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CHURCH OF ST MARY, CHURCHGATE, STOCKPORT, GREATER MANCHESTER
TREE-RING ANALYSIS OF TIMBERS FROM THE VESTRY ROOF

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY

Dendrochronological analysis was undertaken on 10 of the 13 core samples obtained from timbers to the vestry roof of the Church of St Mary, Stockport. This analysis produced a single dated site chronology comprising six samples having an overall length of 114 rings. These rings are dated as spanning the years AD 1510–1623. Interpretation of the sapwood on the dated samples would suggest the likelihood that the timbers represented were cut as part of a single episode of felling in AD 1623.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to take this opportunity to thank the Reverend Scoones of St Mary's Church, for his enthusiasm and support for this programme of tree-ring analysis, and for being so helpful and cooperative at the time of sampling. We would also like to thank Mike Goulding, site agent for Lambert Walker Conservation and Restoration Ltd, building contractors. Finally we would like to thank Shahina Farid and Cathy Tyers (English Heritage Scientific Dating Team) for commissioning this programme of tree-ring dating, and for their valuable contributions to this report.

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CONTENTS

Introduction 1
Sampling 1
Analysis and Results 2
Interpretation and Conclusion 2
Bibliography 4
Tables 5
Figures 7
Data of Measured Samples 12
Appendix: Tree-Ring Dating 15
The Principles of Tree-Ring Dating 15
The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory 15
1. Inspecting the Building and Sampling the Timbers. 15
2. Measuring Ring Widths. 20
3. Cross-Matching and Dating the Samples 20
4. Estimating the Felling Date. 21
5. Estimating the Date of Construction. 22
6. Master Chronological Sequences. 23
7. Ring-Width Indices. 23
References 27

INTRODUCTION

The parish church of St Mary occupies an elevated position adjacent to the market place in Stockport, dominating the old town centre (Fig 1). According to the listed building description, the church comprises a three-bay chancel, a five-bay nave which is galleried on the north and south sides, and a west tower with north-west and south-west porches. Much of the church was rebuilt in AD 1813–17 in the Perpendicular Gothic style to the design of Robert Goldsmith (revised by Lewis Wyatt on advice from John Soane). It then underwent further repair and alteration in AD 1882 to the designs of J S Crowther. The church also has an attached north-east two-cell block which forms the rector's and choir vestry (Fig 2), these currently being used as a heritage centre. It is the roof of the vestry which is the subject of this programme of dating.

An earlier programme of tree-ring sampling and analysis was carried out in 2010 by the Nottingham Tree-ring Dating Laboratory on the chancel roof (Arnold and Howard 2011). This was undertaken to inform grant aided repairs to this Grade I listed church that featured in the Places of Worship at Risk campaign. The programme of tree-ring analysis reported upon here was undertaken when access became available to the roof timbers in the family chapel/vestry, which were exposed by the dismantling of a later Georgian ceiling.

The vestry roof comprises two principal rafter with tiebeam trusses, there being raking struts from tiebeams to principals, the tiebeams themselves being slightly cambered. The trusses support single purlins to each pitch of the roof, the purlins in turn carrying a number of common rafters. The roof also has a ridge beam.

SAMPLING

Sampling and analysis by dendrochronology of the family chapel/vestry of St Mary's Church were requested by Peter Barlow (English Heritage Heritage at Risk Architect/Surveyor). It was hoped that the dating of these timbers would enhance understanding of the chronological development of the church and contribute to the strategy for its repair. Although it is believed that the roofs might be of fifteenth, or possibly fourteenth century in date, it was hoped that tree-ring analysis would confirm this with greater reliability and precision, and provide information as to how much primary timberwork remained.

Thus from the suitable timbers available a total of 13 samples was obtained by coring. Each sample was given the code STK-C, and numbered 13–25 following on from STK-C01–12 obtained in the earlier programme of sampling. A plan of the vestry roof is given in Figure 3, with the locations of the new samples being shown in the annotated photographs shown as Figure 4. Details of the samples are given in Table 1. The trusses have been numbered from north to south, with individual timbers then being further identified on an east–west basis as appropriate.

ANALYSIS AND RESULTS

Each of the 13 samples obtained from the vestry roof was prepared by sanding and polishing. It was seen at this point that three samples, STK-C22, C23, and C24, had fewer than the 40 rings deemed necessary for reliable dating, and these were thus rejected from this programme of analysis. The annual growth ring widths of the remaining 10 samples were measured, the data of these measurements being given at the end of this report.

The data of the 10 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing a single group of six cross-matching samples to be formed as shown in Figure 5. The six cross-matching samples were combined at their indicated offset positions to form site chronology, STKCSQ01, this having an overall length of 114 rings.

Site chronology STKCSQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a number of chronologies when the date of its first ring is AD 1510 and the date of its last measured ring is AD 1623. The evidence for this dating is given in Table 2.

Site chronology STKCSQ01 was also compared to the four remaining measured but ungrouped samples, but there was no further satisfactory cross-matching. These four ungrouped samples were then compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and these samples must, therefore, remain undated.

INTERPRETATION AND CONCLUSION

Analysis by dendrochronology of samples from the roof timbers of St Mary's Church has produced a single dated site chronology comprising six of the 10 cores analysed, its 114 rings dated as spanning the years AD 1510–1623.

As may be seen from Table 1 and Figure 5, one of the dated samples, STK-C14, in site chronology STKCSQ01 retains complete sapwood and hence the last ring produced by the tree before it was cut down. This last growth ring, and thus the felling of the tree represented, is dated to AD 1623. The other five dated samples in the site chronology retain some sapwood or at least the heartwood/sapwood boundary, the date of which only varies by five years. The average heartwood-sapwood boundary date is AD 1603 which, using the sapwood estimate of 15–40 (95% confidence range) produces a felling date range of AD 1618–43 which encompasses the precise felling date obtained. The relative position and date of the heartwood-sapwood boundaries and the amount of sapwood these samples retain, is such that it is likely that all these other timbers were felled in, or around, AD 1623 as well. This interpretation is supported by the overall level of cross-matching between the dated individual samples. Thus all dated samples appear to represent timbers cut as part of a single episode of felling specifically for the construction of the vestry roof which would have taken place shortly thereafter.

The overall cross-matching between the six-dated samples suggests that most of the timbers were probably derived from a single, or closely spaced woodland source. Furthermore, although compared with reference data for all parts of England, the highest levels of similarity between site chronology and reference chronologies are found predominantly with other sites in the surrounding area suggesting that the timbers used in the construction of the vestry roof are from relatively local woodland.

Four of the 10 measured samples obtained remain ungrouped and undated. Although one sample, STK-C18, has only the minimum number of rings required for reliable dating, the other undated samples are sufficiently long, and none of the four shows any problems such as distortion or compression, which would make cross-matching difficult. It is, however, a common feature of tree-ring analysis for one or more samples not to combine with the main group or to date individually. It will, though, be seen from Table 1, that most of the undated samples are from truss 2 and the common rafters and therefore, it is not clear if this has any major significance for the dating of this truss in particular.

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TABLES

Table 1: Details of tree-ring samples from the vestry roof, Church of St Mary, Stockport

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
STK-C13	Tiebeam, truss 1	46	h/s	1561	1606	1606
STK-C14	East principal rafter, truss 1	114	29C	1510	1594	1623
STK-C15	West principal rafter, truss 1	104	14	1513	1602	1616
STK-C16	East strut, truss 1	88	h/s	1514	1601	1601
STK-C17	West strut, truss 1	51	4	1558	1604	1608
STK-C18	Ridge beam, truss 1 – 2	40	10	------	------	------
STK-C19	West common rafter 4	104	no h/s	------	------	------
STK-C20	West common rafter 5	109	no h/s	------	------	------
STK-C21	Tiebeam, truss 2	58	13	------	------	------
STK-C22	East principal rafter, truss 2	nm	---	------	------	------
STK-C23	West principal rafter, truss 2	nm	---	------	------	------
STK-C24	East strut, truss 2	nm	---	------	------	------
STK-C25	West strut, truss 2	57	h/s	1547	1603	1603

h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented.

Table 2: Results of the cross-matching of site sequence STKCSQ01 and relevant reference chronologies when the first-ring date is AD 1510 and the last-ring date is AD 1623

Reference chronology	Span of chronology	*t*-value	Reference
Staircase House, Stockport, Greater Manchester	AD 1489–1656	8.6	(Howard *et al* 2003)
Sinai Park, Burton on Trent, Staffordshire	AD 1227–1750	7.9	(Tyers 1997)
Tonge Hall, Rochdale, Lancashire	AD 1449–1687	6.7	(Arnold and Howard 2014)
Cromford Bridge House, Cromford, Derbyshire	AD 1550–1662	6.4	(Arnold and Howard 2007 unpubl)
England Master Chronology	AD 401–1981	6.3	(Baillie and Pilcher 1982 unpubl)
Aston Hall, Aston, Birmingham	AD 1457–1624	6.3	(Howard 2005 unpubl)
158–60 High Street, Newton-le-Willows, Merseyside	AD 1470–1627	5.9	(Arnold *et al* 2003)
Upper Hall, Hartshorne, Derbyshire	AD 1448–1611	5.8	(Arnold *et al* 2008)

FIGURES

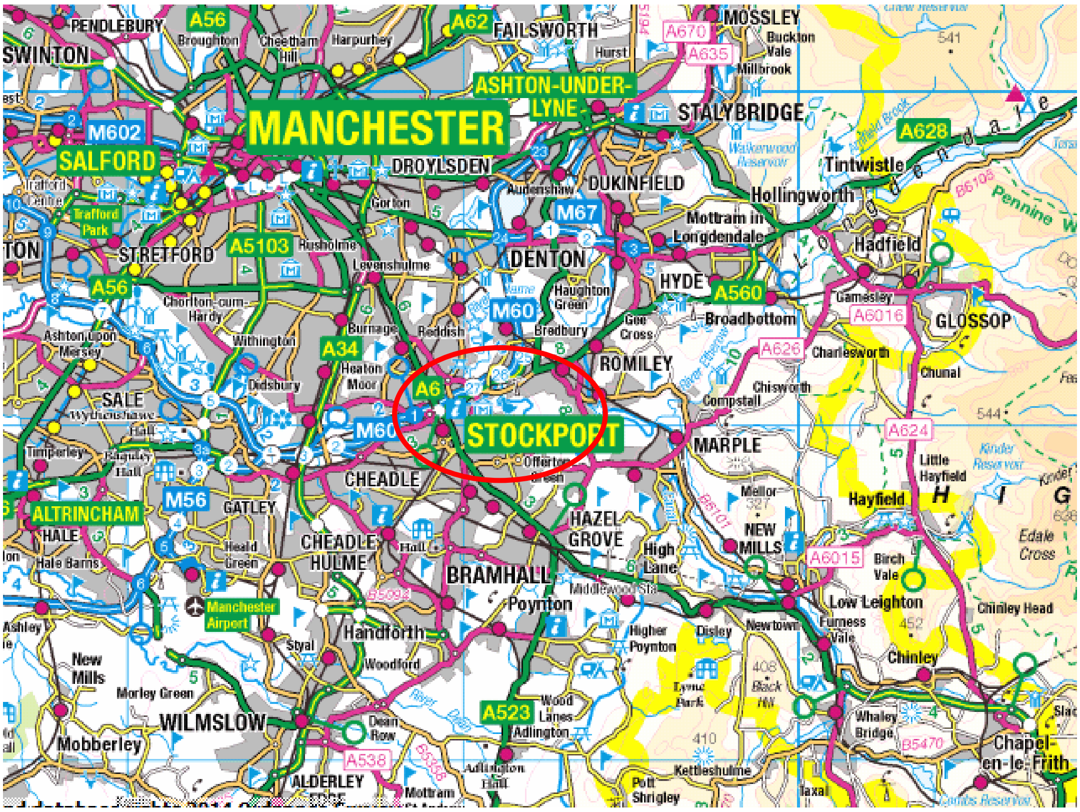


Figure 1: Maps to show the location of St Mary's Church, Stockport © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: View of the Vestry from the north (photograph Lloyd Evans Pritchards)

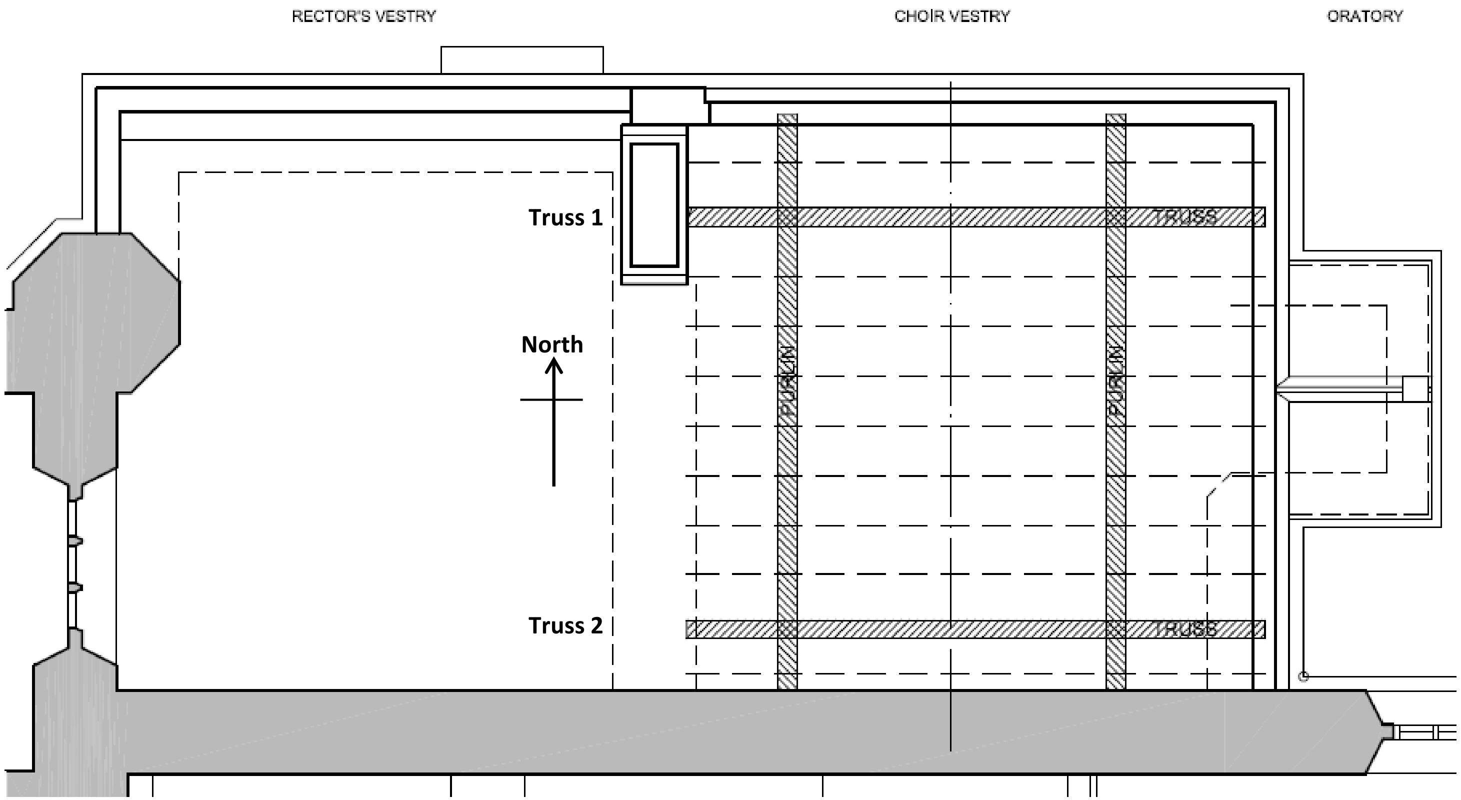


Figure 3: Plan of the Vestry to show layout and arrangement of the timbers (after Lloyd Evans Pritchards)

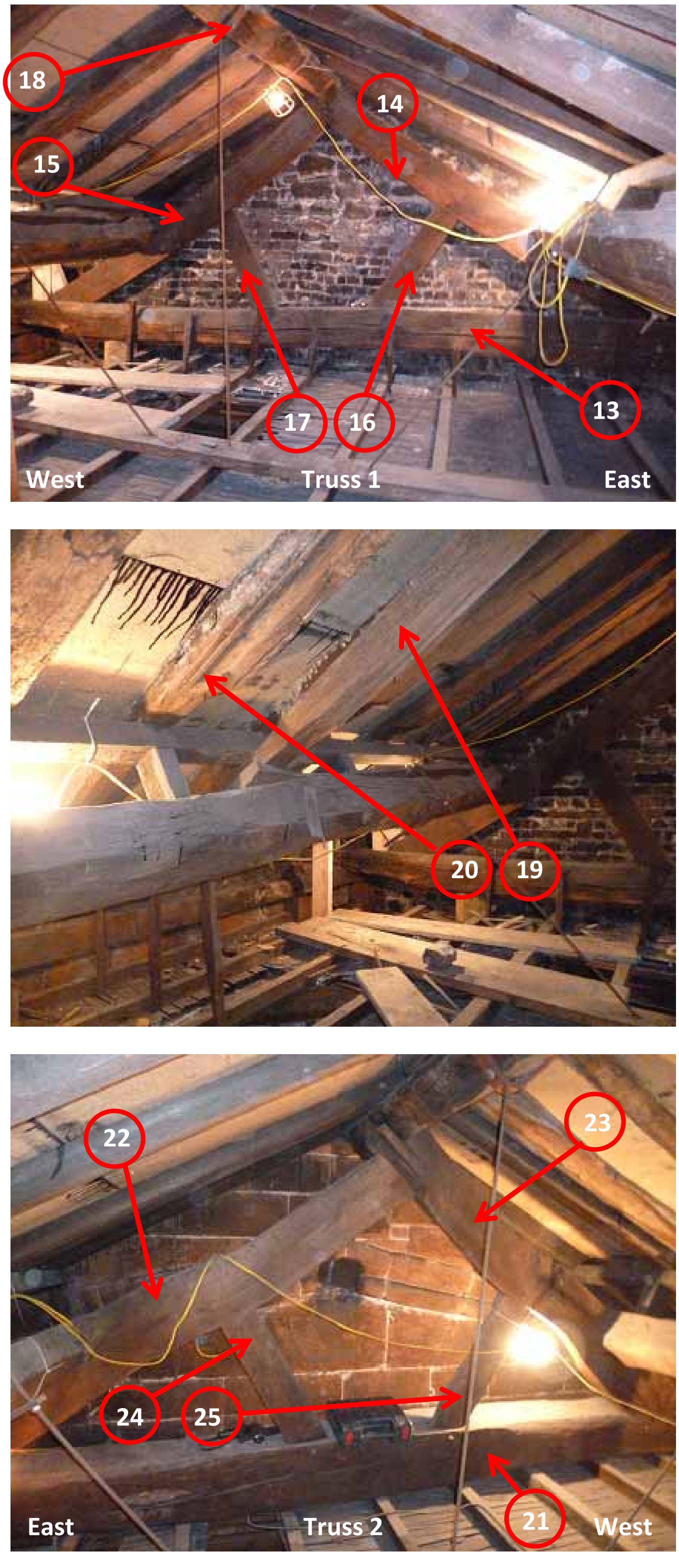
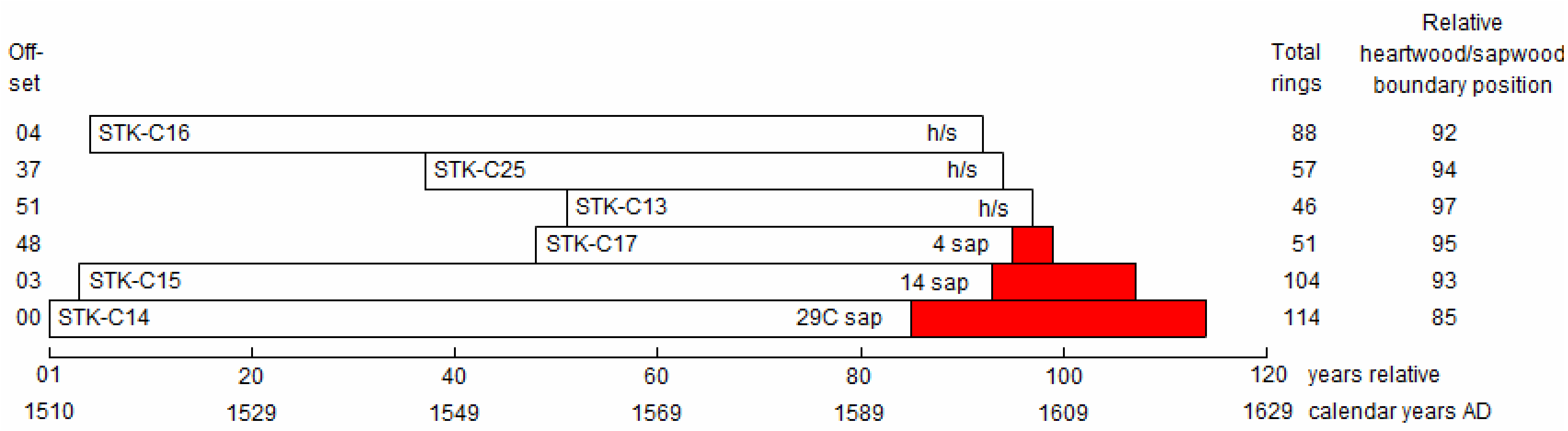


Figure 4: Views of the vestry roof to show sampled timbers (photographs Robert Howard)



White bars = heartwood rings, shaded bars = sapwood rings;
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree represented
h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the samples in site chronology STKCSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

STK-C13A 46
387 350 340 427 337 263 314 287 310 268 300 184 229 207 196 184 147 134 167 187
134 132 162 160 225 252 275 257 242 171 220 187 271 321 350 270 223 243 232 192
215 137 140 220 210 229
STK-C13B 46
389 345 332 409 335 280 314 275 321 275 254 171 240 233 203 209 144 140 161 164
146 150 139 180 212 256 262 228 204 191 214 184 279 315 350 260 225 253 242 193
202 145 154 222 195 218
STK-C14A 114
172 229 214 191 106 83 51 52 49 50 56 108 46 46 47 51 53 53 46 32
24 25 30 25 33 44 47 50 42 94 168 94 130 121 128 85 91 76 116 149
135 112 100 133 82 78 42 42 74 148 156 153 146 93 100 37 32 32 46 71
96 60 81 64 57 57 57 38 39 64 62 70 39 65 53 67 64 44 32 46
40 39 47 75 82 84 67 53 51 37 45 35 32 54 68 65 51 46 48 39
40 26 32 43 26 35 29 39 35 40 47 59 62 60
STK-C14B 114
126 213 193 175 115 75 55 48 46 49 65 109 52 51 57 44 46 58 45 31
20 21 28 30 35 42 44 50 50 82 124 72 101 105 98 85 91 97 126 130
132 114 105 126 79 77 50 45 73 119 150 149 145 92 94 33 37 29 49 74
90 67 72 67 53 60 47 39 40 71 63 64 35 81 53 70 68 37 32 39
39 31 53 67 78 89 65 55 52 39 44 31 40 48 76 56 54 51 50 39
35 31 29 40 34 33 34 32 35 40 48 68 58 54
STK-C15A 104
102 83 62 52 41 32 25 34 24 33 20 37 26 48 51 70 33 34 42 49
53 63 116 108 105 144 126 188 85 103 110 87 78 81 103 141 167 200 211 142
168 132 101 53 42 95 178 239 256 219 154 155 89 77 51 66 89 104 107 89
88 93 101 98 77 72 81 109 82 67 75 109 101 111 115 75 70 67 78 85
120 134 151 129 100 103 110 86 96 96 89 112 103 104 114 128 84 87 76 76
76 82 62 69
STK-C15B 104
101 85 63 52 36 31 25 30 32 29 24 33 29 44 51 73 35 29 41 56
43 63 116 108 106 146 127 191 91 97 116 79 80 80 100 150 166 196 215 132
166 133 95 57 48 94 176 235 268 224 154 164 87 85 61 68 90 116 112 87
94 89 103 84 78 68 84 110 90 69 78 106 107 114 118 75 71 68 76 90
120 136 145 129 114 110 114 84 96 87 93 115 101 104 114 126 90 84 81 70
70 77 62 75
STK-C16A 88
70 57 38 36 34 27 32 25 17 23 14 15 26 38 28 25 17 14 25 31
28 37 72 81 136 172 300 94 200 246 248 214 169 249 254 245 271 239 174 232
174 103 82 47 99 157 192 278 325 214 189 92 114 96 106 109 153 140 157 126
150 129 101 107 102 178 152 139 120 140 134 135 182 111 84 125 100 95 109 151
214 240 142 98 157 134 100 95
STK-C16B 88
67 62 41 39 33 31 27 25 18 25 18 18 23 29 34 20 19 19 18 33
30 45 60 70 134 165 295 93 184 257 239 212 173 237 253 239 271 245 178 257
162 100 77 54 98 157 186 271 325 203 179 97 110 89 98 104 176 137 162 134
146 120 93 85 115 158 160 145 159 121 117 105 178 113 84 115 104 75 110 157
173 226 151 102 130 123 103 92

STK-C17A 51
137 184 196 198 220 166 163 95 125 110 134 145 203 217 189 196 219 247 198 185
128 215 276 212 112 150 178 175 177 153 85 91 64 47 85 139 143 192 99 88
104 79 82 83 66 89 148 123 134 149 139
STK-C17B 51
139 187 188 199 218 167 161 100 129 100 134 146 209 219 196 178 221 242 201 177
154 222 286 204 122 165 192 210 184 160 82 92 53 85 89 155 164 172 106 81
114 79 84 84 58 96 151 120 131 142 140
STK-C18A 40
641 505 527 559 597 548 453 457 364 347 422 518 488 479 457 393 372 277 204 232
215 271 381 376 384 389 230 307 308 232 232 310 223 209 175 225 239 237 263 218
STK-C18B 40
607 507 528 564 600 543 446 456 357 392 419 506 472 477 462 370 380 275 198 228
192 276 384 391 370 406 228 306 310 222 237 318 215 203 190 209 238 241 272 226
STK-C19A 104
128 120 114 65 100 104 121 108 105 83 107 106 125 107 91 82 82 90 73 110
94 82 98 97 113 106 85 123 117 89 100 83 106 107 107 108 75 89 102 96
126 152 85 81 102 98 100 96 103 93 78 82 106 75 103 75 74 89 80 84
104 100 107 86 102 103 87 110 90 109 101 92 99 100 93 93 110 137 88 97
107 103 94 98 65 53 43 54 59 57 67 82 92 76 104 68 75 66 75 75
89 69 57 73
STK-C19B 104
173 121 106 71 92 110 117 111 104 83 107 109 117 108 86 91 78 87 76 112
101 75 81 107 111 87 89 133 121 91 83 96 117 103 117 117 76 89 107 90
107 126 85 80 118 101 104 93 104 93 78 96 91 82 100 78 80 91 67 93
103 95 108 85 100 104 87 116 90 101 98 93 96 97 96 92 107 143 112 93
121 92 74 97 70 57 52 50 54 73 70 73 86 85 102 72 69 64 79 60
87 73 59 78
STK-C20A 109
112 121 116 94 115 146 146 158 147 150 142 142 117 112 112 123 103 117 130 96
135 155 159 146 142 126 105 136 107 100 89 78 66 114 138 121 143 103 101 170
124 153 150 136 95 151 121 242 91 98 102 130 129 120 113 109 85 82 84 82
76 108 98 112 134 151 110 117 89 81 92 97 101 150 120 139 154 153 150 145
112 115 164 120 150 150 172 164 145 159 129 115 143 118 82 85 73 103 110 85
81 92 129 96 100 97 115 147 127
STK-C20B 109
110 146 123 92 135 143 150 164 175 153 138 136 110 104 120 115 89 110 101 91
103 136 178 159 139 146 108 128 118 84 106 67 78 117 137 128 152 108 111 163
124 146 152 142 103 144 116 208 101 108 94 128 137 118 112 112 90 81 82 82
75 104 95 115 134 153 112 104 101 78 93 95 105 145 121 141 149 154 142 148
120 106 170 118 151 157 173 165 139 157 125 118 146 111 89 79 80 104 95 96
71 112 117 100 104 93 124 115 147
STK-C21A 58
294 276 313 299 257 316 430 384 241 264 263 169 180 117 221 118 146 260 286 304
222 335 242 270 384 223 229 217 209 292 397 445 464 340 373 349 291 329 256 378
386 289 305 310 196 241 200 204 240 253 241 193 200 145 150 168 146 115
STK-C21B 58
314 270 321 292 254 267 450 370 260 282 263 167 176 123 221 118 143 275 296 303
218 332 239 276 374 236 216 217 221 286 402 446 464 335 378 347 285 307 258 356
393 282 311 309 200 244 196 213 232 253 224 186 201 153 143 165 141 114
STK-C25A 57
97 120 101 107 97 67 92 63 50 51 44 96 117 145 138 123 94 105 56 83
57 73 89 128 156 150 101 85 78 56 50 67 105 112 84 66 100 146 132 121

159 82 107 106 132 111 163 176 189 166 85 119 99 84 119 85 110
STK-C25B 57
107 115 106 104 100 69 92 56 58 48 49 94 116 143 140 119 98 104 58 78
60 73 96 119 159 150 99 82 71 62 58 62 92 121 71 71 109 164 153 189
167 86 98 110 126 123 160 176 195 153 85 114 96 86 111 86 108

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. As m 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

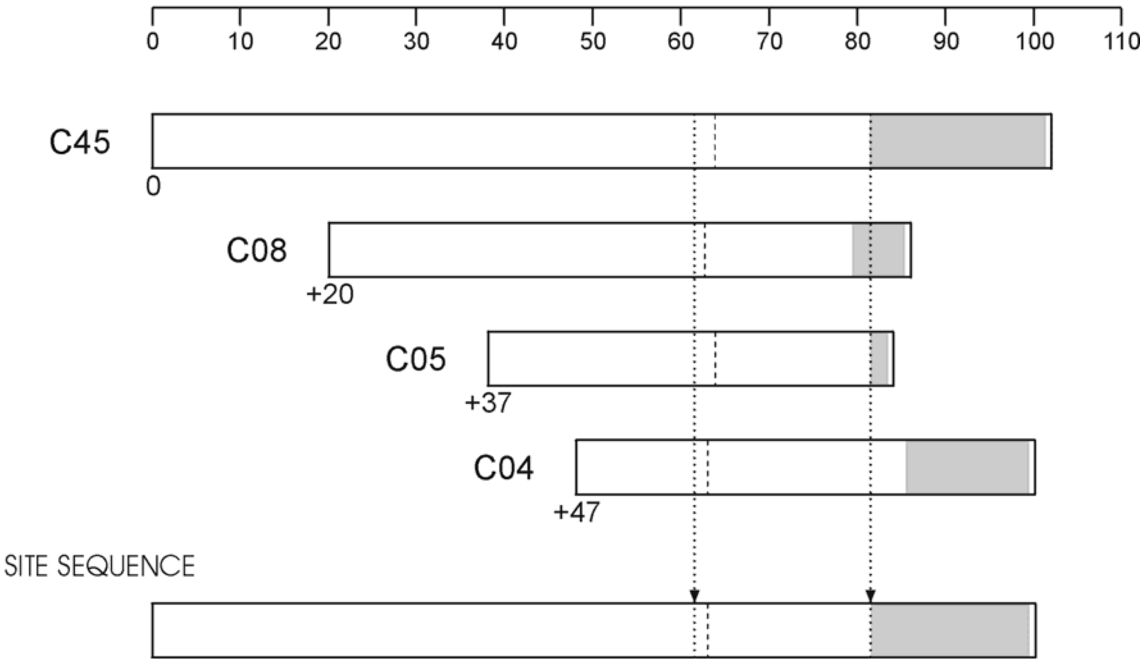


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

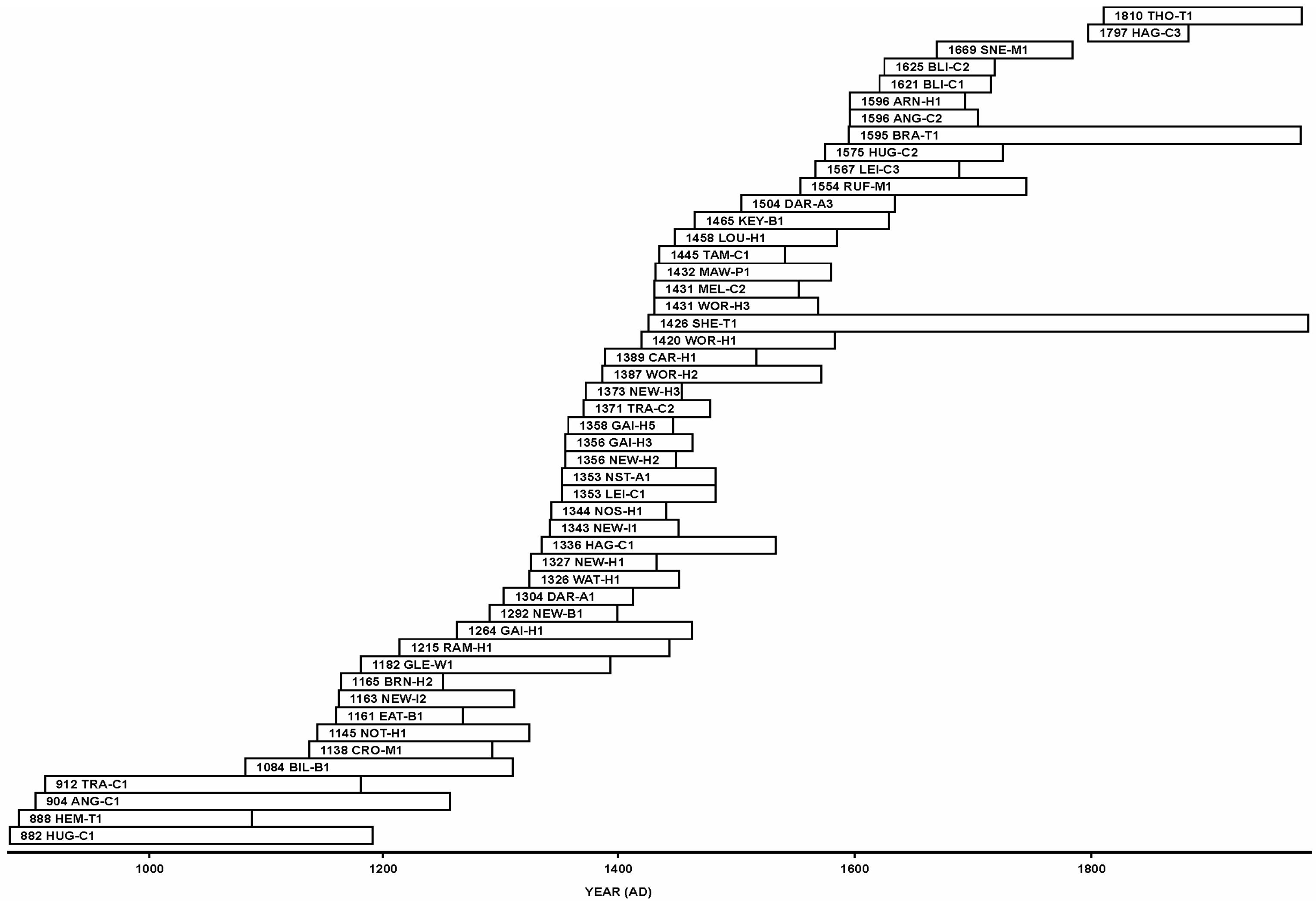
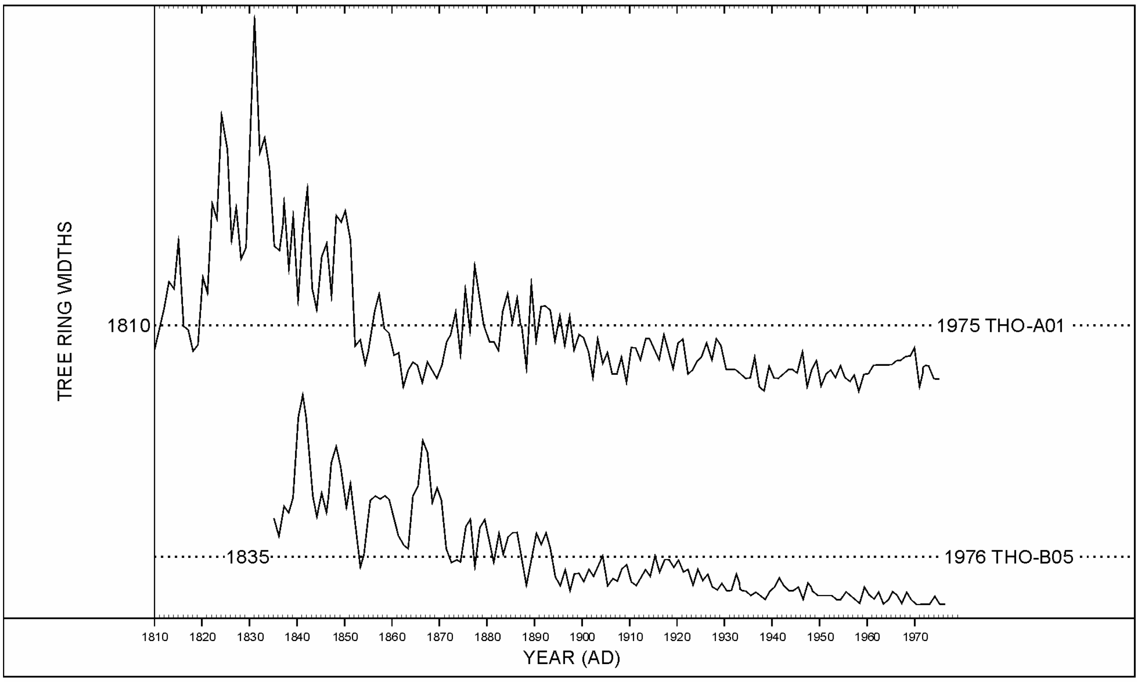


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

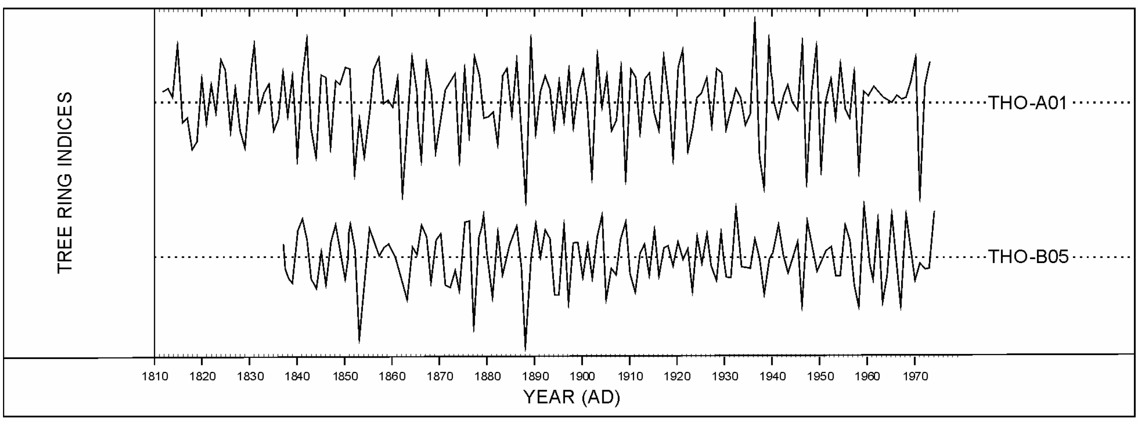


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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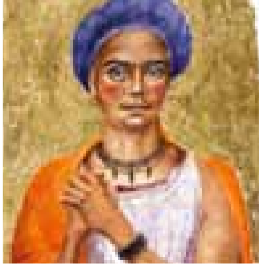


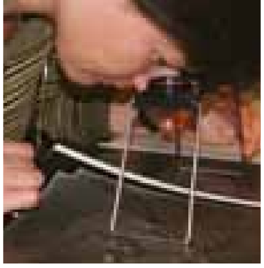


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