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CHURCH OF ST LAURENCE, ALVECHURCH, WORCESTERSHIRE
TREE-RING ANALYSIS OF TIMBERS FROM THE BELFRY FLOOR

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY
Samples were taken from four primary (or main) beams and five secondary (or common) joists of the belfry floor. Analysis undertaken on these resulted in the successful dating of two timbers.
One of the primary beams was found to span the period AD 1511–1665 and to have been felled in AD 1666–71. The second timber, a common joist, was found to span the period AD 1602–68, with an estimated felling date within the range AD 1669–93. These two timbers may represent separate fellings or, as their felling date ranges overlap, it is possible that they were felled contemporaneously, some time within the range AD 1669–71.
With the tower, housing the belfry, known to have been rebuilt in AD 1676, these results demonstrate that the floor containing these two timbers is likely to have been inserted as part of this work.

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INTRODUCTION

The Grade II* listed parish church of St Laurence is situated on the south side of Bear Hill in Alvechurch, Worcestershire (SP 027 724; Figs 1 and 2). Although the majority of the church was rebuilt in AD 1859–61 by William Butterfield, there remain some remnants of its earlier origins. The north aisle dates to the fourteenth century, but incorporates fifteenth-century alterations. The three-stage west tower displays some fifteenth-century features, but is known to have been rebuilt in AD 1676 (datestone) by the Richards brothers. This description is based on the building's Listing Description (www.imagesofengland.org.uk).

Belfry floor

This consists of four primary beams, running north-south, above which are seven secondary joists, running east west. These latter beams are normally hidden by a modern ceiling but for the purpose of sampling a strip was removed, exposing six of them (Fig 3). The central two primary beams are similar in appearance to the secondary beams and may, therefore, be of the same date.

SAMPLING

Tree-ring dating of the primary and secondary beams of the belfry floor was requested by Graham Pledger, to inform works to the tower. It was hoped that successful dating of the timbers would confirm the age of the belfry floor and improve the understanding of the development of the church in general.

In accordance with the brief provided by English Heritage, a total of nine timbers was sampled. Each sample was given the code ALV-C (for Alvechurch Church) and numbered 01–09. Four of these were taken from the primary beams (ALV-C01–04) and five from the secondary joists (ALV-C05–09). The location of samples was noted at the time of sampling and has been marked on Figure 4. Further details relating to the samples can be found in Table 1. Timbers were numbered from east to west (primary) and south to north (secondary). It was not possible to safely reach joist 1 to sample and joist 7 was not visible.

ANALYSIS AND RESULTS

At this stage it was noticed that one of the samples (ALV-C07) had too few rings to make secure dating a possibility and so it was rejected prior to measurement. The remaining eight 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. These samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

Unfortunately, no grouping was noted between the samples, and so attempts were made to individually date the samples by comparing each one against the reference chronologies, resulting in the successful dating of two of the samples.

Sample ALV-C02, taken from primary beam 2, was found to match consistently and securely at a first-ring date of AD 1511 and a last-measured ring date of AD 1665. This sample has the heartwood/sapwood boundary ring date of AD 1631, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1666–71.

Sample ALV-C09, from one of the secondary joists, was found to span the period AD 1602–68. With the heartwood/sapwood boundary ring date of AD 1653, this timber has an estimated felling date within the range AD 1669–93.

Felling date ranges have been calculated using the estimate that 95% of mature oak trees have between 15 and 40 sapwood rings.

DISCUSSION

Prior to tree-ring analysis being undertaken the tower containing the belfry was known to have been rebuilt in AD 1676, on the evidence of a datestone.

Two of the timbers of the belfry floor have now been dated. A primary beam is known to have been felled in AD 1666–71 and a secondary joist in AD 1669–93. It is possible that these two timbers represent separate, albeit not too dissimilar, fellings in the second half of the seventeenth century. Alternatively, the felling date ranges allow for them to have been felled contemporaneously in AD 1669–71. (This is perhaps supported by the similarity in appearance noted above.) This reduced felling date range would allow both timbers to have been felled shortly before the tower is known to have undergone rebuilding, and hence suggest that the extant belfry floor was inserted as part of this work.

It is unfortunate that only two timbers have been successfully dated. The fact that there is no grouping between the samples does not necessarily mean that they are of different dates, as has been demonstrated by the two dated timbers both being felled in the second half of the seventeenth century, but could simply mean that a disparate group of timbers has been utilised in the construction of the belfry floor. Additionally, a number of the samples show unusual growth patterns, such as ALV-C08, which has recurring bands of narrower rings, and ALV-C02 and ALV-C03, which both display very restricted growth in their latter decades. These anomalies may reflect non-climatic influences specific to the trees concerned, which, by unduly influencing the growth patterns, could have hindered intra-site grouping and (at least in the case of ALV-C03 and ALV-C08) the successful matching of these samples against reference chronologies.

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TABLES AND FIGURES

Table 1: Details of tree-ring samples from the belfry floor, St Laurence's Church, Alvechurch, Worcestershire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
ALV-C01	Primary 1	56	--	----	----	----
ALV-C02	Primary 2	155	34	1511	1631	1665
ALV-C03	Primary 3	86	20	----	----	----
ALV-C04	Primary 4	72	04	----	----	----
ALV-C05	Joist 2	56	h/s	----	----	----
ALV-C06	Joist 3	62	20C	----	----	----
ALV-C07	Joist 4	NM	--	----	----	----
ALV-C08	Joist 5	72	h/s	----	----	----
ALV-C09	Joist 6	67	15	1602	1653	1668

*NM = not measured

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

C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of sample ALV-C02 and relevant reference chronologies when the first-ring date is AD 1511 and the last-ring date is AD 1665

Reference chronology	*t*-value	Span of chronology	Reference
Wakelyn Old Hall, Hilton, Derbys	7.5	AD 1415–1573	Arnold and Howard 2007 unpubl
Manor House, Alford, Lincs	7.3	AD 1500–1668	Arnold *et al* 2003a
Western House, Wanborough, Oxon	6.9	AD 1473–1574	Hadddon-Reece *et al* 1990
Church of St Andrew, Welham, Leics	6.8	AD 1443–1633	Arnold *et al* 2005
Low Farmhouse, Maplebeck, Notts	6.8	AD 1385–1587	Arnold and Howard 2007
Warren Farm Barn, Hoby, Leics	6.1	AD 1461–1615	Howard *et al* 1998 unpubl
Lord Leicester's Stables, Kenilworth Castle, Warwicks	6.3	AD 1482–1599	Howard *et al* 2006

Table 3: Results of the cross-matching of sample ALV-C09 and relevant reference chronologies when the first-ring date is AD 1602 and the last-ring date is AD 1668

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	6.2	AD 882–1981	Laxton and Litton 1988
Worcester Cathedral, Worcs	6.5	AD 1484–1772	Arnold *et al* 2003b
Daneway House, Bisley, Glos	5.9	AD 1528–1673	Howard *et al* 1995
Angel Choir (roof), Lincoln Cathedral, Lincs	5.5	AD 1596–1703	Howard *et al* 1985
Combermere Abbey, Cheshire	5.5	AD 1602–1727	Howard *et al* 2003
Wigmore Abbey, Herefordshire	5.5	AD 1055–1729	Tyers 2002
Church Farm House, Ockbrook, Derbys	5.4	AD 1560–1672	Arnold and Howard 2008

Figure 1: Map to show the general location of Alvechurch (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

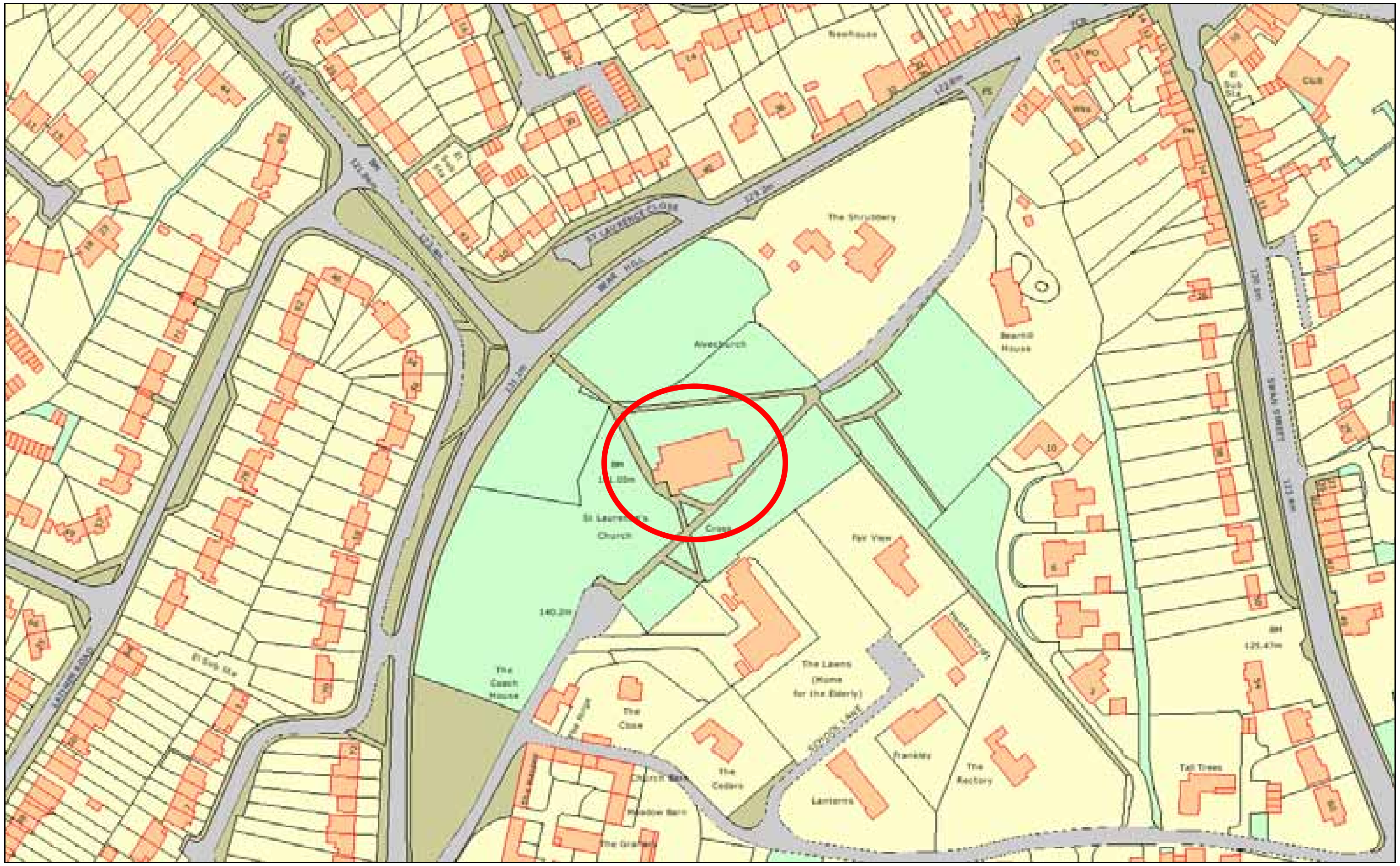


Figure 2: Map to show the location of the Church of St Lawrence (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 3: The underside of the belfry floor, primary beam 4 is against the wall to the far left of the photograph

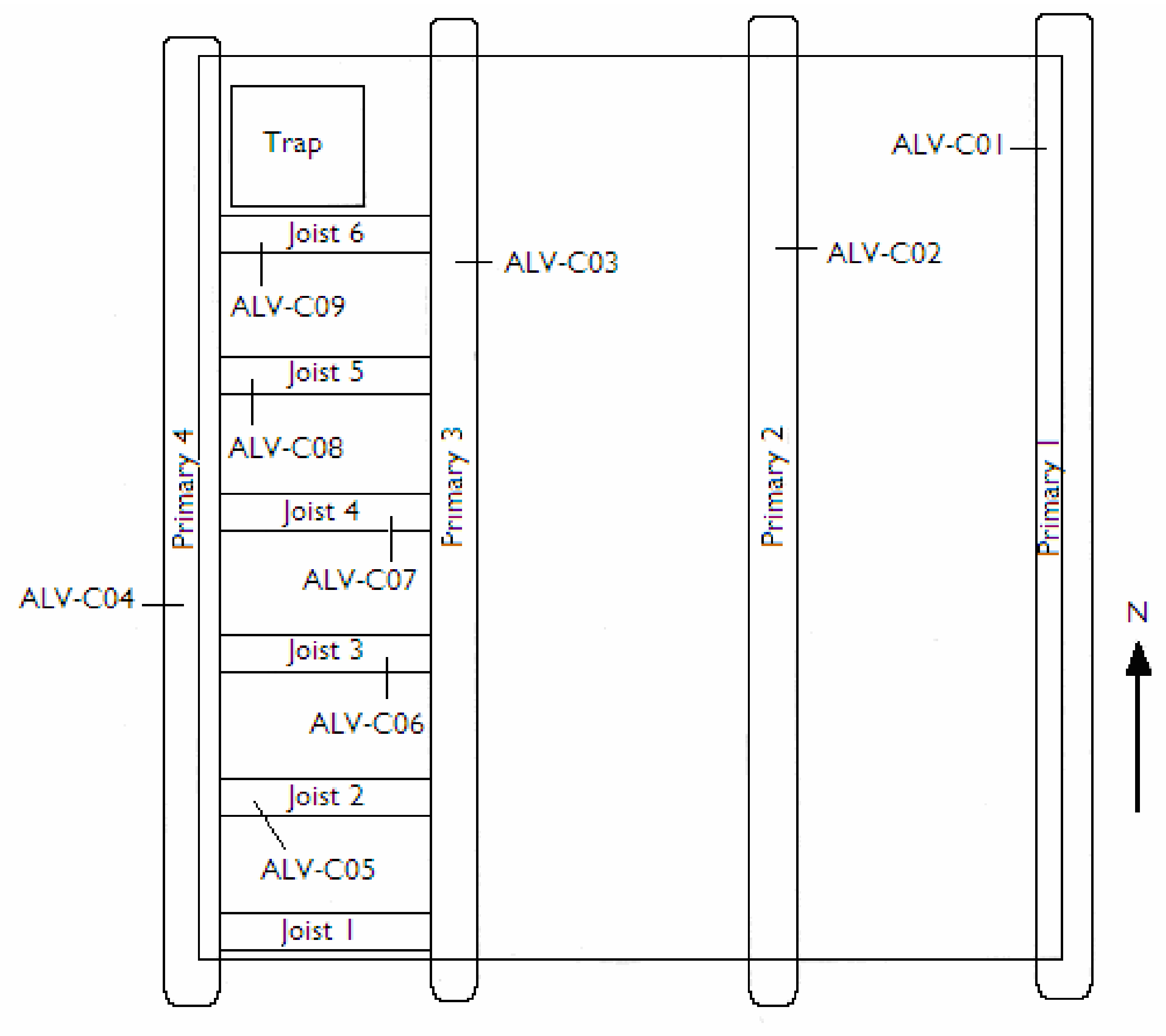


Figure 4: Sketch of the belfry floor, showing the location of samples ALV-C01–09

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

ALV-C01A 56
186 245 162 276 316 310 254 279 284 159 288 473 400 455 185 295 326 344 365 257
146 157 163 175 156 155 247 195 222 298 241 296 287 382 370 361 193 285 208 332
327 451 408 392 350 227 277 312 353 434 512 354 316 392 322 390
ALV-C01B 56
186 249 177 283 314 294 268 284 281 163 267 448 395 458 193 298 325 347 357 253
152 157 164 186 165 156 247 209 220 300 241 314 289 384 383 367 198 301 214 329
332 436 390 389 366 227 272 317 357 440 515 350 313 378 333 379
ALV-C02A 56
147 93 155 171 233 307 282 227 259 247 248 241 158 193 174 61 90 85 128 139
227 83 107 116 99 99 114 98 144 36 23 24 30 28 47 26 54 52 58 38
85 48 55 69 56 20 23 24 23 26 34 34 27 52 49 49
ALV-C02B 155
307 247 215 169 152 133 35 65 123 99 98 185 127 106 86 112 126 220 152 104
241 150 87 86 230 172 321 323 259 252 238 142 279 226 234 149 111 184 233 190
184 196 166 158 169 214 68 53 149 112 123 174 145 187 169 152 119 144 104 130
157 115 116 313 233 178 268 299 269 368 266 238 235 318 354 356 207 167 167 106
122 88 138 98 155 64 59 67 70 65 81 62 100 29 21 32 45 39 46 37
46 46 34 28 57 40 34 43 37 18 21 22 23 22 21 17 25 39 27 26
45 31 27 37 38 31 46 25 49 25 58 48 50 64 45 40 34 24 28 30
43 37 48 50 64 65 50 70 64 71 66 76 97 97 98
ALV-C03A 75
244 192 305 319 348 481 410 287 282 307 270 227 239 231 283 270 277 320 324 312
88 50 80 81 65 77 107 78 126 168 122 161 154 117 140 106 46 43 27 52
59 53 75 60 56 49 66 73 85 128 153 133 179 117 165 61 33 41 44 44
55 51 82 120 142 52 43 54 70 101 90 100 107 121 115
ALV-C03B 66
188 195 364 230 201 247 351 402 425 379 307 226 175 284 289 348 461 402 279 273
279 225 220 221 224 283 279 283 326 331 319 89 53 84 64 75 73 89 77 111
144 99 141 125 117 133 104 50 30 33 48 53 47 61 68 58 57 75 66 86
126 160 130 191 122 162
ALV-C04A 72
189 292 407 295 282 287 277 340 275 110 138 170 182 149 198 195 154 135 152 154
201 181 145 144 70 62 41 46 87 81 157 189 173 165 164 293 304 259 250 124
154 191 237 273 271 185 246 330 195 247 226 234 181 179 260 254 300 238 308 244
151 90 291 136 146 151 278 233 189 146 116 180
ALV-C04B 72
195 286 412 291 288 296 254 321 255 119 140 156 150 143 185 195 147 126 156 157
217 192 158 149 69 67 41 45 83 82 158 185 173 154 169 295 295 260 245 121
154 183 242 280 270 186 244 330 194 245 229 229 176 186 264 254 288 240 304 240
150 91 294 138 138 159 280 237 200 149 102 179
ALV-C05A 56
97 114 94 113 114 144 165 214 264 266 249 500 248 245 299 325 378 391 393 361 370
276 98 104 164 197 224 307 321 284 438 77 62 70 99 201 250 208 213 249 283
282 311 375 428 381 483 429 369 392 137 199 309 442 455 256

ALV-C05B 56
92 112 103 104 127 151 173 285 259 280 231 485 249 249 306 325 380 382 397 365
361 273 97 97 156 198 230 292 323 270 438 72 69 75 90 208 244 200 227 247
269 287 320 365 417 398 495 450 367 369 134 179 315 436 462 358
ALV-C06A 62
209 324 259 165 182 220 215 303 345 301 373 301 244 262 323 295 367 264 255 71
40 30 38 58 87 126 104 109 150 123 138 159 144 229 138 230 208 205 163 138
123 169 243 181 217 91 49 80 61 45 94 74 93 57 50 43 58 70 74 83
86 85
ALV-C06B 62
192 317 267 165 183 225 215 299 349 307 361 297 240 267 307 293 370 260 247 73
45 33 45 56 87 134 113 110 161 138 158 148 140 246 134 228 203 206 164 146
122 172 253 166 217 105 47 72 53 45 111 74 93 53 51 50 50 72 76 90
78 84
ALV-C08A 72
129 146 179 202 330 242 219 238 329 362 284 310 282 284 153 153 189 202 110 129
134 119 111 134 138 176 197 158 257 201 316 413 229 280 286 88 58 90 74 96
95 149 225 181 243 273 219 235 95 79 75 88 77 130 123 118 183 123 80 94
72 42 61 72 108 88 76 82 83 75 146 116
ALV-C08B 72
137 148 177 192 322 228 212 230 313 346 300 310 300 320 159 158 182 212 105 129
132 113 112 135 135 173 183 159 253 196 326 414 234 290 271 89 62 85 71 81
104 144 228 185 226 259 217 239 100 73 86 88 78 136 120 117 174 128 74 101
73 48 66 70 92 82 92 81 103 70 141 103
ALV-C09A 67
440 428 349 258 531 597 649 591 501 267 255 393 361 370 327 236 306 265 261 280
330 320 232 179 225 187 190 284 282 229 358 275 82 72 42 76 108 101 98 147
97 76 91 64 90 84 89 67 71 62 48 63 102 189 140 148 173 124 108 103
113 129 101 93 62 49 45
ALV-C09B 67
414 423 355 278 554 603 636 538 506 267 247 355 383 366 321 229 321 271 259 277
321 316 233 192 229 190 196 254 259 215 352 275 75 74 43 76 110 91 102 141
98 72 77 69 79 85 86 76 80 63 45 66 106 197 131 141 177 114 115 109
99 118 107 94 56 51 47

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 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

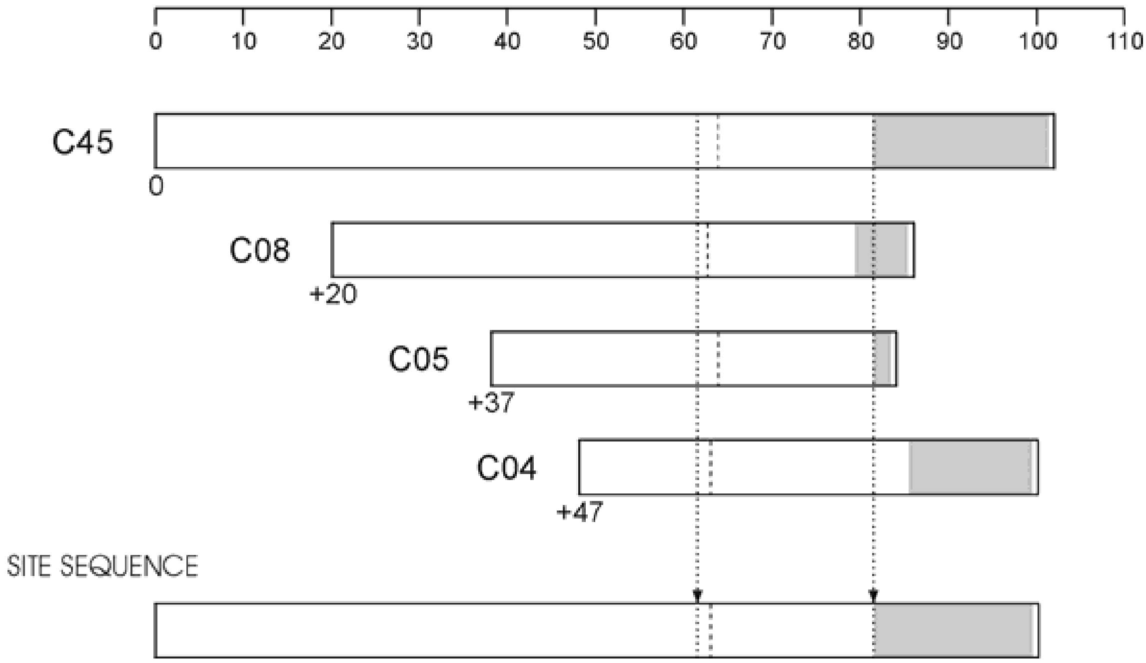


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

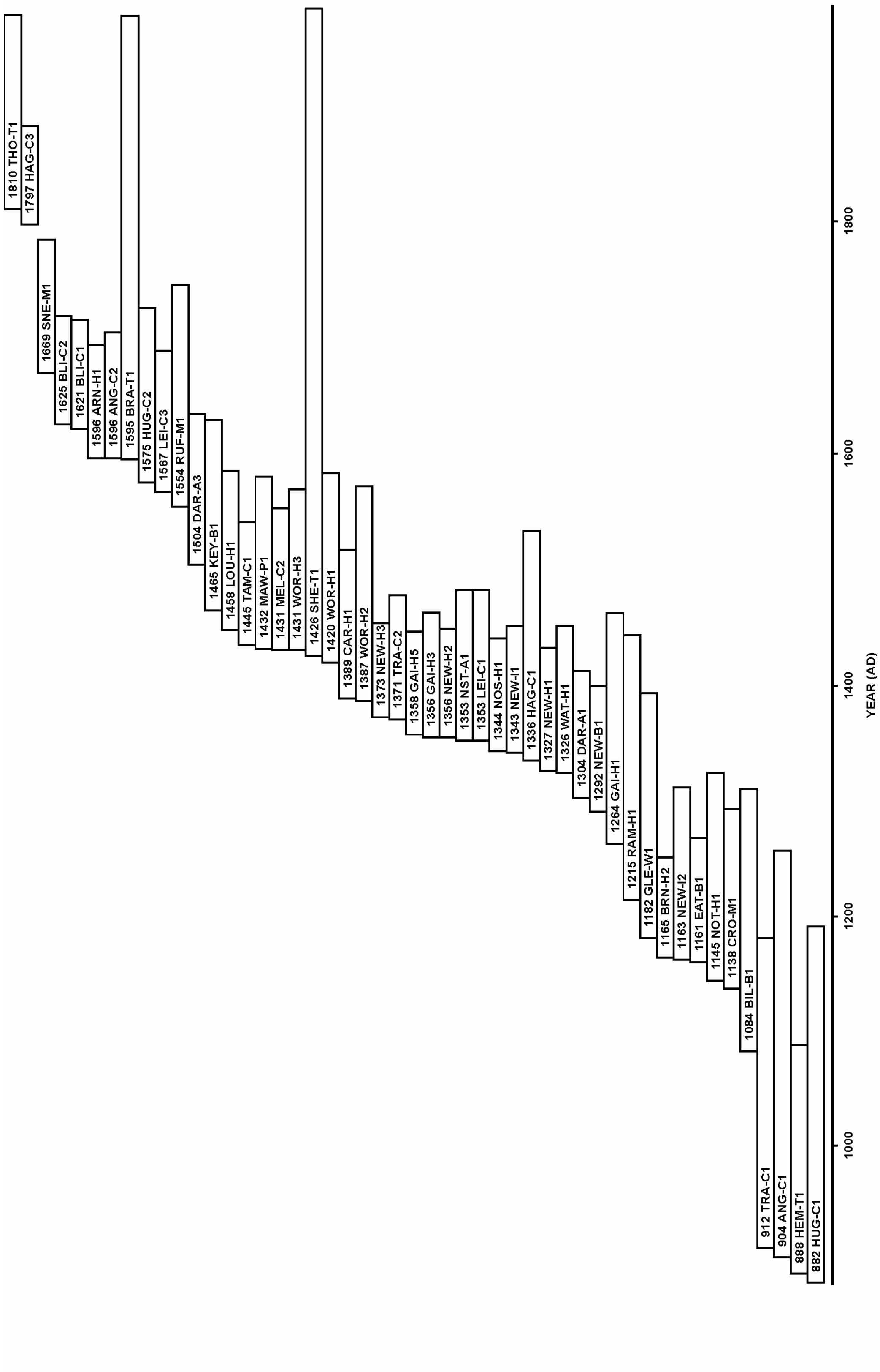
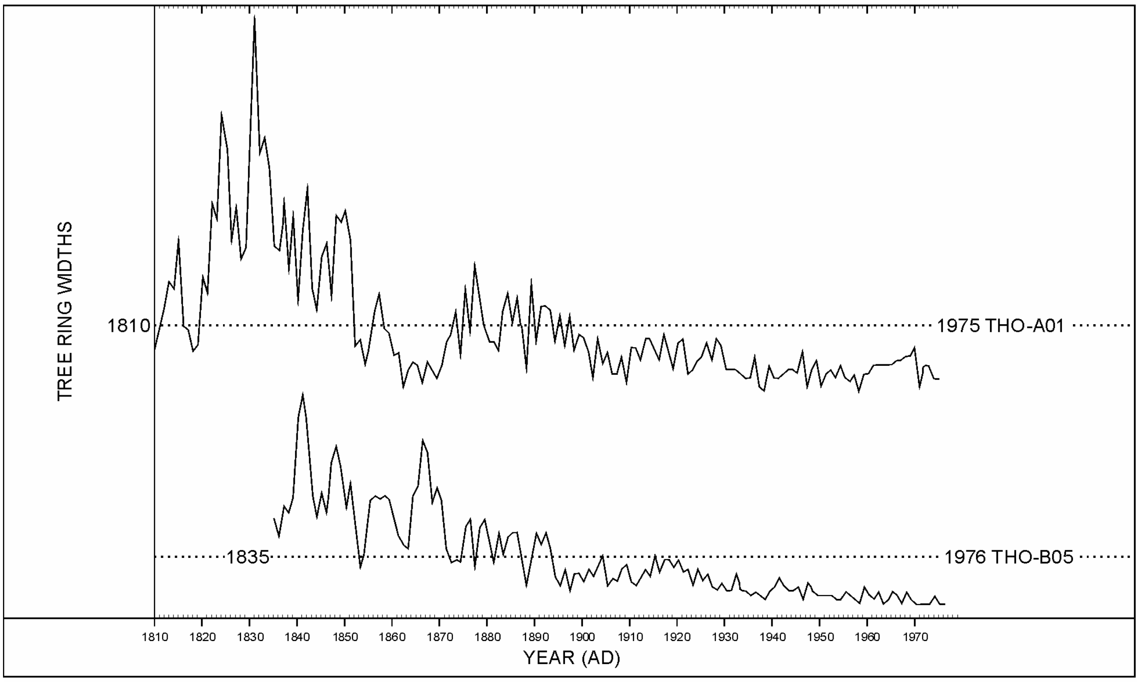


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

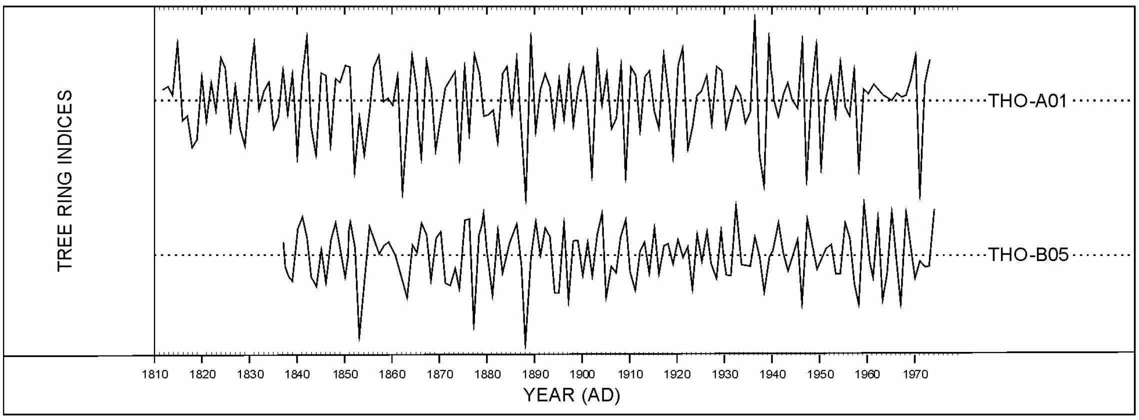


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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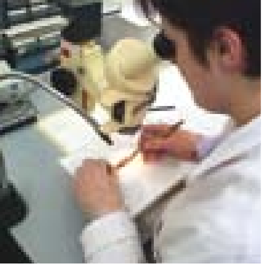
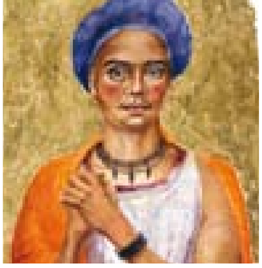



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