(Howard *et al* 1998b)

Figure 1: Map to show general location of Brockworth

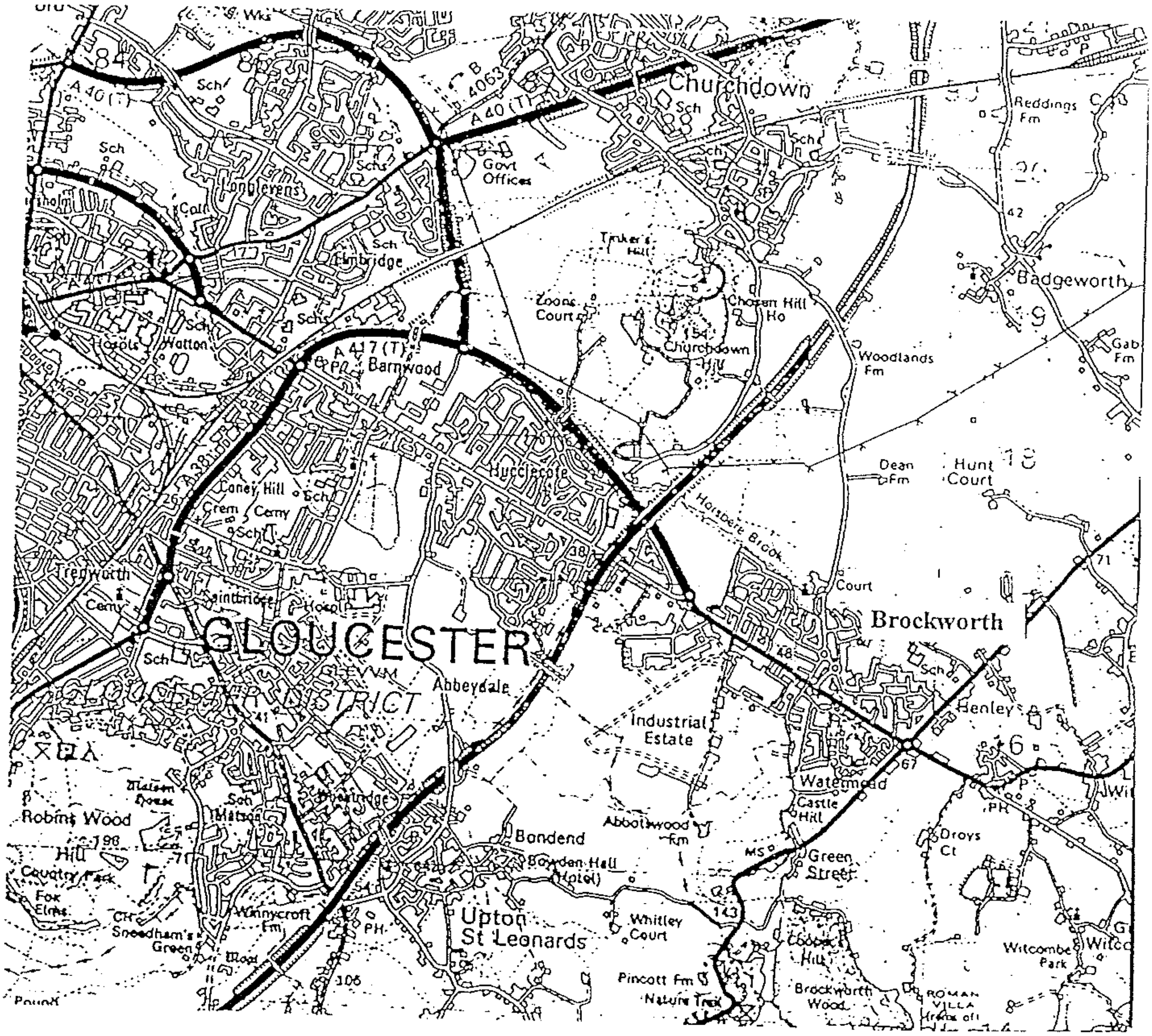
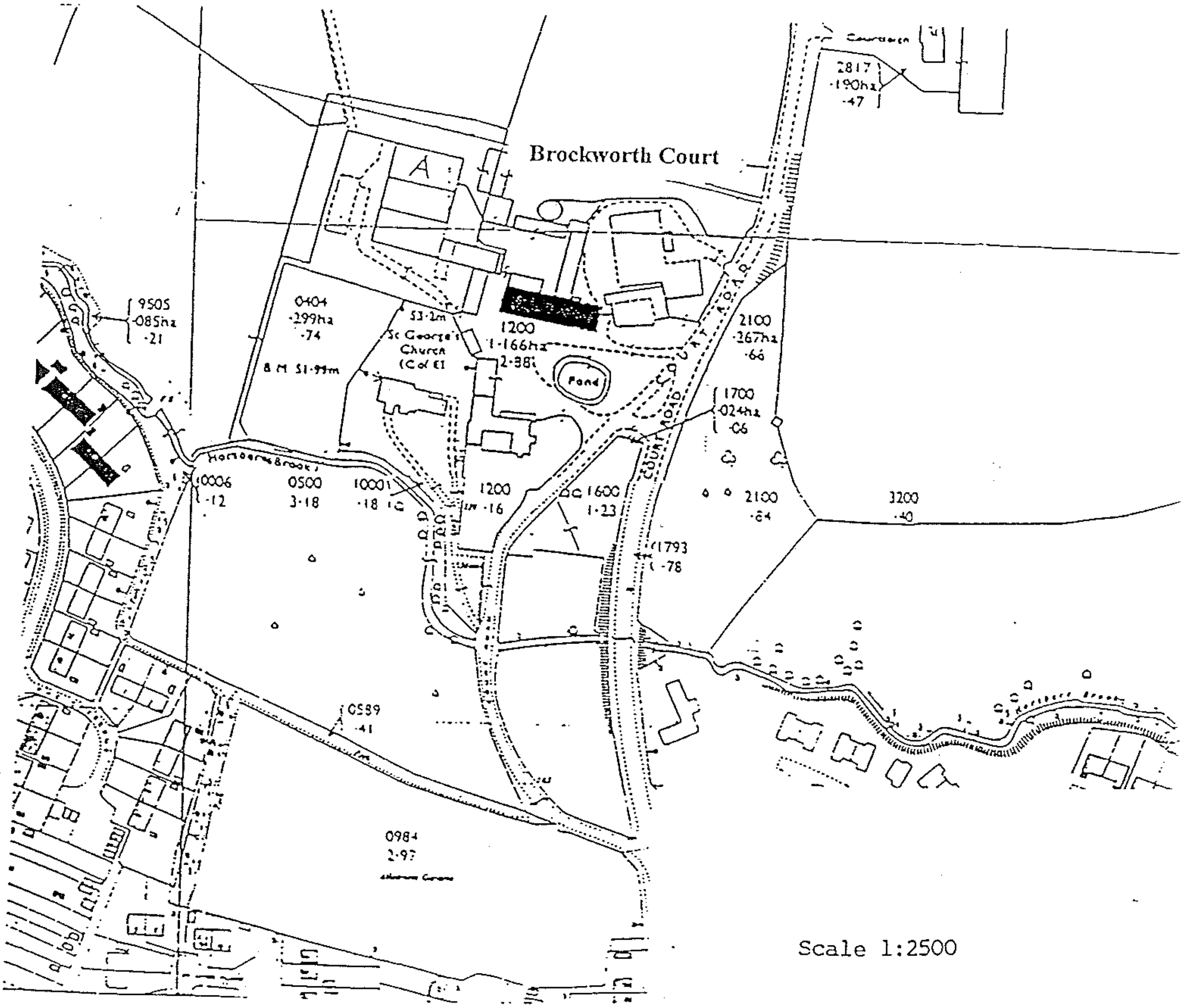
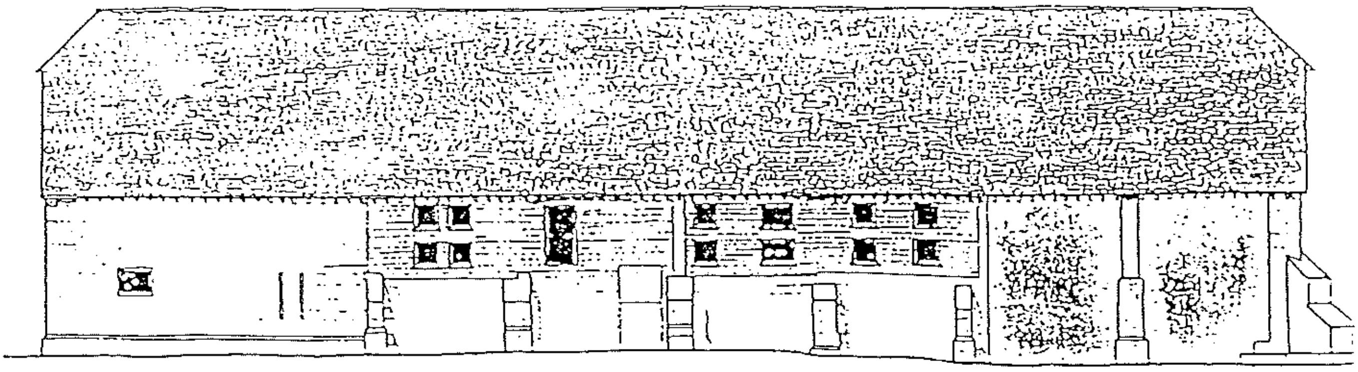


Figure 2: Map to show specific location of Brockworth Court



Scale 1:2500

Figure 3: Drawing to show south elevation of Brockworth Court Barn and long-section looking north (Bruton Knowles 1997)



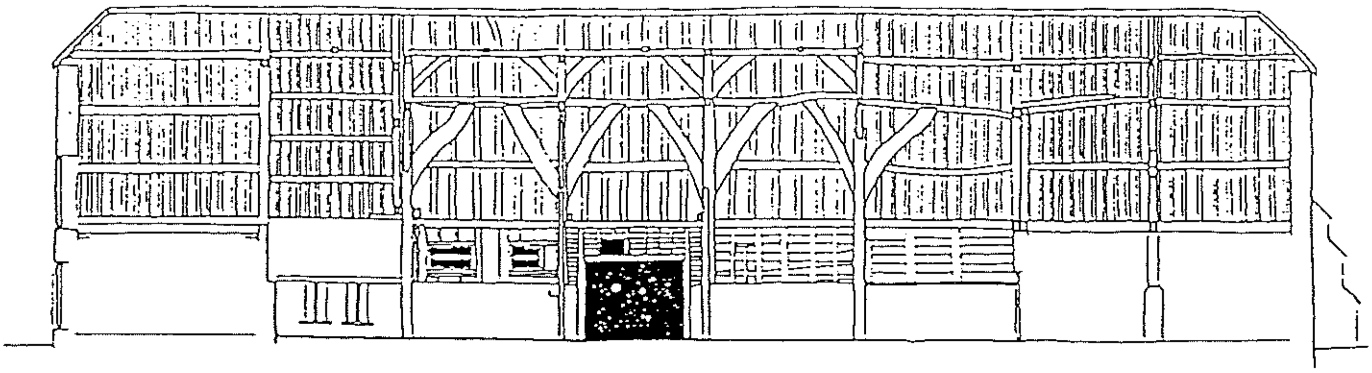


Figure 4: Drawing of east face of truss 5 to show example of medieval base-cruck (Bruton Knowles 1997)

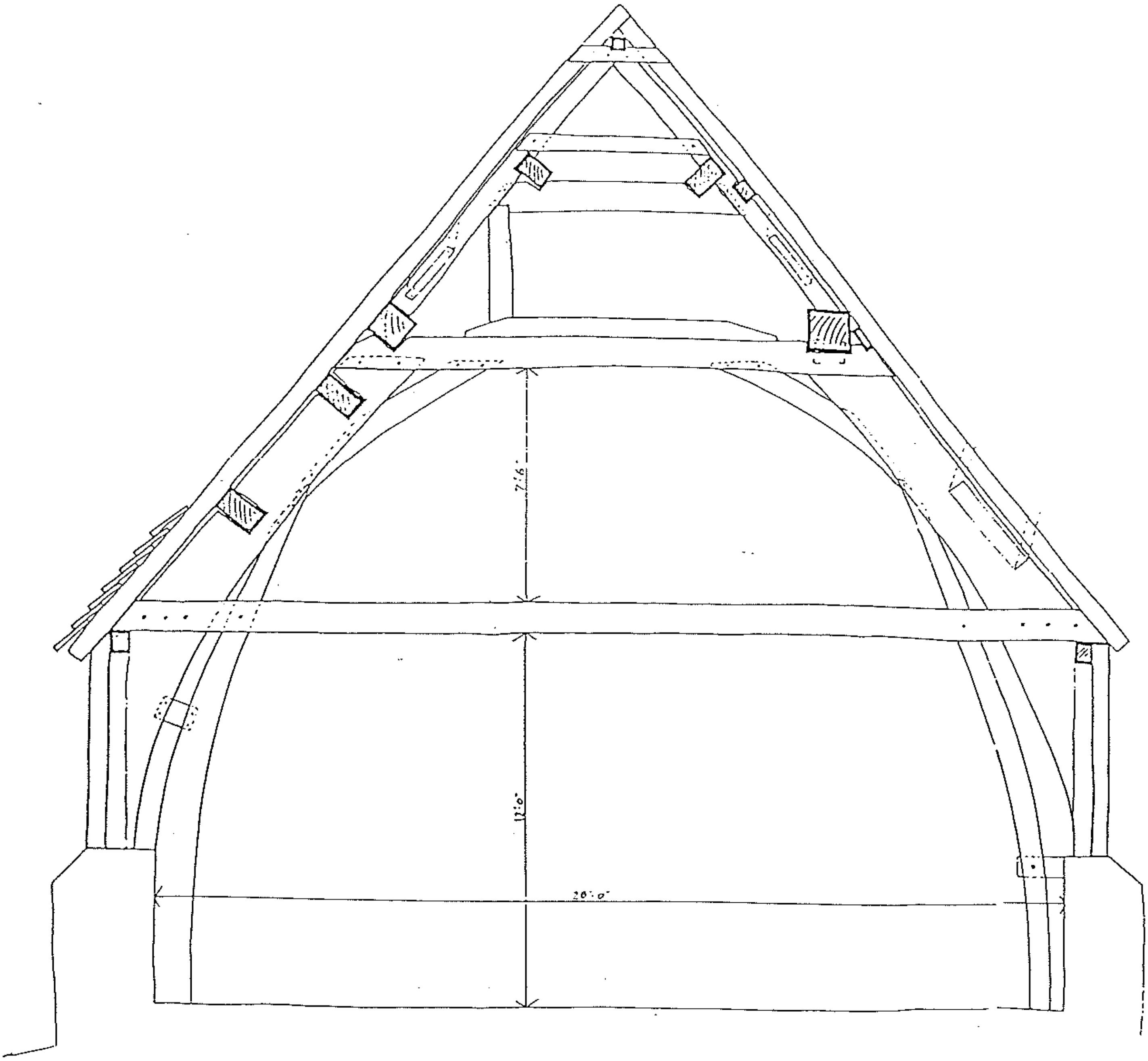


Figure 5a: Truss 3 viewed from east side showing timbers sampled
(after Bruton Knowles 1997)

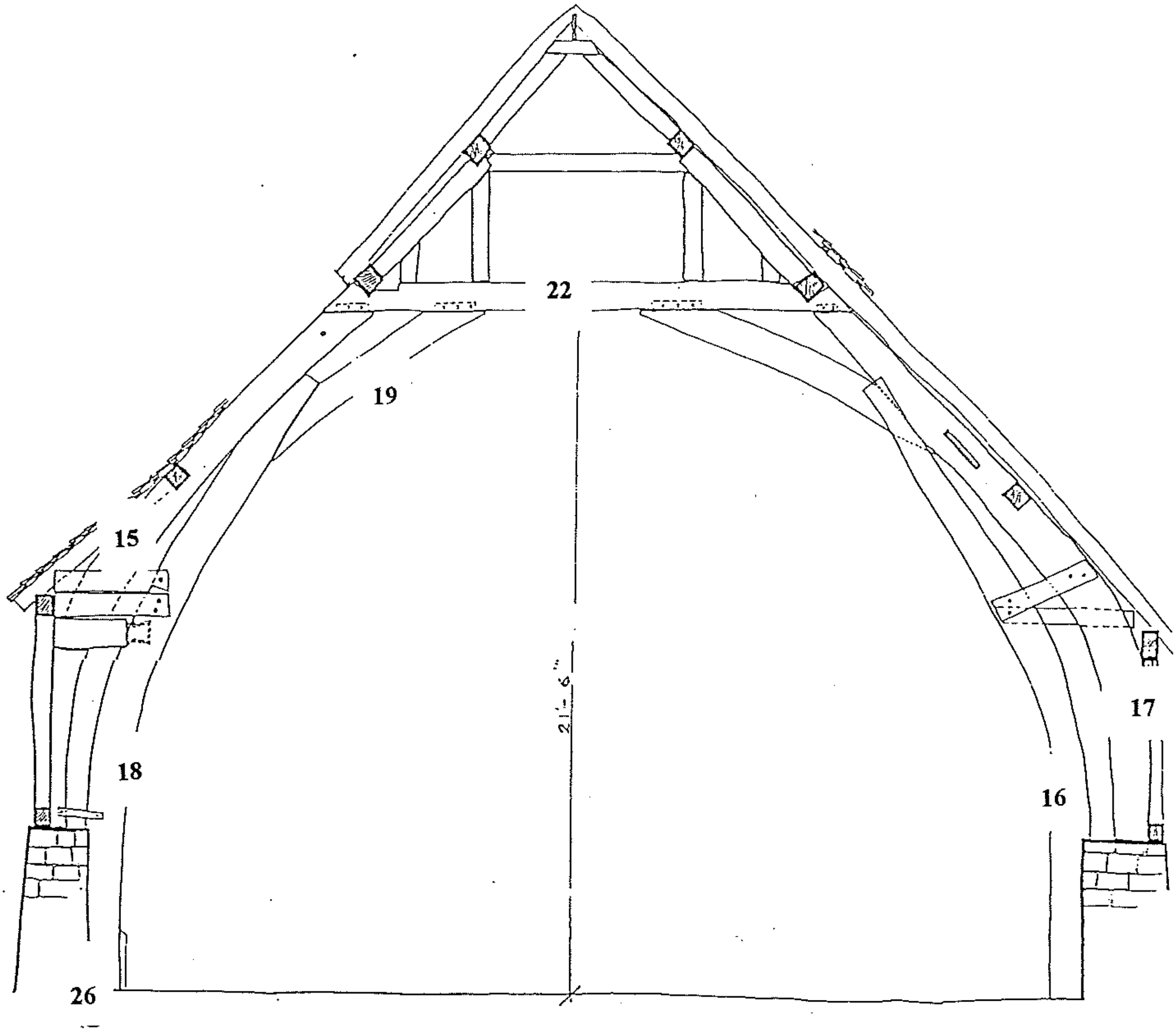


Figure 5b: Truss 4 viewed from east side showing timbers sampled
(after Bruton Knowles 1997)

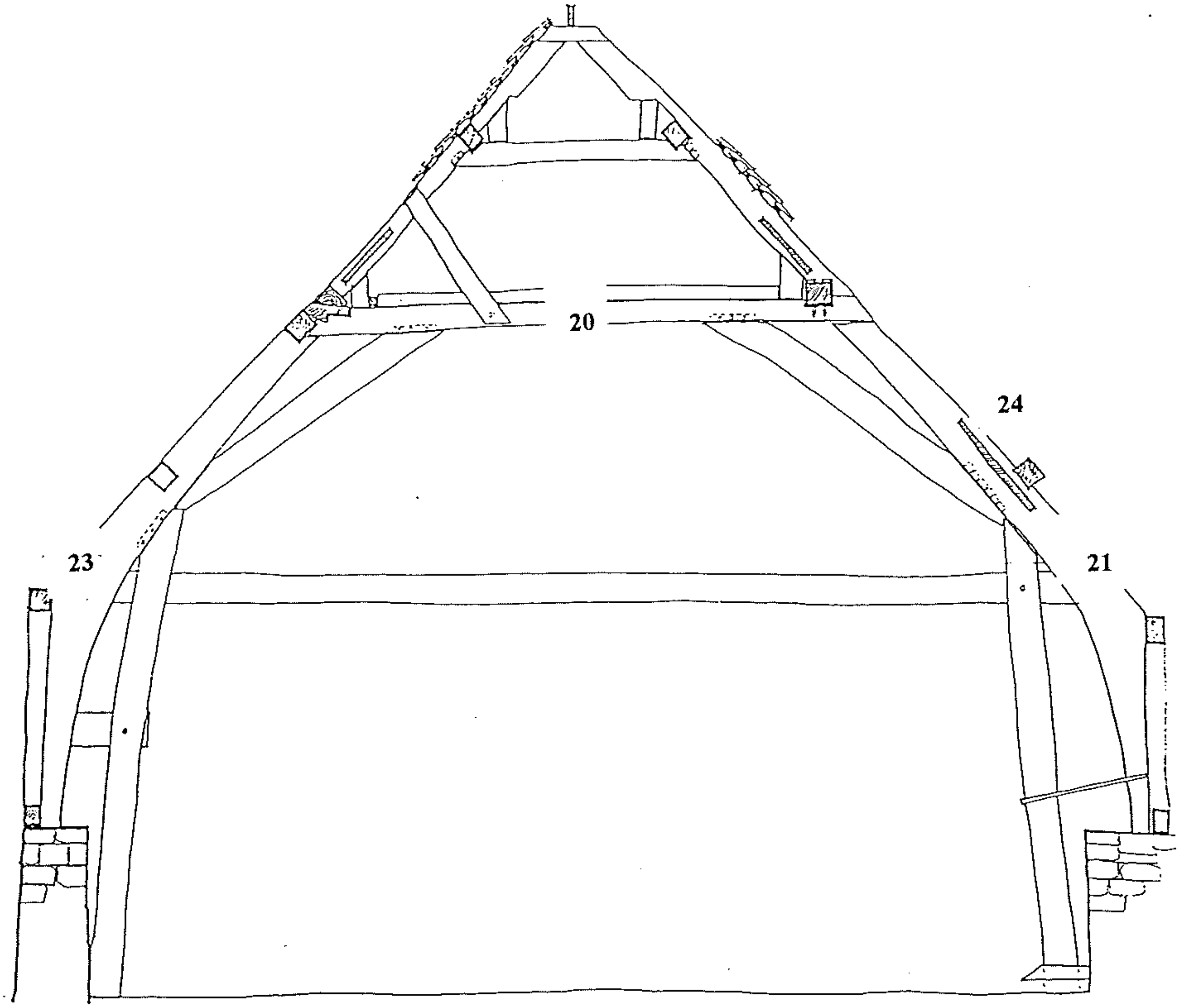


Figure 5c: Truss 2 viewed from east side showing timbers sampled (after Bruton Knowles 1997)

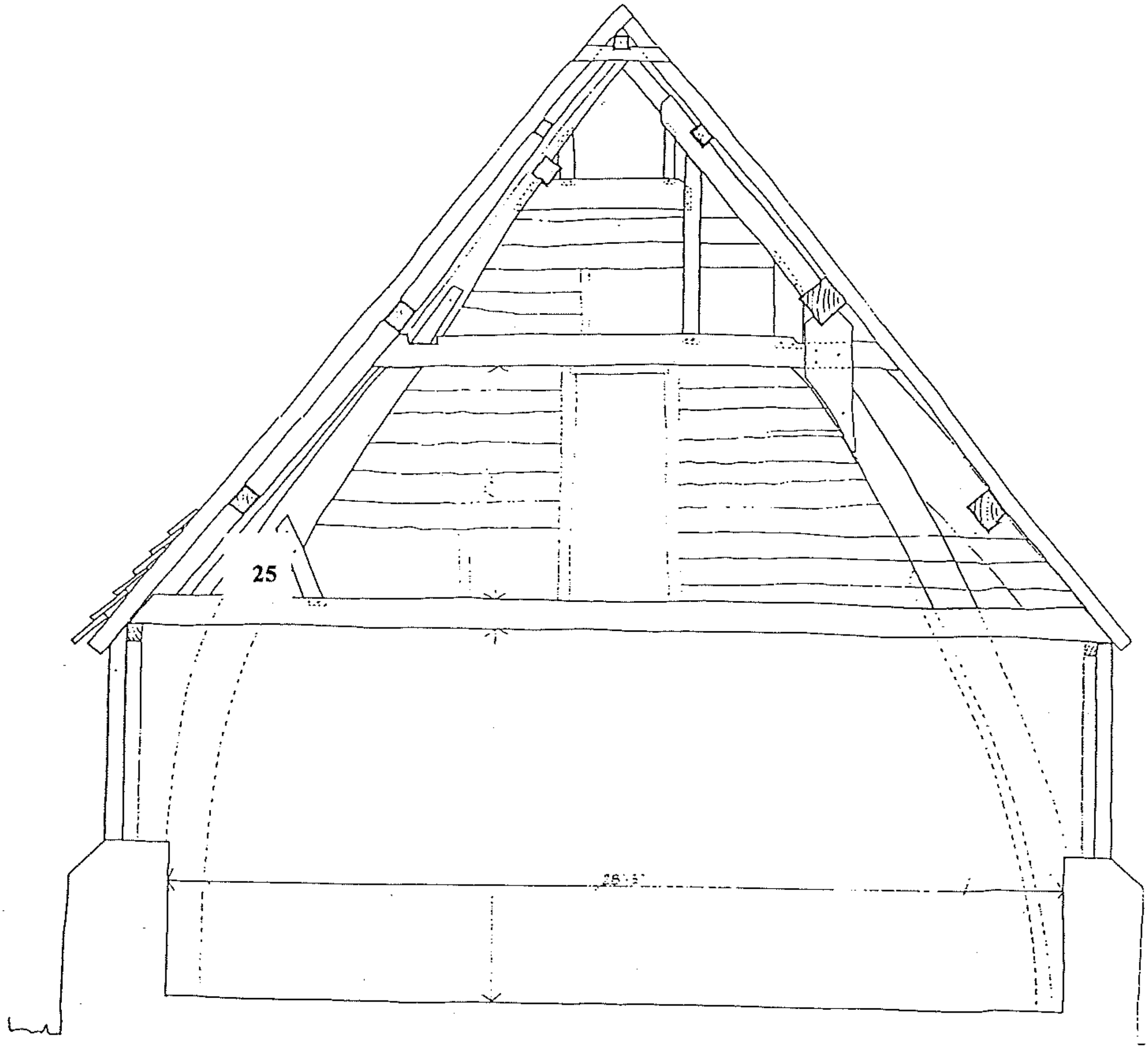


Figure 5d: Truss 5 viewed from east side showing timbers sampled (after Bruton Knowles 1997)

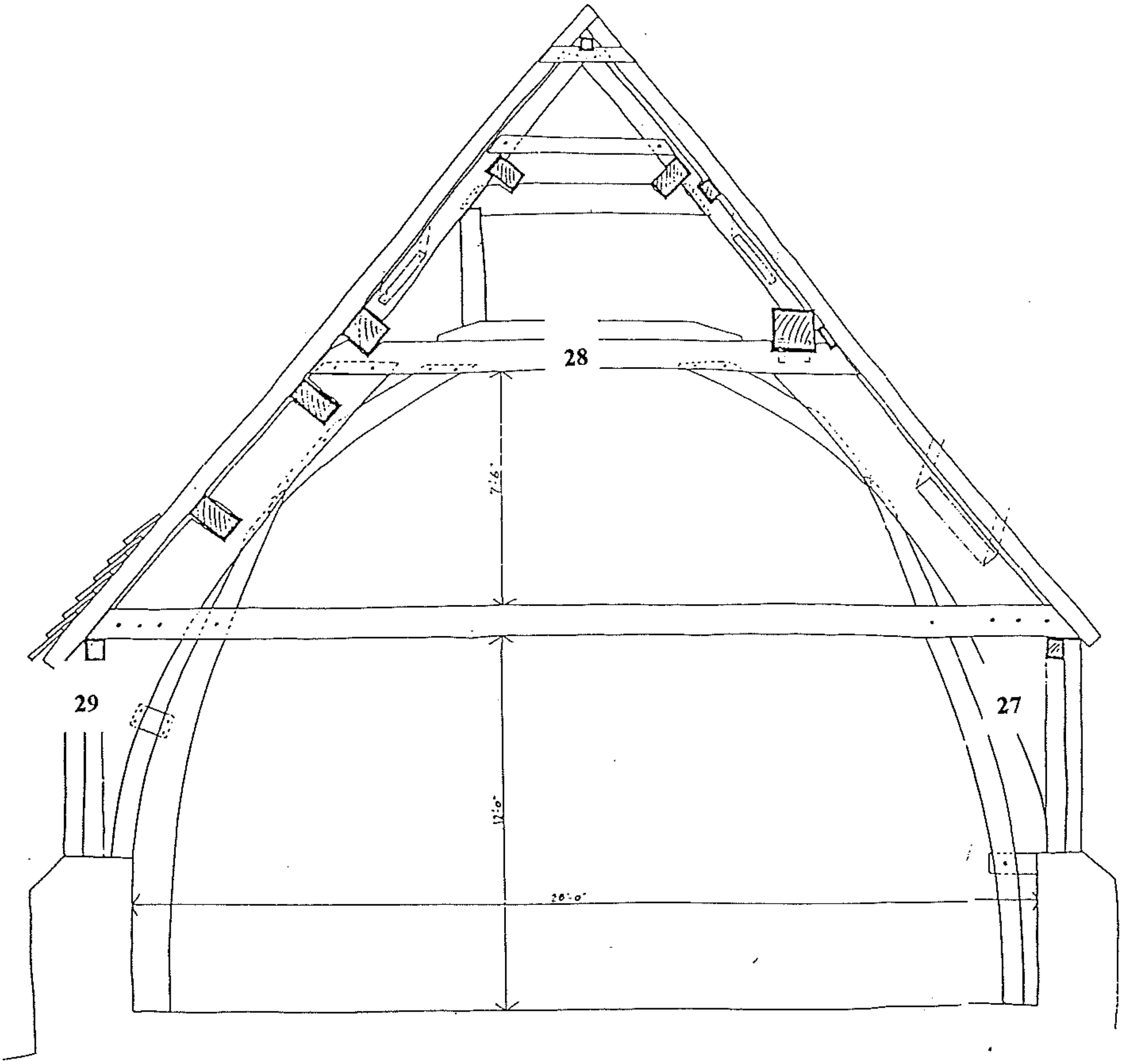
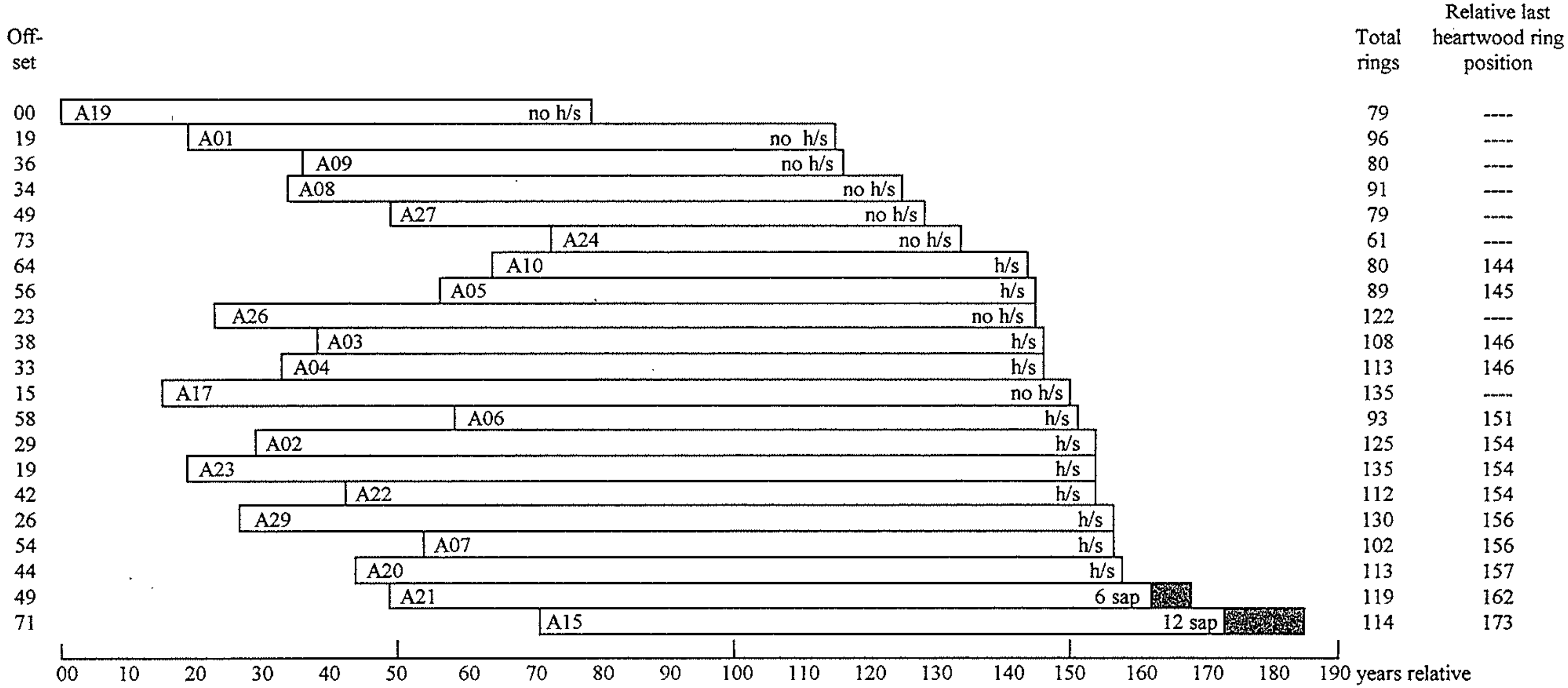
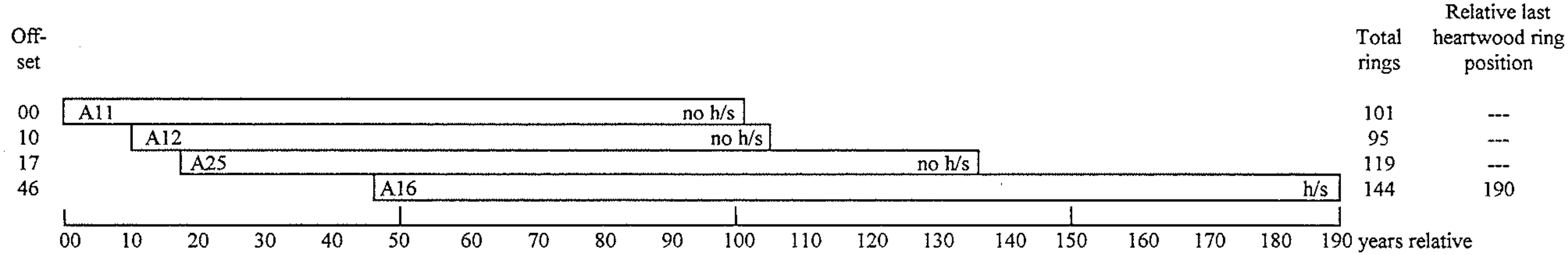


Figure 6: Bar diagram of samples in site chronology BRKASQ01



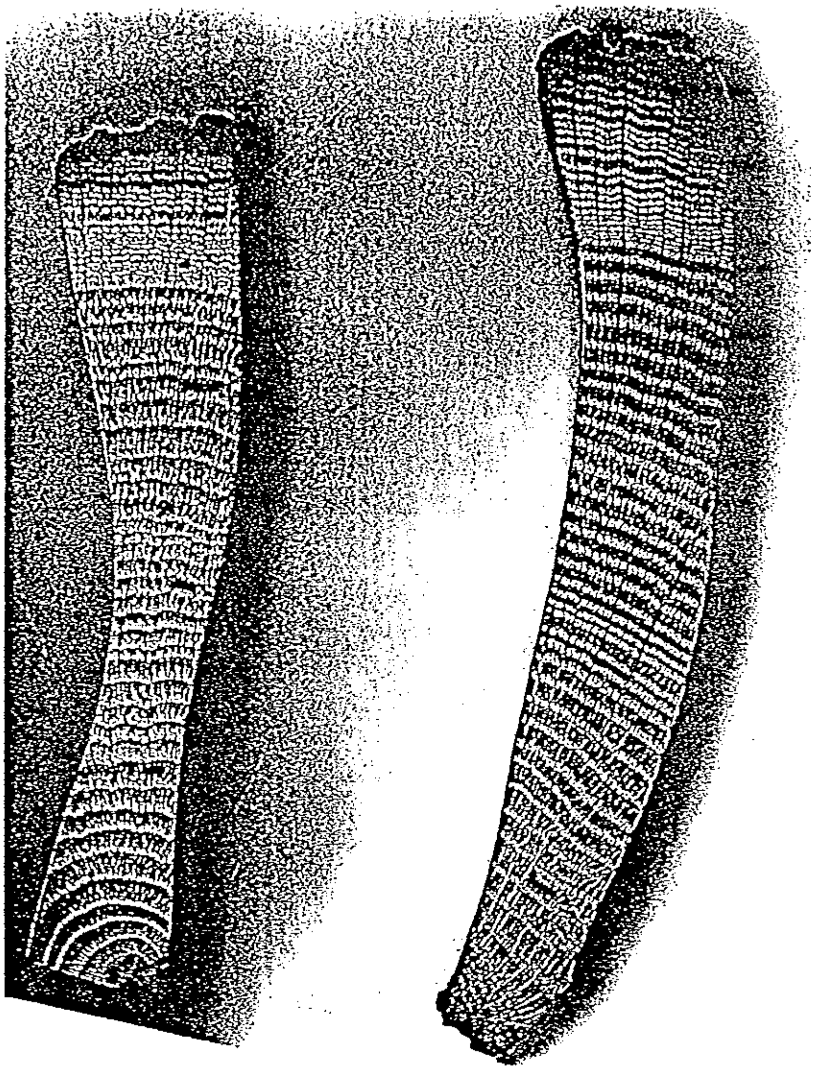
White bar = heartwood rings, shaded area = sapwood rings
h/s = the heartwood/sapwood boundary is the last ring on the sample

Figure 7: Bar diagram of samples in site chronology BRKASQ02



White bar = heartwood rings
h/s = the heartwood/sapwood boundary is the last ring on the sample

Figure 8: Undated samples BRK-A13 and BRK-A14 showing sudden change to narrower growth-rings in later years



Data of measured samples - measurements in 0.01 mm units

BRK-A01A 96
524 462 340 344 491 516 588 619 493 426 496 424 560 506 426 588 602 606 593 658
423 310 396 431 394 296 260 290 449 409 543 436 468 298 241 347 283 322 304 266
259 371 368 194 276 344 283 246 401 337 253 221 253 305 338 318 289 228 280 356
346 345 271 191 252 251 168 285 217 228 225 199 182 191 189 210 226 217 219 232
256 215 240 148 171 201 303 333 230 250 180 155 152 123 245 227
BRK-A01B 96
541 425 358 355 488 486 611 620 494 435 489 437 555 516 445 587 598 625 558 630
422 350 400 444 418 309 249 328 447 419 555 410 461 280 247 348 243 318 303 297
265 377 353 202 284 368 283 225 387 345 238 201 247 316 339 312 297 240 282 343
350 331 264 198 245 270 168 280 226 223 234 197 200 189 182 218 229 217 218 225
257 237 233 129 197 225 303 350 235 236 184 167 158 139 222 210
BRK-A02A 125
432 407 605 539 484 576 542 411 438 608 480 398 327 374 424 393 249 301 312 280
324 228 151 149 150 218 127 236 325 283 215 223 169 147 180 250 222 149 307 324
225 178 236 217 207 219 238 166 261 296 371 240 262 250 271 316 159 276 213 229
193 276 229 220 207 202 216 162 173 202 217 166 146 106 156 172 242 232 195 217
200 148 115 118 196 103 176 153 113 217 157 116 90 114 159 126 236 161 141 133
147 99 113 114 135 172 149 151 90 114 123 116 103 136 126 137 130 136 99 94
204 177 197 90 95
BRK-A02B 125
439 422 581 540 483 574 552 399 439 630 484 412 340 360 417 388 231 282 289 268
341 201 145 136 157 220 117 248 322 277 266 203 173 138 184 246 216 142 316 310
237 173 259 211 205 224 216 186 260 301 365 238 244 245 261 314 154 258 213 237
193 273 224 232 212 202 253 141 181 215 235 191 151 101 163 203 266 226 185 190
180 140 116 112 196 107 176 152 128 218 146 106 86 109 160 126 231 162 140 119
140 99 135 107 122 161 140 144 90 124 139 121 112 146 126 141 127 121 104 139
164 132 192 89 116
BRK-A03A 108
368 312 199 250 210 291 286 200 265 259 225 234 172 113 88 178 292 179 98 157
142 99 190 162 203 388 291 452 201 473 532 481 492 558 504 491 565 518 359 524
380 466 317 469 448 464 234 177 292 365 517 435 432 419 294 236 359 484 327 356
292 300 169 290 253 280 294 211 240 301 262 248 233 137 119 168 143 146 162 189
163 158 97 90 120 142 128 141 141 152 149 133 120 187 192 225 317 262 212 178
160 161 250 208 254 267 164 187
BRK-A03B 108
350 310 193 255 217 303 272 205 276 258 199 247 169 114 80 164 296 170 98 157
158 99 188 145 191 389 280 465 203 468 520 489 491 551 505 487 563 561 353 548
349 458 341 448 472 431 244 154 302 354 504 444 442 419 309 228 378 487 314 350
297 293 187 284 274 309 303 192 258 281 285 245 228 129 131 170 144 143 171 177
160 151 107 87 118 144 138 133 138 154 138 129 143 177 190 227 302 237 233 171
128 162 242 223 261 248 182 192
BRK-A04A 113
426 652 593 434 510 502 328 322 345 482 352 275 331 504 520 473 515 332 375 291
250 359 154 297 186 195 141 171 157 187 264 158 225 125 161 220 159 176 196 180
212 242 189 152 190 201 213 116 120 107 111 108 120 191 171 182 189 173 192 150
154 153 183 210 180 189 177 151 203 181 169 217 190 239 177 133 179 152 141 146

203 134 242 251 205 229 191 225 244 224 206 228 258 251 224 222 201 165 213 171
156 220 173 194 175 185 107 155 160 167 136 137 172
BRK-A04B 113
448 635 586 440 525 458 327 328 346 491 350 274 353 499 540 477 534 322 363 282
258 372 144 304 190 207 154 183 161 188 254 175 201 123 169 211 156 202 194 182
211 211 205 159 174 206 191 116 117 114 102 117 117 176 180 186 182 177 198 148
155 150 187 211 177 179 175 166 206 180 161 227 180 233 171 138 174 148 150 143
202 153 231 243 205 246 204 212 264 214 207 228 248 250 207 226 199 170 193 171
160 219 172 179 174 190 152 151 130 168 132 141 179
BRK-A05A 89
148 137 124 110 168 177 144 205 300 363 282 528 662 594 671 617 443 432 516 435
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204 240 307 324 230 313 189 193 217 188 176 252 257 245 213 143 147 179 179 209
229 234 229 225 159 115 146 225 250 330 271 340 268 273 265 318 227 289 412 256
265 218 207 215 324 258 277 275 182
BRK-A05B 89
161 144 129 115 158 165 156 221 281 370 257 520 662 561 678 617 438 439 512 444
360 441 356 453 458 539 454 364 355 170 412 342 403 428 370 359 379 385 197 193
211 236 328 286 247 316 177 220 213 166 228 263 244 234 211 134 152 175 182 186
214 243 243 224 143 101 162 215 259 295 295 325 266 272 259 341 249 293 397 253
262 222 203 250 313 228 287 283 180
BRK-A06A 93
220 282 380 370 256 260 281 357 252 230 194 220 213 244 261 226 242 193 205 218
286 250 201 202 195 230 201 147 267 276 263 243 240 214 310 288 205 220 205 212
251 211 151 239 223 181 230 233 284 263 269 262 225 288 245 296 247 288 262 208
231 209 154 204 193 248 263 234 227 200 195 245 200 226 240 239 297 252 242 206
212 229 271 259 289 284 386 287 266 188 160 218 233
BRK-A06B 93
232 241 310 343 230 261 293 343 249 238 262 251 214 279 275 235 262 210 207 205
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218 237 258 271 280 292 378 275 279 192 147 232 266
BRK-A07A 102
245 182 237 272 227 197 210 161 167 261 227 270 210 272 336 388 373 380 378 292
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224 221 252 239 211 224 217 230 161 164 156 148 213 285 318 337 271 209 195 225
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149 167
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229 182 227 335 231 197 194 142 141 275 279 285 188 256 310 375 372 421 384 304
344 328 282 257 270 297 289 291 234 221 193 178 246 243 289 297 278 243 279 221
247 220 257 235 236 240 213 245 148 170 171 168 238 339 328 348 284 214 193 252
159 181 167 156 151 132 150 127 139 160 197 172 179 174 155 183 151 166 143 202
221 182 158 132 122 143 144 173 166 186 132 98 126 108 102 104 111 179 189 164
131 152
BRK-A08A 91
622 567 437 436 457 367 395 403 468 354 244 386 416 412 352 520 327 377 312 239
321 116 238 169 199 131 140 117 81 123 107 162 122 209 280 206 199 172 158 175
196 168 157 201 174 132 93 105 121 89 93 92 141 148 189 166 186 217 152 168

169 203 206 204 180 206 184 191 195 215 195 193 256 221 211 200 192 167 178 241
142 305 242 228 257 224 217 251 200 209 184
BRK-A08B 91
644 564 446 431 461 363 398 398 462 340 274 349 439 422 379 506 312 365 271 245
297 115 223 175 193 143 134 125 81 148 100 190 98 216 291 209 198 179 151 165
179 176 166 198 176 137 107 99 112 95 94 96 147 167 221 153 176 200 150 150
185 213 210 192 183 207 197 189 198 200 216 182 245 215 213 190 178 183 171 234
155 275 249 244 270 228 219 253 199 209 178
BRK-A09A 80
406 564 555 400 441 338 417 337 305 375 434 543 535 622 440 473 354 291 400 148
311 269 218 174 169 119 112 194 126 187 84 157 206 166 136 148 132 137 167 155
145 183 173 153 123 99 122 108 112 123 217 181 179 176 170 196 172 184 166 198
197 220 179 187 144 177 169 195 211 208 233 196 159 207 156 140 173 265 143 234
BRK-A09B 80
397 558 565 402 445 361 431 310 281 331 408 509 524 600 405 483 343 262 370 141
297 241 198 174 181 141 102 201 130 208 90 142 193 174 133 128 123 153 172 163
159 190 176 145 105 109 137 106 137 115 186 169 206 175 169 188 176 160 161 198
217 226 184 185 157 196 183 187 206 244 257 200 190 196 158 142 158 241 159 219
BRK-A10A 80
189 228 98 186 242 215 206 188 180 196 205 177 174 177 204 211 147 129 124 118
140 122 202 171 193 175 187 205 129 126 146 156 192 188 147 166 158 220 196 173
190 199 247 201 149 163 152 152 148 192 139 234 203 229 212 190 198 203 198 185
183 213 180 178 187 175 150 198 148 191 163 183 223 162 168 157 171 142 209 176
BRK-A10B 80
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199 194 237 207 143 160 143 166 135 201 140 226 216 225 223 195 193 211 193 188
185 219 191 186 184 189 155 191 156 176 162 183 202 163 181 173 168 159 189 186
BRK-A11A 101
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229 209 287 219 235 198 224 301 211 154 225 118 65 41 65 103 116 150 143 141
125 159 116 135 119 121 164 203 198 242 143 144 133 110 76 87 103 109 95 137
131 103 105 92 89 135 170 113 40 55 42 96 117 91 68 102 171 117 106 116
226 140 119 135 139 124 94 111 70 119 89 85 116 95 95 79 83 64 83 79
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BRK-A11B 101
193 125 158 173 135 126 184 297 152 178 327 305 425 356 425 363 296 426 130 153
220 199 292 227 225 196 199 305 217 156 224 124 69 45 67 103 117 151 152 135
113 166 104 140 127 114 165 210 200 231 138 151 139 110 83 81 105 100 101 125
142 101 105 100 78 136 172 99 43 53 49 122 124 96 68 128 183 120 96 125
241 123 117 135 151 127 85 116 71 137 81 86 119 102 83 78 77 63 85 86
68
BRK-A12A 95
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227 108 77 58 62 83 108 123 132 135 104 147 113 123 109 103 192 208 182 238
126 144 140 99 76 82 110 122 136 154 158 117 127 115 107 129 162 93 52 64
51 119 126 97 72 125 172 107 90 115 202 119 93 130 116 113 71 86 61 105
60 79 118 92 72 82 73 55 65 95 54 83 59 70 86
BRK-A12B 95
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203 138 67 68 67 66 95 138 133 124 115 139 115 119 125 128 182 214 192 232

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48 116 117 104 81 116 172 118 97 105 195 109 107 129 122 110 70 93 62 102
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219 105 57 63 67 75 62 93 85 86 105 92 132 140 97 83 92 135 140 101
136 177 159 125 152
BRK-A13B 65
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246 133 141 182 257 244 250 215 279 287 298 296 271 262 243 305 319 314 262 281
253 100 57 61 75 71 63 98 82 87 97 98 133 137 90 78 78 143 158 112
117 207 145 130 138
BRK-A14A 60
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87 87 78 46 59 97 118 163 79 89 89 149 121 93 103 93 70 75 82 134
BRK-A14B 60
257 211 217 194 327 351 293 261 304 364 278 232 247 307 292 154 248 242 241 216
217 188 124 168 260 230 324 452 351 285 192 310 224 220 208 98 60 58 44 67
70 70 70 40 46 78 120 162 87 76 85 170 96 89 107 108 70 91 82 123
BRK-A15A 114
347 252 371 466 382 346 359 337 558 481 430 350 488 488 289 594 583 516 476 303
259 341 226 217 255 394 241 284 335 201 157 158 223 249 184 255 235 252 213 137
107 163 247 157 255 320 245 290 189 173 174 175 229 372 241 217 367 183 180 127
254 126 202 208 148 125 120 100 119 263 303 557 350 308 385 291 197 154 160 130
185 207 129 107 101 120 129 129 129 114 148 129 103 221 179 132 137 134 132 213
100 106 87 110 98 156 124 107 143 300 239 217 300 322
BRK-A15B 114
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247 146 211 199 152 131 106 114 127 260 294 539 343 299 382 297 212 160 159 124
184 196 134 107 117 123 129 141 105 140 142 118 100 223 189 152 107 131 108 219
83 106 77 108 98 164 104 116 195 234 216 233 280 248
BRK-A16A 144
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441 510 417 618 443 457 397 390 332 369 360 367 341 201 142 199 172 228 331 411
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144 99 200 153 127 63 58 68 68 86 107 99 147 113 164 93 164 162 128 73
77 75 184 185 135 120 119 147 131 108 131 131 134 120 130 152 67 38 40 39
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BRK-A16B 144
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499 305 192 261 256 385 258 374 242 427 602 395 263 438 388 277 276 372 435 327
441 486 435 584 432 405 389 378 325 354 332 358 345 201 152 193 193 237 349 409
263 222 258 192 128 242 270 254 264 220 242 231 263 259 104 64 64 82 85 101
128 103 70 72 71 110 122 89 101 220 146 243 246 61 61 55 70 90 130 150
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75 71 177 191 140 126 109 143 140 94 156 143 128 127 141 156 93 45 24 45
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BRK-A17A 135
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180 152 153 196 198 199 182 134 118 130 126 193 205 245 186 207 164 168 143 94
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BRK-A17B 135
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204 133 96 118 138 142 139 143 130 158 144 198 230 195 257 249 181 209 187 186
193 158 171 189 198 186 175 137 102 132 145 197 200 220 204 202 165 152 154 97
145 163 162 193 142 160 151 136 131 164 192 170 120 107 118 123 144 135 155 136
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BRK-A18A 109
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90 89 119 112 122 215 137 163 160 324 529 335 208 71 82 103 198 218 269 194
310 372 207 266 557 385 339 454 315
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41 60 59 79 267 458 548 307 241 366 347 378 440 422 446 393 446 251 232 291
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86 87 155 118 124 212 140 152 174 316 462 365 216 62 78 111 197 238 254 188
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303 250 329 288 308 224 302 288 313 278 286 145 108 186 314 183 184 204 197 164
167 197 132 226 250 252 177 264 300 272 208 240 183 160 188 449 252 302 292
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181 202 117 223 357 258 201 196 205 235 225 149 117 466 346 279 164 230 159 218
166 134 218 215 327 246 234 258 265 188 202 268 283 288 258 180 236 248 212 262
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291 238 273 302 242 310 169 303 268 232 233 192 242 209 204 246 182 144 182 210
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BRK-A20B 113
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BRK-A21A 119
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205 275 315 282 312 358 326 279 350 185 305 242 220 237 222 294 178 171 135 162
202 159 303 289 261 356 267 255 236 219 242 273 259 288 266 235 273 202 236 257
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496 443 532 276 259 545 376 283 472 238 277 549 605 322 300 325 155 350 333 449
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BRK-A28A 80
582 767 598 612 630 574 523 505 503 339 368 352 392 378 248 228 270 376 410 364
390 363 330 258 409 365 302 319 630 764 357 330 227 273 263 172 243 277 243 285

233 170 149 207 157 216 210 144 190 186 193 132 131 166 160 167 165 144 154 149
175 167 162 194 226 194 194 194 232 210 220 251 276 224 215 196 147 127 135 188
BRK-A28B 80
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192 173 156 197 221 202 201 185 243 204 227 251 272 222 230 163 150 178 123 174
BRK-A29A 130
610 443 211 314 258 568 427 253 411 446 451 564 568 474 355 292 263 328 352 280
326 220 142 192 165 107 93 162 203 70 70 125 86 133 149 109 108 138 116 127
85 262 317 301 300 386 358 301 299 289 211 199 258 542 409 624 290 388 159 102
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342 351 365 189 145 163 149 193 152 189 153 149 150 167 117 117 123 202 215 279
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231 106 195 180 258 221 237 210 184 179
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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.

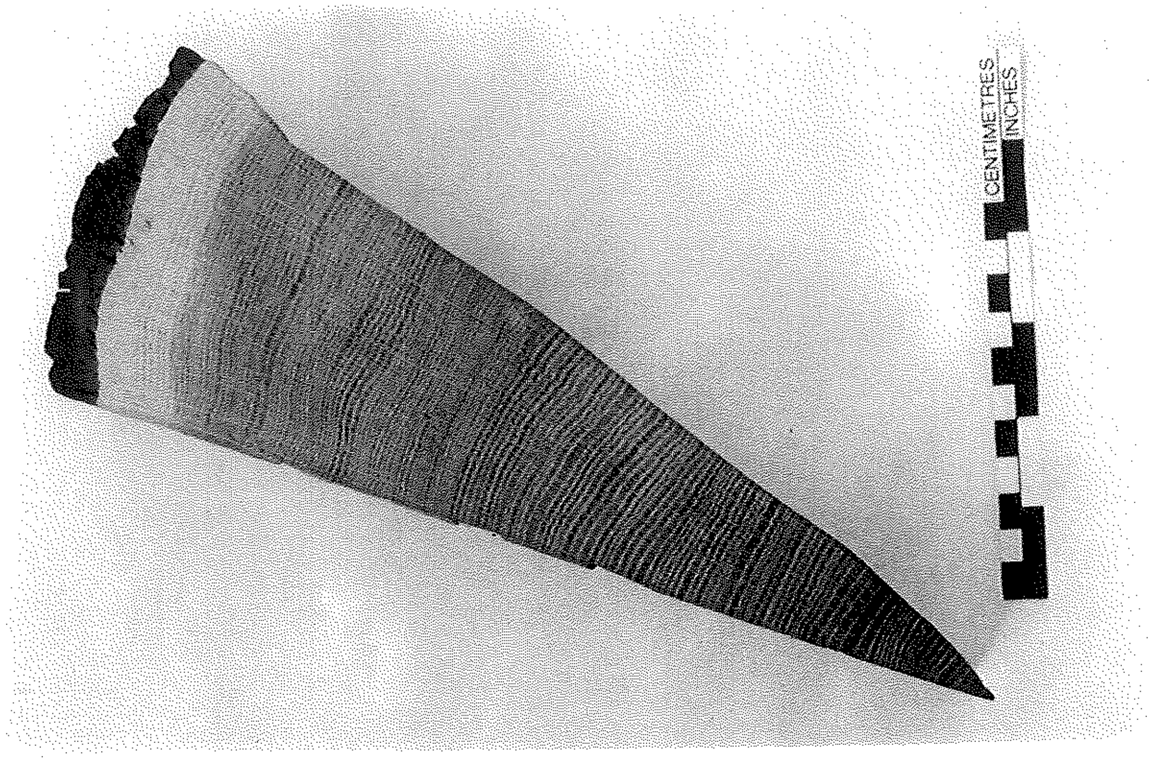

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

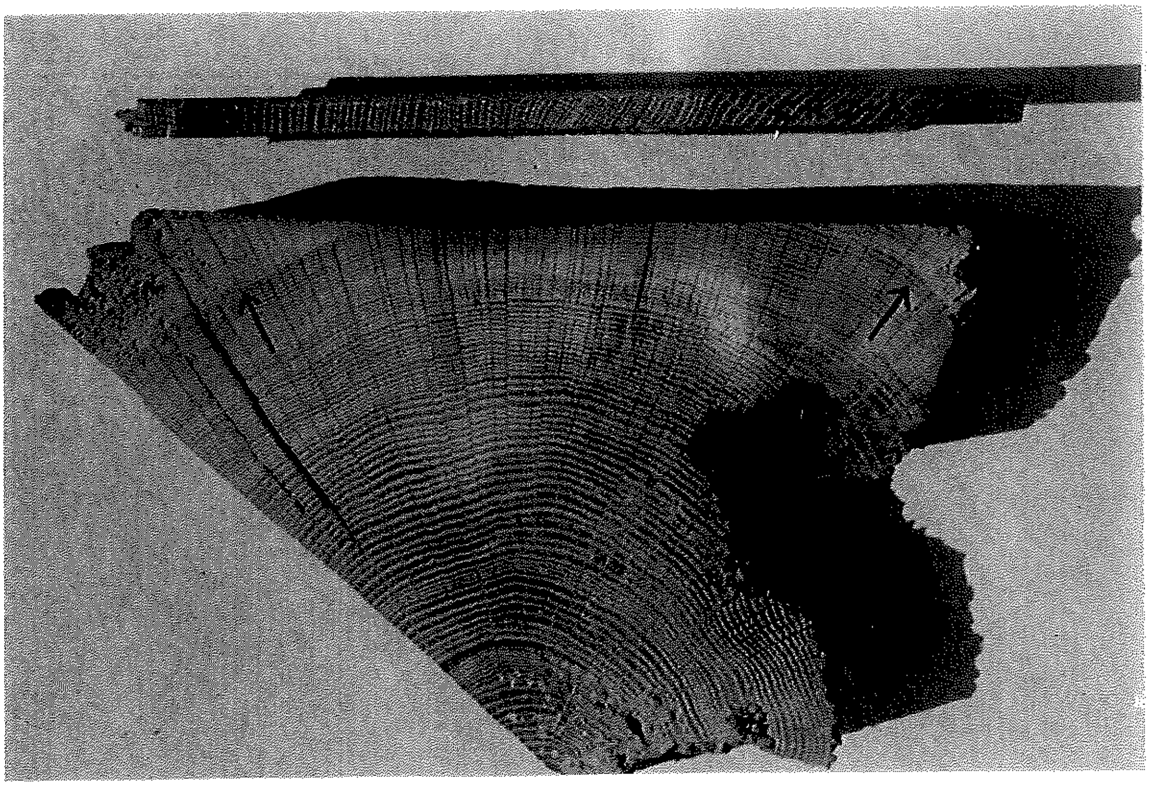

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners; the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

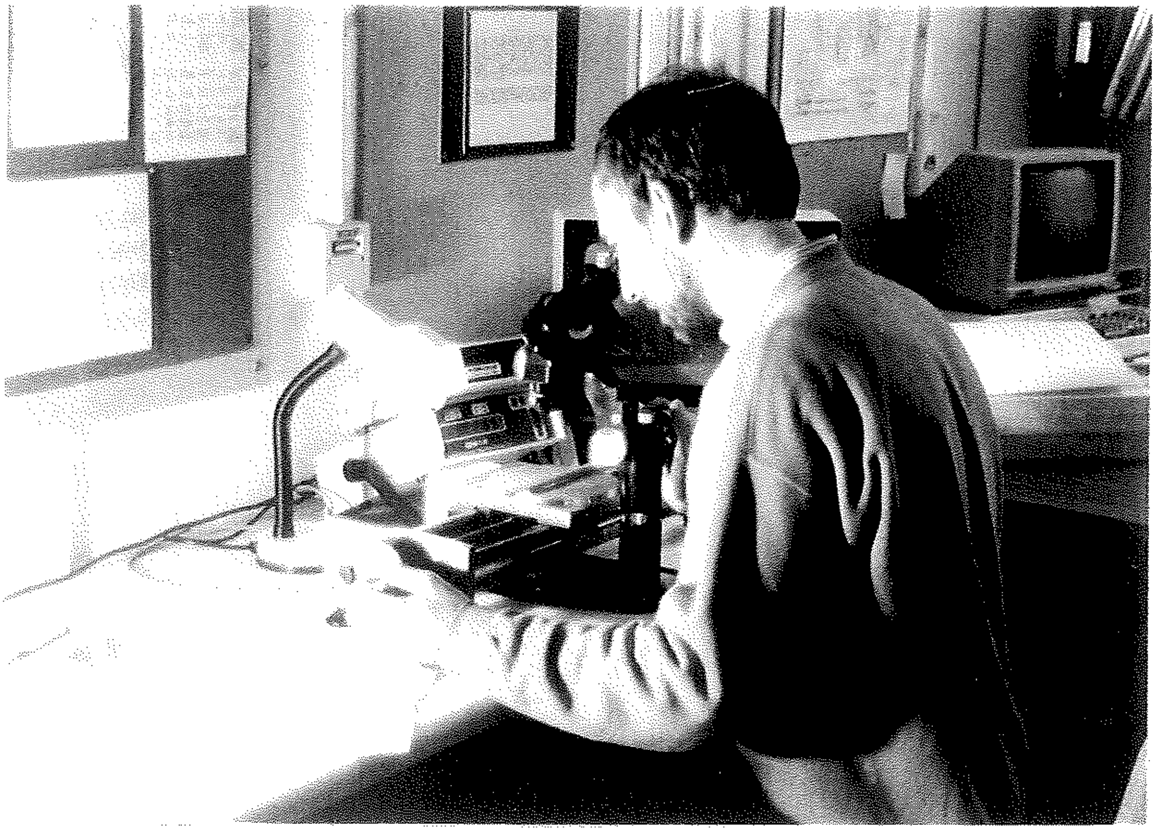

Fig 3. Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

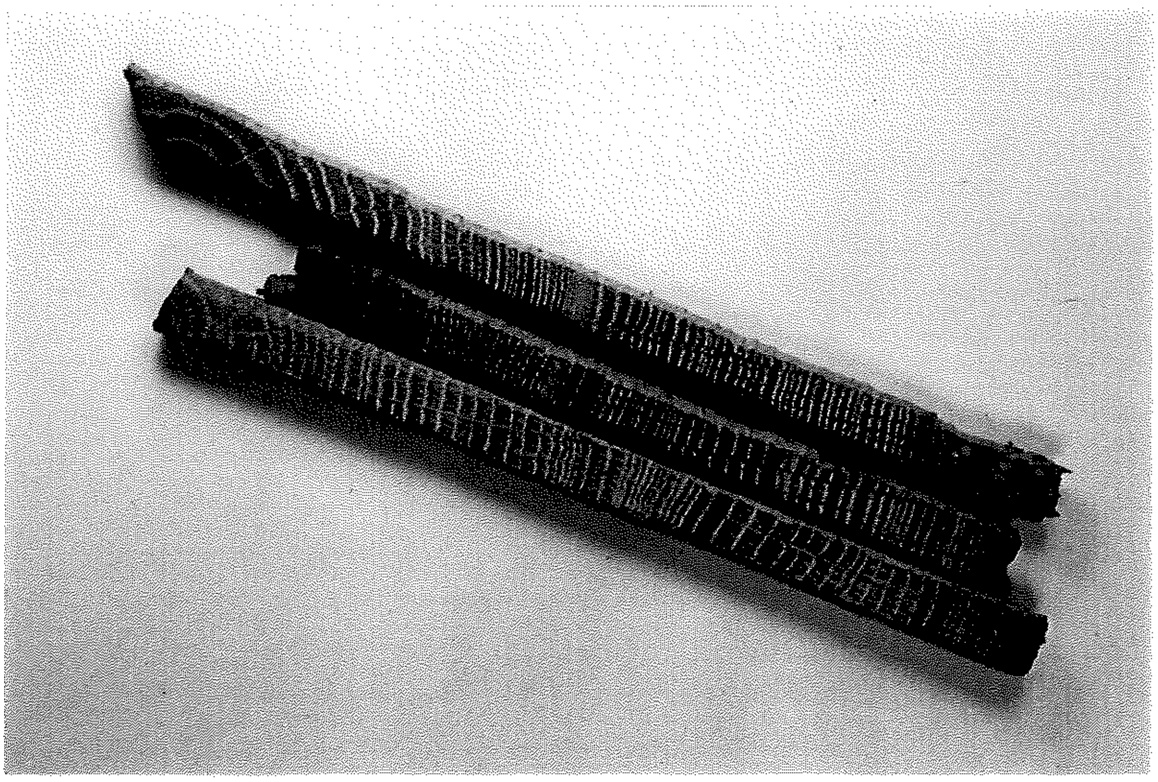

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

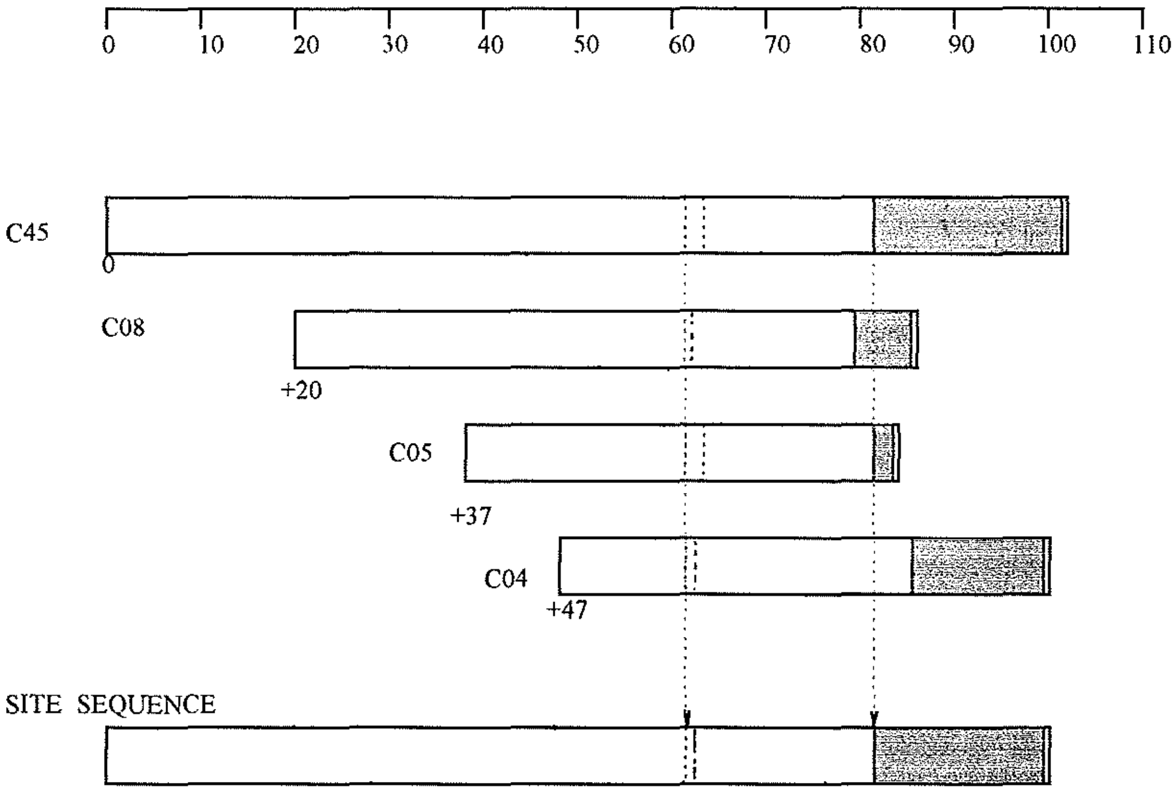

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

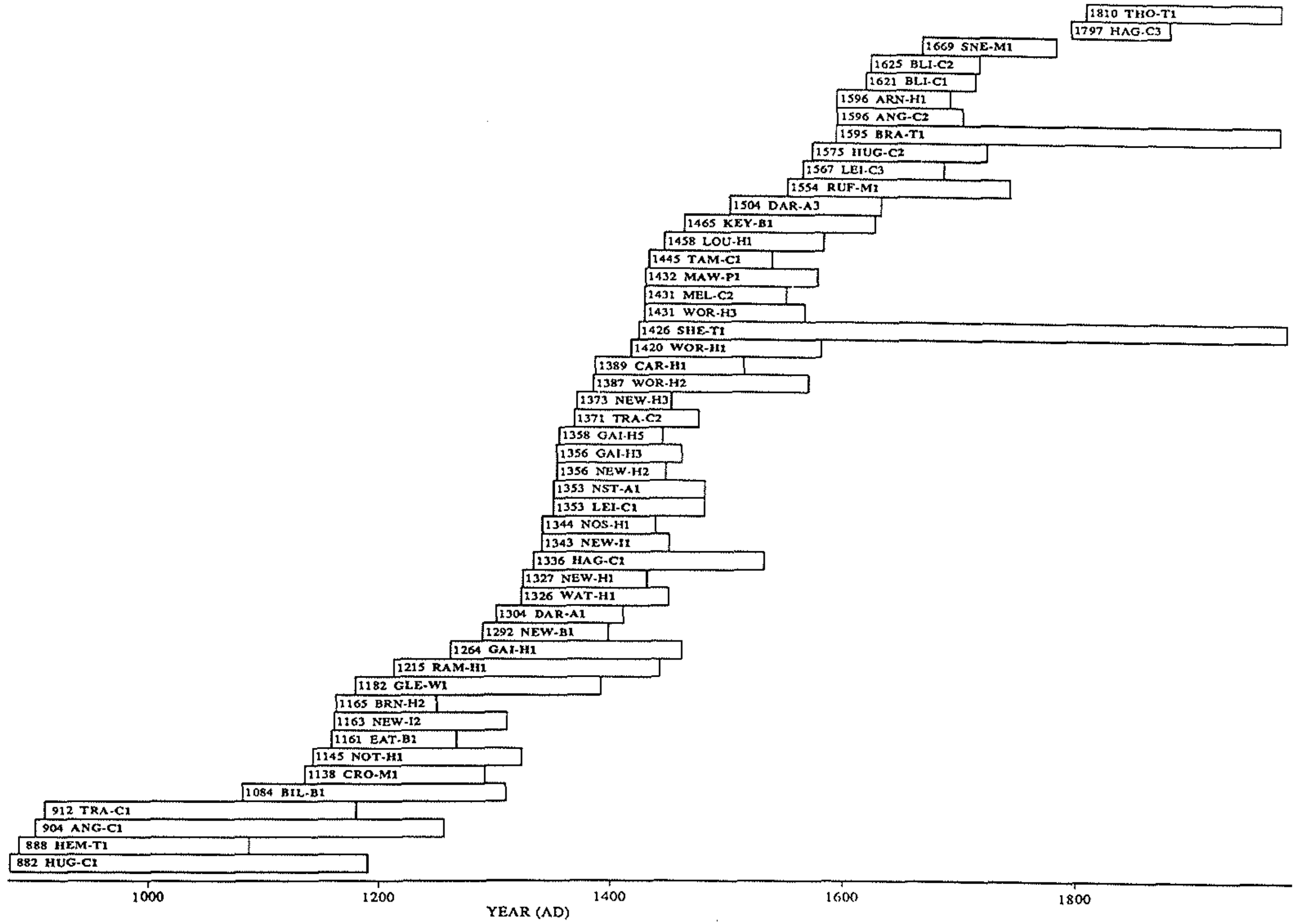

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

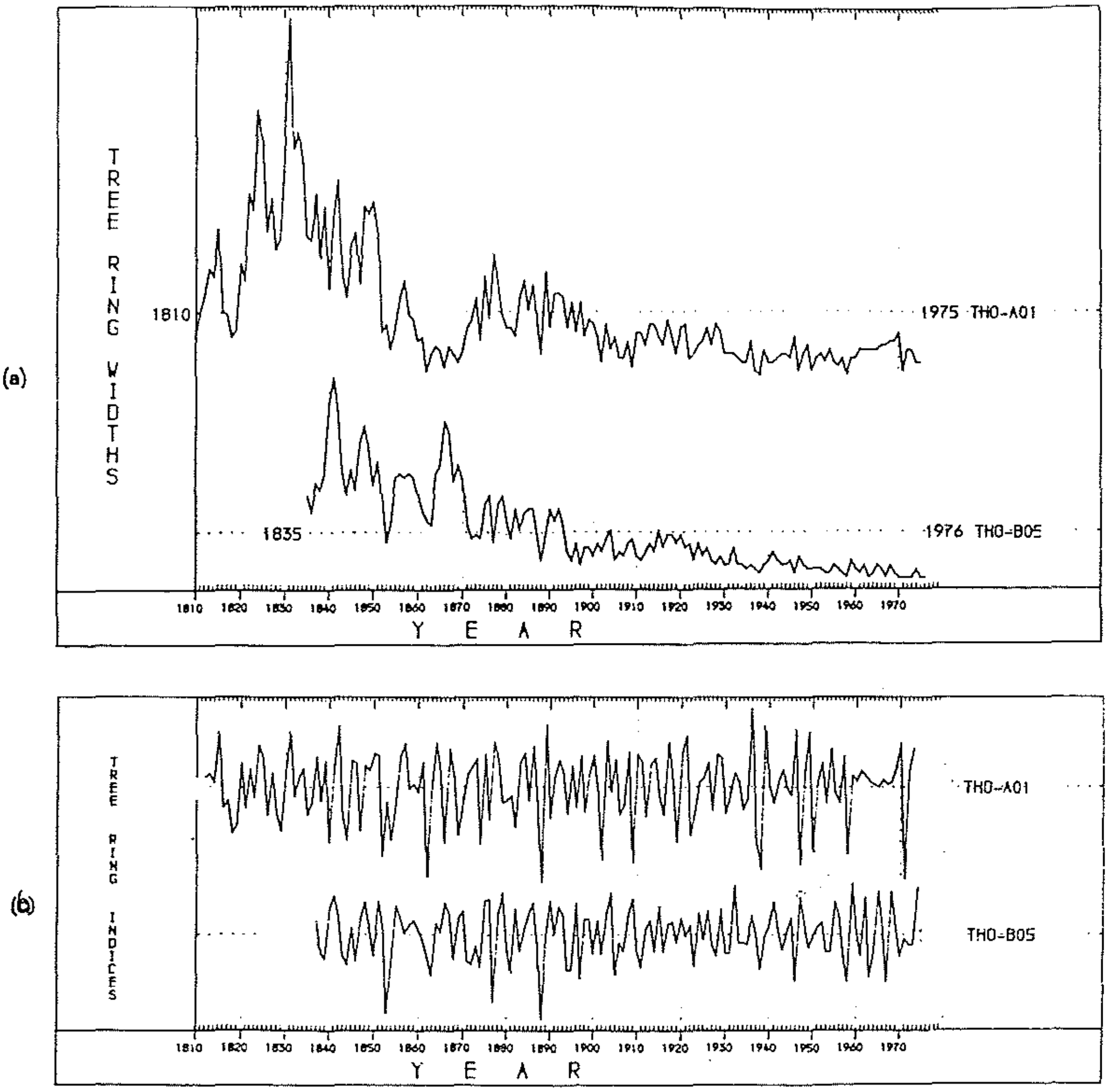

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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