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31 High Street, Droitwich, Worcestershire

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

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31 HIGH STREET, DROITWICH, WORCESTERSHIRE

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SUMMARY

Dendrochronological analysis was undertaken on six of the 15 core samples obtained from both roof and ground-floor timbers of 31 High Street, Droitwich, nine samples having too few rings for dating. This analysis produced a single site chronology comprising two samples, both of them from posts of the screens passage. Although this site chronology, with an overall length of 48 rings, cannot be dated, it is highly likely that the two timbers are coeval. Interpretation of the sapwood on one individually dated sample would suggest that the timber, a purlin, was felled at some point between AD1403–28. Three measured samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Steven and Jo Bond, the owners of 31 High Street, for their enthusiasm and help with this programme of analysis and for their cooperation in arranging sampling. We would also like to thank the tenants of the premises for cooperating with sampling. The Laboratory would also like to thank Nick Joyce Architects for providing information on the history and development of the site used in the introduction below, and for the use of their plans and drawings. Finally we would like to thank Shahina Farid and Cathy Tyers, English Heritage Scientific Dating Team, for commissioning this programme of tree-ring dating, and for providing information and advice throughout this analysis.

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CONTENTS

INTRODUCTION

The Grade II* listed medieval timber town house comprising 31–35 High Street, Droitwich (Figs 1a/b and 2a/b), is currently on the Heritage At Risk register. The building, which is now divided into three separate premises, has undergone alteration and addition in the seventeenth, eighteenth, nineteenth, and twentieth centuries, but is believed on stylistic evidence to originally date from the period around AD 1400.

The property under consideration in this report, 31 High Street, is the solar wing of the fourteenth-century hall house, its street facing gabled wing also including the cross passage. An extension to the north was added in the seventeenth century and largely rebuilt in the nineteenth century. A scheme of renovation was also undertaken to the external elevations fronting High Street in the early nineteenth century, which contributes to the buildings' current external rendered appearance.

At the street frontage at first-floor level there is a large, tripartite, sash window, and at ground-floor level there is a round-headed doorway to the cross passage. There is internal evidence that the first floor was formerly jettied and that the ground floor has been underbuilt in brick. Despite the many changes to the building, the timber frame of the solar wing is complete in all its essential details and the central truss and structural timbers of the hall range are also intact, as is the outer form of the eastern end.

SAMPLING

The owners of 31 High Street have permission for conservation and conversion works and hence a dendrochronological survey was requested by Sarah Lewis (English Heritage, Principal Adviser Heritage at Risk) to obtain, if possible, independent dating evidence for the primary construction of the timber framing to inform listed building consent and to provide for the future protection of this early town house.

The assessment of dendrochronological potential undertaken prior to sampling concluded that the timbers were of borderline suitability but given the potential significance of this early hall house the decision was taken, following discussion, to proceed with sampling. Thus, from the timbers available at ground first-floor, and roof level a total of 15 samples was obtained by coring. Each sample was given the code DTW-A (for Droitwich, site 'A') and numbered 01–15 (Table 1). Six samples, DTW-A01–A06, were obtained from the roof, with a further nine samples, DTW-A07–A15, being obtained from the screens passage timbers and ground-floor ceiling beams.

There are other timbers which could potentially be sampled, for example, those to roof trusses 1 and 2, which are currently only accessible via small and potentially unsafe holes in walls or ceilings. Sampling was also restricted by the nature of the premises as a popular and busy computing and electrical shop and its use as domestic residence. This led to sampling being somewhat restricted and also meant that the timbers that were sampled were not necessarily cored at the optimum position or angle to maximise the number of rings which was of particular importance with such an assemblage that was considered borderline during the assessment.

Where possible, the locations of these samples were recorded at the time of sampling on both plans made by Nick Joyce Architects and provided by English Heritage, as well as by photographic record, these being shown as Figures 3a–4d. Details of the samples are given in Table 1. In this table the trusses and other timbers have been numbered from north to south, with individual timbers then being further identified on an east–west basis as appropriate.

ANALYSIS AND RESULTS

Each of the 15 samples obtained from 31 High Street was prepared by sanding and polishing. It was seen at this time that no less than nine samples, from both the roof and ground-floor timbers, had less than the 40 rings deemed necessary for possible dating and were rejected from this programme of analysis. The annual growth ring widths of the remaining six samples were measured, the data of these measurements being given at the end of this report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing a single group comprising two samples to be formed, the samples cross-matching with each other as shown in Figure 5. The two samples were combined at their indicated offset positions to form site chronology DTWASQ01, this having an overall length of 48 rings.

Site chronology DTWASQ01 was then compared to an extensive corpus of reference material for oak held not only by the Nottingham Laboratory but also by other institutions, but there was no satisfactory cross-matching. This site chronology must therefore remain undated.

The four remaining measured but ungrouped single samples were then compared individually to the full corpus of reference data. This comparative process indicated a cross-match for sample DTW-A04 alone, when the date of its first ring is AD 1321 and the date of its last ring is AD 1396. The evidence for this dating is given in Table 2.

INTERPRETATION AND CONCLUSION

Dating evidence

Analysis by dendrochronology of the timbers of 31 High Street has produced a single site chronology comprising two samples, DTW-A09 and A10, both from posts of the screens passage. This site chronology cannot be dated. However, although undated, the fact that the two samples cross-match with each other, and that they have a heartwood/sapwood boundary at virtually the same relative position, does show that the timbers are coeval. Indeed, given that they cross-match with a value of t=9.7 it is probable that the timbers are derived from two trees growing close to each other in the same woodland, or possibly even derived from a single tree.

Another sample, DTW-A04, from the lower west purlin to bay 3, has been dated, its 76 rings spanning AD 1321–96. This sample does not retain complete sapwood (the last ring produced by the tree before it was cut down), and it is thus not possible to determine the precise felling date with reliability. The sample does, though, retain the heartwood/sapwood boundary, this being dated to AD 1388. Using the usual 95% confidence interval range of 15–40 sapwood rings would thus give the timber an estimated felling date in the range AD 1403–28.

Woodland source

Although of limited data in being a singleton, despite being compared with reference chronologies from all parts of England, the highest levels of similarity for sample DTW-A04 are found predominantly with other sites in the south-west Midlands. This suggests that the timber used in the construction of 31 High Street is from a relatively local woodland source.

Unmatched samples

Three measured samples remain ungrouped and undated. As may be seen from Table 1, although one of these samples, DTW-A02, has 54 rings (the usual minimum requirement), the other two, DTW-A 14 and A15, have only 42 rings each. It is probable that the lack of cross-matching and dating is caused by them having such low numbers of rings. If better access becomes possible sometime in the future more extensive sampling may produce more samples with more rings and hence facilitate both cross-matching and dating.

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TABLES

Table 1: Details of tree-ring samples from 31 High Street, Droitwich Spa, Worcestershire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Roof timbers					
DTW-A01	West common rafter 4, bay 5 (from north)	nm	---	------	------	------
DTW-A02	Collar, truss 5	54	no h/s	------	------	------
DTW-A03	West archbrace, truss 5	nm	---	------	------	------
DTW-A04	West lower purlin, bay 5	76	8	1321	1388	1396
DTW-A05	East archbrace, truss 5	nm	---	------	------	------
DTW-A06	Collar, truss 3	nm	---	------	------	------
	Ground floor timbers					
DTW-A07	Screens passage post 4 (from north)	nm	---	------	------	------
DTW-A08	Screens passage post 3	nm	---	------	------	------
DTW-A09	Screens passage post 2	46	h/s	------	------	------
DTW-A10	Screens passage post 1	47	h/s	------	------	------
DTW-A11	Ground floor ceiling, common joist 4 (from east)	nm	---	------	------	------
DTW-A12	Ground floor ceiling, common joist 5	nm	---	------	------	------
DTW-A13	Ground floor ceiling, common joist 6	nm	---	------	------	------
DTW-A14	Screens passage ceiling beam at north end	42	h/s	------	------	------
DTW-A15	Ground floor, main ceiling cross-beam	42	h/s	------	------	------

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

nm = sample not measured

Table 2: Results of the cross-matching of sample DTW-A04 and relevant reference chronologies when the first-ring date is AD 1321 and the last-ring date is AD 1396

Reference chronology	Span of chronology	*t*-value	Reference
66/68 Westgate Street, Gloucester	AD 1209–1518	6.5	(Tyers and Wilson 2000)
Halesowen Abbey, Dudley, West Midlands	AD 1310–1535	6.2	(Arnold and Howard 2008)
Mercer's Hall, Mercer's Lane, Gloucester	AD 1289–1541	5.6	(Howard *et al* 1996)
Manor House, West Bromwich, West Midlands	AD 1318–1590	5.6	(Arnold and Howard 2009)
Bowhill, Exeter, Devon	AD 1292–1468	5.5	(Groves 2004)
Tusmore Granary, Tusmore Park, Bicester, Oxfordshire	AD 1359–1545	5.3	(Howard *et al* 1992)
Pedagogues' House, Stratford upon Avon, Warwickshire	AD 1305–1403	5.2	(Arnold and Howard 2006)
Upwich 2, Droitwich, Hereford and Worcester	AD 946–1415	5.3	(Groves and Hillam 1997)
Tithe Barn, Ashleworth, Gloucestershire	AD 1319–1475	5.3	(Bridge 2002)

FIGURES

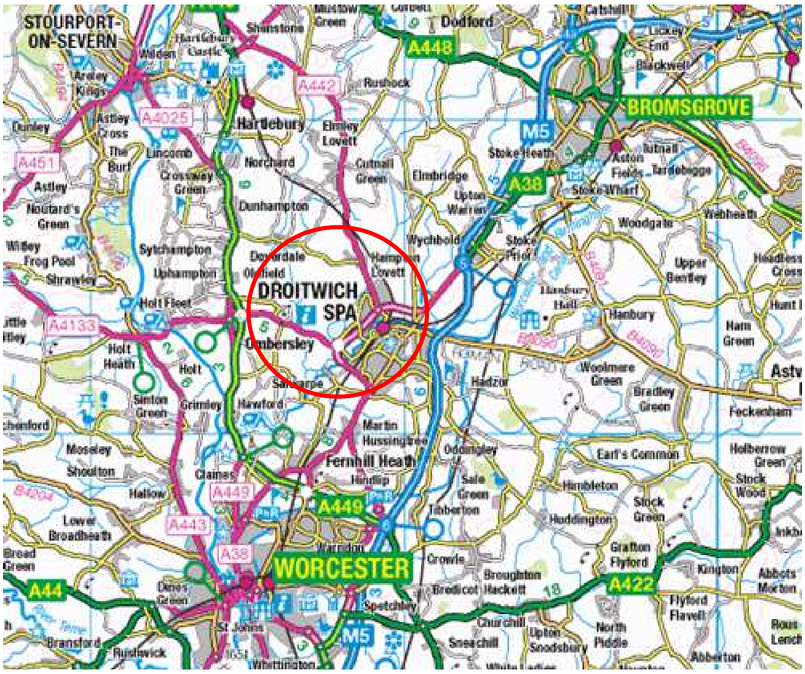


Figure 1a: Map to show the location of Droitwich. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

Figure 1b: Map to show the location of 31–35 High Street. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

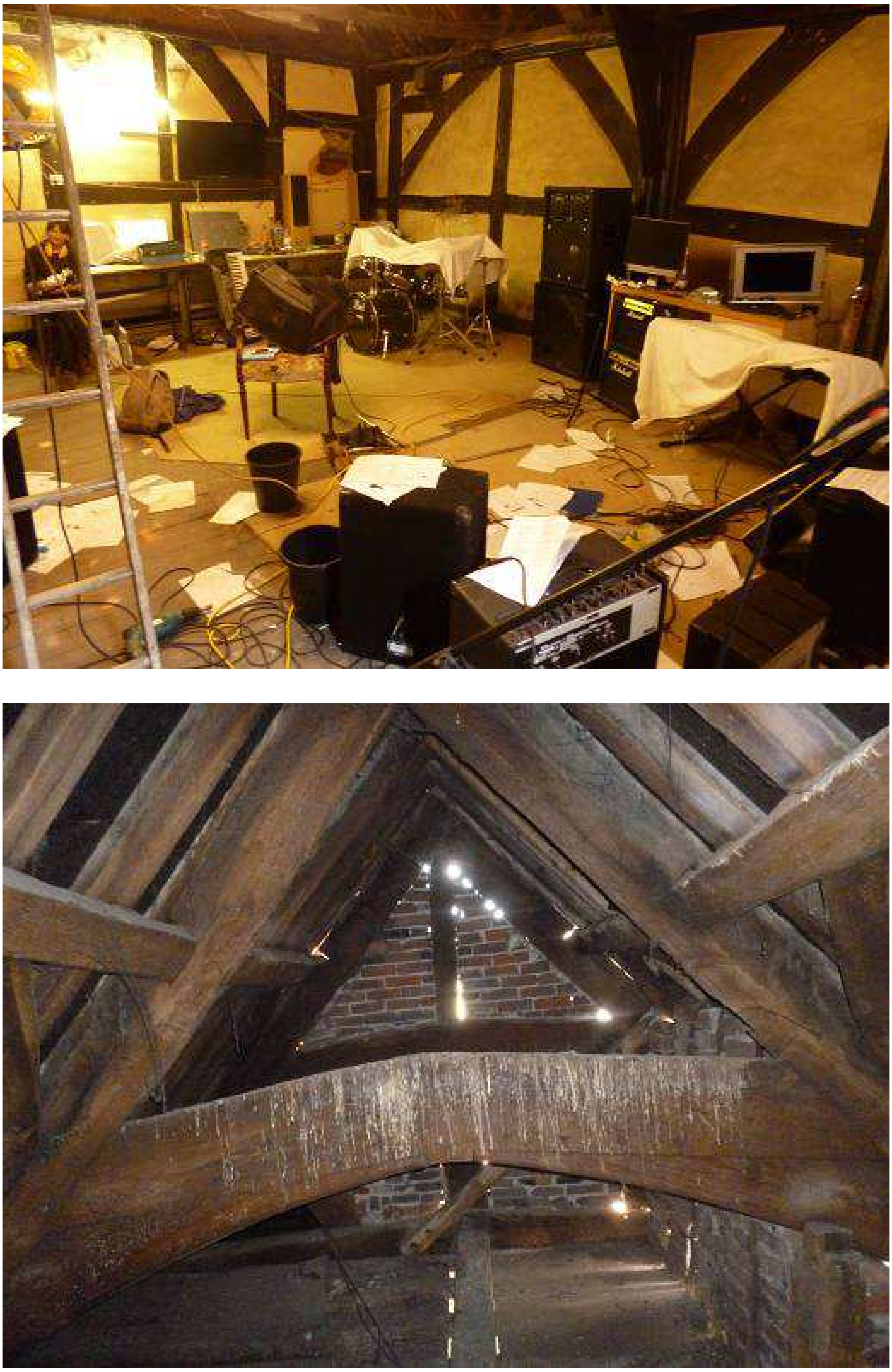


Figure 2a/b: Views of the impressive timber framing to the first floor (top) and the inaccessible trusses (bottom) (photographs Robert Howard)

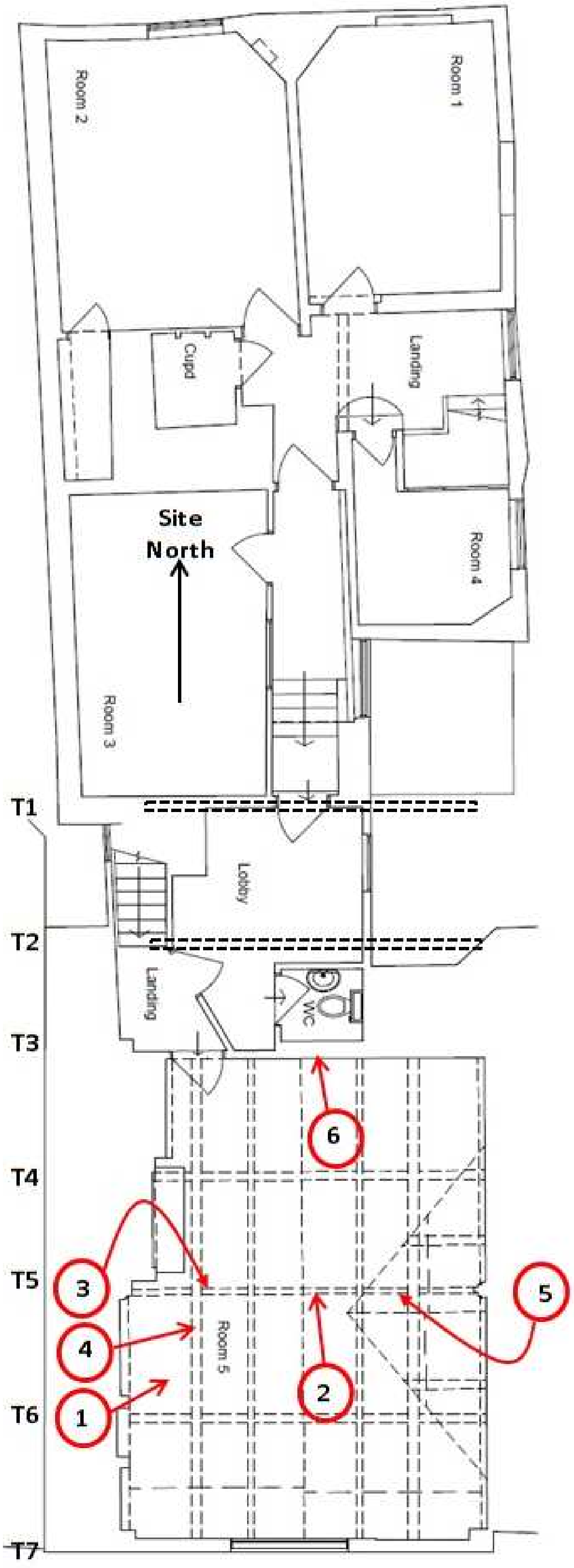


Figure 3a: Plan to locate sampled roof timbers (after Nick Joyce Architects)

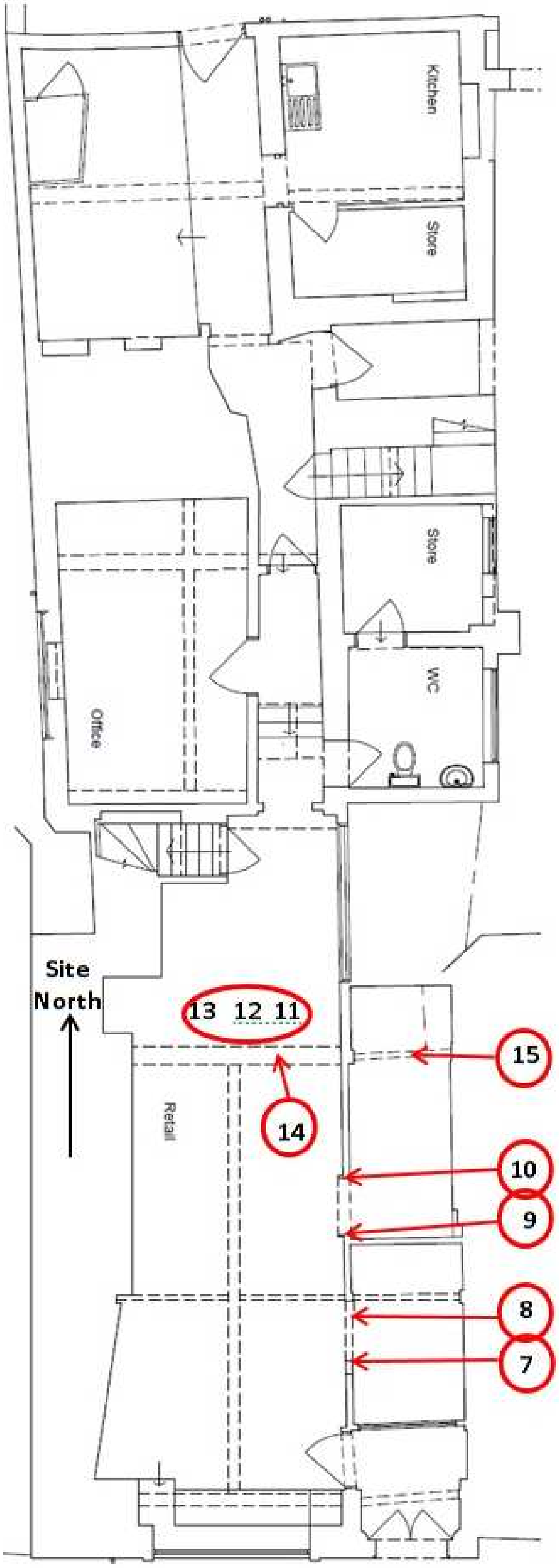


Figure 3b: Plan to locate sampled ground-floor timbers (after Nick Joyce Architects)

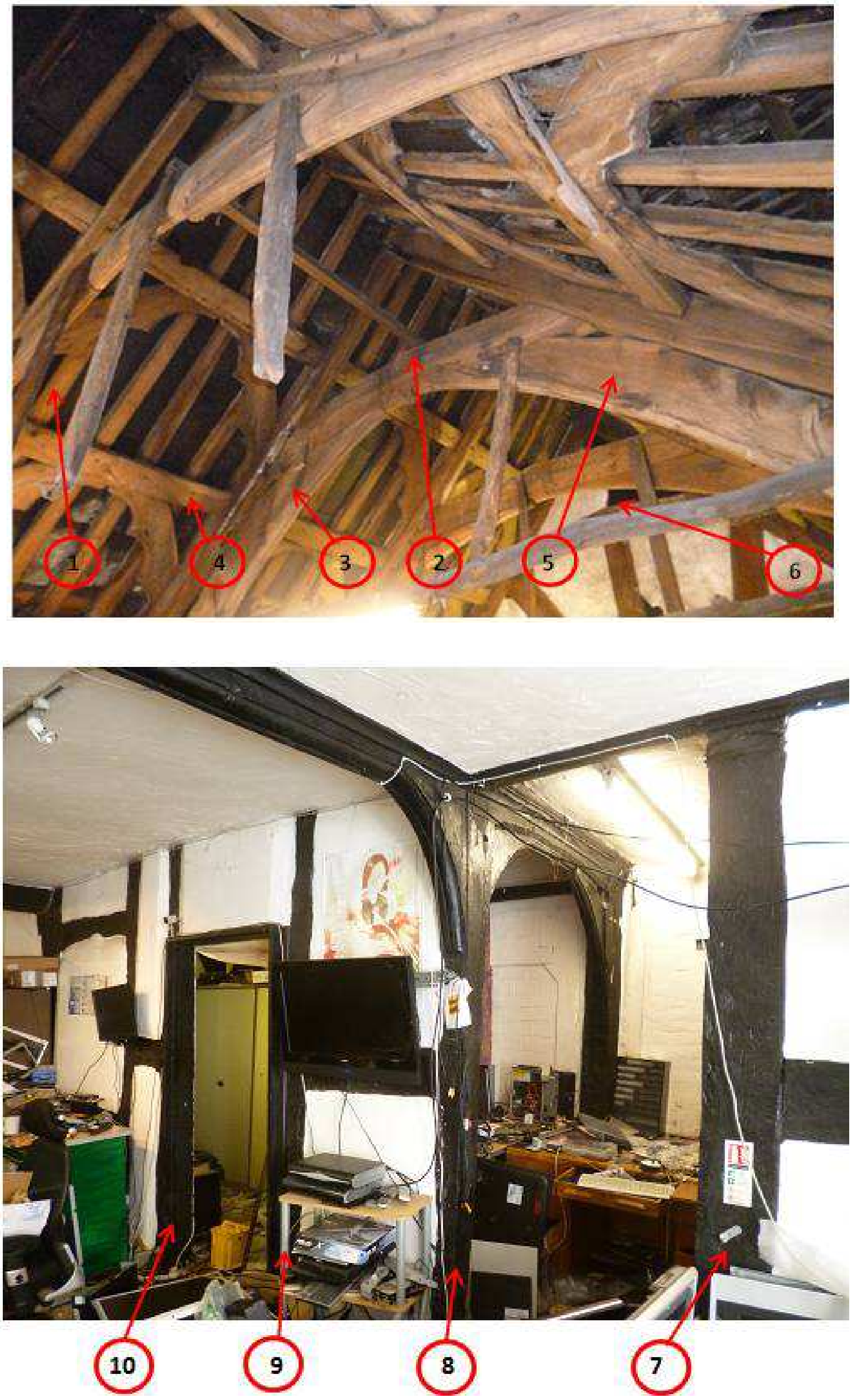
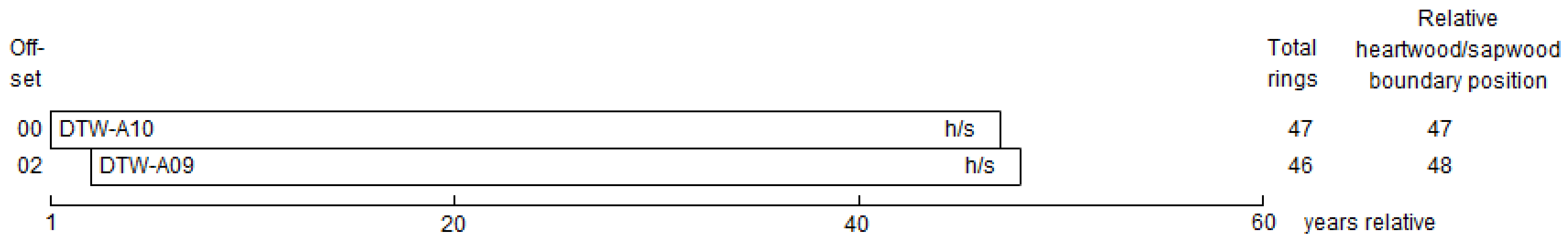


Figure 4a/b: Views to help locate sampled roof (top) and ground-floor timbers (bottom) (photographs Robert Howard)

Figure 4c/d: Views to help locate sampled ground-floor timbers (photographs Robert Howard)



White bars = heartwood rings

h/s = heartwood/sapwood boundary

Figure 5: Bar diagrams of the samples in site chronology DTWASQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

DTW-A02A 54
99 166 267 400 271 205 128 314 146 105 117 243 246 293 318 396 307 312 318 340
310 283 329 450 734 739 407 584 553 573 634 437 538 465 370 549 439 393 315 337
362 377 459 469 471 581 578 460 475 408 457 525 550 537
DTW-A02B 54
96 172 248 408 297 220 125 294 162 116 119 227 229 288 305 415 347 364 332 398
357 275 268 395 724 743 403 582 550 594 604 423 520 453 364 543 443 389 303 333
358 369 470 463 468 590 587 493 478 397 462 518 528 506
DTW-A04A 76
444 355 540 593 337 362 752 536 593 591 464 439 357 403 632 470 482 526 518 406
587 518 592 563 570 384 387 398 396 307 351 275 362 363 228 250 118 84 101 96
104 158 184 271 215 421 264 283 341 214 321 400 460 469 354 527 422 456 582 381
330 384 347 374 390 496 423 309 287 207 271 192 320 244 349 403
DTW-A04B 76
445 346 544 602 331 382 739 534 590 627 460 450 340 365 606 485 492 535 523 400
590 516 601 568 574 384 381 390 387 302 351 278 358 360 212 255 119 92 100 101
109 175 183 268 221 403 262 275 358 221 329 425 468 481 367 518 437 432 576 391
322 391 333 381 396 496 427 311 285 187 287 178 325 253 310 396
DTW-A09A 46
349 341 404 516 376 331 194 194 248 209 182 164 192 278 182 175 131 164 189 171
203 159 163 161 195 138 117 90 125 149 158 208 177 156 157 215 257 239 309 235
189 275 206 96 96 136
DTW-A09B 46
335 342 401 501 364 312 222 190 259 214 193 158 195 282 179 182 133 153 195 170
203 156 171 166 193 143 108 96 118 146 168 212 175 153 168 208 264 234 312 234
207 263 203 118 96 121
DTW-A10A 47
266 335 388 364 432 479 241 212 116 107 116 163 130 72 107 157 142 123 125 183
234 217 222 149 187 190 216 157 121 112 125 150 157 201 177 178 178 212 264 226
298 220 197 240 179 112 135
DTW-A10B 47
255 344 378 354 432 398 257 210 107 101 130 171 112 104 128 198 177 146 128 219
237 203 225 157 182 184 215 159 118 103 128 151 163 195 171 173 179 216 259 231
299 218 196 252 176 111 133
DTW-A14A 42
367 493 509 479 737 597 425 573 472 520 394 524 210 101 69 57 62 60 71 200
254 190 265 216 311 501 468 570 563 632 775 362 553 549 318 454 490 568 587 440
480 394
DTW-A14B 42
353 487 515 469 732 594 421 570 478 510 392 532 214 107 72 55 70 54 73 202
249 187 272 199 322 504 478 567 562 629 762 343 559 570 326 469 506 568 623 427
465 397
DTW-A15A 42
444 454 284 402 272 244 482 467 426 510 434 385 582 419 350 278 575 296 75 92
125 107 251 223 175 125 115 101 248 245 276 193 224 537 429 430 263 221 221 186
414 409

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DTW-A15B 42
 437 465 297 410 287 253 446 428 401 507 442 385 595 425 346 287 579 296  71  88
  97 129 239 201 164 115 112 100 253 246 261 202 235 517 440 465 283 212 223 192
 409 395
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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 Nottingham Tree-ring Dating 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 1998). 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 A1 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 A1, 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 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 A2 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 8–10 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.

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 A2; it is about 150mm long and 10mm 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.

Figure A1: 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

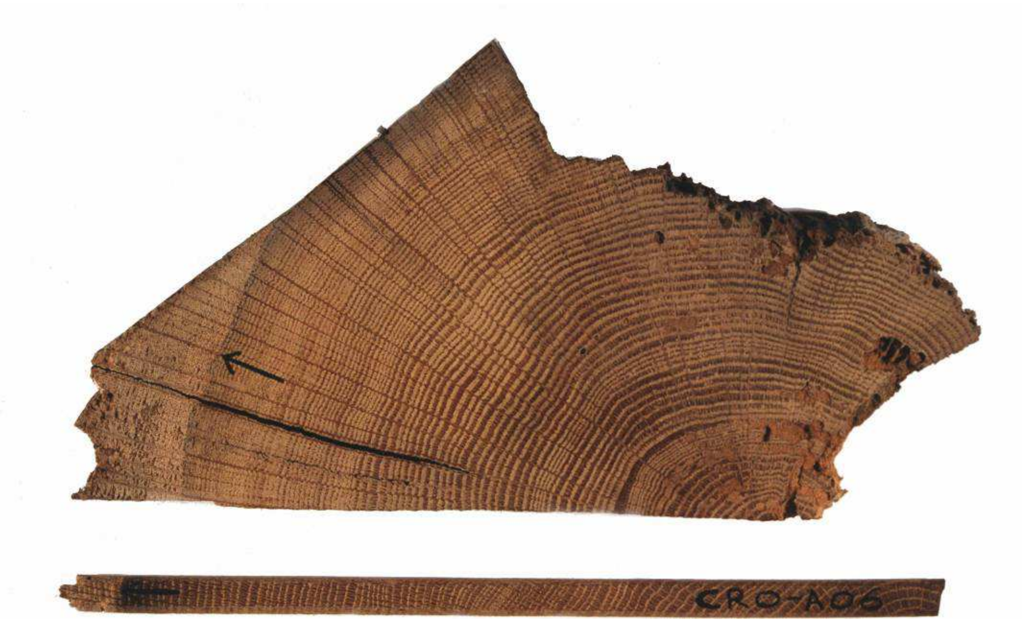


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: 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

Figure A4: 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

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 A2. 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 A3).

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 A4). 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 Figure A5 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 Figure A5. 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 A5 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 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.

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 straightforward 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 (or the last full year before felling, if it was felled in the first three months of the following calendar year, 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 A2, 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 region 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 A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, 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 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; Miles 1997, 50–5). Hence, provided that 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, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage 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 Figure A6 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 Figure A6. 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 Figure A7. 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 phenomenon 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.

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

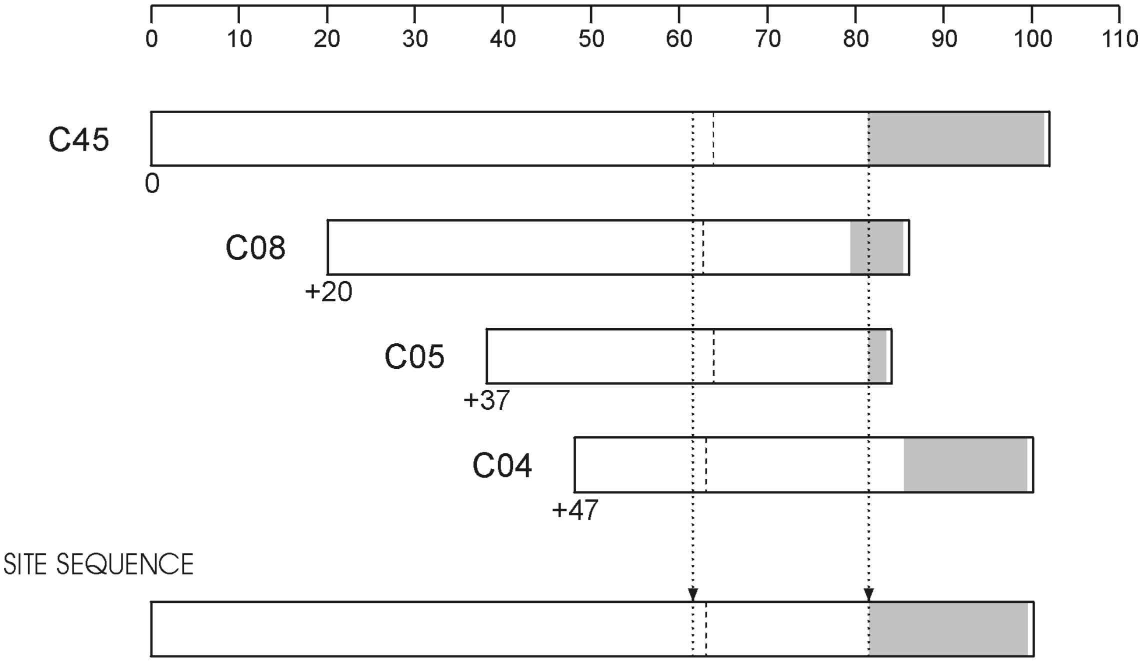


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

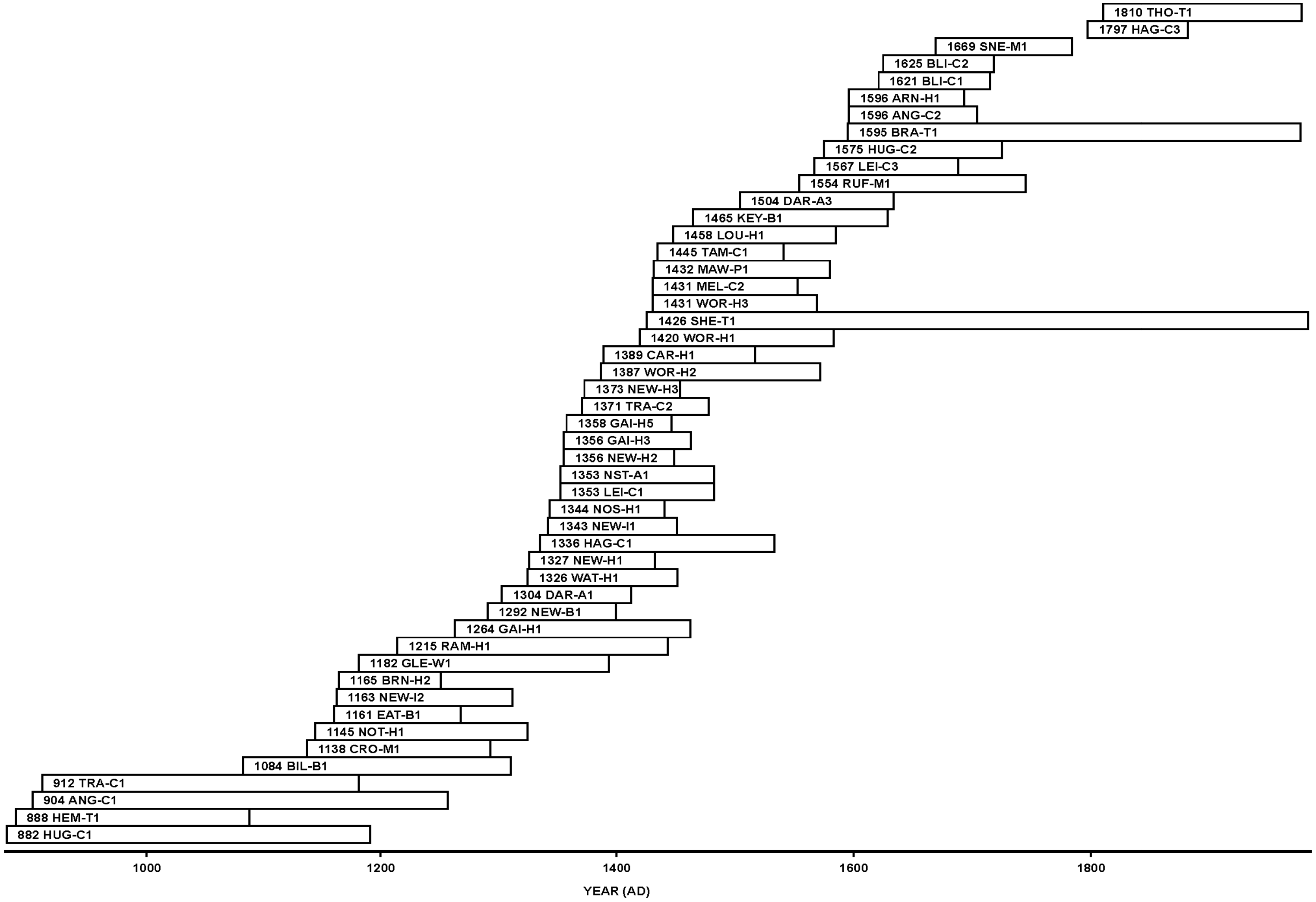
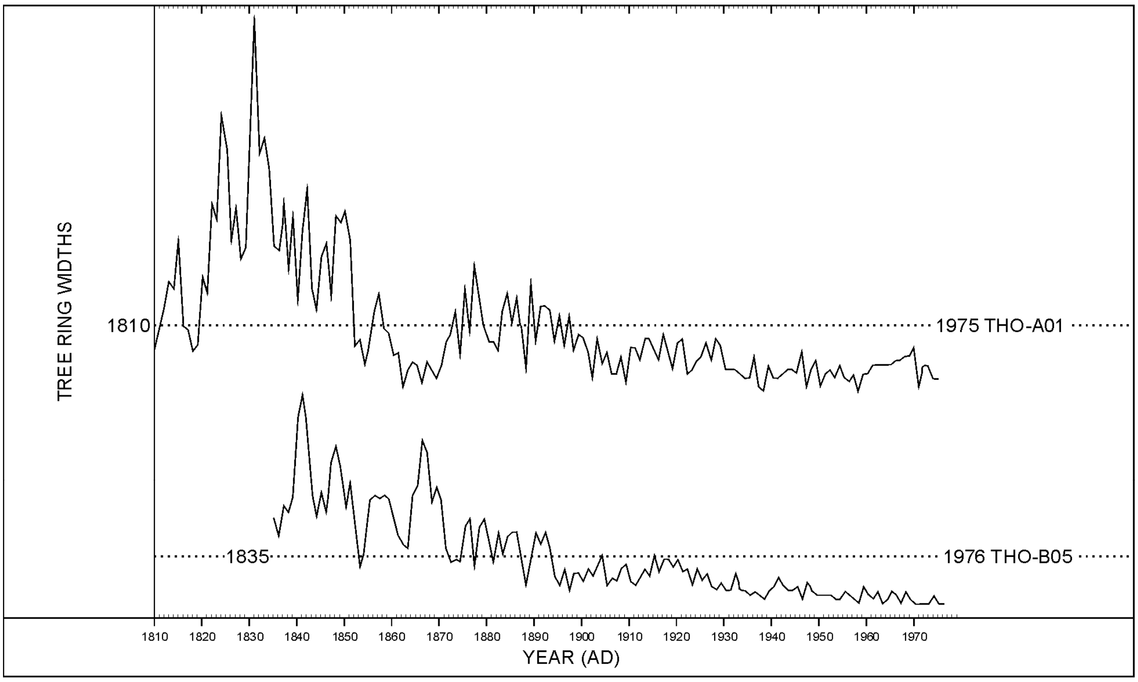


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

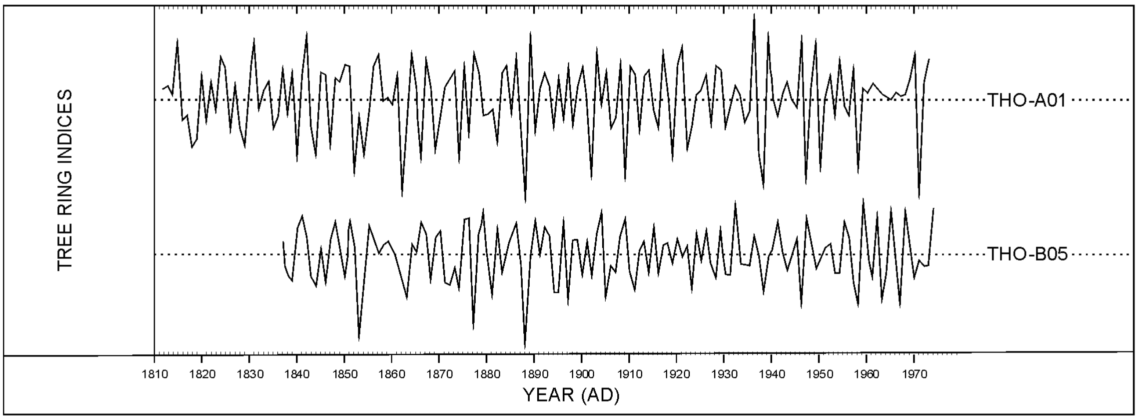


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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