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Summary

Analysis undertaken on seven samples taken from the timbers of the roof of this building resulted in the construction and dating of a single site sequence.

This site sequence contains six samples and spans the period AD 1366-1445. Three of these samples have complete sapwood and a last ring date of AD 1445, the felling date of the timbers represented. Interpretation of the sapwood rings, where present, of the other dated samples points to these timbers also having been felled in AD 1445.

Prior to tree-ring analysis being carried out this building was thought to date from the fifteenth century. The timbers of its roof are now known to have been felled in AD 1445.

Keywords

Dendrochronology
Standing Building

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Introduction

Springfield (ST 329 051; Fig 1), thought to date from the fifteenth century, is a through passage plan house of three rooms (Fig 2). It was originally open to the roof from end to end, and divided by low partitions. At a later date floors were inserted, although not at the same time; the hall remained open after the high end had been floored. In the early-seventeenth century a chamber was formed at the lower end of the house and a large kitchen fireplace built on the gable end. A little later in the seventeenth century a floor and partition were inserted into the hall forming an axial passage behind an unheated central service room. In about the early-mid eighteenth century the central service room was converted into a parlour and panelled, and a timber-frame chimney stack was inserted backing onto the through-passage.

The building has a fairly standard side-pegged jointed cruck truss roof (of five trusses) with straight mortice and tenoned collar trenched purlins and a trenched-diagonally set ridgepiece. The hall/high end truss has been infilled and is smoke-blackened on the hall side, but clean on the high end side, indicating that the hall was still open when the high end was floored. Having said this, the roof over the high end has been cleaned and painted so the smoke-blackening evidence might have been destroyed here.

The Laboratory would like to take this opportunity to thank the owners of the property, Mr and Mrs Cladingboel, for allowing sampling to be carried out.
John Dallimore and members of the Somerset Vernacular Buildings Group undertook the recording and provided the information used in the above site description.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was hoped that dendrochronological investigation would establish the date of this type of medieval house, typical of the south-west of England. Additionally, it was hoped to aid research into the origin and development of this house and inform a potential listing upgrade.

Sampling

Although sampling had been requested of timbers from three potentially separate phases, only those from the earliest phase, the roof, were considered suitable for tree-ring analysis. Timbers from the other two phases were either not oak, or oak but without the necessary minimum number of rings for secure dating, or inaccessible. Eleven samples were taken from the timbers of the roof, from principal rafters, collars, and upper purlins. Each sample was given the code SPO-L (for Somerset, Post Office Lane) and numbered 01-11. The position of all samples was noted at the time of sampling and has been marked on Figures 4-6. Further details relating to the samples can be found in Table 1.

Analysis and Results

At this stage it was noticed that four of the samples (SPO-L03, SPO-L06, SPO-L10, and SPO-L11) had too few rings for secure dating, and so were rejected prior to measurement. The remaining seven samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. Two of these samples (SPO-L01 and SPO-L02) had less than the usual minimum number of 54 rings preferred by this Laboratory. However, both of these samples had more than 45 rings and complete sapwood, and so it was decided to measure these two samples. These seven samples were then compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a least value of *t*=4.5, two samples matched each other and were combined at the relevant offset positions to form SPOLSQ01, a site sequence of 78 rings (Fig 7). This site sequence was then compared with a large number of relevant reference chronologies for oak indicating a consistent match when the date of its first ring is AD 1366 and of its last measured ring is AD 1443. The evidence for this dating is given by the *t*-values in Table 2.

At a least value of *t*=3.9, four samples matched each other and were combined at the relevant offset positions to form SPOLSQ02, a site sequence of 62 rings (Fig 8). This site sequence was then compared with the reference material where it was found to match at a first-ring date of AD 1384 and a last ring date of AD 1445. The evidence for this dating is given by the *t*-values in Table 3.

These two site sequence were then seen to match each other at the expected offsets at a value of *t*=3.90. A third and final site sequence, SPOLSQ03, of 80 rings was then constructed containing all six samples at the offsets shown in Figure 9. This site sequence was again compared against the reference chronologies where it was found to span the period AD 1366-1445. The evidence for this dating is given by the *t*-values in Table 4.

Attempts to date the remaining sample by comparing it individually against the reference chronologies proved unsuccessful and this sample remains undated.

Interpretation and Discussion

Analysis of seven samples taken from timbers of the roof at Springfield resulted in the construction and dating of a single site sequence.

Site sequence SPOLSQ03, of 80 rings, contains six samples and spans the period AD 1366-1445. Three of the samples contained within this site sequence have complete sapwood and a last ring date of AD 1445, the felling date of the timbers represented. A fourth sample, SPO-L05, was taken from a beam that had complete sapwood, however, *c* 2mm of sapwood was lost during the coring process. Taking into account the average width of the last intact 2mm of ring pattern on this sample it is possible to estimate that *c* 2 sapwood rings have been lost, which added to the last ring date of AD 1443 also gives this timber a felling date of *c* AD 1445. The heartwood/sapwood boundary ring date of a fifth sample, SPO-L09, is broadly contemporary with that of SPO-L01, SPO-L02, and SPO-L05 and, therefore, consistent with a felling date of AD 1445. The sixth sample, SPO-L04 does not have the heartwood/sapwood boundary ring but with a last measured ring date of AD 1425 it is possible that this sample was also from a tree felled in AD 1445.

Prior to the dendrochronological analysis being carried out Springfield was thought to date to some time in the fifteenth century. Tree-ring analysis has demonstrated that its roof is constructed from timbers felled in AD 1445.

Although the intra-site crossmatching is relatively low all dates have been checked by comparing each sample individually with the reference chronologies, where they can be found to match at the date indicated by site sequence SPOLSQ03.

The one measured sample that could not be dated, SPO-L07, demonstrates a major growth disturbance in the middle of its ring sequence pointing towards the tree represented having experienced some non-climatic growth conditions/stresses. This interruption in the tree's usual growth pattern is likely to have interfered with the matching against the reference material and is probably the reason for the Laboratory's inability to successfully date this sample.

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Table 1: Details of tree-ring samples from Springfield, Post Office Lane, South Chard, Somerset

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
SPO-L01	East principal rafter, truss 1	48	10C	1398	1435	1445
SPO-L02	West principal rafter, truss 1	46	10C	1400	1435	1445
SPO-L03	Collar, truss 1	NM	--	----	----	----
SPO-L04	East principal rafter, truss 2	60	--	1366	----	1425
SPO-L05	West principal rafter, truss 2	67	10c(+c2 lost)	1377	1433	1443
SPO-L06	Collar, truss 2	NM	--	----	----	----
SPO-L07	East principal rafter, truss 3	75	--	----	----	----
SPO-L08	West principal rafter, truss 3	60	20C	1386	1425	1445
SPO-L09	Collar, truss 3	54	01	1384	1436	1437
SPO-L10	West upper purlin, truss 2-3	NM	--	----	----	----
SPO-L11	East upper purlin, truss 3-4	NM	--	----	----	----

*NM = not measured
C = Complete sapwood on timber, last measured ring is the felling date
c = all or part lost in sampling (estimated number of rings lost)

Table 2: Results of the cross-matching of site sequence SPOLSQ01 and relevant reference chronologies when the first-ring date is AD 1366 and the last-ring date is AD 1443

Reference chronology	*t*-value	Span of chronology	Reference
Southern England and Wales	5.3	AD 1386-1585	Fletcher 1980
England, South West	6.0	AD 770-1833	Tyers pers comm
Ightfield Hall (barn), Shropshire	6.2	AD 1341-1566	Groves 1997
Clunbury Church, Shropshire	5.9	AD 1239-1494	Tyers and Groves 2000
107/8 High Street, Stourbridge, West Mids	5.7	AD 1389-1462	Esling *et al* 1989
Naas House, Lydney, Glos	5.5	AD 1373-1568	Howard *et al* 1998
Tusmore Granary, Tusmore Park, Bicester, Oxon	5.0	AD 1359-1545	Howard *et al* 1992
Mercers Hall, Gloucester, Glos	5.4	AD 1289-1541	Howard *et al* 1997a

Table 3: Results of the cross-matching of site sequence SPOLSQ02 and relevant reference chronologies when the first-ring date is AD 1384 and the last-ring date is AD 1445

Reference chronology	*t*-value	Span of chronology	Reference
England, West Midlands	4.8	AD 860-1790	Tyers pers comm
England, South West	5.2	AD 770-1833	Tyers pers comm
Cathedral Barn, Hereford, Herefordshire	6.1	AD 1359-1491	Tyers *et al* 1997
Combermere Abbey, Cheshire	4.9	AD 1371-1564	Howard *et al* 2003
Cradley Village Hall, Herefordshire	5.1	AD 1347-1530	Miles and Worthington 2004
Mercers Hall, Gloucester, Gloucestershire	4.9	AD 1289-1541	Howard *et al* 1997a
Foresters Lodge, Upper Millichope, Shropshire	4.8	AD 1352-1450	Miles and Haddon-Reece 1995
Anne of Cleves House, Melton Mowbray, Leics	4.8	AD 1372-1479	Howard *et al* 1997b

Table 4: Results of the cross-matching of site sequence SPOLSQ03 and relevant reference chronologies when the first-ring date is AD 1366 and the last-ring date is AD 1445

Reference chronology	*t*-value	Span of chronology	Reference
England, West Midlands	5.3	AD 860-1790	Tyers pers comm
England, South West	6.2	AD 770-1833	Tyers pers comm
Cottage Farm, Easthope, Shropshire	7.0	AD 1308-1454	Miles and Haddon-Reece 1994
Ightfield Hall (barn), Shropshire	6.4	AD 1341-1566	Groves 1997
Combermere Abbey, Cheshire	6.2	AD 1371-1564	Howard *et al* 2003
Clunbury Church, Shropshire	6.0	AD 1239-1494	Tyers and Groves 2000
Cradley Village Hall, Herefordshire	5.9	AD 1347-1530	Miles and Worthington 2004
Broomham, Kings Nympton, Devon	5.8	AD 1370-1464	Tyers *et al* 1997

Figure 1: Map to show South Chard and the general location of Springfield

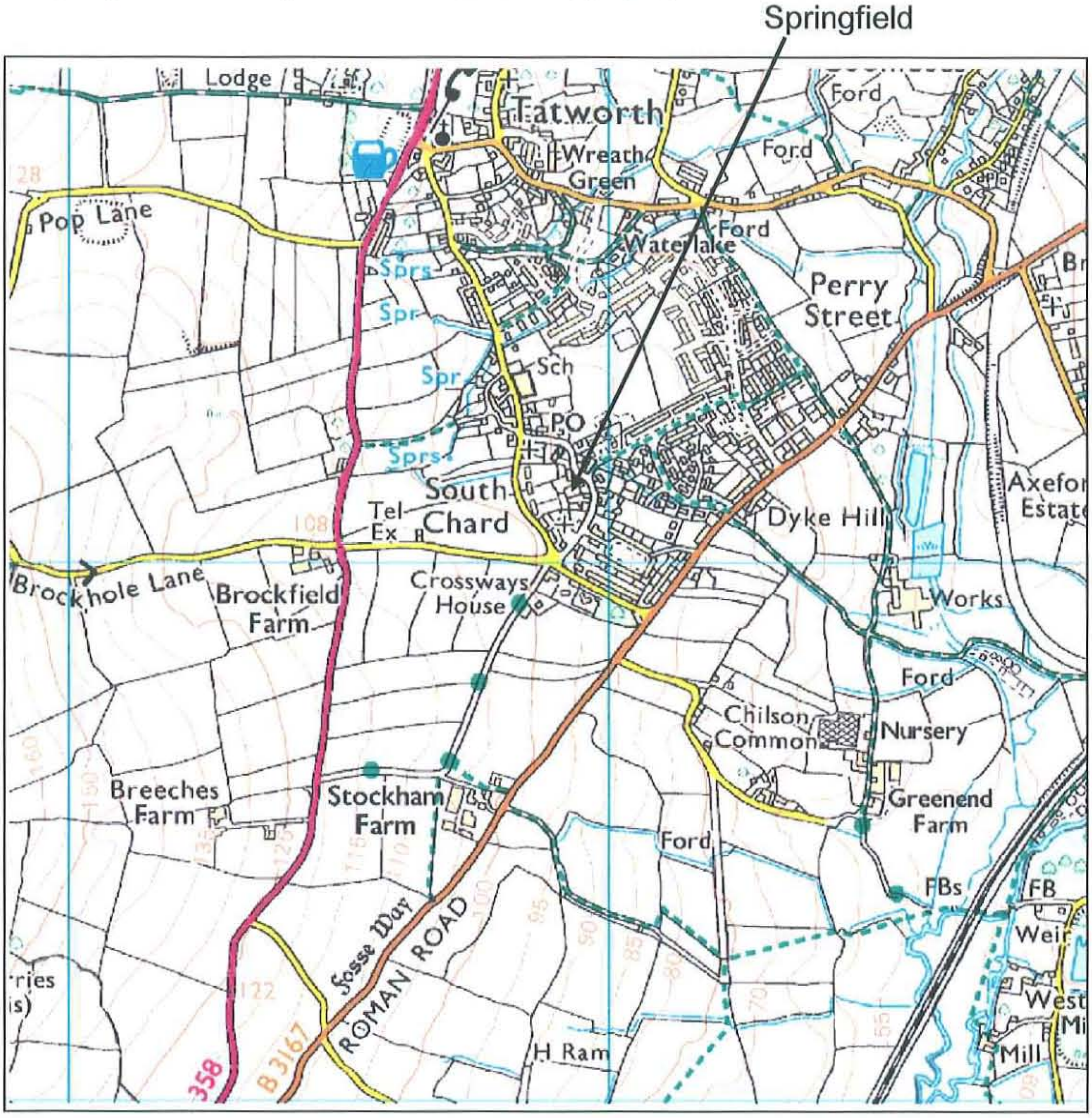


Figure 2: Ground-floor plan (drawn by John Dallimore)

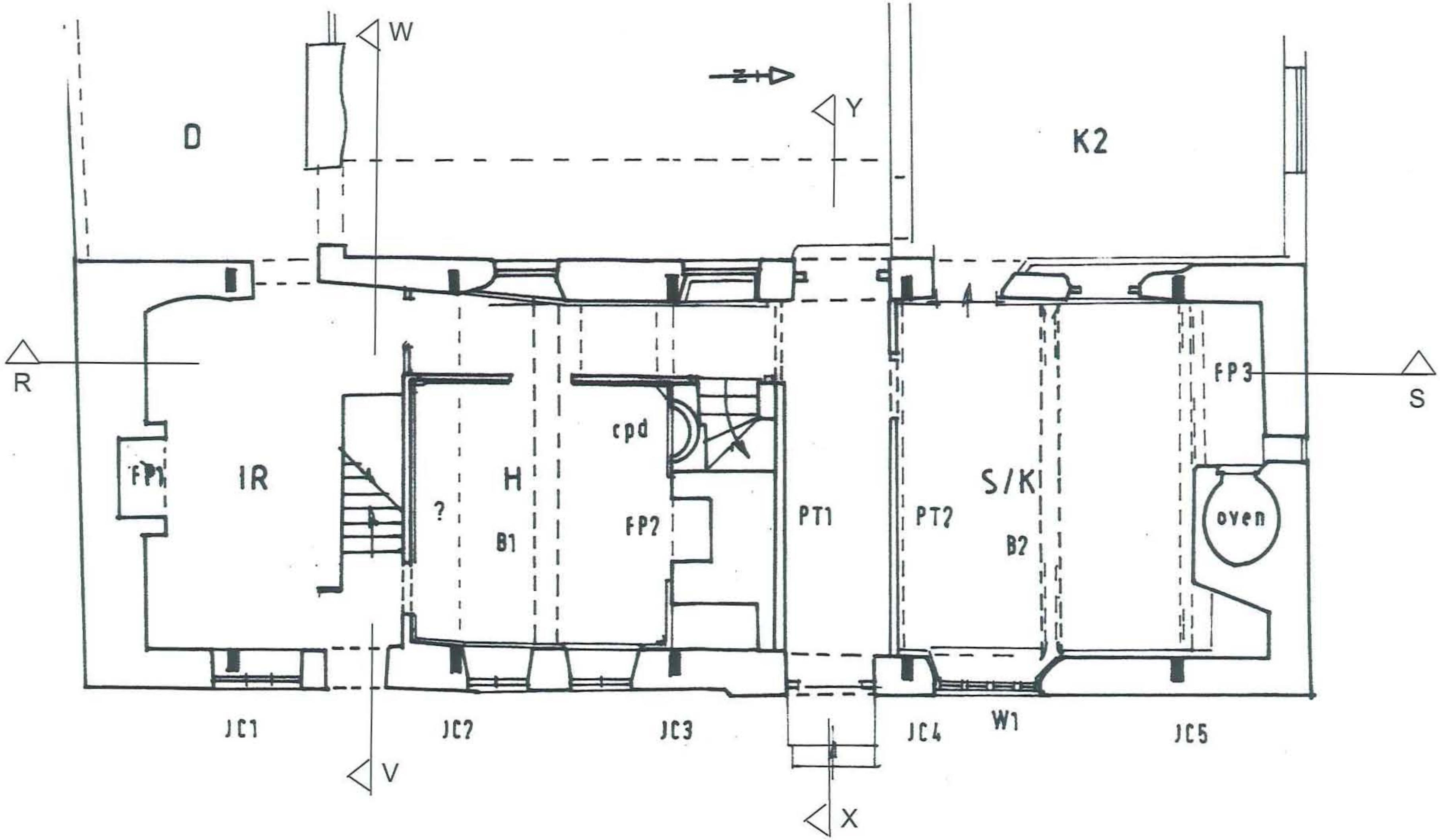
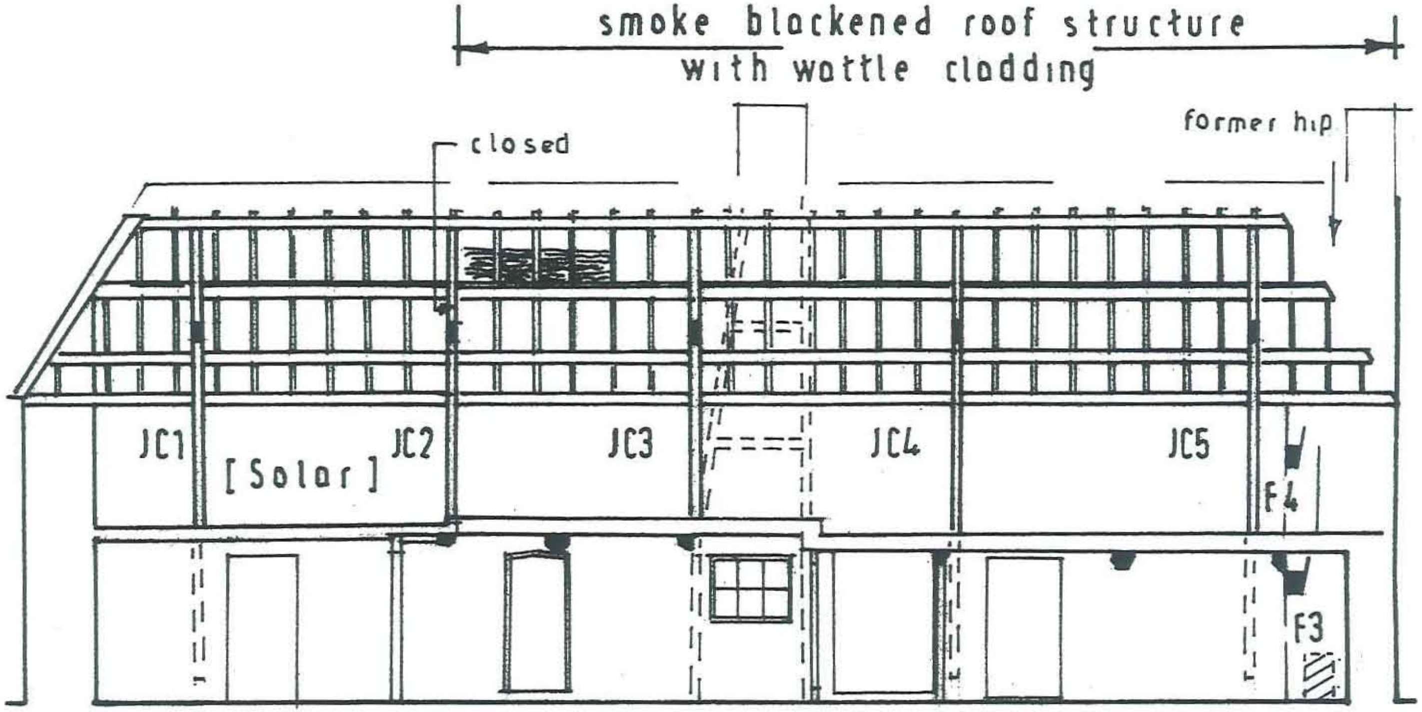


Figure 3: Long Section R-S (drawn by John Dallimore)



long. section R-S

Figure 4: Section V-W (Truss 1), showing the location of samples SPO-L01-03, (drawn by John Dallimore)

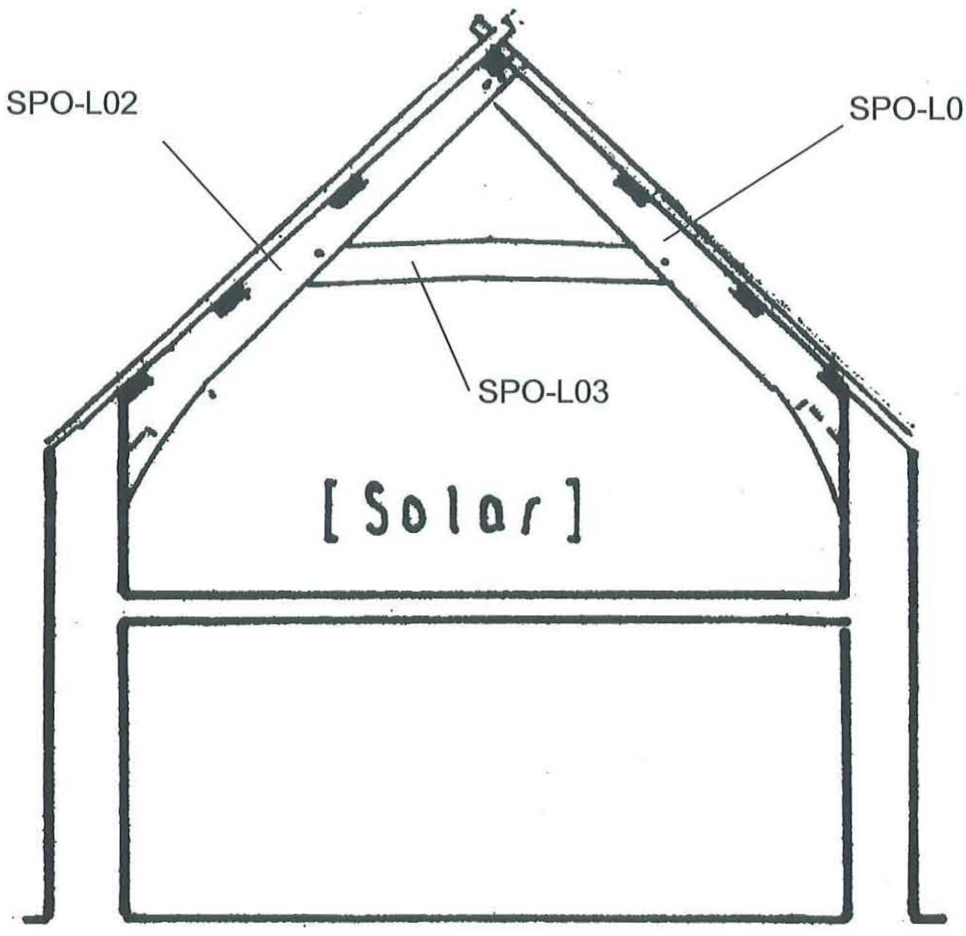


Figure 5: Truss 2, showing the location of samples SPO-L04-06 and SPO-L10 (after John Dallimore)

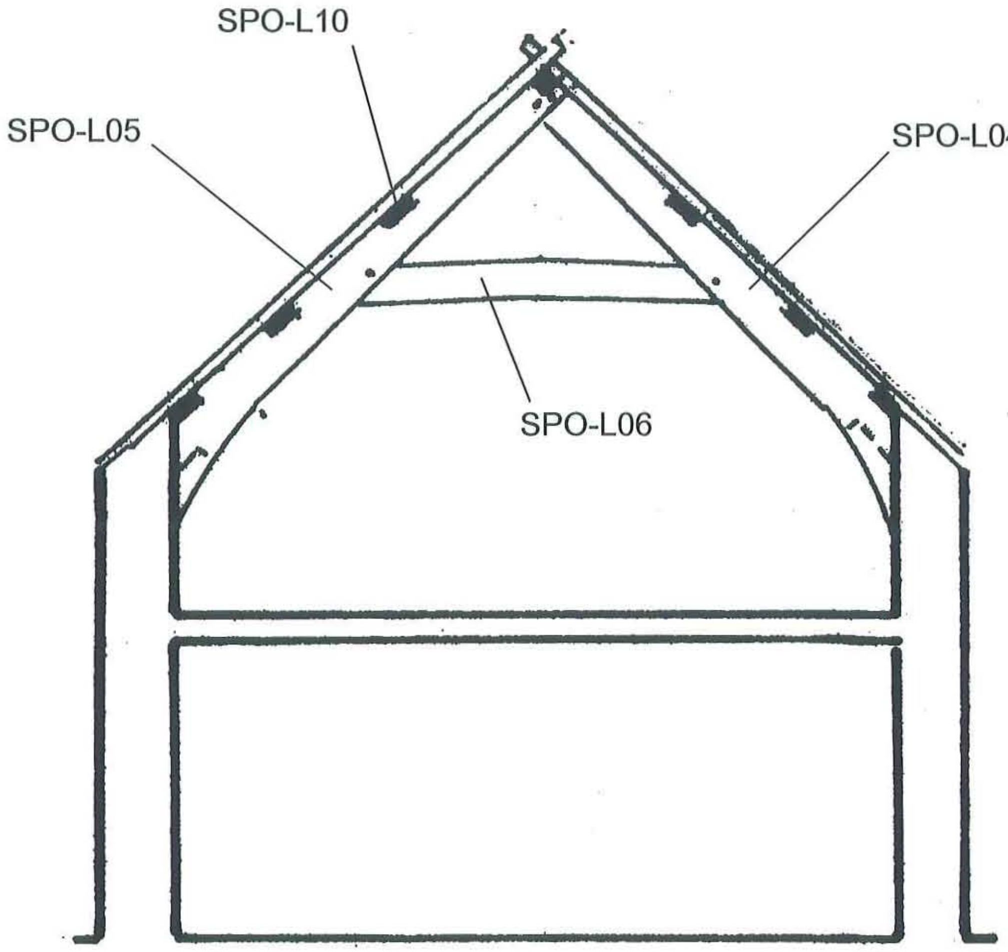


Figure 6: Section X-Y, showing the location of samples SPO-L07-09, and SPO-L11 (Truss 3; drawn by John Dallimore, after R Gilson)

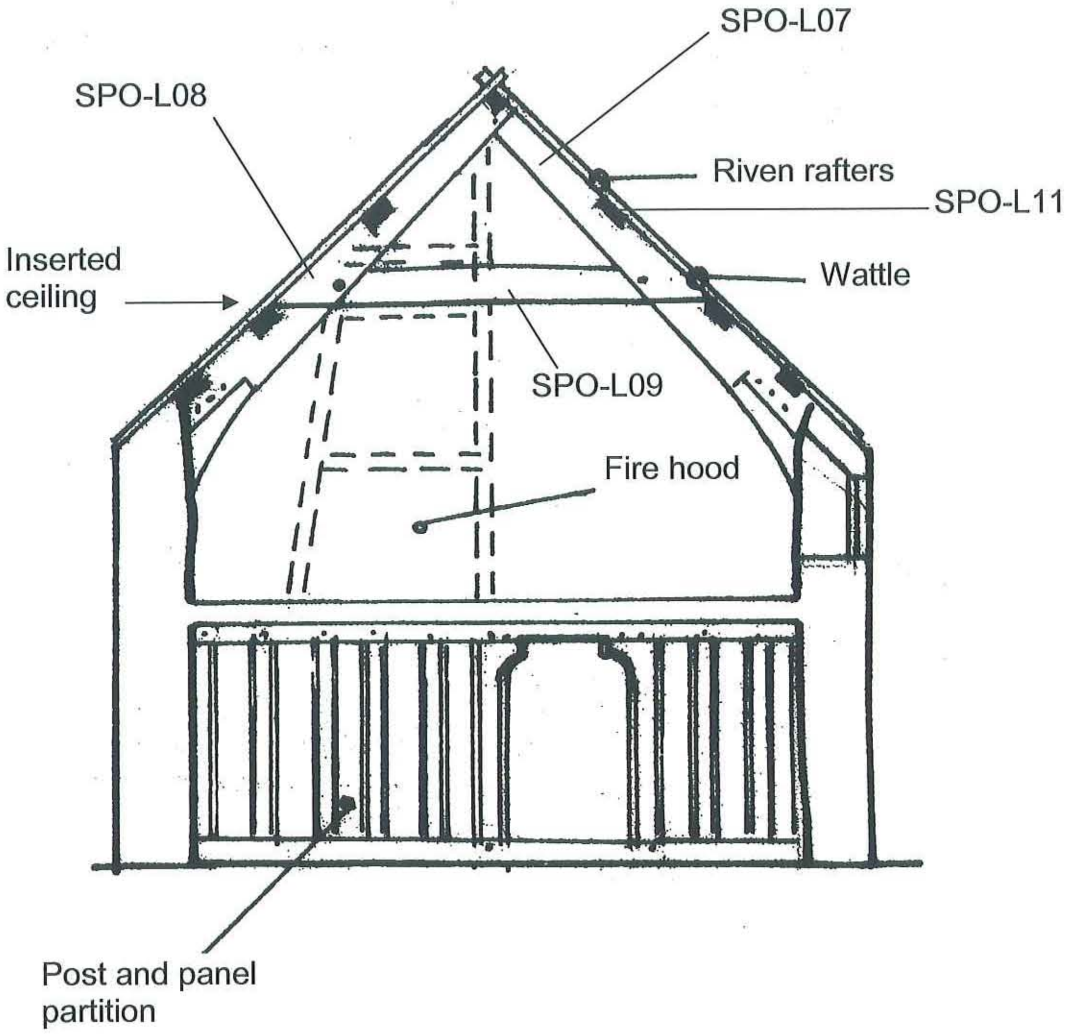
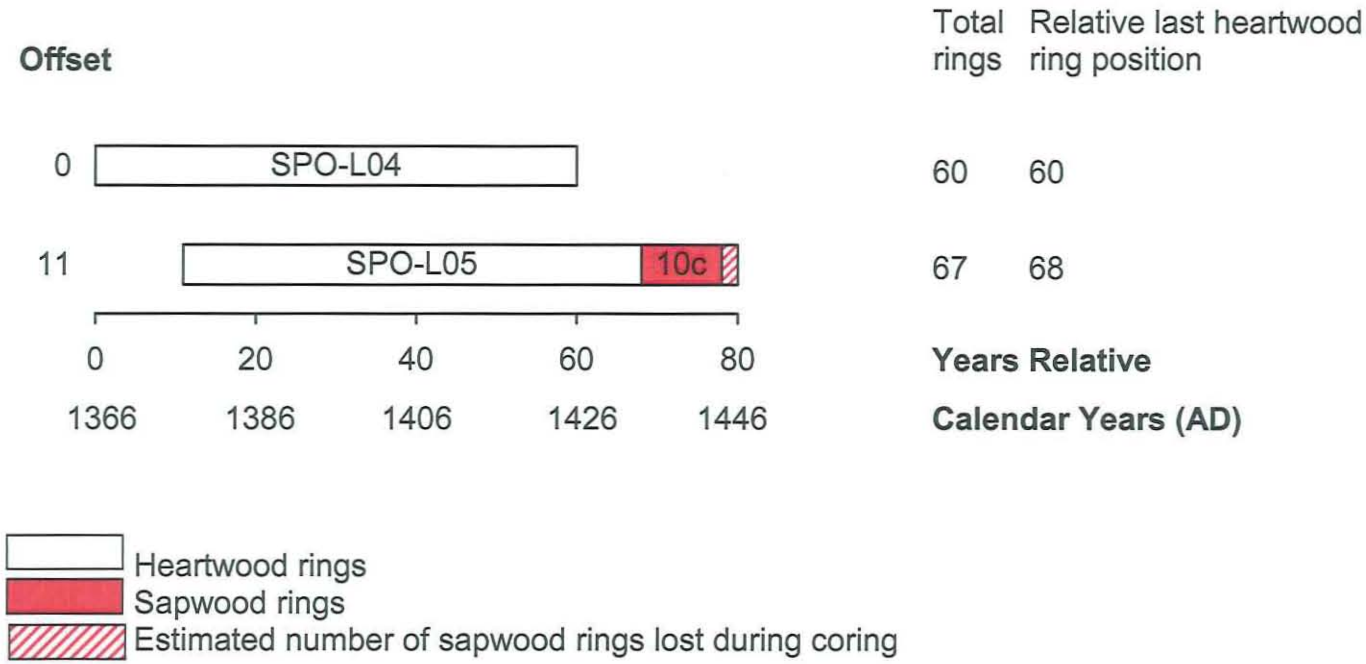
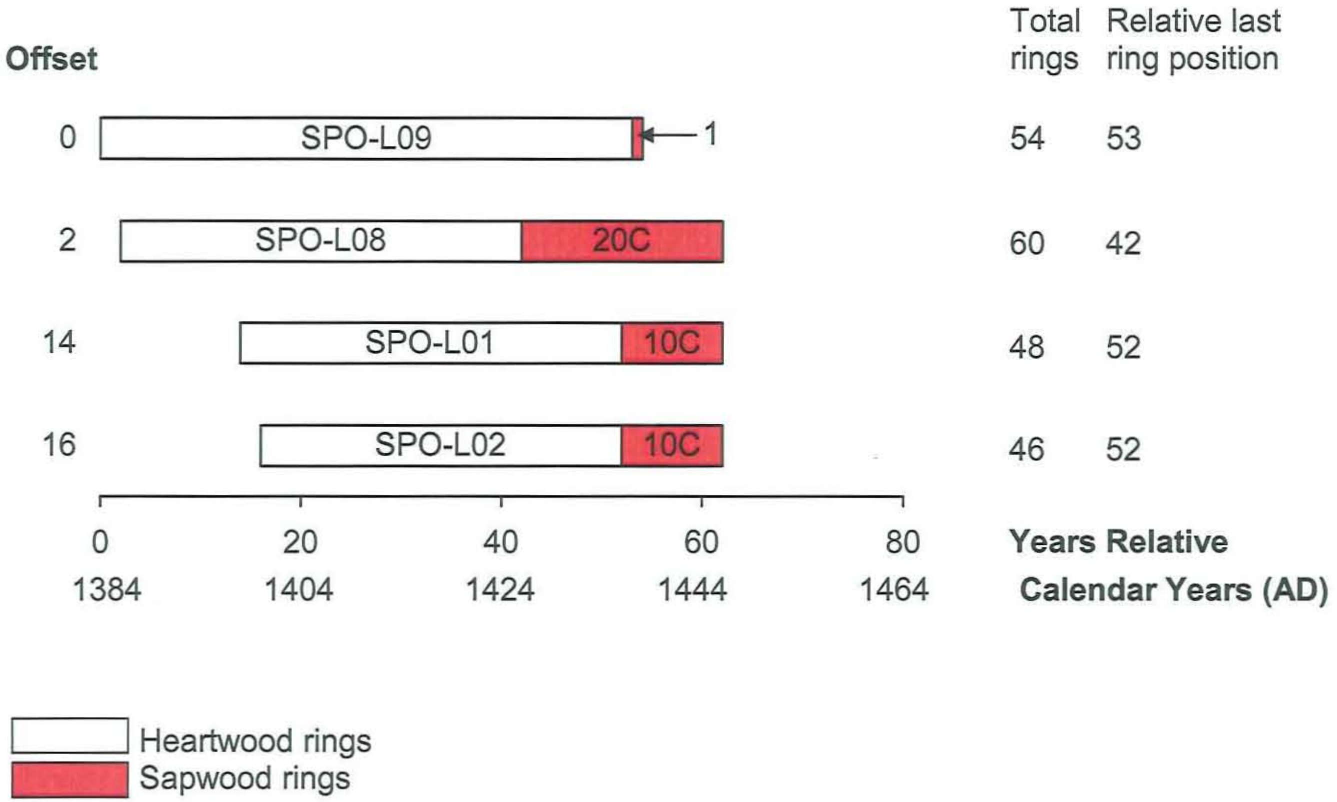


Figure 7: Bar diagram of samples in site sequence SPOLSQ01



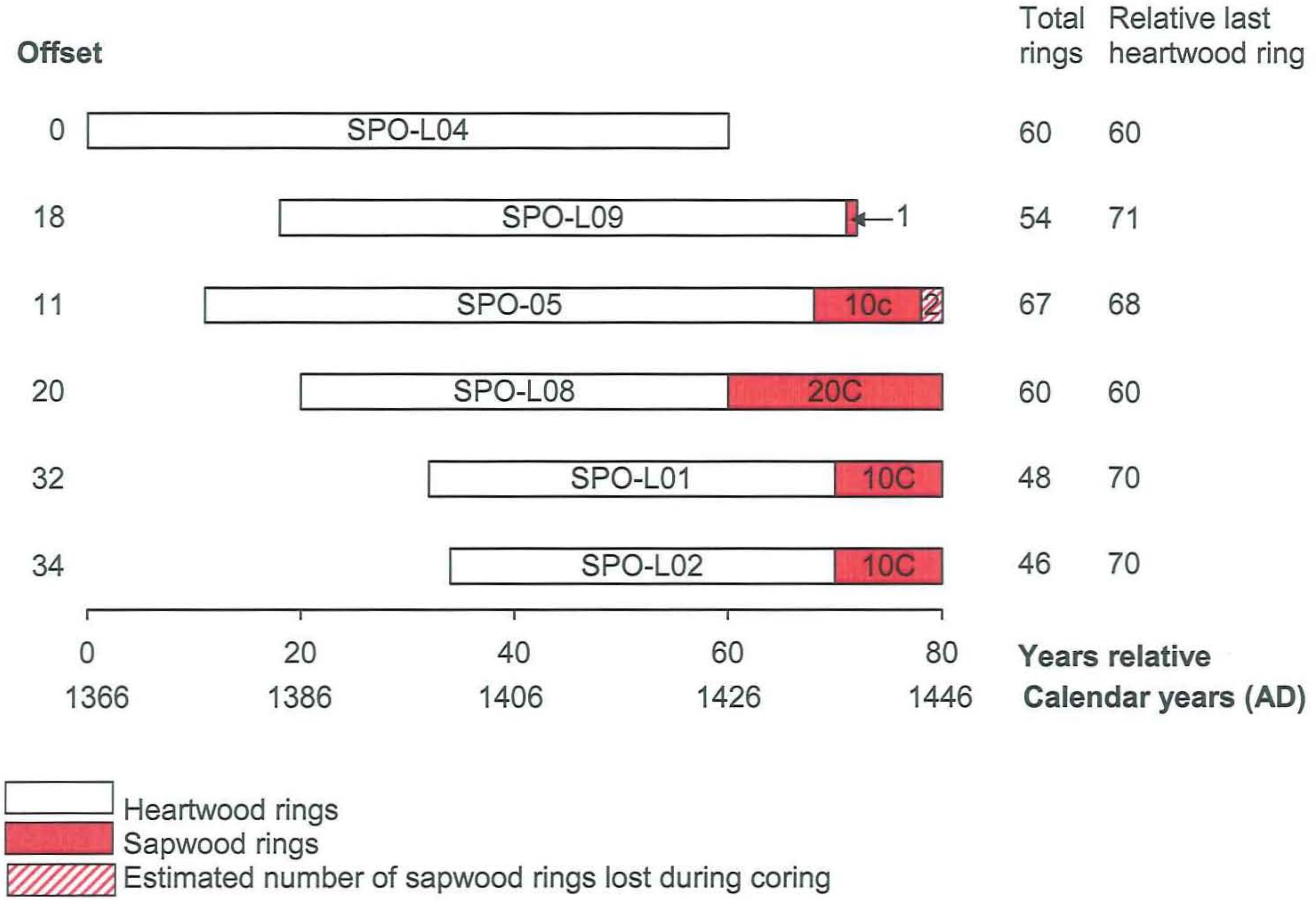
c = complete sapwood on timber, part lost in sampling

Figure 8: Bar diagram of samples in site sequence SPOLSQ02



C = complete sapwood on timber, last ring is the felling date

Figure 9: Bar diagram of samples in site sequence SPOLSQ03



C = complete sapwood on sample, last measured ring is the felling date; c = complete sapwood on timber, part lost in sampling

Data of measured samples – measurements in 0.01mm units

SPO-L01A 48
292 438 509 439 383 408 504 613 618 328 330 415 350 316 432 563 401 425 495 417
279 354 487 324 368 509 457 317 239 168 205 172 332 433 383 419 323 602 340 422
386 281 406 445 521 489 416 354
SPO-L01B 48
202 459 506 441 359 420 485 609 585 358 366 400 346 294 451 550 378 436 499 416
271 363 484 324 383 528 448 313 230 174 220 179 327 435 400 404 342 602 351 419
374 296 399 464 499 502 409 344
SPO-L02A 46
439 561 370 641 626 814 891 719 577 646 446 422 497 628 432 591 583 629 540 410
534 397 499 589 437 404 274 212 337 279 396 558 657 524 439 668 538 164 133 112
194 164 198 201 163 143
SPO-L02B 46
443 553 360 648 682 829 856 732 629 632 442 423 496 633 437 588 593 626 463 405
559 458 475 630 609 328 275 247 273 251 389 567 671 554 468 687 549 166 136 97
185 160 200 187 154 161
SPO-L04A 60
210 359 419 389 173 235 306 279 413 260 297 350 355 348 278 215 229 253 222 169
319 217 251 247 199 307 206 271 228 314 288 268 325 342 290 369 277 304 510 345
254 220 234 261 264 265 325 281 316 244 201 223 179 161 318 246 183 356 286 305
SPO-L04B 60
225 358 414 410 181 237 303 271 361 264 296 345 334 345 294 221 240 260 223 178
306 234 242 232 221 291 213 274 218 304 296 270 320 337 294 385 273 290 502 360
243 214 235 265 263 252 309 270 301 272 192 219 189 170 323 258 166 356 270 331
SPO-L05A 67
361 348 308 259 230 289 255 264 187 243 176 272 235 199 250 163 215 200 362 362
297 289 283 253 281 182 198 234 220 170 139 185 223 170 188 257 203 245 224 213
212 221 175 297 269 219 225 264 299 274 194 226 180 199 213 262 172 198 244 211
198 182 177 279 278 187 285
SPO-L05B 67
350 327 314 279 227 287 253 266 188 238 172 280 186 198 312 166 218 202 335 359
307 285 289 252 294 173 216 235 216 168 144 185 219 166 195 265 193 247 228 219
213 216 181 279 266 226 220 255 281 280 221 220 192 187 197 249 175 200 252 213
207 186 153 282 276 188 286
SPO-L07A 75
169 144 85 288 419 256 243 313 360 273 156 250 418 345 358 479 419 406 303 344
471 561 543 491 301 271 356 431 412 312 155 164 167 345 352 486 612 193 49 39
43 44 44 38 44 79 90 82 113 228 356 272 345 404 553 637 242 200 118 178
169 185 196 177 345 451 335 340 450 369 280 253 334 358 268
SPO-L07B 75
138 142 95 284 429 260 247 292 355 290 140 226 375 346 350 476 429 437 312 338
473 540 545 494 304 267 356 428 396 292 169 153 165 341 357 556 583 189 55 53
39 45 28 37 43 74 81 89 104 225 368 286 346 391 548 618 237 204 124 207
220 197 212 208 290 468 303 346 454 339 253 270 307 400 272
SPO-L08A 60
83 103 89 121 166 298 154 110 149 174 217 208 249 416 384 346 188 199 246 265
403 297 291 294 237 199 257 231 313 308 265 225 171 138 267 199 186 339 394 338
192 129 176 156 195 246 280 192 186 269 219 240 211 146 142 224 221 224 248 241

SPO-L08B 60

77 117 124 123 176 264 150 113 160 156 224 207 247 407 398 363 205 188 236 281
388 304 298 277 233 202 251 273 313 311 261 219 169 132 261 192 186 326 421 339
202 126 175 152 191 249 288 198 201 274 226 247 191 157 144 241 190 229 247 256

SPO-L09A 54

78 126 133 76 38 59 167 223 117 137 142 227 278 323 354 386 313 465 374 442
388 346 411 342 298 384 294 211 210 308 228 249 387 200 163 129 260 262 294 488
514 499 353 189 377 318 355 262 263 174 209 314 182 121

SPO-L09B 54

89 125 120 79 36 65 168 232 114 139 149 231 282 318 345 395 311 458 400 428
384 347 425 332 319 372 284 211 268 283 230 250 371 208 164 125 259 262 292 496
507 519 367 195 365 330 355 263 262 191 210 289 191 120

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 Building*' (Laxton and Litton 1988) and, *Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). 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 Figure 1 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 for oaks, 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 oak 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 or soon after. 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 the timbers in a building are inspected 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 – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood 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.

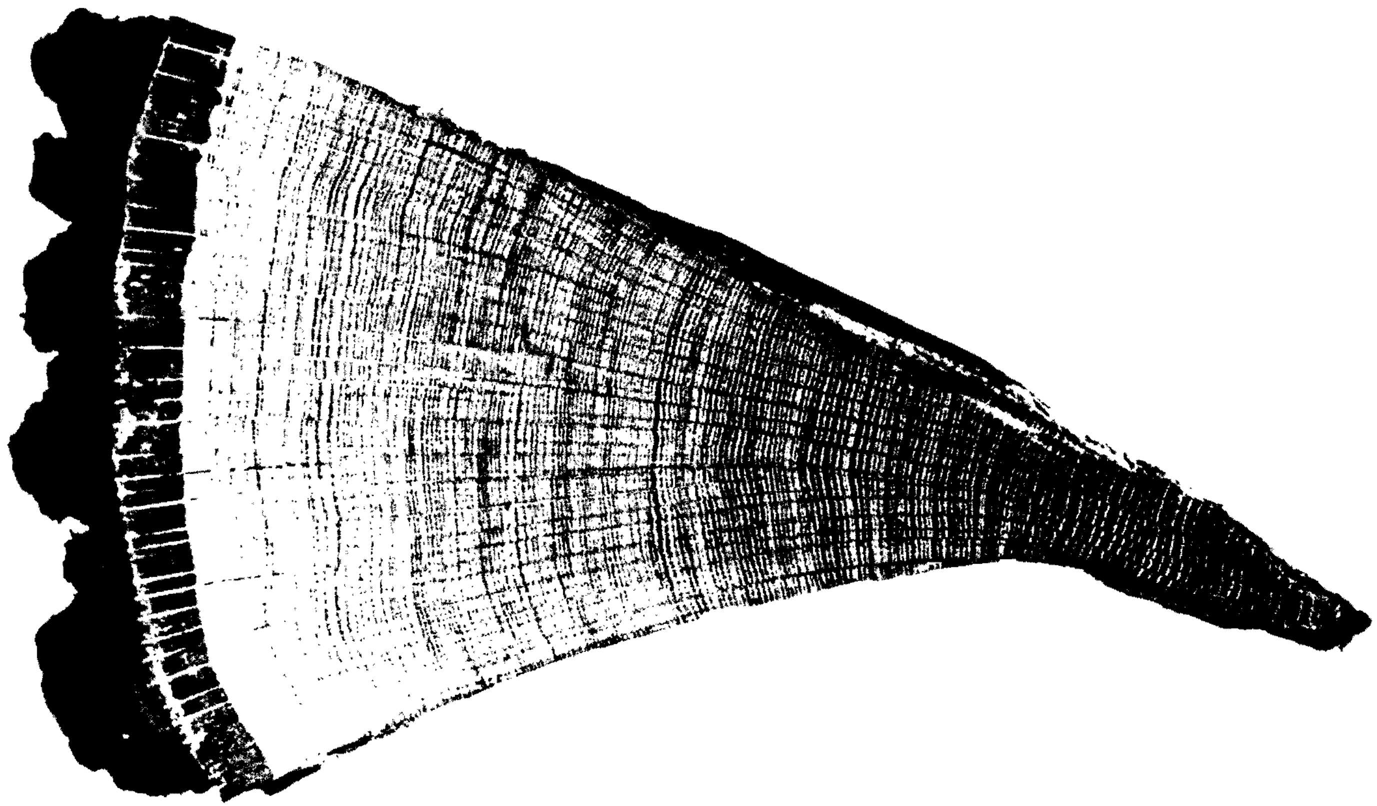


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

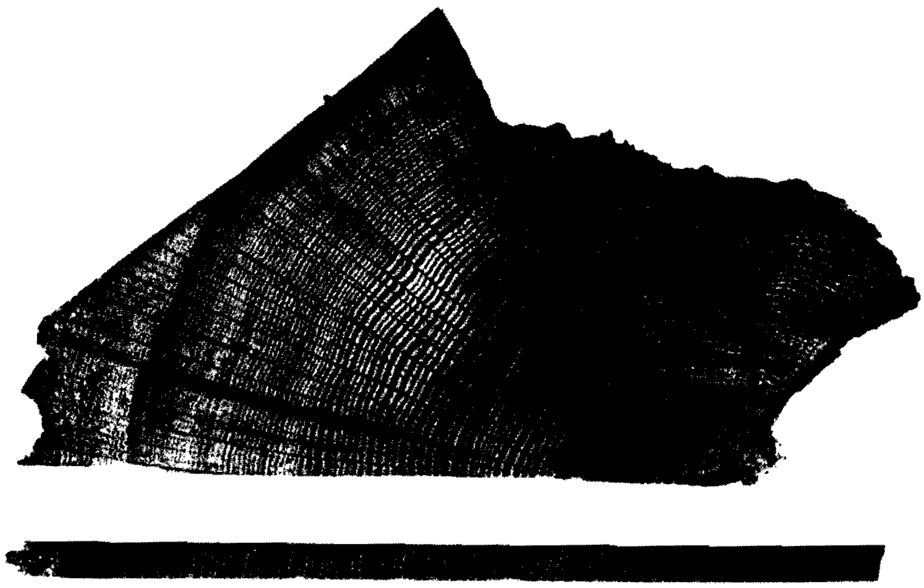


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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 measure 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.

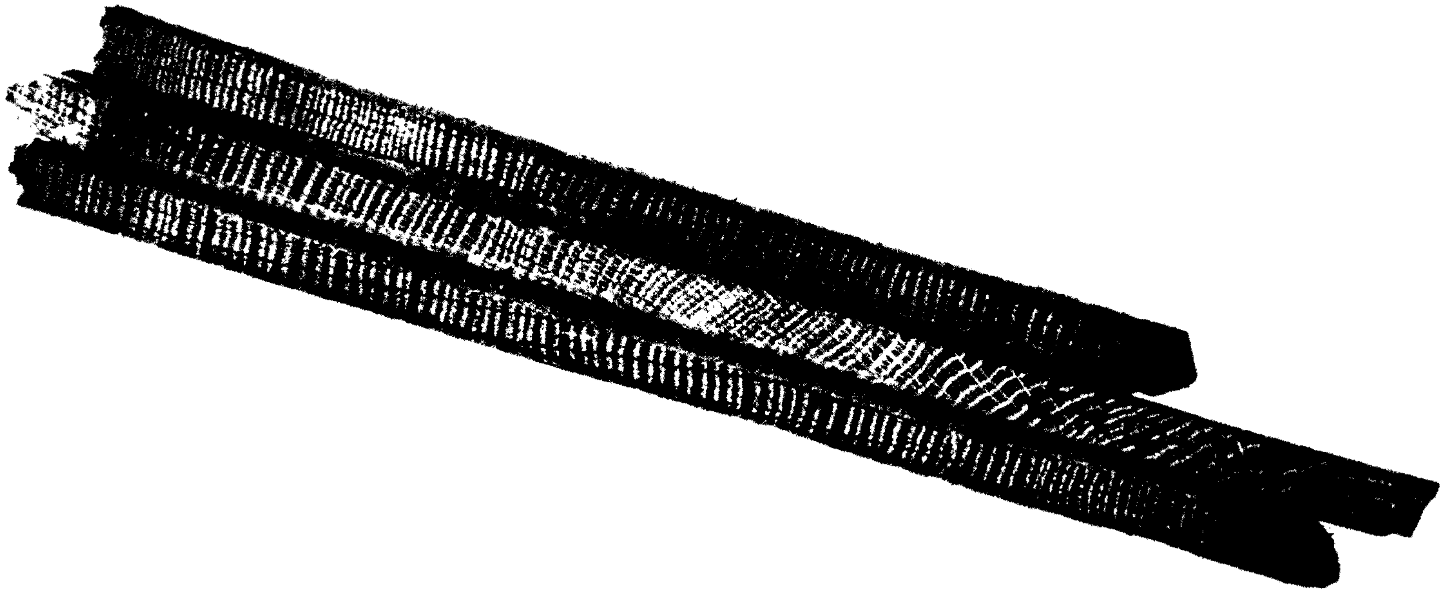


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

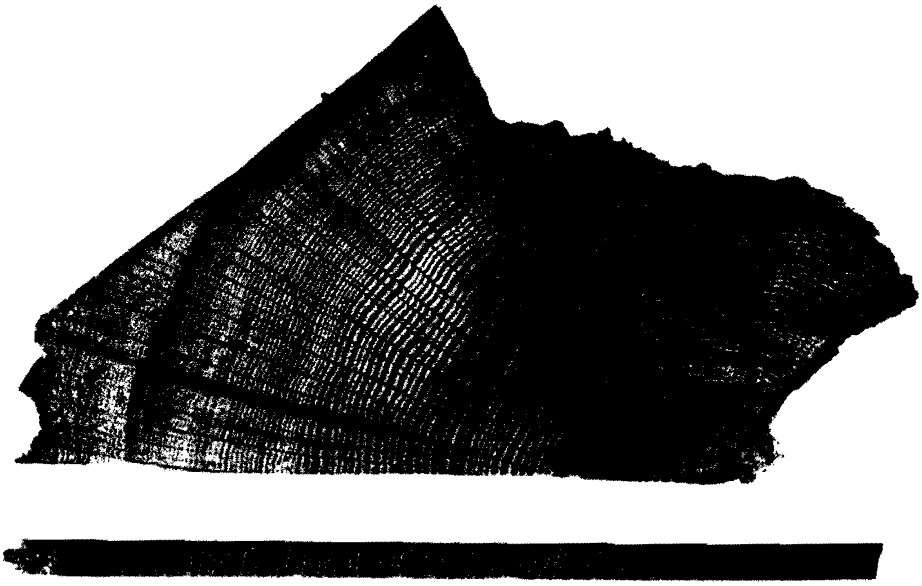


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Fig. 3 Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure twice to ensure that an error has not been made. This type of apparatus is needed to process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

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 in coring. 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 inspection 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's dendrochronologists are insured.

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 at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; 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 the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, 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 found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width 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 of the 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. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence

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The 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'. It is a modification of the straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. ***Estimating the Felling Date***. As mentioned above, 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, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows. 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 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 so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. (Oak boards quite often come from the Baltic and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56)).

Even 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 but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, 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 35 years later we would have estimated without this observation. In the example, the felling is now estimated to *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

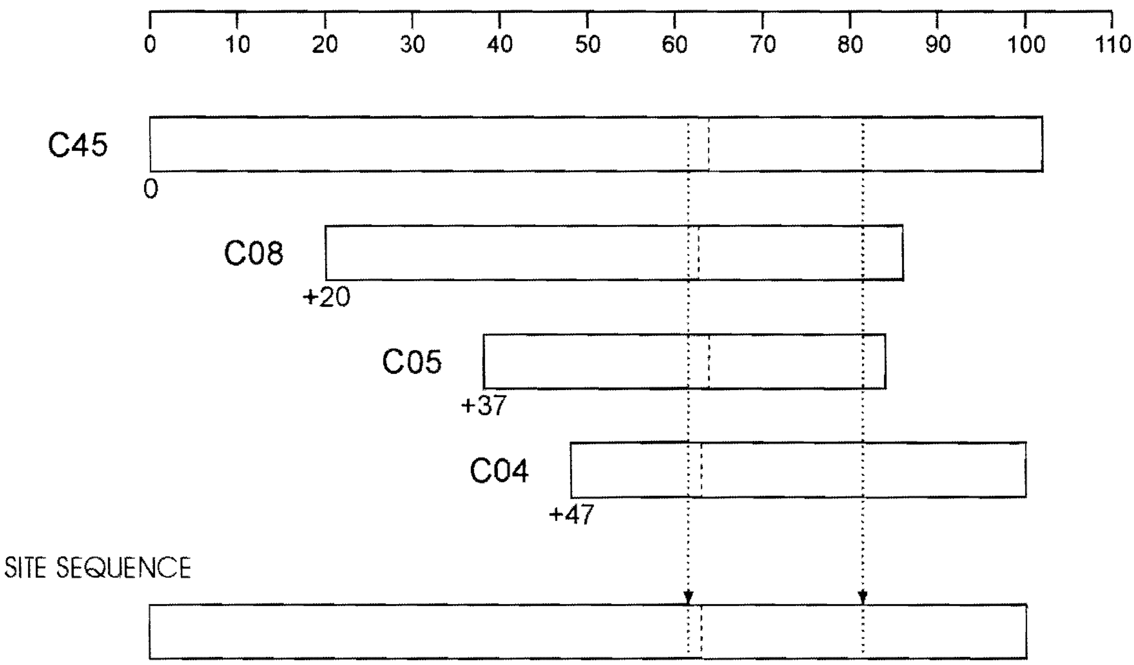


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction***. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made 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 (1988), 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* 1988). 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 (1988) 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 of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomena can be observed in the lower sequence of (a) 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 corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

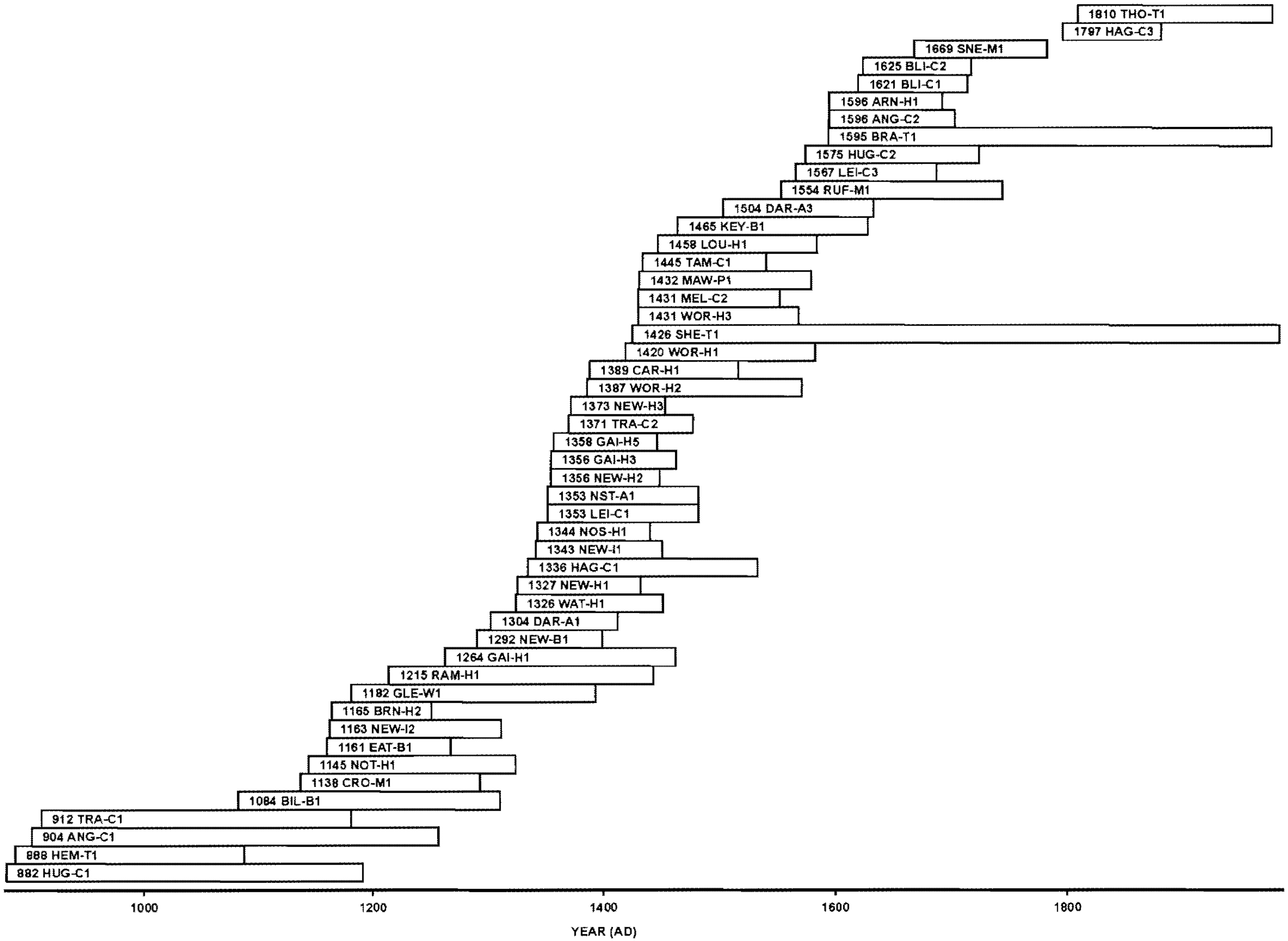
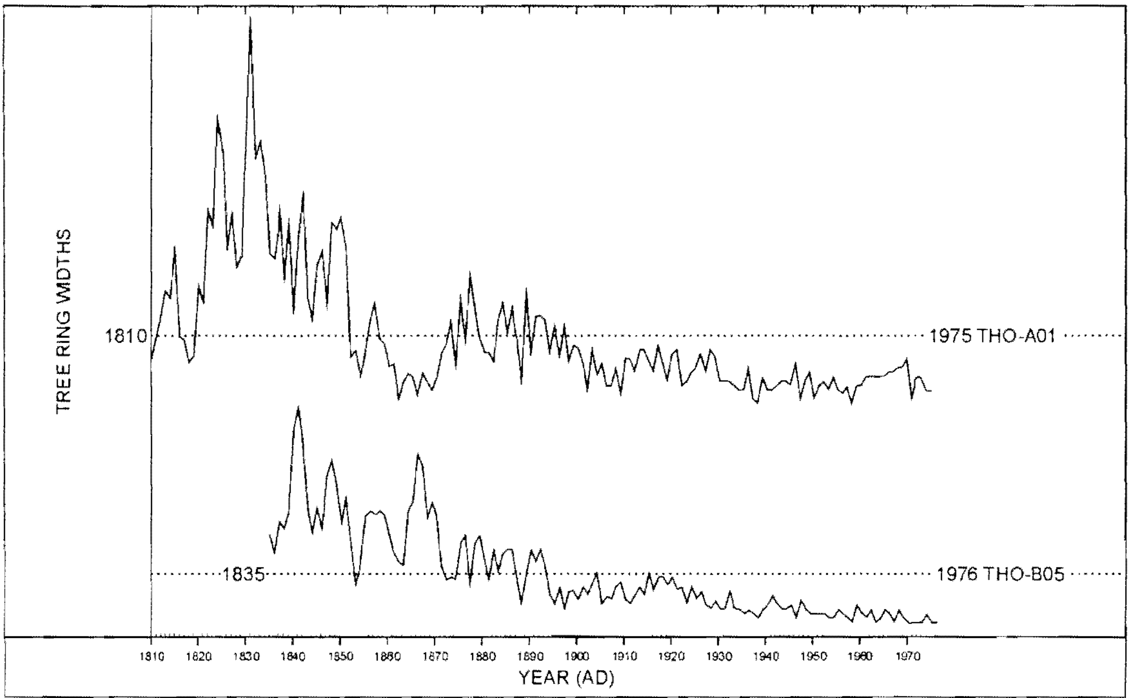


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

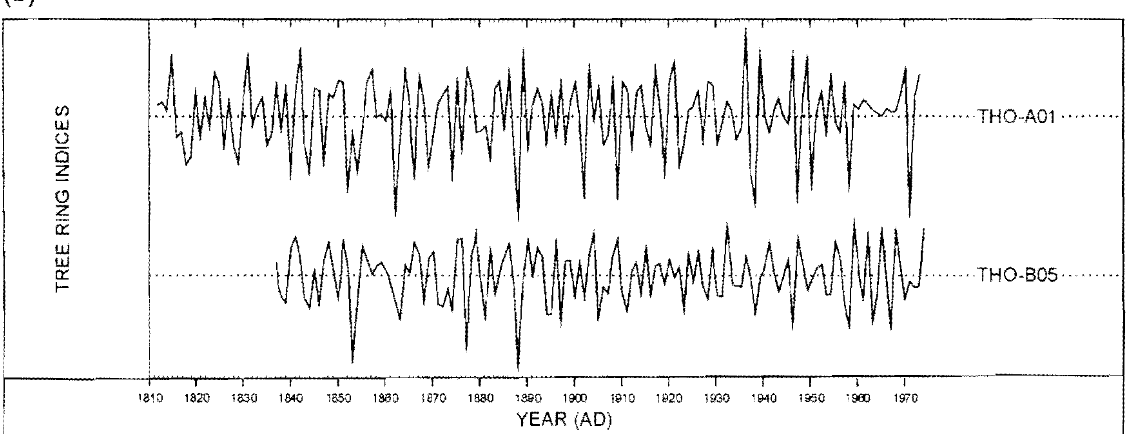


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

Fig 7. (b) The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

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