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GREYFRIARS CHURCH, GREYFRIARS WALK, OFF SOUTHGATE STREET, GLOUCESTER
TREE-RING ANALYSIS OF TIMBERS REUSED IN THE ADJACENT GREYFRIARS HOUSE

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard and Cliff Litton

ARCHAEOLOGICAL SCIENCE

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Research Department Report Series 80/2007

Greyfriars Church, Greyfriars Walk, off Southgate Street, Gloucester Tree-Ring Analysis of Timbers Reused in the Adjacent Greyfriars House

Alison Arnold[1], Robert Howard[1] and Cliff Litton[2]

Summary

Core samples were obtained from five different oak timbers originally belonging, it is believed, to an early-sixteenth century re-roofing phase of the former Franciscan Greyfriars Church, Gloucester, these timbers being possibly subsequently reused within Greyfriars House, an adjacent early nineteenth century building. The analysis of these five samples produced a single site chronology, GLOESQ01, having a combined overall length of 134 rings. This site chronology was dated as spanning the years AD 1321 to AD 1454.

None of the sampled timbers retain a clearly identifiable heartwood/sapwood boundary and it is thus not possible to give a reliable estimate of the likely felling date range for the timbers. The timber with the latest dated ring is, however, unlikely to have been felled before AD 1469. It is possible therefore, but not proven by tree-ring analysis, that the timbers do belong to a pre- Dissolution phase of Greyfriars Church, which, on the basis of documentary evidence, is known to have been re-roofed by AD 1519.

Other timbers, thought to have been removed from Greyfriars during stabilization works in the AD 1960s, are held in store at Toddington near Cheltenham. These timbers were also examined for possible tree-ring dating but all of them proved to be unsuitable for analysis.

Keywords

Dendrochronology
Standing Building

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Introduction

A church of the Greyfriars, or Franciscan, order is believed to have been established on this site in Gloucester (SO 831 184, Figs 1 and 2) as early as AD 1230, this foundation being funded chiefly by a bequest of Thomas of Berkeley. Subsequently, further monastic buildings were constructed to the south of the church, with a cemetery to the north of it. These early-thirteenth century buildings were then replaced in the early-sixteenth century, the work again being funded by the Berkeley family. It is known from documentary sources that the church was substantially rebuilt from AD 1519 onwards by Maurice, Lord Berkeley (Ferris *et al* 2001, 99). At the Dissolution of the monasteries in AD 1538, the site, described at that time as *'a goodly house, much of it newly builded'*, passed to Henry VIII. Of these early-sixteenth century buildings, all that now remains is the roofless shell of the nave and north aisle. These are divided by a central arcade of seven bays supported on lozenge-shaped moulded piers with moulded capitols and bases. Views of the ruins are given in Figures 3a/b.

Although now open to the sky, one small area of the pre-Dissolution roof, at the east end of the nave, appears to have survived *in situ* until it was dismantled by the Ministry of Works in AD 1968 (Fig 4). The surviving timbers were then dispersed to various sites, some, for example, possibly being held at the Toddington Museum Store, near Cheltenham. It is not certain, however, that the timbers held there are definitely from the Greyfriars site.

It is believed that other medieval timbers from Greyfriars were incorporated into Greyfriars House, now occupied by Gloucester Library Services, built in the early-nineteenth century and attached to, and forming part of, the nave and north aisle of the church (Fig 5). These incorporated timbers form lintels over four second-floor windows to the west front of the nineteenth century building and a wall plate along its south side. All such timbers contain lap-mortices and joint beds which of course serve no purpose in their present locations. Views of the timbers are given in Figure 6a/b.

Sampling

Sampling and analysis by tree-ring dating of the small number of timbers incorporated into Greyfriars House was commissioned by English Heritage, as was an assessment of the timbers at the Toddington store that were thought likely to be associated with Greyfriars Church. The purpose of this was to determine whether or not these timbers could be from the early-sixteenth century rebuilding phase of the monastic site.

The majority of these stored timbers, particular those which are full-sized beams, are stored in large loose piles on shelves, or more correctly, racks. There are a good number of other slightly smaller beams held, as well as what appear to be still-smaller, almost offcut-sized, timbers held in large wire-mesh bins or containers. Unfortunately any documentation relating to these timbers has been misplaced. In many cases not only is the beam type not recorded, but the location within the building is also not known. In many cases it is even uncertain as to which particular building some timbers have come from.

In respect of the timbers most strongly believed to come from Greyfriars, it is clear that all of them, a series of wind braces, have too few rings for reliable analysis; one timber had as few as 10 rings, the best had only 30 rings or so. Not only are they derived from fast-grown trees, but they are very thin pieces, with little cross-sectional growth, and have been cut tangentially. In any case, of the dozen or so timbers potentially available, only one appeared to be possibly original, being more curved than the others and in an advanced state of decay. All the other wind braces appeared to straighter and to be more cleanly cut, and showed some evidence of working with a mechanical, possibly circular, saw. It is possible that these other timbers are later repair pieces.

Samples were thus obtained, by coring, only from the five timbers available in Greyfriars House itself. Each sample was given the code GLO-E (for Gloucester, site 'E') and numbered 01–05. The positions of these samples are marked on a simple plan made by Quattro Design, Architects Ltd, Bristol and Gloucester, and provided by English Heritage. This plan is reproduced here as Figure 7. Details of the samples are given in Table 1. In this Table the samples are identified and located from north to south.

The Laboratory would like to take this opportunity to thank the Peter Clark and other members of Gloucester Library Services for their help in arranging access to the building and for their cooperation in sampling. We would also like to thank Heather Bird, Tony Musty, and Nicholas Molyneux for their considerable help in examining the timbers in the Toddington store.

Analysis

Each of the five samples obtained was prepared by sanding and polishing, and their annual growth-ring widths were measured. The data of these growth-rings were then compared with each other. At a minimum value of t=4.5 a single group comprising all five samples could be formed, the samples cross-matching with each other at relative off-set positions as shown in the bar diagram Figure 8.

The samples were combined at these offset positions to form GLOESQ01, a site chronology of 134 rings. Site chronology GLOESQ01 was then satisfactorily dated by comparison to a number of relevant reference chronologies for oak as spanning the years AD 1321–1454. The evidence for this dating is given in the t-values of Table 2.

Interpretation and conclusion

Analysis by dendrochronology has produced a single site chronology, GLOESQ01, comprising five samples, its 134 rings dated as spanning the years AD 1321–1454. From a visual inspection at the time of sampling, it would appear that none of the five timbers retain any clear trace of sapwood on them, nor do they appear to retain the heartwood/sapwood boundary. This has either been removed by the original carpenters or is hidden by the brickwork presently surrounding the timbers. It is thus not possible to calculate a reliable felling date range for these timbers. It is unlikely, however, that the timber with the latest dated ring, the wall beam along the south side, was felled before AD 1469, this range being based on a 95% probability limit of 15–40 sapwood rings the timber is likely to have had. It is of course possible that the timbers were felled much later than AD 1469.

Thus, while the exact felling date of any of the timbers cannot be reliably calculated, it would certainly be possible for the timbers to have been felled from the later fifteenth century onwards. As such it is certainly possible that they are from the monastic Greyfriars site.

The timbers stored at Toddington, on the other hand, remain undated, and it is not possible to say whether they are from Greyfriars Church or not.

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Table 1: Details of samples from Greyfriars House, Gloucester

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
GLO-E01	Window lintel 1 (north)	110	no h/s	AD 1336	------	AD 1445
GLO-E02	Window lintel 2	98	no h/s	AD 1335	------	AD 1432
GLO-E03	Window lintel 3	93	no h/s	AD 1347	------	AD 1439
GLO-E04	Window lintel 4	104	no h/s	AD 1321	------	AD 1424
GLO-E05	Beam along south wall	113	no h/s	AD 1342	------	AD 1454

* h/s = heartwood/sapwood boundary

Table 2: Results of the cross-matching of site chronology GLOESQ01 and relevant reference chronologies when first ring date is AD 1321 and last ring date is AD 1454

Reference chronology	Span of chronology	*t*-value	
16–18 Hightown, Hereford	AD 1302–1498	9.6	(Boswijk and Tyers 1997)
Worcester Commandery	AD 1284–1473	8.2	(Arnold *et al* forthcoming)
Mercer's Hall, Gloucester	AD 1289–1541	8.1	(Howard *et al* 1996)
2 School Rd, Wellesbourne, Warwicks	AD 1287–1429	6.7	(Alcock *et al* 1989)
England	AD 401–1981	6.6	(Baillie and Pilcher 1982 unpubl)
Worcester Cathedral	AD 1286–1424	6.6	(Arnold *et al* 2003)
Sinai Park, Burton on Trent, Staffs	AD 1227–1750	6.6	(Tyers 1997)
East Midlands	AD 882–1981	6.1	(Laxton and Litton 1988)

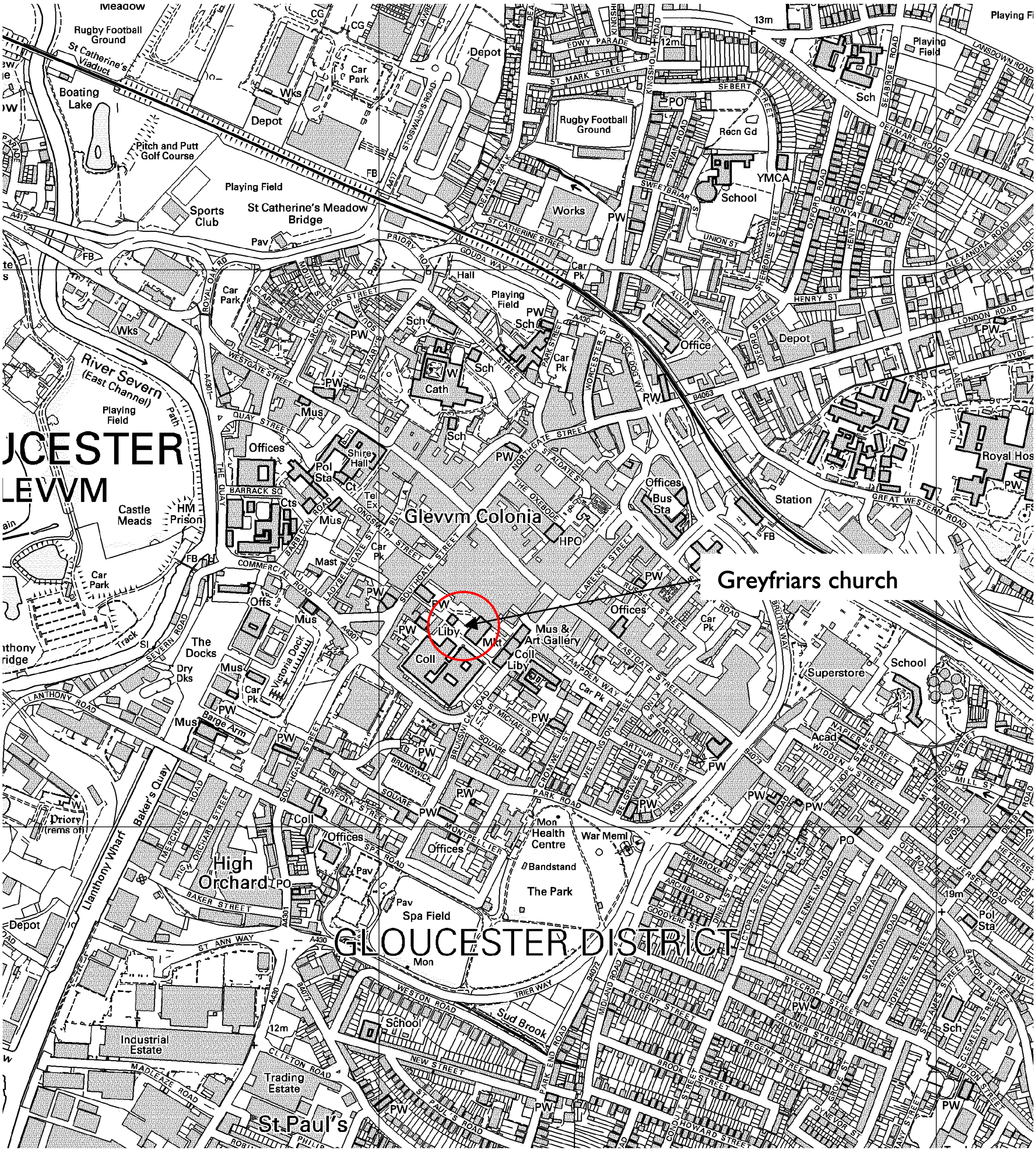


Figure 1: Map to show general location of the Greyfriars Church and Greyfriars House.

Figure 2: Map to show location of Greyfriars.

Figure 3a/b: Views of Greyfriars Church, from the south (left (note the rear of Greyfriars House attached to the west end)) and from the east looking west (right)

Figure 4: View of the roof of Greyfriars Church during dismantling works (viewed from the east looking west) (English Heritage/NMR)

Figure 5: View of the west frontage of Greyfriars House

Figure 6a/b: The incorporated timbers; the window lintels (above) and wall plate (below)

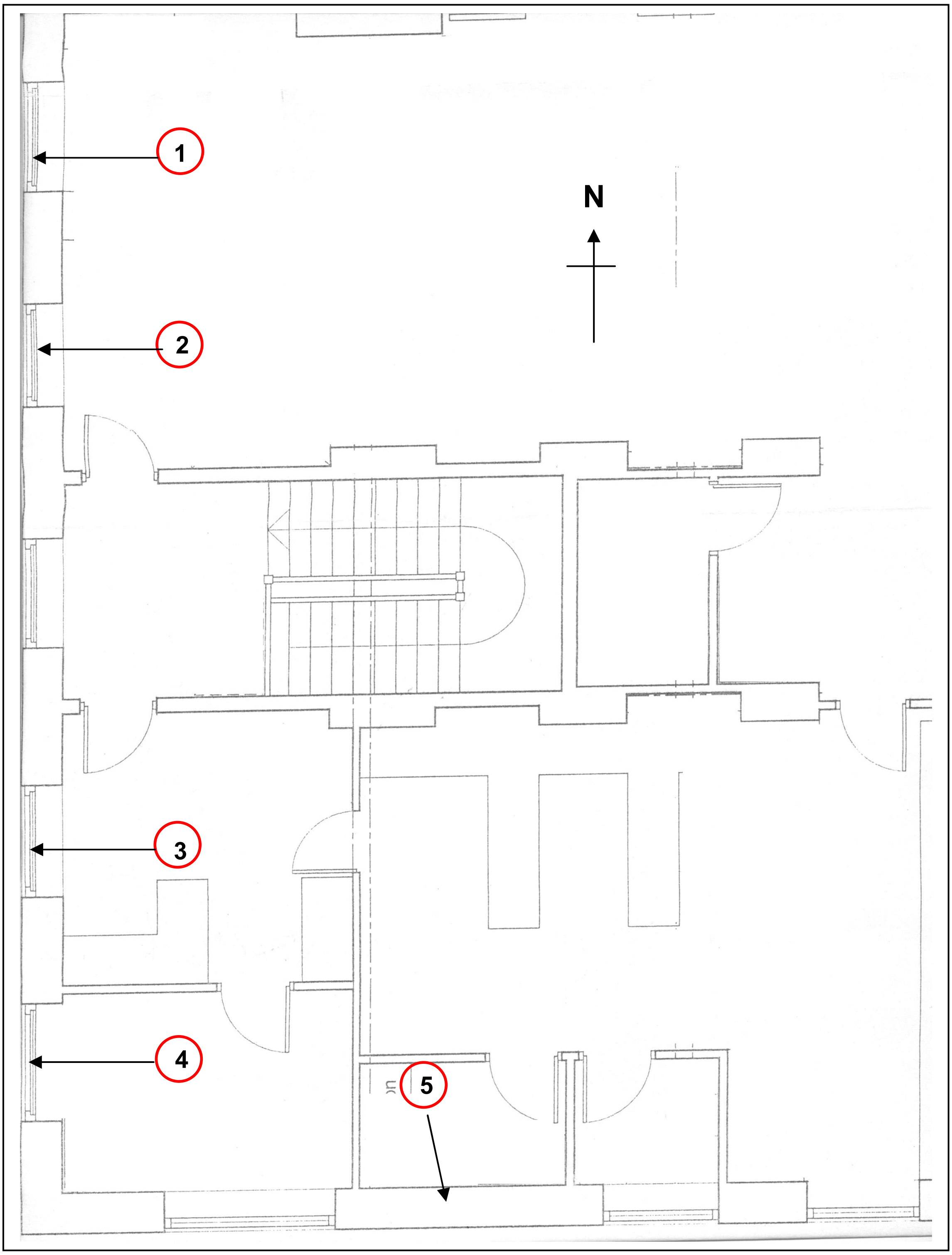
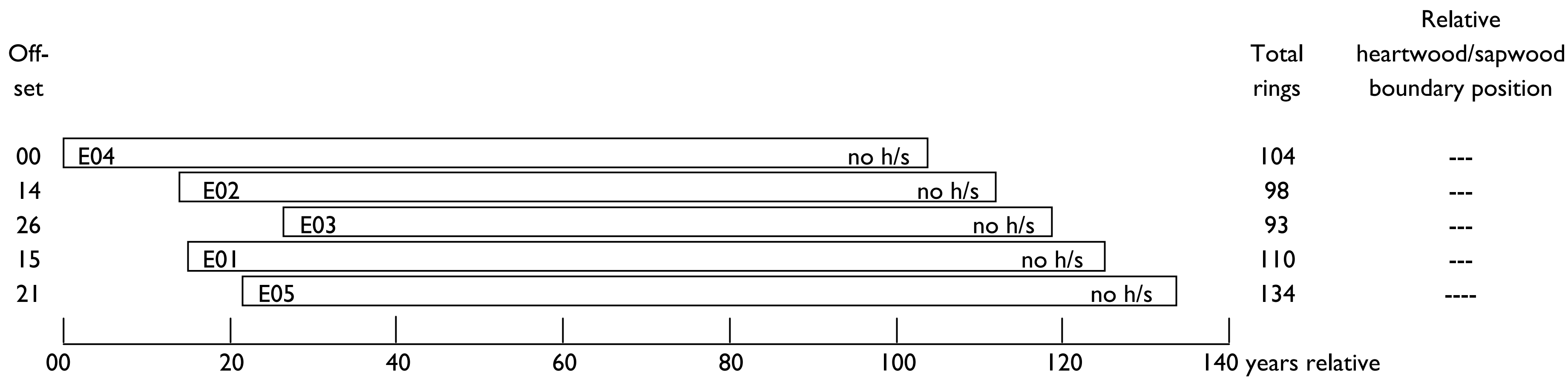


Figure 7: Plan to show sample locations (after Quattro Design, Architects Ltd)



white bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 8: Bar diagram of the samples in site chronology GLOESQ01

Data of measured samples – measurements in 0.01 mm units

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GLO-E01A 110
 385 383 334 342 308 334 317 322 264 502 330 219 280 283 191 221 196 211 129  85
 117 164 125 125 127 153 254 199 209 206 197 134 138 187 145 139 137 156 135 160
 123 126 147 237 205 149 171 156 160 184 168 218 223 251 209 194 160 118 115 137
 110 149 138 150 139 157 125 157 220 223 199 186 193 185 225 215 123 130 133 156
 143 135 109 105 131 146 164 187 173 190 156  95 195 144 205 170 171 136 190 229
 139 116 171 109 148 128 156 139 158 150
GLO-E01B 110
 424 398 333 343 320 357 290 325 283 475 347 209 275 298 215 188 184 219 132  87
 112 158 123 132 133 162 255 195 228 200 200 138 137 177 159 141 138 127 151 148
 102 128 159 239 178 166 185 138 170 173 165 219 231 243 203 200 155 119 124 129
 106 143 153 155 134 153 121 171 200 226 212 192 194 197 220 197 144 145 118 173
 130 138 107 122 114 151 153 199 165 173 162  98 184 145 201 175 171 131 189 239
 141 127 164  92 139 130 160 145 152 172
GLO-E02A 98
  85  59  98 128 117 116 150  92  74 116 108 118 156 122 114  75  82  79 120 148
 171 194 244 334 475 333 343 461 426 374 213 248 193 235 286 226 186 204 154 186
 185 208 176 183 279 216 150 193 156 169 177 195 200 195 219 170 229 176 140 142
 143 212 158 158 175 232 231 190 238 187 146 125 155 190 168 121 135 161 166 178
 178 142 189 144  82 135 151 128 165 161 159 119 171 184 170 134 106 197
GLO-E02B 98
  78  62 112 143 116 118 156  91  82 143 119 115 138 126 111  79  84  99 122 150
 172 177 207 366 436 333 340 424 411 366 205 245 194 231 277 233 185 207 146 174
 178 210 176 193 269 255 167 186 157 167 177 195 192 184 232 161 233 156 160 131
 155 211 141 159 170 222 233 206 246 172 148 143 151 193 164 126 133 160 165 188
 176 157 121 141  90 132 150 128 151 159 146 143 168 178 171 146 114 195
GLO-E03A 93
 356 400 399 265 278 184 264 256 146 160 216 235 174 135 210 334 379 368 275 245
 181 238 246 185 189 223 176 165 201 164 155 180 288 238 188 161 170 165 205 399
 262 311 264 258 235 202 227 226 198 198 187 201 209 193 213 198 177 203 230 249
 271 241 253 266 197 165 116 119 139 121 147 126 109 149 165 163 217 162 200 139
  75 113 115 136 156 147 125 119 174 146 113 130 116
GLO-E03B 93
 412 410 384 264 207 244 279 264 161 167 189 179 174 138 207 339 375 366 269 246
 177 231 255 183 183 206 178 163 207 164 133 166 245 228 166 170 191 228 223 306
 260 316 309 324 245 188 223 260 190 211 197 207 187 197 206 205 173 197 236 250
 235 269 238 285 203 168 118 122 147 120 149 125 119 160 158 169 154 171 188 135
  80 121 128 139 185 144 125 120 174 152 111 123 110
GLO-E04A 104
 155 195 160 100  82  54  54  62  67  98 120 131 123 153 238 184 191 234 226 198
 240 191 228 301 284 261 226 294 302 213 206 194 294 342 228 195 232 190 265 162
 195 225 279 265 134 156  99 139 178 159 125 116 132 112 118 145 147 138 135 127
  89 118 111  96 121 158 138 167 160 168 205 211 148 156 146 198 172 191 161 154
 149 123 149 159 106 142 109 134 176 134 123 140 122 144 108 168 146 137  98 170
 195 140 167 197
GLO-E04B 104
 167 192 164 119  88  44  57  59  71  86 117 113 126 161 212 218 186 247 246 194
 237 198 210 294 280 261 221 277 321 231 209 206 294 352 225 182 232 194 228 175
 183 234 267 268 138 143 103 125 190 155 121 126 118 116 122 135 144 138 136 137
 104 100 122  98 123 150 154 173 168 164 194 198 162 148 157 185 186 188 166 144
 145 124 162 164 105 145 104 130 169 140 123 145 114 142 112 169 154 129  89 173
 170 149 154 194
GLO-E05A 113
 198 209 138 178 150 127 210 207 146 168 136 186 181  77 174 211 152 165 113 150
 178 224 244 193 185 146 117 178 146 142 123 106 150 135 104 118 128 134 127 108
  96 110 107  77 139 145 188 159 184 167 167 181 185 161 235 266 282 306 261 261
 215 172 230 213 188 209 197 237 166 167 204 192 141 178 172 185 150 104 167 186
 188 290 211 223 222 166 190 219 246 244 262 215 237 263 233 188 159 100 141 129
 117 124 165 162 154 150 161 152 124 159 177 207 117
GLO-E05B 113
 239 201 145 180 152 129 210 211 143 157 149 179 174  80 173 207 159 166 111 149
 177 230 268 163 183 162 128 193 115 130 122 110 147 122 108 112 137 133 109 107
 103  98  97  81 113 153 188 170 166 190 165 181 182 167 247 225 285 294 245 256
 159 215 216 197 205 221 212 197 171 179 194 196 147 182 188 170 158  98 172 189
 194 305 178 242 196 154 208 205 250 242 227 200 253 266 241 182 140 119 141 130
  89 129 165 161 166 145 154 158 141 165 165 157 116
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building*' (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. *Inspecting the Building and Sampling the Timbers*. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8 to 10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

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

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

Figure 3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is 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 4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

2. *Measuring Ring Widths*. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. *Cross-matching and Dating the Samples*. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

   This is illustrated in Figure 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a *site sequence* of the building being dated and is illustrated in Figure 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence 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 straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. *Estimating the Felling Date*. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree. Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases. The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called *sapwood* rings, are usually lighter than the inner rings, the *heartwood*, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

5. *Estimating the Date of Construction*. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. *Master Chronological Sequences*. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. *Ring-width Indices*. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar 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	

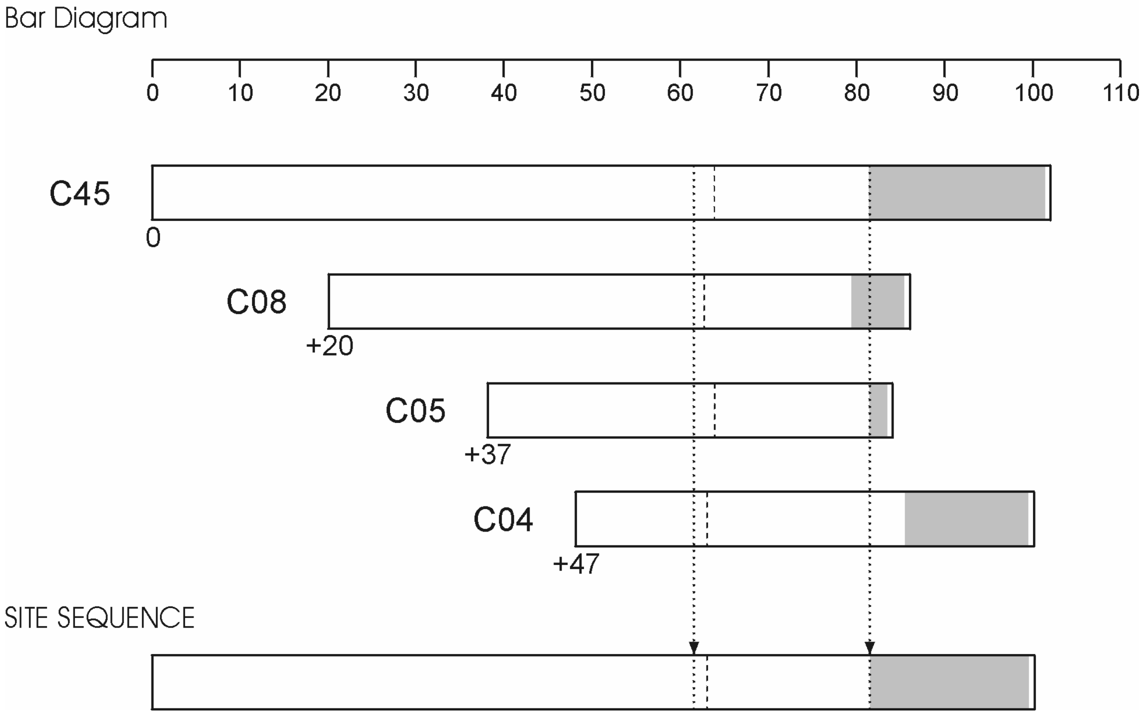


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t*-values.

The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

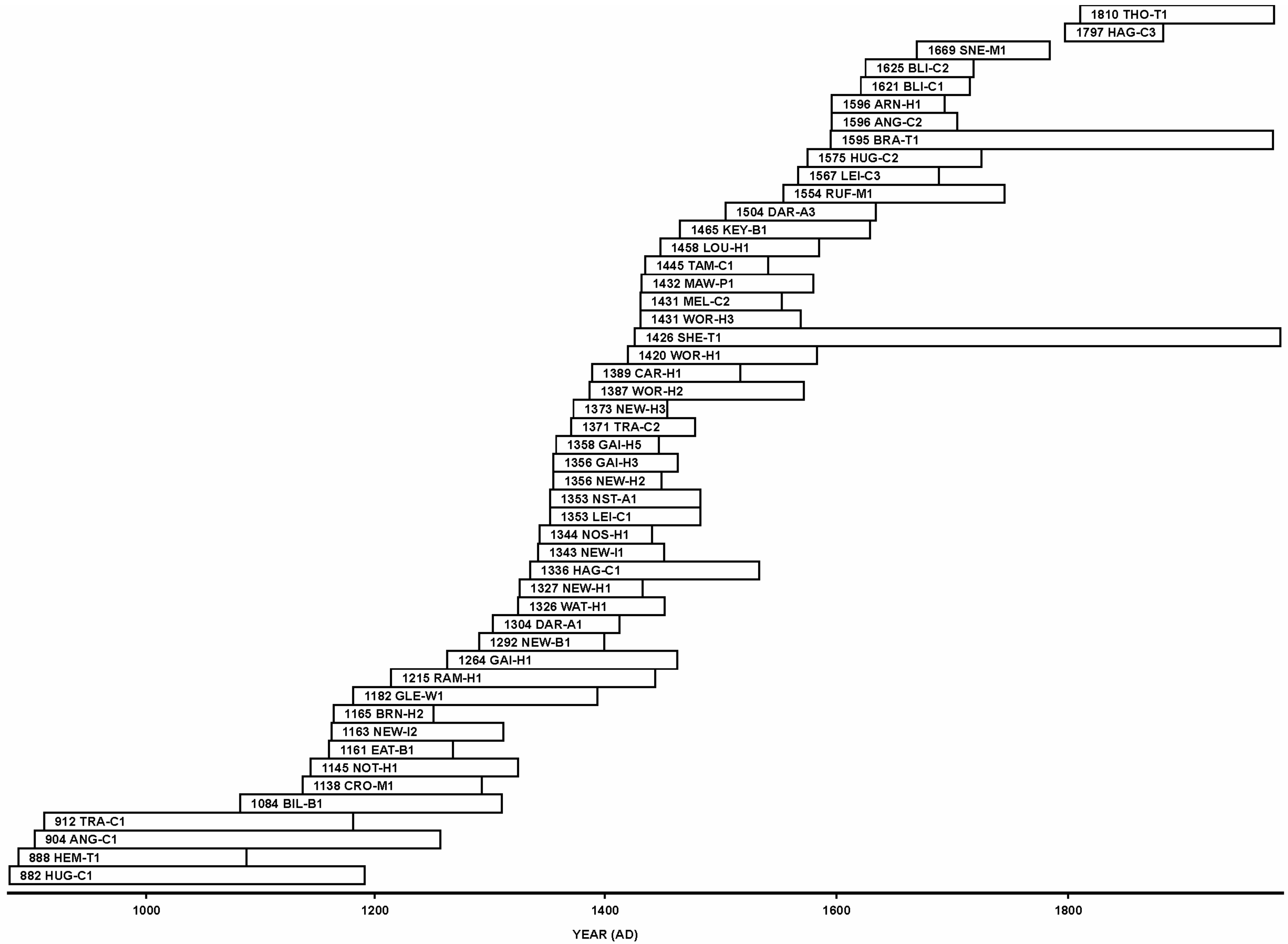
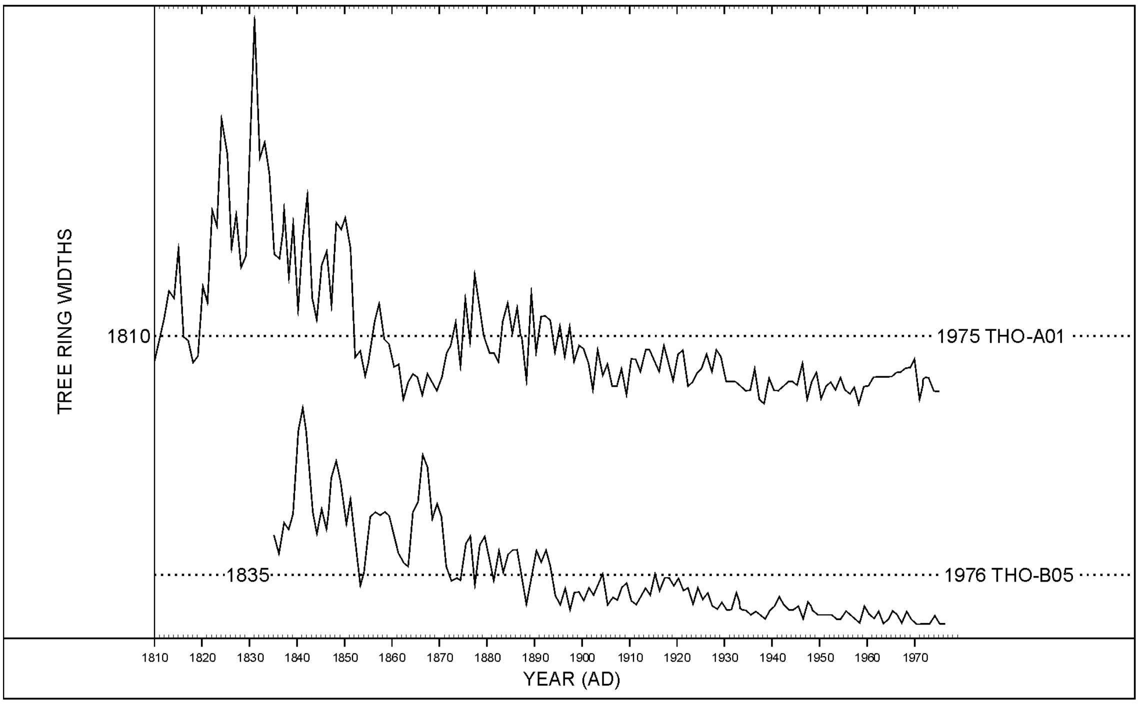


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

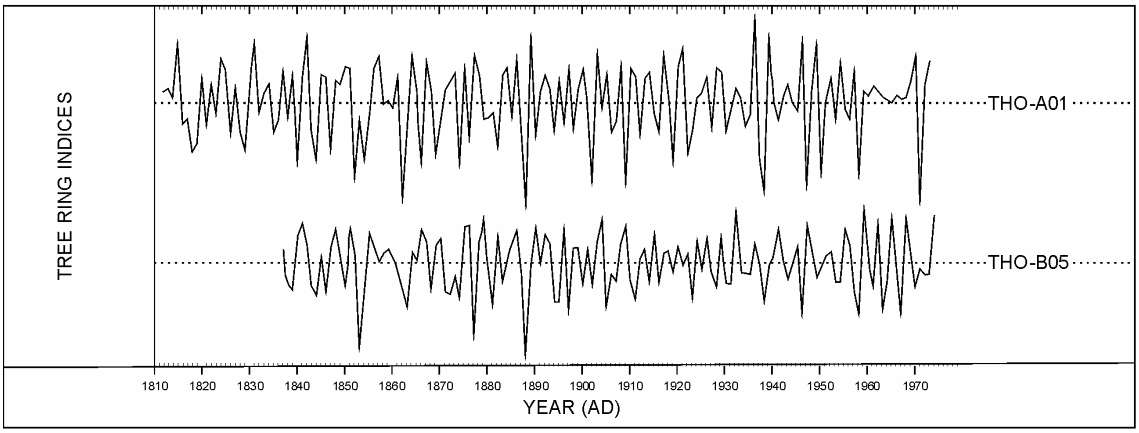


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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