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BARLBOROUGH HALL, WARD LANE, BARLBOROUGH, DERBYSHIRE
TREE-RING DATING OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

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SUMMARY

Timbers from the Banqueting Hall and the Hall roof of this building complex proved unsuitable for analysis. However analysis undertaken on samples from the roof of the stables at Barlborough Hall resulted in the construction of two site sequences, only one of which could be securely dated.

Site sequence BARLSQ01 contains two samples and spans the period AD 1580–1663. Interpretation of the sapwood suggests felling of both timbers in AD 1678–1703, with construction of the roof following shortly after.

CONTRIBUTORS

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INTRODUCTION

The Grade I listed Barlborough Hall is located 1km north of the village of Barlborough, *c* 16km south east of Sheffield (Figs 1 and 2). It is attributed to Robert Smythson, and was built as a country house for Sir Francis Rodes in *c* AD 1583–4. The interior of the house was much altered in AD 1825 with further alterations taking place after 1938 when the hall was sold and converted for use as a school. To the west of the house is a rectangular complex of service buildings, connected by an enclosed corridor. Amongst these buildings are the stables and banqueting house.

The Hall

The hall is square in plan with canted and polygonal bays and consists of basement and two storeys with the bays having an extra storey. The front (south) elevation is of five symmetrical bays with a projecting central porch bay. The roof over this part of the building is very shallow-pitched and consists of large tiebeams, ridge, purlins, and common rafters. The appearance of the timbers suggests they belong to the AD 1825 alterations (Fig 3).

Stables

The roof over the Grade II Listed stables consists of six principal rafter trusses with collars and tiebeams, supporting double purlins and common rafters. Later pine struts have been inserted to support the collars (Fig 4).

Banqueting House

The Grade II* listed small two-storey banqueting house (also known as the gazebo) has a large semi-circular two-storey projecting central bay dominating the south-facing elevation. It is divided at ground-floor level into two rooms whilst the single first-floor room is open to the roof. This roof, consisting of rafters, purlins, and collars is thought to be a twentieth-century replacement. This building is believed to be contemporary with the Hall, but is presently unused and has been on the Heritage-at-Risk register since 1998.

SAMPLING

A dendrochronological survey was requested by Amanda White (English Heritage Heritage-at-Risk Architect/Surveyor) to ascertain independent dating evidence for the primary construction of the main hall and associated buildings. In particular it was hoped that the analysis would inform grant aided repair works undertaken with respect to establishing a future use for the banqueting house and its subsequent removal from the Heritage at Risk register.

Assessment of the timbers of the stables' roof determined that the majority of them were derived from fast-grown trees and were unlikely to have sufficient growth rings for secure dating. However, seven of the timbers from this roof did appear to have slightly more growth rings and so were sampled by coring. Each sample was given the code BAR-L and numbered 01–07. The location of all samples was noted at the time of sampling and has been marked on Figure 5. Further details relating to the samples can be found in Table 1.

Access to the timbers of the hall roof was found to be severely restricted which would have made sampling nearly impossible. Additionally, the extant roof is of a relatively modern appearance and is thought likely to belong to the AD 1825 renovations. Although there were some additional timbers included within this roof that looked more ancient and showed signs of reuse, as with the majority of the stables' roof, these beams could be seen to be wide ringed and therefore unsuitable for analysis. The roof of the Banqueting House is thought to be a twentieth-century replacement; a floor frame, one of the spine beams of which has been removed from the building, was thought to be primary but as seen elsewhere the timber was fast grown with insufficient growth rings for secure dating (Fig 6).

ANALYSIS AND RESULTS

All seven samples from the stable roof 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 seven samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in four samples matching to form two groups.

Firstly, two samples (BAR-L04 and BAR-L05) matched each other and were combined at the relevant offset positions to form BARLSQ01, a site sequence of 84 rings (Fig 7). This site sequence was compared against a wide range of reference chronologies for oak and was found to span the period AD 1580–1663. The evidence for this dating is given in Table 2.

Two further samples (BAR-L03 and BAR-L06) matched each other and were again combined at the relevant offset position to form BARLSQ02, a site sequence of 57 rings (Fig 8). Attempts to date this site sequence and the remaining ungrouped samples were unsuccessful and all remain undated.

INTERPRETATION

Two samples, both taken from the principal rafters of truss 2, have been successfully dated. The two samples have broadly contemporary heartwood/sapwood boundary ring dates, the average of which is AD 1663, allowing an estimated felling date to be calculated for the two principal rafters represented of AD 1678–1703.

DISCUSSION

The dendrochronological analysis has demonstrated the inclusion within the stable roof of at least two timbers dating to AD 1678–1703. Although it has only been possible to date the principal rafters of truss 2 neither showed any sign of having been reused or inserted and there was nothing in the appearance of the roof itself (with the exception of obvious later strengthening pine supports) to suggest it was anything other than the result of a single phase of construction. Additionally, although the second site sequence is undated, the relative heartwood/sapwood positions of the two samples (Fig 8), suggest that the timbers represented, taken from different trusses (1 and 3) are likely to have been felled at the same time. It therefore seems reasonable to suggest that this late seventeenth- or very early eighteenth- century felling date range for truss 2 reflects the construction date of the roof.

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TABLES

Table 1: Details of tree-ring samples from the stable range at Barlborough Hall, Barlborough, Derbyshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last measured heartwood ring date (AD)	Last measured ring date (AD
Stable range						
BAR-L01	Tiebeam, truss 5	97	25C	----	----	----
BAR-L02	Tiebeam, truss 4	64	h/s	----	----	----
BAR-L03	South principal rafter, truss 3	57	h/s	----	----	----
BAR-L04	North principal rafter, truss 2	75	h/s	1589	1663	1663
BAR-L05	South principal rafter, truss 2	84	01	1580	1662	1663
BAR-L06	North principal rafter, truss 1	48	h/s	----	----	----
BAR-L07	South principal rafter, truss 1	65	11	----	----	----

h/s = heartwood/sapwood boundary
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BARLSQ01 and reference chronologies when the first-ring date is AD 1580 and the last-measured ring date is AD 1663

Reference chronology	*t*-value	Span of chronology	Reference
Sherwood trees, Nottinghamshire	6.9	AD 1426–1981	Laxton and Litton 1988
Staircase House, Stockport, Greater Manchester	6.0	AD 1489–1656	Howard *et al* 2003
Auckland Castle, Bishop Auckland, County Durham	5.8	AD 1425–1698	Arnold and Howard 2013a
Oak House Barn, West Bromwich, West Midlands	5.8	AD 1562–1655	Howard *et al* 1991
Langford Manor, Nottinghamshire	5.8	AD 1467–1632	Esling *et al* 1989
The Commandery, Worcester, Worcestershire	5.7	AD 1608–1708	Howard *et al* 2006
Linnels Mill, Hexham, Northumberland	5.5	AD 1541–1712	Arnold and Howard 2013b

FIGURES

Figure 1: Map to show the location of Barlborough, Derbyshire, circled. ©Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location of Barlborough Hall and the areas under investigation; main hall (red), the stables (black), and the banqueting house (green). ©Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Hall roof (Robert Howard)

Figure 4: Stable roof (Robert Howard)

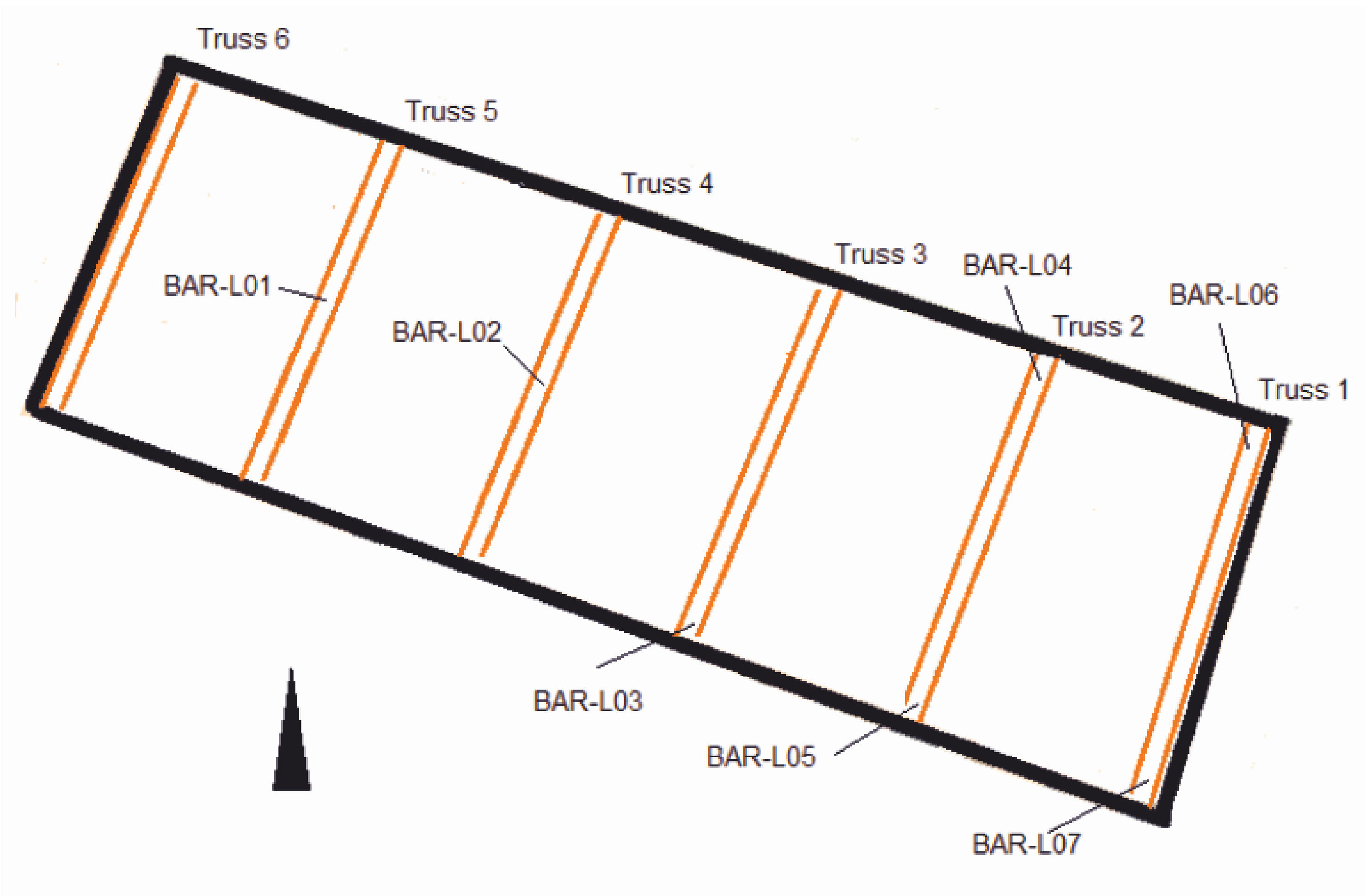


Figure 5: Sketch plan of Stables showing the location of samples BAR-L01–07

Figure 6: An *ex situ spine beam from the Banqueting House ceiling; the wide growth pattern can clearly be seen (Robert Howard)*

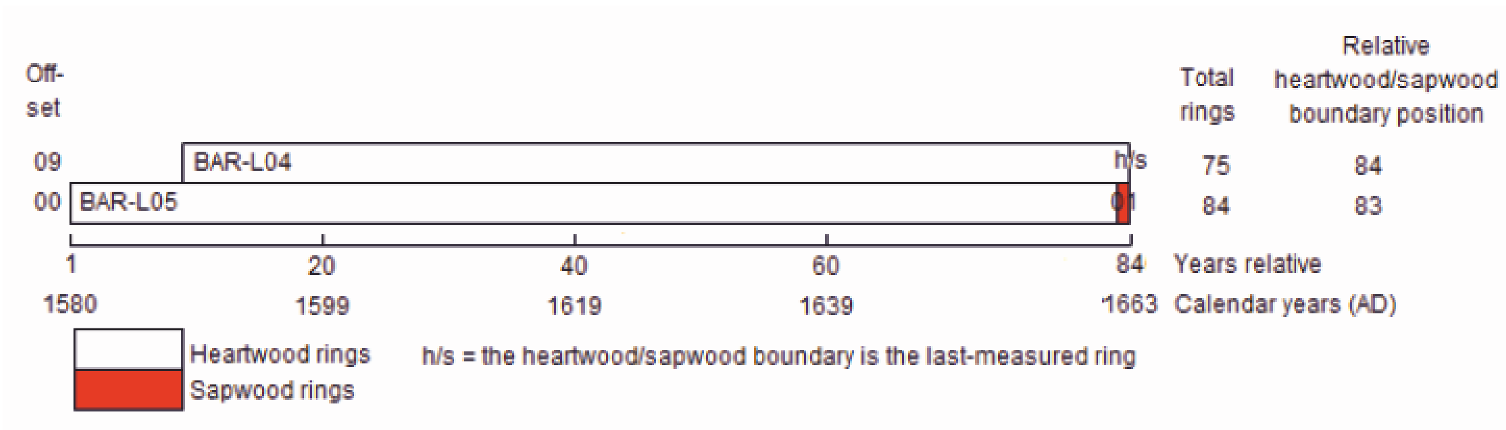


Figure 7: Bar diagram of samples in site sequence BARLSQ01

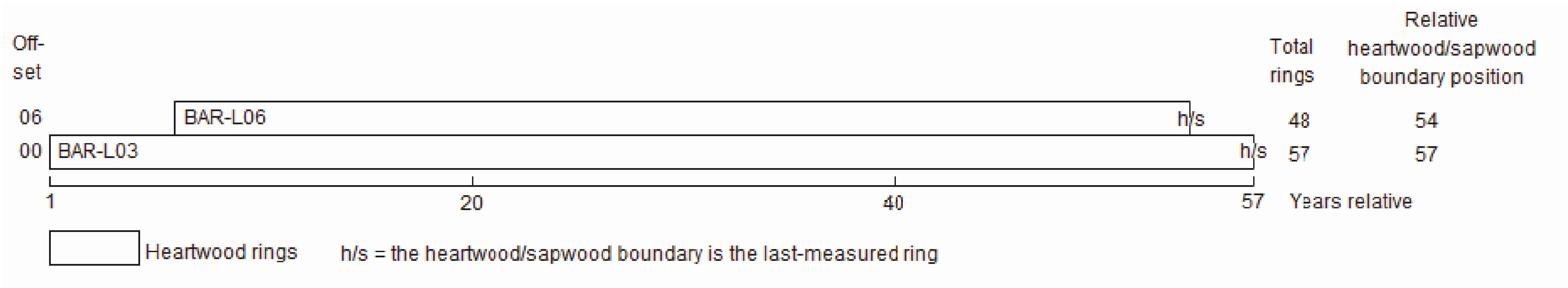


Figure 8: Bar diagram of samples in site sequence BARLSQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units
BAR-L01A 97
158 148 172 173 165 176 226 238 189 192 151 188 213 249 250 255 259 217 263 221
175 239 243 348 228 169 191 208 155 169 172 124 163 191 139 147 121 152 211 128
113 68 112 90 78 66 87 105 92 132 85 127 145 96 74 105 60 90 55 61
46 65 53 66 56 51 78 65 75 62 65 67 109 158 148 85 74 102 151 127
116 81 107 132 111 115 93 112 96 122 149 109 114 117 124 109 76
BAR-L01B 97
152 151 174 181 175 199 219 245 180 188 185 220 212 255 240 238 274 224 259 226
176 241 224 329 230 167 193 209 156 170 173 129 166 204 136 141 118 158 208 132
118 62 121 85 79 57 90 100 100 125 84 137 145 91 88 89 73 82 62 62
48 72 52 47 57 60 74 79 65 63 73 62 117 167 142 87 61 113 143 126
116 86 95 128 107 98 105 104 95 126 110 146 115 123 111 108 82
BAR-L02A 64
275 276 293 315 355 297 457 456 365 410 413 461 430 439 383 306 330 271 324 386
380 356 285 329 338 372 413 341 365 233 278 353 181 153 120 201 200 198 216 209
248 201 209 176 213 220 282 356 325 264 184 165 136 222 254 273 280 211 316 382
260 201 194 110
BAR-L02B 64
279 266 275 317 357 294 456 461 366 411 415 462 433 426 397 309 323 281 313 386
389 361 283 338 344 373 405 335 366 230 283 343 176 151 123 193 193 200 212 212
252 201 203 189 220 220 289 323 327 272 177 166 137 208 235 295 277 193 305 373
245 196 197 120
BAR-L03A 57
312 274 271 311 297 357 357 282 326 378 454 474 506 351 452 336 311 322 305 399
327 238 190 168 155 146 173 196 333 282 247 213 228 183 210 119 118 157 146 171
179 98 105 100 123 129 135 135 151 134 117 114 86 70 57 103 99
BAR-L03B 57
339 277 337 296 318 352 355 295 341 377 455 475 504 354 448 336 313 321 312 394
331 231 193 172 158 162 184 228 343 290 249 222 219 184 209 128 109 145 149 167
173 103 104 108 123 132 136 137 147 130 123 109 86 73 53 102 95
BAR-L04A 75
193 205 143 138 170 169 168 133 128 140 147 119 145 124 153 105 157 205 337 361
388 422 387 255 335 225 256 47 49 83 69 86 69 63 68 61 71 80 116 106
155 146 157 179 135 105 123 113 163 180 113 169 205 148 104 112 141 202 171 184
213 264 214 199 171 172 329 340 316 325 321 339 294 288 244
BAR-L04B 75
198 208 141 137 160 157 166 132 126 135 152 126 140 126 154 108 160 219 319 341
398 416 393 254 340 226 258 43 49 84 70 88 73 58 73 59 73 83 113 96
164 142 156 174 141 107 129 113 162 178 105 172 210 149 104 117 142 202 178 185
217 260 212 194 170 178 338 327 314 335 327 335 290 285 244
BAR-L05A 84
292 237 217 274 375 266 608 476 256 252 245 320 348 456 407 398 379 298 321 405
397 282 224 319 614 507 520 635 437 386 474 574 434 491 394 415 169 100 145 155
159 124 155 150 90 108 172 229 219 499 339 325 359 370 258 299 228 182 230 309
317 494 405 167 138 163 279 211 198 264 230 204 132 114 102 265 390 306 314 399
377 304 243 205
BAR-L05B 84
293 242 212 275 384 259 612 474 262 243 267 349 377 449 407 399 378 302 315 402
402 285 214 318 612 504 524 637 437 393 464 578 434 483 380 427 170 88 125 122
160 115 158 156 91 105 175 213 246 477 352 342 353 351 259 301 233 183 228 308

315 500 403 167 131 167 273 218 193 253 235 202 125 121 104 255 393 302 322 394
387 312 248 201
BAR-L06A 48
452 378 401 193 150 240 290 196 239 217 254 282 259 309 249 122 104 107 103 79
98 164 224 191 174 196 133 111 132 76 69 96 110 152 182 78 91 86 94 123
107 91 90 82 81 57 41 40
BAR-L06B 48
444 381 389 190 150 255 282 185 249 215 244 289 257 309 252 122 102 115 86 78
99 159 226 189 177 195 135 107 128 74 73 95 113 153 182 75 89 91 94 121
101 101 88 74 86 57 41 49
BAR-L07A 65
243 230 138 148 160 126 279 237 223 238 253 220 252 246 328 359 309 260 390 322
295 315 321 371 301 216 196 217 202 173 136 160 247 236 175 156 123 108 116 83
86 113 127 181 166 115 92 87 70 103 83 89 78 53 49 36 38 66 63 70
72 57 43 39 40
BAR-L07B 65
237 234 134 144 163 125 280 226 194 239 248 220 234 262 318 358 313 256 398 319
297 320 320 370 293 214 191 213 194 173 141 164 251 226 185 162 128 102 121 88
83 114 126 177 171 109 95 87 76 108 89 87 76 52 47 43 48 71 68 61
69 58 43 41 36

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 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

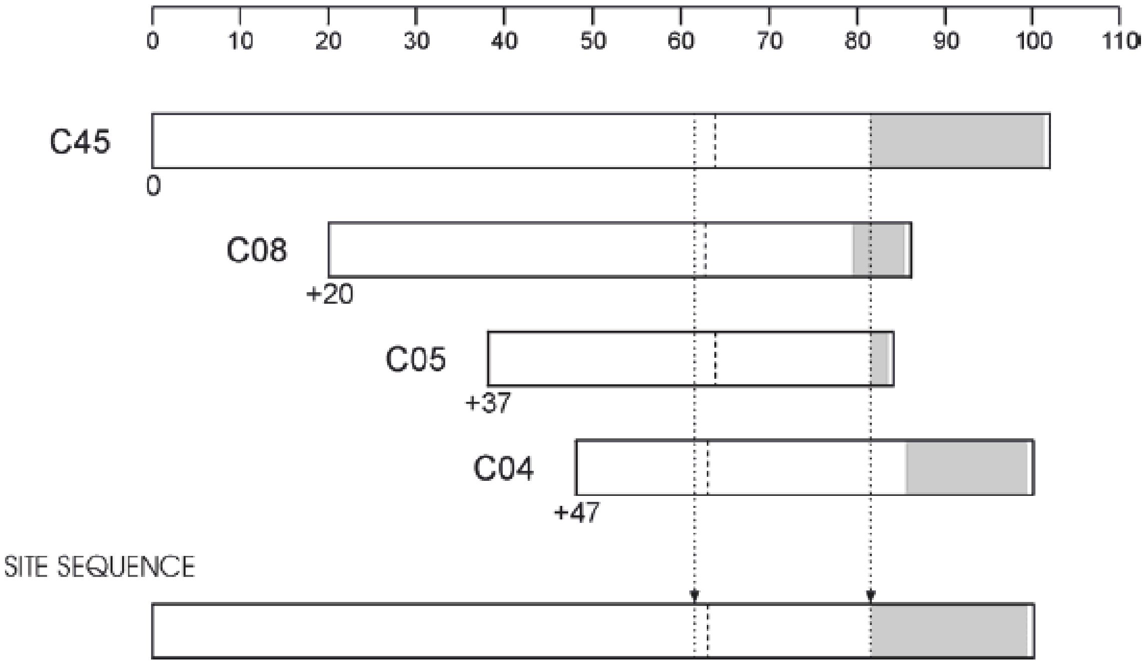


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

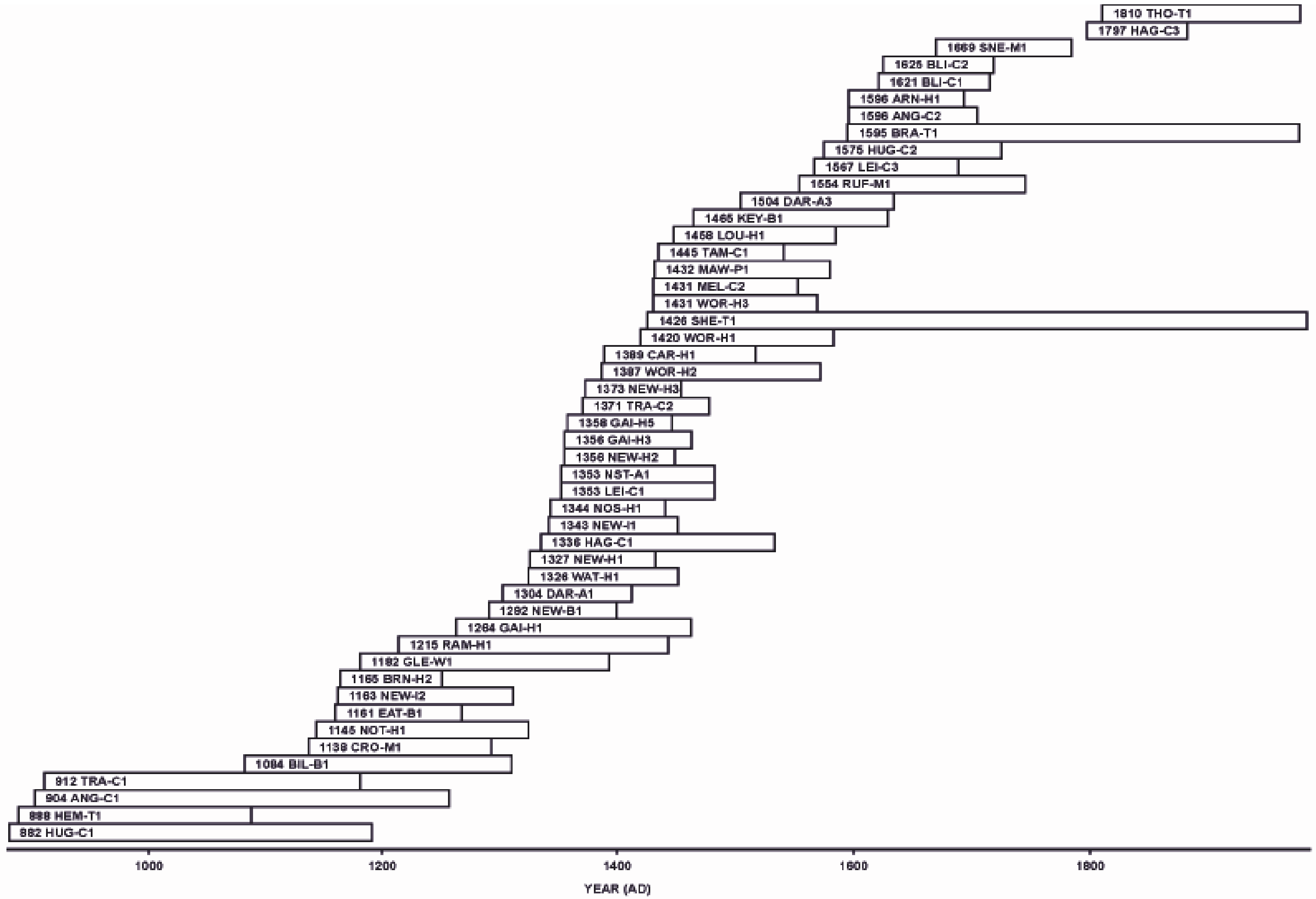
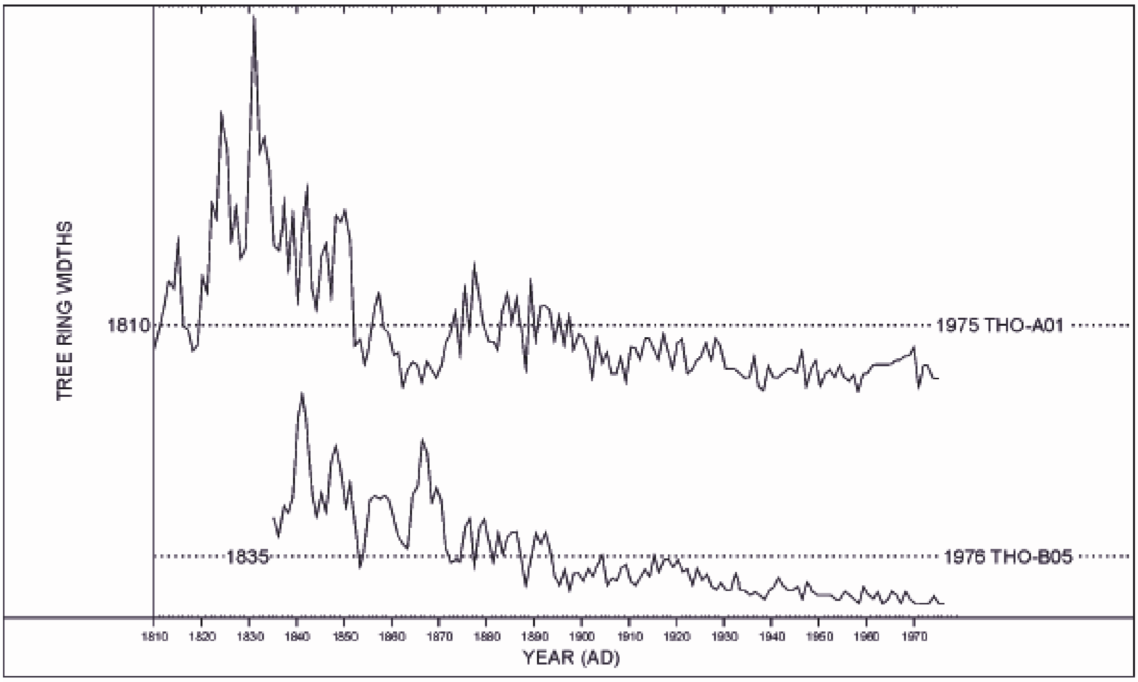


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

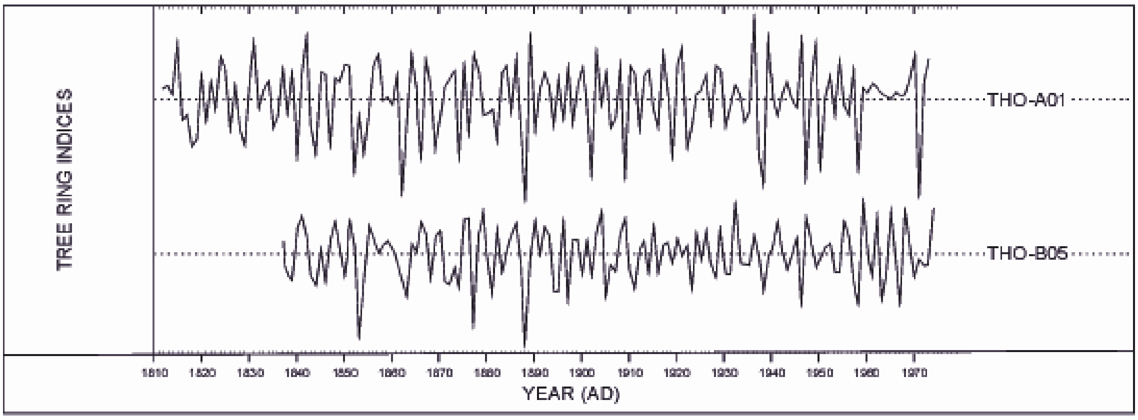


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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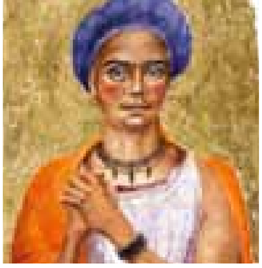


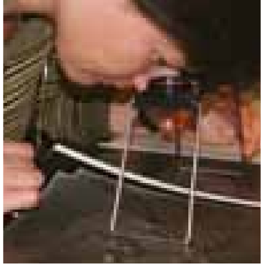


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