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DOVE COTTAGE, TOWN END, GRASMERE, CUMBRIA
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

A total of 17 samples was obtained from a series of different timbers within Dove Cottage, Grasmere. Seven samples were found to contain less than the minimum of 50 rings deemed necessary for reliable dating, and these were excluded from further analysis. The 10 remaining samples which were measured did not match each other, and did not date independently. The timbers, therefore, remain undated and hence provide no independent dating evidence for the chronological development of the cottage.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Jeff Cowton, Sally Hall, and other members of the National Trust team at Dove Cottage, for helping to arrange this programme of analysis, and for suffering our sampling visit with much patience. We would also like to thank Adam Menuge, Senior Investigator in English Heritage's Architectural Investigations team based in York for his help and advice during sampling, for providing background material used in the introduction, and for the provision of plans and drawings used in this report. We would also like to thank Dr Peter Marshall, Scientific Dating Coordinator, also of English Heritage, for commissioning the tree-ring analysis at this site.

ARCHIVE LOCATION

Lake District Historic Environment Record
Lake District National Park Authority
Murley Moss
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DATE OF INVESTIGATION

2010

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INTRODUCTION

Dove Cottage, standing beside the old Ambleside to Keswick road at the north end of Grasmere in Cumbria (NY 3420 0703, Figs 1 and 2), is best known as the home of William Wordsworth and his sister Dorothy, who lived here from December 1799 to May 1808. During this period William wrote much of the poetry for which he is best remembered today, including his Ode: 'Intimations of Immortality' and 'I Wandered Lonely as a Cloud'. William married his wife Mary in 1802, and she and her sister joined the Wordsworths at Dove Cottage. The family quickly expanded, with the arrival of three children in four years, and the Wordsworths left Dove Cottage in 1808 to seek larger accommodation.

It is believed that the Cottage was purpose-built as an inn in the early seventeenth century, being first recorded as the 'Dove and Olive' in a list of public houses in Westmoreland in 1617. It remained an inn until it closed in 1793, the history of the cottage being referred to in Wordsworth's 1806 poem, 'The Waggoner', in which the protagonist passes by...

> 'where once the Dove and Olive-bough
> offered a greeting of good ale
> to all who entered Grasmere Vale'

The building is constructed from local stone, with limewashed walls and a slate roof. There are four rooms downstairs, and another four upstairs. The ground-floor rooms retain the oak panels and slate floors often found in well-built Lakeland houses of the period, and appropriate to their original function as drinking rooms in a public house. The cottage was acquired by the Wordsworth Trust in 1890 and opened to the public in 1891. The house is Grade 1 listed, and remains largely unchanged from Wordsworth's day. It receives approximately 70,000 visitors a year.

SAMPLING

Sampling and analysis by tree-ring dating of the timbers within Dove Cottage was requested by Adam Menuge, Senior Investigator in English Heritage's Architectural Investigations team, to complement a recently completed survey of the building (Menuge 2010) and to better understand its chronological development. It was hoped that dating the timbers would establish their age and determine the survival of the historic fabric.

This programme of tree-ring analysis was primarily concerned with the two sections (front and rear) of the main or 'house' range roof, of single principal-rafter trusses with double purlins (Fig 3a/b), along with its ground and first-floor ceiling beams (Fig 4a/b), and certain door and window lintels. In addition, a single cruck truss and window and door lintels to a rear 'museum' wing and undercroft store (Fig 5a/b) were thought to represent different phases of work. Other timbers were also considered of potential interest, if they were to prove suitable for tree-ring dating, where dating could potentially demonstrate the sequential development of the house as a whole.

A thorough and careful pre-sampling assessment was made of the potential of the timbers in all these areas for tree-ring analysis. This showed that the ground-floor ceiling beams of the 'house' range, along with the door and window lintels here, being derived from very fast-grown timbers, were unlikely to provide samples with the minimum of 50 rings deemed necessary for reliable analysis. The remaining timbers (those to the first-floor ceiling, the roof, and those to the museum wing and undercroft), however, although appearing to be somewhat marginal, were considered worth sampling.

Thus, from the oak timbers available, a total of 17 samples was obtained by coring. Each sample was given the code GSM-A (for Grasmere, site 'A') and numbered 01–17. The positions of these samples are marked on drawings made and provided by Adam Menuge, reproduced here as Figures 6a/b. Details of the samples are given in Table 1. In this table the timbers have been located or numbered on a site east to west, or south to north, basis as appropriate.

ANALYSIS

Each of the 17 samples obtained was prepared by sanding and polishing. It was seen at this time that seven samples had less than the minimum of 50 rings deemed necessary for reliable dating, and these samples were rejected from this programme of analysis. The annual growth-ring widths of the remaining 10 samples were, however, measured, the data of these measurements being given at the end of this report. The data of these 10 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), but unfortunately, there was no conclusive cross-matching between any samples, and no site sequences could be formed. Each of the 10 measured samples was then compared individually to an extensive series of reference chronologies for oak both that held by the Nottingham Tree-ring Dating Laboratory, and by others, such as the Sheffield Dendrochronology Laboratory, but there was no satisfactory cross-matching and dating.

INTERPRETATION AND CONCLUSION

None of the17 measured samples from this site can be combined to form a site sequence, and none of them can be dated individually. The lack of cross-matching and dating is possibly due to a combination of factors. Firstly, as may be seen from Table 1, although the two longest measured samples have 59 rings, a number of others are at, or close to, the lower limit of acceptability; while it is not impossible to cross-match shorter samples with each other, or sometimes to date them individually, it is often more difficult.

This difficulty may be compounded by the second factor. Although it cannot be conclusively proven by tree-ring analysis, it is possible, judging by the variation in the average ring-widths of the samples, that the Cottage contains timbers derived from trees originally growing in different places. Some trees may potentially have grown in woodlands, with others potentially growing in more open aspect conditions and even hedgerows; variation in sourcing makes makes cross-matching more difficult, particularly with samples as short as those found here.

It is possible, finally, that more than one phase of felling is represented by these 10, short, samples, again adding to the difficulties in developing well-replicated site data with greater potential for dating.

BIBLIOGRAPHY

Menuge, A, 2010 *Dove Cottage, Cumbria: An architectural analysis of Wordsworth's Grasmere home (1799–1808), its origins and evolution*, Engl Heritage Res Dep Rep Ser, 84/2010

TABLES

Table 1: Details of tree-ring samples from Dove Cottage, Grasmere, Cumbria

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Museum wing					
GSM-A01	East principal	nm	no h/s	------	------	------
GSM-A02	West principal	59	no h/s	------	------	------
GSM-A03	Lintel to ground-floor storeroom door	54	h/s	------	------	------
GSM-A04	Inner lintel to ground-floor storeroom window	59	h/s	------	------	------
GSM-A05	Outer lintel to ground-floor storeroom window	57	h/s	------	------	------
	House wing					
GSM-A06	Lower south purlin, bay 1	55	h/s	------	------	------
GSM-A07	Upper north purlin, bay 1	51	h/s	------	------	------
GSM-A08	Lower north purlin, bay 1	51	h/s	------	------	------
GSM-A09	First-floor ceiling spine beam, bay 1	54	h/s	------	------	------
GSM-A10	First-floor ceiling, south joist 3 from W, bay 1	nm	---	------	------	------
GSM-A11	First-floor ceiling, south joist 5 from W, bay 1	nm	---	------	------	------
GSM-A12	North principal rafter, central truss	nm	---	------	------	------
GSM-A13	Collar, central truss	nm	---	------	------	------
GSM-A14	Upper north purlin, bay 2	nm	---	------	------	------
GSM-A15	First-floor ceiling, north joist 2, bay 2	nm	---	------	------	------
GSM-A16	Upper west purlin, bay 3	55	h/s	------	------	------
GSM-A17	Lower west purlin, bay 3	56	h/s	------	------	------

*h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured

FIGURES

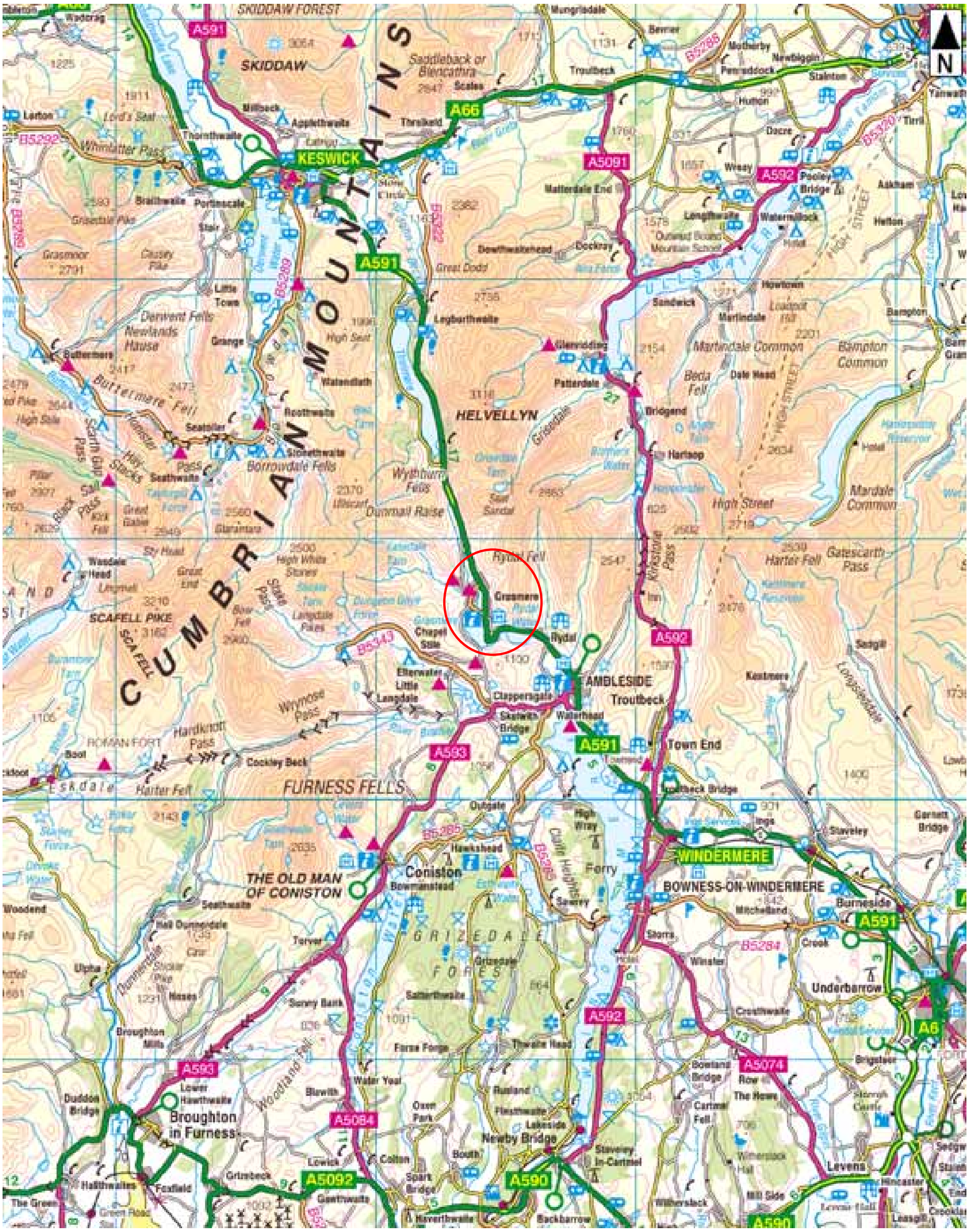

Figure 1: location of Grasmere, Cumbria (circled)

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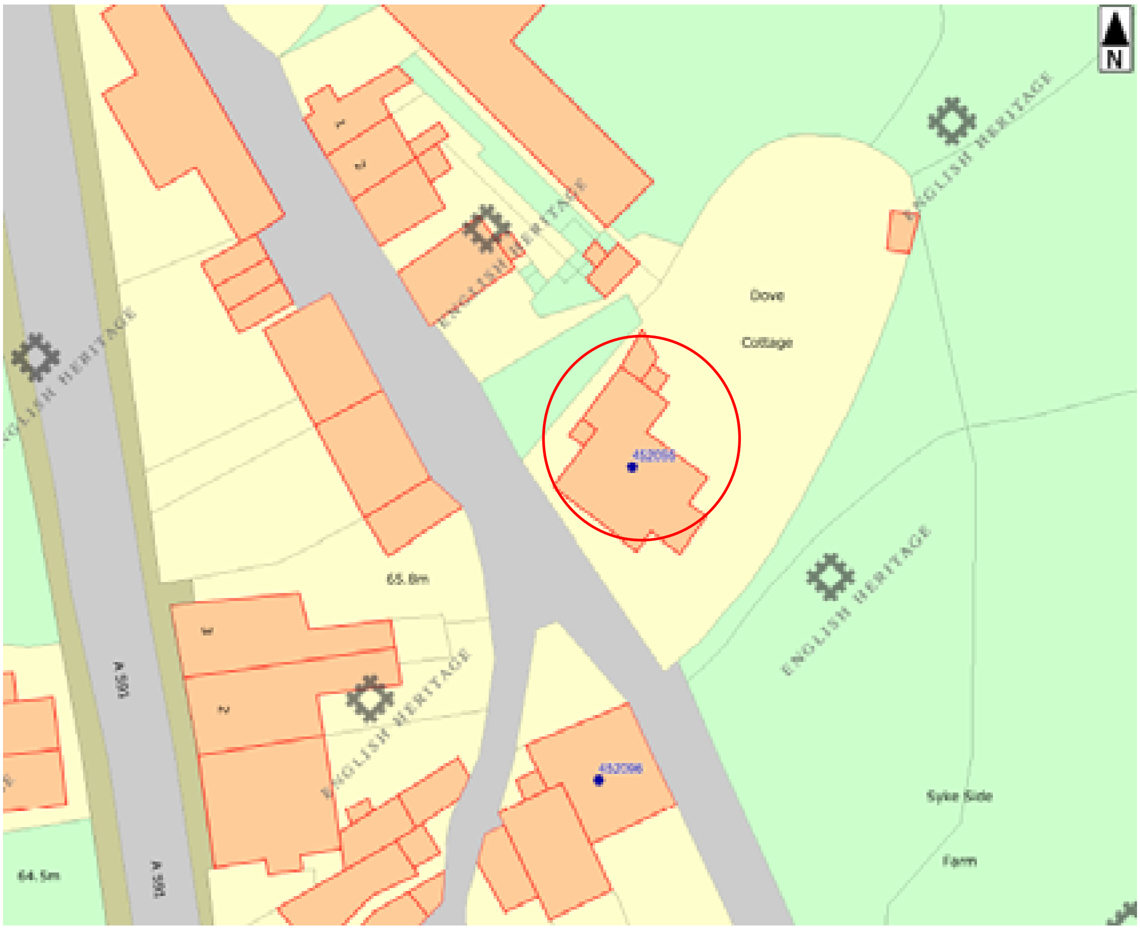

Figure 2: location of Dove Cottage

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Figure 3a/b: Front (top) and rear (bottom) roofs of the house range

Figure 4a/b: Ground (top) and first-floor (bottom) ceiling beams of the house range

Figure 5a/b: Cruck truss (top) and window lintels (bottom) to the 'museum wing'

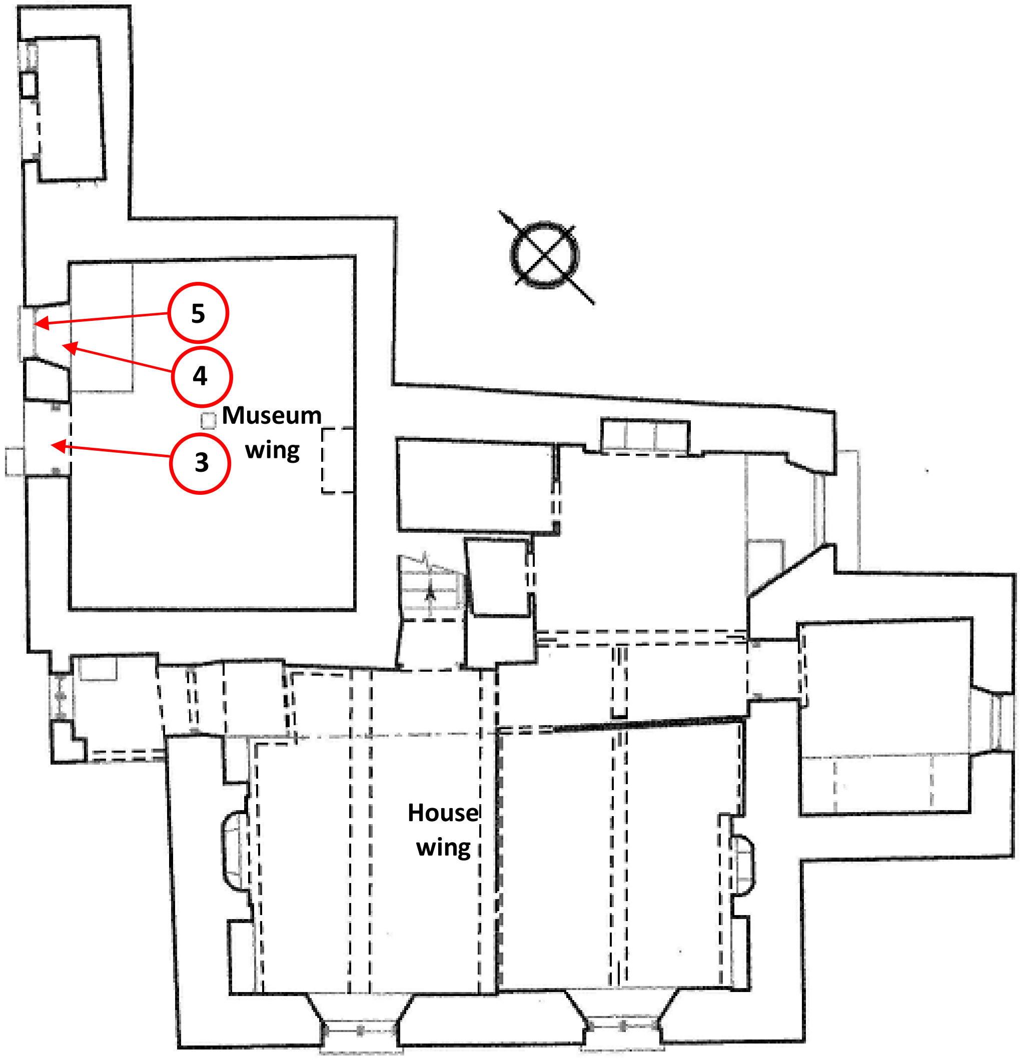


Figure 6a: Plan at ground-floor level showing approximate positions of sampled timbers (after Adam Menuge)

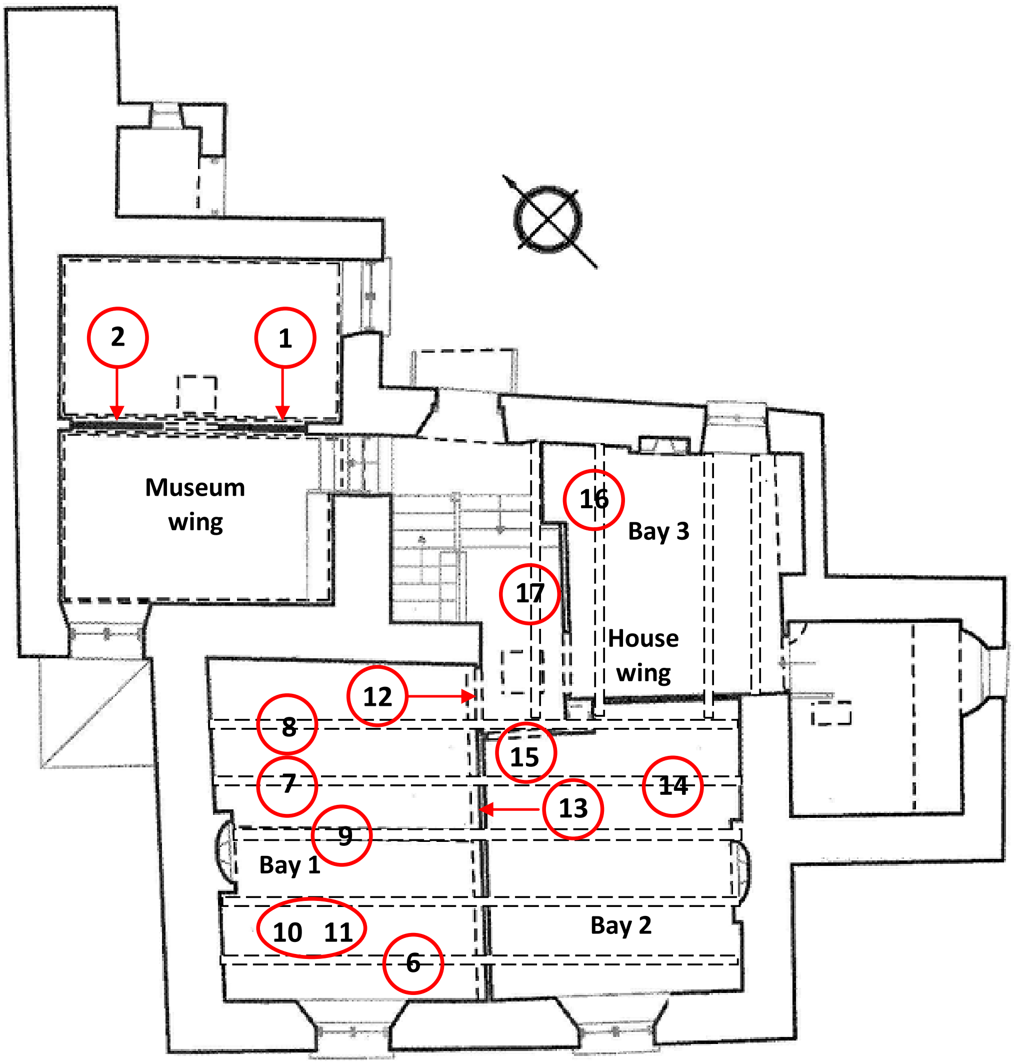


Figure 6b: Plan at first-floor level with roof timbers (dashed lines) superimposed, showing approximate positions of sampled timbers (after Adam Menuge)

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

GSM-A02A 59
26 40 37 49 26 29 26 34 32 24 19 24 20 24 21 25 25 18 29 44
39 37 39 57 39 40 72 91 140 172 152 184 155 210 131 143 103 123 92 124
132 99 146 81 97 99 154 138 96 173 107 114 84 99 177 118 125 191 398
GSM-A02B 59
22 42 35 49 30 28 28 32 29 26 14 26 19 26 24 23 19 22 33 46
34 39 45 56 49 33 78 85 144 168 160 176 153 215 119 136 111 132 78 118
121 110 151 78 97 102 151 135 103 163 115 107 89 94 172 125 117 190 462
GSM-A03A 54
207 175 189 168 175 145 120 150 158 134 126 98 113 241 193 53 73 61 60 55
70 94 59 51 51 58 50 141 137 153 126 177 116 88 48 47 79 189 161 110
191 125 203 131 179 236 134 220 275 262 133 180 163 177
GSM-A03B 54
185 186 188 172 171 151 112 156 169 134 125 111 105 195 204 45 98 64 68 57
65 88 61 51 49 48 68 127 146 145 123 163 122 87 45 48 71 191 163 118
193 118 202 141 182 219 134 217 302 244 131 179 160 170
GSM-A04A 59
302 252 220 255 332 314 319 235 261 204 201 282 273 237 252 192 432 338 355 299
259 315 190 213 190 203 235 262 236 346 288 203 169 164 123 149 155 167 111 106
112 67 65 53 71 87 67 77 119 92 110 77 111 103 59 55 54 77 68
GSM-A04B 59
317 236 246 272 358 298 318 232 262 214 187 271 278 249 258 200 442 359 380 285
247 314 197 195 183 209 238 245 276 386 246 188 182 163 126 146 164 165 113 110
110 63 67 53 66 91 72 83 115 100 103 78 103 103 55 50 58 70 59
GSM-A05A 57
247 234 245 285 313 291 300 306 243 301 243 199 295 301 244 224 232 218 176 166
143 134 127 106 76 105 77 92 110 133 104 104 89 124 64 75 59 49 68 102
58 51 55 88 101 60 84 199 212 309 256 431 606 446 596 181 243
GSM-A05B 57
247 266 274 283 324 282 318 283 248 287 239 209 289 306 248 226 228 218 178 181
141 147 124 97 83 106 78 94 105 140 106 115 92 114 76 76 52 47 61 115
62 40 57 79 99 69 67 210 200 316 258 411 616 440 566 179 244
GSM-A06A 55
450 315 462 320 357 375 458 461 488 427 284 183 163 194 321 311 267 400 393 254
313 273 262 323 272 239 222 198 164 235 234 191 218 229 169 198 255 190 196 284
258 176 152 201 155 242 148 142 172 133 200 162 135 135 198
GSM-A06B 55
467 322 482 321 344 378 447 445 486 415 269 172 157 198 339 308 257 390 395 252
307 286 246 317 269 237 230 201 176 228 241 186 223 216 160 182 258 200 199 271
257 169 160 179 172 232 152 150 176 135 199 158 135 132 190
GSM-A07A 51
170 312 176 221 168 140 156 117 146 142 204 175 139 134 106 139 98 119 119 152
174 134 139 123 128 127 114 160 143 169 156 148 151 176 164 119 129 128 122 153
145 156 179 159 124 107 122 130 127 131 141
GSM-A07B 51
169 319 177 238 162 121 159 117 139 158 191 164 148 128 95 129 100 120 122 155
169 136 148 122 121 134 110 152 147 170 151 149 155 170 163 120 130 128 126 150
141 158 180 159 124 104 120 131 122 131 143
GSM-A08A 51
297 215 321 213 241 209 124 115 163 229 275 169 206 222 202 266 233 182 241 264

140 125 231 290 310 294 255 339 295 265 294 165 175 281 223 270 269 222 146 147
158 213 144 127 230 226 209 193 108 182 207
GSM-A08B 51
300 215 316 232 220 218 134 108 160 231 254 176 198 230 197 275 229 182 242 284
143 117 225 292 321 295 238 350 299 264 294 175 169 283 226 256 276 201 182 143
153 196 156 123 242 235 197 199 104 166 214
GSM-A09A 54
889 908 769 950 970 980 840 488 695 612 606 721 655 522 626 473 143 89 129 195
295 412 185 168 179 155 158 154 162 237 284 231 240 180 338 345 339 282 165 122
136 243 383 589 592 482 332 318 233 169 173 283 341 380
GSM-A09B 54
858 926 817 959 972 974 854 490 674 635 636 731 676 525 649 463 143 99 143 248
325 405 207 220 218 153 134 151 155 206 262 219 241 202 341 376 338 287 170 138
143 252 403 588 595 515 330 307 247 159 189 260 344 380
GSM-A16A 55
209 304 577 577 548 400 262 251 415 312 419 334 268 347 332 607 434 257 337 290
224 258 198 181 223 220 184 194 293 158 165 301 180 208 149 159 143 221 207 119
114 80 103 154 122 86 106 121 114 117 110 307 538 445 534
GSM-A16B 55
209 271 596 606 620 435 280 255 418 298 407 360 261 341 344 561 450 262 351 311
205 242 205 190 216 220 176 188 302 142 186 296 209 224 146 172 149 209 194 136
121 73 104 153 137 73 101 103 126 114 108 298 540 480 514
GSM-A17A 56
467 303 119 109 104 289 389 371 204 111 117 162 288 338 568 307 350 269 217 507
672 417 270 267 353 542 605 275 384 293 266 240 487 518 533 678 716 429 335 229
153 140 148 199 224 263 243 264 307 175 146 80 107 133 127 210
GSM-A17B 56
478 318 138 107 103 247 385 415 181 109 107 176 296 347 557 306 351 261 207 545
656 344 290 280 335 465 569 283 401 344 242 227 495 541 530 700 705 396 345 225
157 148 161 231 239 261 242 261 299 173 149 74 116 139 128 191

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	

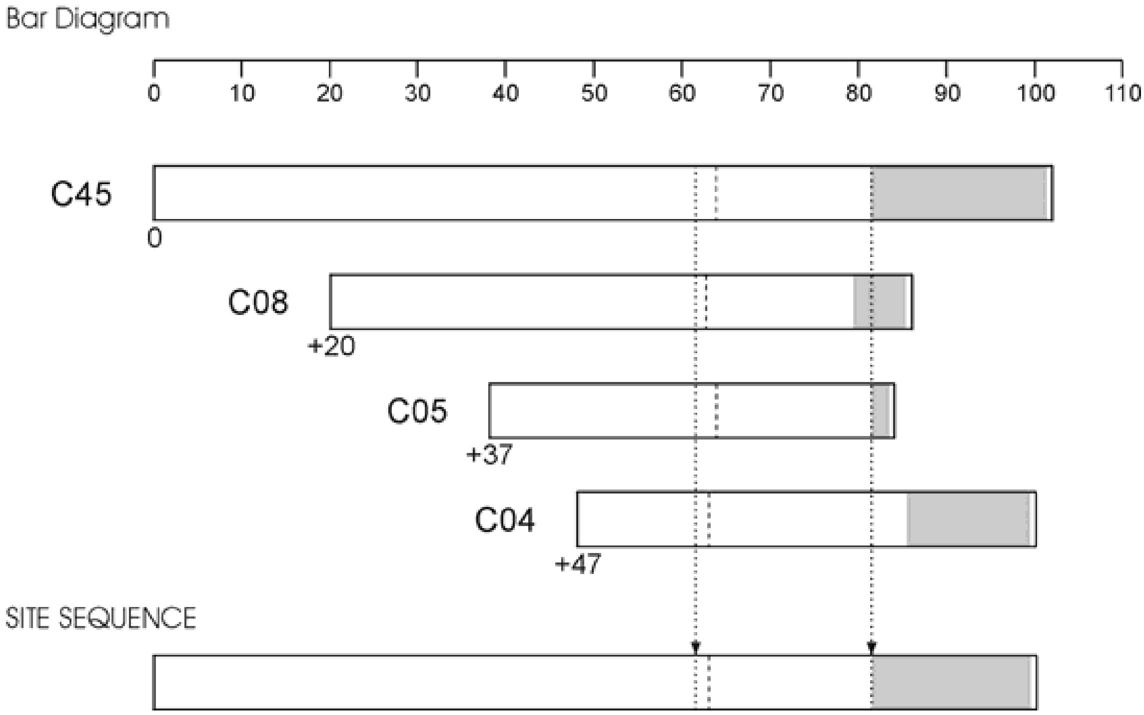


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

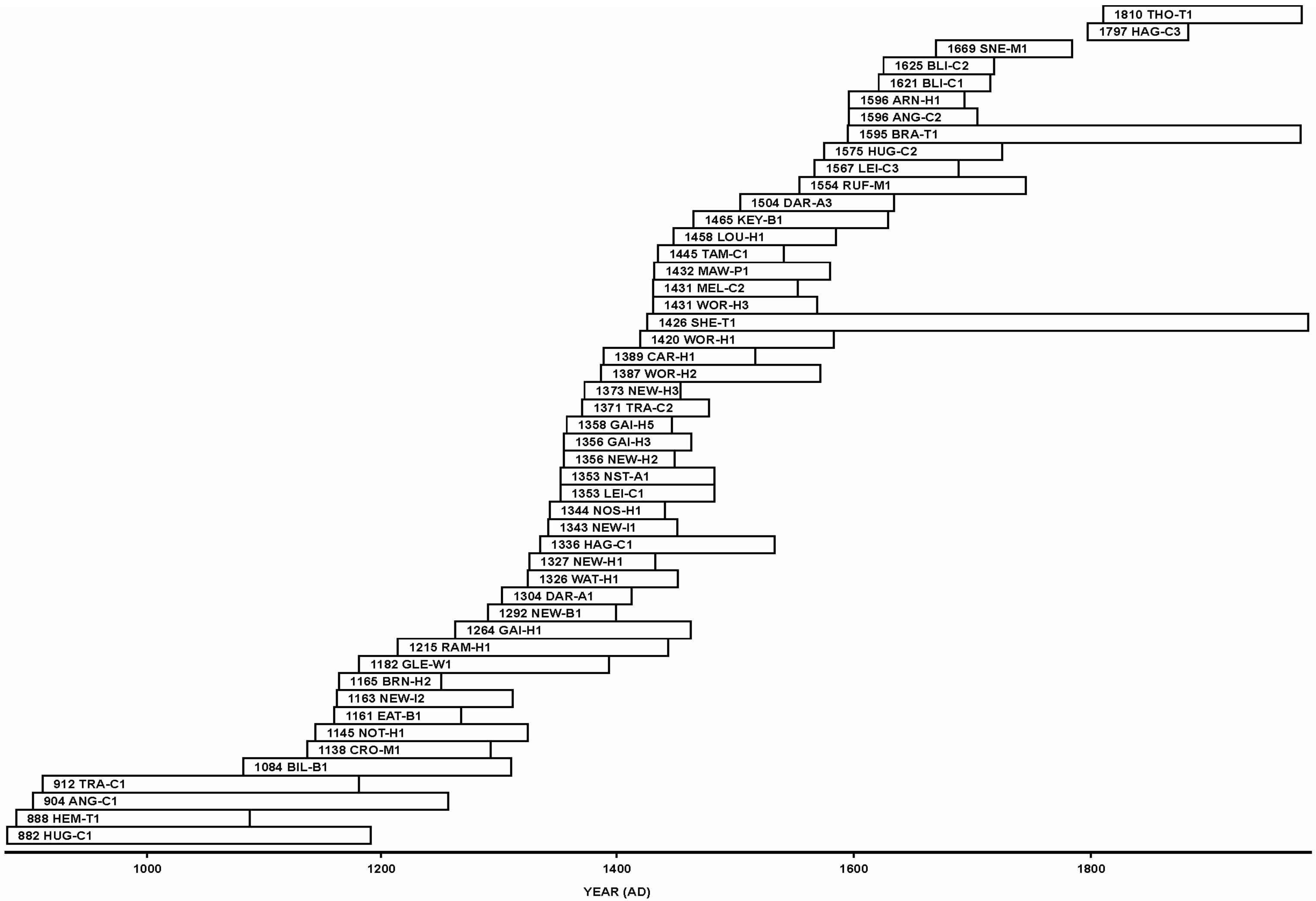
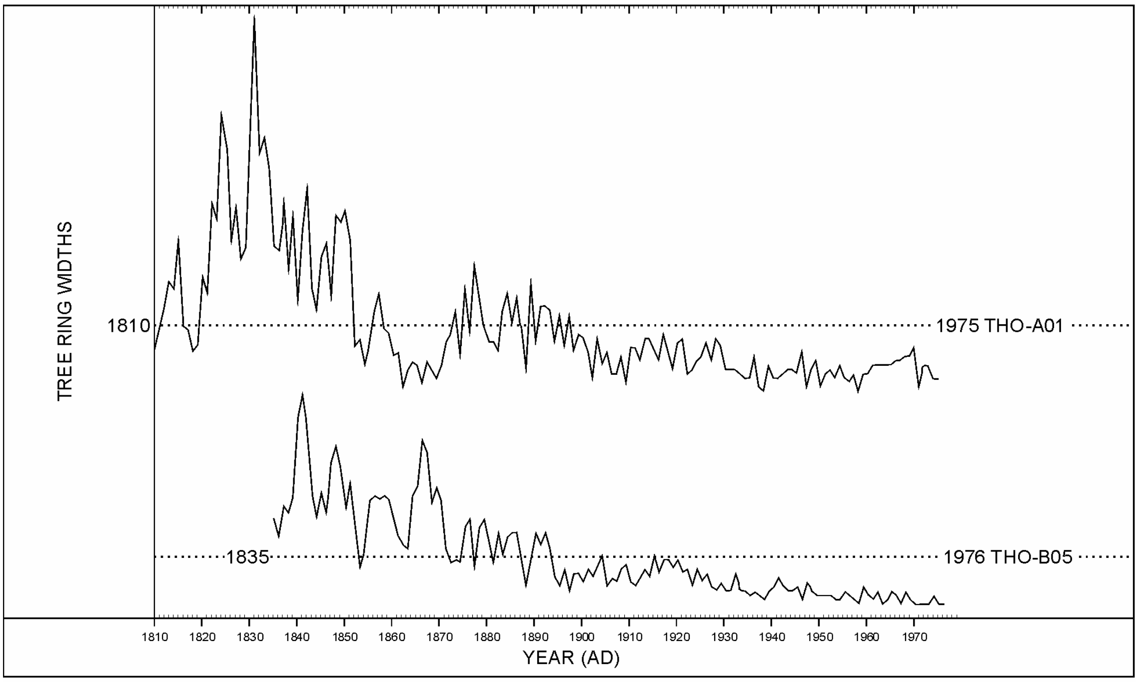


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

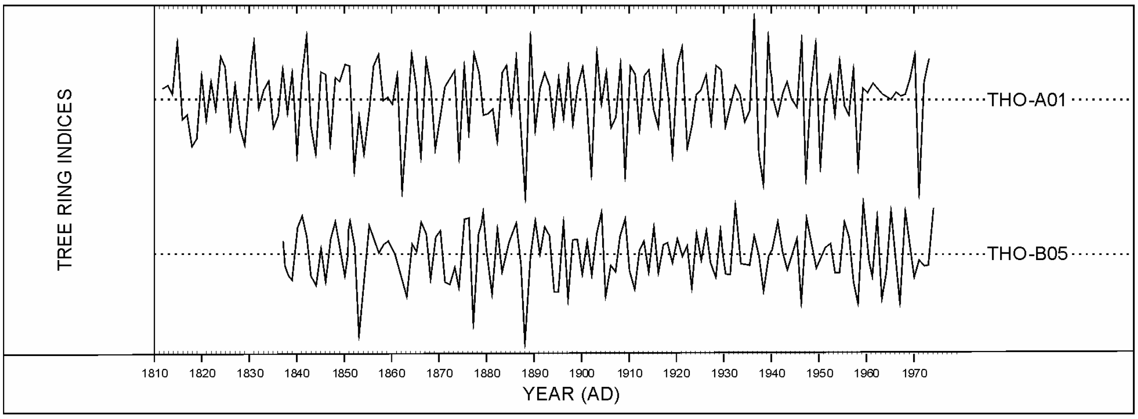


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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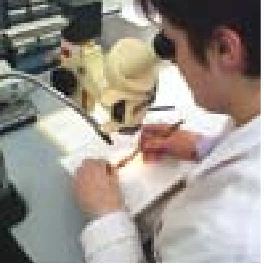
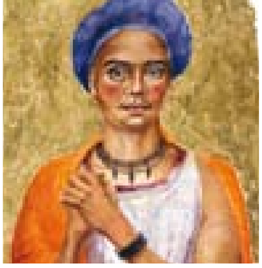



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