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Exeter Cathedral, Exeter, Devon Tree-Ring Analysis of Timbers from the Roof of the Chapel of St John the Baptist

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Tree-Ring Analysis of Timbers from the Roof of the Chapel of St John the Baptist

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Summary

Core samples were obtained from the five available oak beams forming the roof of the Chapel of St John the Baptist at Exeter Cathedral, Devon. The analysis of this material produced a single site chronology, EXTCSQ09, comprising three samples, and having a combined overall length of 108 rings. This site chronology was dated as spanning the years AD 1698 to AD 1805. Interpretation of the sapwood would suggest that the three timbers represented were felled in the period AD 1806–27.

Two other samples were dated individually. The felling date of one timber cannot be accurately determined because it is missing the heartwood/sapwood boundary. It is unlikely, however, to have been before AD 1248. The second individual has an estimated felling date in the range AD 1303–28.

It is probable that the early-nineteenth century material represents the most recent re-roofing of the chapel, with some timbers felled especially for this work. Whilst it is possible that the two medieval timbers here are reused there is no direct evidence for this so it is possible that they are remnants of the original early-fourteenth century covering.

Keywords

Dendrochronology
Standing Building

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Frontispiece: Exterior view of Exeter Cathedral.

Introduction

Although Exeter Cathedral (SX 921 925; Fig 1) has substantial Norman remains, it is, as seen today, primarily a cathedral of the English Decorated period (Frontispiece). A collection of documents, mainly Fabric Rolls, allows for the general progress of the post-Norman building work to be followed in broad outline. According to these documents, alterations to the Cathedral began between AD 1275 and AD 1280, with the presbytery, at the east end, being vaulted, glazed, and painted by AD 1302. Work on the choir followed in AD 1302–3, its vault bosses being carved in AD 1303–4, and its arcade corbels in AD 1303–4, and AD 1306–7. The new choir dates to between AD 1303–10, with work proceeding westwards into bays 4–6 after about AD 1328.

Since 1983 an extensive programme of sampling and analysis has been undertaken of the timbers of the high roofs of the Cathedral, that is, the presbytery, the choir, and the western bays (Mills 1988, Arnold *et al* 2003(a)). In 2005 grant-aided repair work was begun on the roof of the Chapel of St John the Baptist, to the east side of the southern central tower (Fig 2). This involved the removal of the lead covering and the lifting of the boards beneath, exposing the timber structure of the roof and making the beams within more accessible.

Although there are no specific early historic fabric records relating directly to this roof, it is believed that it dates from the early part of the fourteenth century and is possibly all of one phase. Following the completion of the choir in AD 1309–10, the building programme moved immediately to the crossing and towers, and it was probably for the tower chapels of St Paul and St John that marble shafts were bought in AD 1310, with payments for vaulting and glazing following in AD 1310–11.

Sampling

Sampling and analysis by tree-ring dating of the roof timbers of the Chapel of St John the Baptist were commissioned by English Heritage. The purpose of this was to inform the repair programme and to contribute to the on-going research into the roofs of the Cathedral. It was hoped that tree-ring analysis would determine with greater reliability the felling date of the material used here and establish whether or not any early repairs or alterations had taken place.

This small roof contains only five beams forming shallow pitched joists upon which the roof boards are laid, these in turn being covered by lead sheets. The centre three joists, which show signs of mechanical sawing to their surfaces, are all of regular dimensions, neatly sawn and trimmed. The two joists to either side, those at the east and west walls of the roof, are less regular in their size, and are not always squarely cut. These timbers show surface signs of having been cut by hand, and are also slightly cranked. A view of the timbers is given in Figure 3.

Each of these five timbers was sampled by coring. Each sample was given the code EXT-C (for Exeter Cathedral) and, following on from the previous programme of tree-ring analysis (Howard *et al* 2003), was numbered 297–301. The positions of these samples are marked on a plan made at the time of sampling, reproduced here as Figure 4. Details of the samples are given in Table 1. In this Table the joists have been numbered from east to west.

The Laboratory would like to take this opportunity to thank John Allan of Exeter Archaeology, who, as Consultant Archaeologist to the Dean and Chapter, advised on the scope of the project, assisted with the administrative detail, and liased with the cathedral authorities. We would also like to thank the Clerk of Works, Tony LeRiche, and the Cathedral Administrator, Paul Snell for their enthusiasm and help with this programme. Finally we would like to thank Norman Lee Ltd, Roofing Contractors, for their ever-active help and cooperation during sampling.

Analysis

Each of the five samples obtained was prepared by sanding and polishing and its annual growth-ring widths were measured. The growth-ring widths of all five samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum value of t=4.5 a single group of three samples was formed cross-matching with each other as shown in the bar diagram Figure 5.

The samples were combined at these off-set positions to form EXTCSQ09 (sequences 1–8 having been formed during pervious programmes of tree-ring analysis), a site chronology of 108 rings. Site chronology EXTCSQ09 was then satisfactorily dated by comparison to a number of relevant reference chronologies for oak as spanning the years AD 1698 to AD 1805. The evidence for this dating is given in the *t*-values of Table 2.

Site chronology EXTCSQ09 was also compared to the two remaining ungrouped samples but there was no further satisfactory cross-matching. Each of the ungrouped samples was than compared individually to the full range of reference chronologies.

This indicated cross-matches and dates for both samples, the 70 rings of sample EXT-C297 being dated as spanning AD 1164 to AD 1233, and the 123 rings of sample ECT-C301 being dated as spanning AD 1168 to AD 1288. Evidence for this cross-matching is given in the *t*-values of Tables 3 and 4.

Interpretation and conclusion

Analysis by dendrochronology has produced a further site chronology, EXTCSQ09, comprising three samples, its 108 rings dated as spanning the years AD 1698–1805. The average date of the heartwood/sapwood boundary on these three samples is AD 1787. Using a 95%confidence limit of 15–40 rings for the amount of sapwood the trees might have had, and allowing that the latest dated ring on any sample is AD 1805, would give the timbers represented, the centre three, regular, mechanically cut timbers, an estimated felling date in the range AD 1806–27.

Two other samples have been dated individually, both from the less regular, less neatly sawn, timbers. The felling date of one individual sample, EXT-C297, cannot be accurately determined because it is missing the heartwood/sapwood boundary. It is unlikely, however, to have been felled before AD 1248, this date being based on a 95% confidence limit of 15 rings as the minimum amount of sapwood the tree might have had.

The second individual sample, EXT-C301, has an estimated felling date in the range AD 1303–28. This felling date range is based on the same sapwood estimate as above. In theory it is possible that EXT-C297 and C301 could have identical felling dates and form part of the original roof.

The medieval timbers are possibly reused in their present location though this is unlikely. There is no direct evidence in the form of redundant mortices or peg holes to suggest that the timbers have been used elsewhere, and there is no evidence in the structure of the walls for any removal or replacement. It would, however, be possible to replace these timbers without greatly disturbing the wall structure. It is possible therefore that these two beams are remnants of the original early-fourteenth century roof. Tree-ring analysis has thus established with greater reliability the date of the original roof to this chapel and shown that it is not of one phase, but has undergone some repair.

Bibliography

Alcock, N W, Warwick University, Howard, R E, Laxton, R R, and Litton, C D, Nottingham University Tree-ring Dating Laboratory, and Miles, D H, 1991 List 41 no 4 – Leverhulme Cruck Project Results: 1990, *Vernacular Architect,* **22**, 45–7

Arnold, A J, Howard, R E, and Litton, C D, 2003(a) *Tree-ring analysis of timbers from Exeter Cathedral, Exeter, Devon: Paper 3 (western roof, bays 1–4),* Centre for Archaeol Rep, **49/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2003(b) *Tree-ring analysis of timbers from the roofs of the Lady Chapel north and south aisle, and the Choir south aisle, Worcester Cathedral, Worcester,* Centre for Archaeol Rep, **96/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2003(c) *Tree-ring analysis of timbers from Clothall Bury Farmhouse, Near Baldock, Wallingford Parish, Hertfordshire*, Centre for Archaeol Rep, **87/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2004 *Tree-ring analysis of samples from the roof of the 'Red Wing' Croome Court, Croome D'Abitot, near Upton upon Severn, Gloucestershire,* Centre for Archaeol Rep, **80/2004**

Arnold, A J, Howard, R E, and Litton, C D, 2005 *Tree-ring analysis of timbers from 7–9 Stourport Road, Bewdley, Worcestershire,* Centre for Archaeol Rep, **45/2005**

Baillie, M G L, and Pilcher, J R, 1982 unpubl A master tree-ring chronology for England, unpubl computer file *MGB-EOI,* Queens Univ, Belfast

Briffa, K R, Wigley, T M L, Jones, P D, Pilcher, J R, and Hughes, M K, 1986 The reconstruction of past circulation patterns over Europe using tree-ring data, final report to the Commission of European Communities, contract no CL.111.UK(H), unpubl rep

Esling, J, Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1989 List 29 no 6a - Nottingham University Tree-Ring Dating Laboratory: Results, *Vernacular Architect,* **20**, 39–41

Esling, J, Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1990 List 33 no 8a/b - Nottingham University Tree-ring Dating Laboratory Results: general list, *Vernacular Architect*, **21**, 37–40

Howard, R E, 2002 unpubl, composite site chronology for Ightham Mote, Ivy Hatch, Kent, unpubl computer file *KIMASQ01,* Nottingham Univ Tree-Ring Dating Laboratory

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1985 List 15 no 3 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect,* **16**, 39–40

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 19a/b - Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect,* **23**, 51–6

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1993 unpubl site chronology for Quenby Hall, Leicestershire, unpubl computer file *QBYHSQ01,* Nottingham Univ Tree-Ring Dating Laboratory

Howard, R E, Laxton, R R, and Litton, C D, 1998 unpubl site chronology for The Manor House, Abbey Green, Burton upon Trent, Staffordshire, unpubl computer file *BUTCSQ01,* Nottingham Univ Tree-Ring Dating Laboratory

Howard, R E, Laxton, R R, and Litton, C D, 1998 *Tree-ring analysis of timbers from Chicksands Priory, Chicksands, Bedfordshire,* Anc Mon Lab Rep, **30/98**

Howard, R E, Laxton, R R, and Litton, C D, 2000, *Tree-ring analysis of timbers from Stoneleigh Abbey, Stoneleigh, Warwickshire*, Anc Mon Lab Rep, **80/2000**

Laxton, R R, and Litton, C D, 1988 An East Midlands master tree-ring chronology and its use for dating vernacular buildings, University of Nottingham, Dept of Classical and Archaeol Studies, Monograph Series, **III**

Miles, D, 2003 Dating Buildings and Dendrochronology in Hampshire in *Hampshire Houses 1250-1700: Their Dating and Development* (E Roberts), 220–6

Mills, C M, 1988, Dendrochronology in Exeter and its application, PhD thesis, Univ Sheffield

Tyers, I, and Groves C, 1999 unpubl England London, unpubl computer file *LON1175,* Sheffield Univ

Table 1: Details of samples from the roof of the Chapel of St John the Baptist, Exeter Cathedral

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
EXT-C297	Joist 1 (from east)	70	no h/s	AD 1164	------	AD 1233
EXT-C298	Joist 2	78	h/s	AD 1709	AD 1786	AD 1786
EXT-C299	Joist 3	108	24	AD 1698	AD 1781	AD 1805
EXT-C300	Joist 4	70	8	AD 1734	AD 1795	AD 1803
EXT-C301	Joist 5	123	h/s	AD 1166	AD 1288	AD 1288

*h/s = the heartwood/sapwood boundary is retained on the sample

Table 2: Results of the cross-matching of site chronology EXTCSQ09 and relevant reference chronologies when first-ring date is AD 1698 and last-ring date is AD 1805

Reference chronology	Span of chronology	*t*-value	
Hampshire county chronology	AD 443–1972	7.4	(Miles 2003)
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1646–1813	6.5	(Howard *et al* 2000)
East Midlands	AD 882–1981	6.2	(Laxton and Litton 1988)
Savernake, Wilts	AD 1651–1982	5.9	(Briffa *et al* 1986 unpubl)
Croome Court, Worcestershire	AD 1639–1753	5.5	(Arnold *et al* 2004)
Clothall Bury Farmhouse, Baldock, Herts	AD 1636–1753	5.4	(Arnold *et al* 2003(c))
Quenby Hall, Quenby, Leics	AD 1648–1765	5.3	(Howard *et al* 1993 unpubl)
Chicksands Priory, Beds	AD 1670–1814	5.0	(Howard *et al* 1998)

Table 3: Results of the cross-matching of sample EXT-C297 and relevant reference chronologies when first-ring date is AD 1164 and last-ring date is AD 1233

Reference chronology	Span of chronology	*t*-value	
East Midlands	AD 882–1981	6.0	(Laxton and Litton 1988)
The Hollies, Bathley, Notts	AD 1150–1295	5.3	(Alcock *et al* 1991)
Manor House, Cropwell Bishop, Notts	AD 1138–1293	5.2	(Howard *et al* 1985)
Angel Choir, Lincoln Cathedral	AD 904–1257	5.0	(Laxton and Litton 1988)
7–9 Stourport Road, Bewdly, Worcs	AD 1060–1301	5.0	(Arnold *et al* 2005)
Manor House, Donnington-le-Heath, Leics	AD 1127–1269	4.9	(Esling *et al* 1989)
Hansacre Hall, Staffs	AD 965–1279	4.8	(Esling *et al* 1990)
Manor House, Burton-on-Trent, Staffs	AD 1162–1339	4.6	(Howard *et al* 1998 unpubl)

Table 4: Results of the cross-matching of sample EXT-C301 and relevant reference chronologies when first-ring date is AD 1166 and last-ring date is AD 1288

Reference chronology	Span of chronology	*t*-value	
Exeter Cathedral, Exeter, Devon	AD 1137–1332	6.6	(Mills1988)
Worcester Cathedral, Worcestershire	AD 1057–1285	5.6	(Arnold *et al* 2003(b))
Ightham Mote, Ivy Hatch, Kent	AD 1157–1327	5.4	(Howard 2002 unpubl)
England, London	AD 413–1728	5.3	(Tyers and Groves 1999 unpubl)
East Midlands	AD 882–1981	4.9	(Laxton and Litton 1988)
Angel Choir, Lincoln Cathedral	AD 904–1257	4.6	(Laxton and Litton 1988)
Chichester Cathedral, West Sussex	AD 1173–1295	4.6	(Howard *et al* 1992)
England	AD 401–1981	4.6	(Baillie and Pilcher 1982 unpubl)

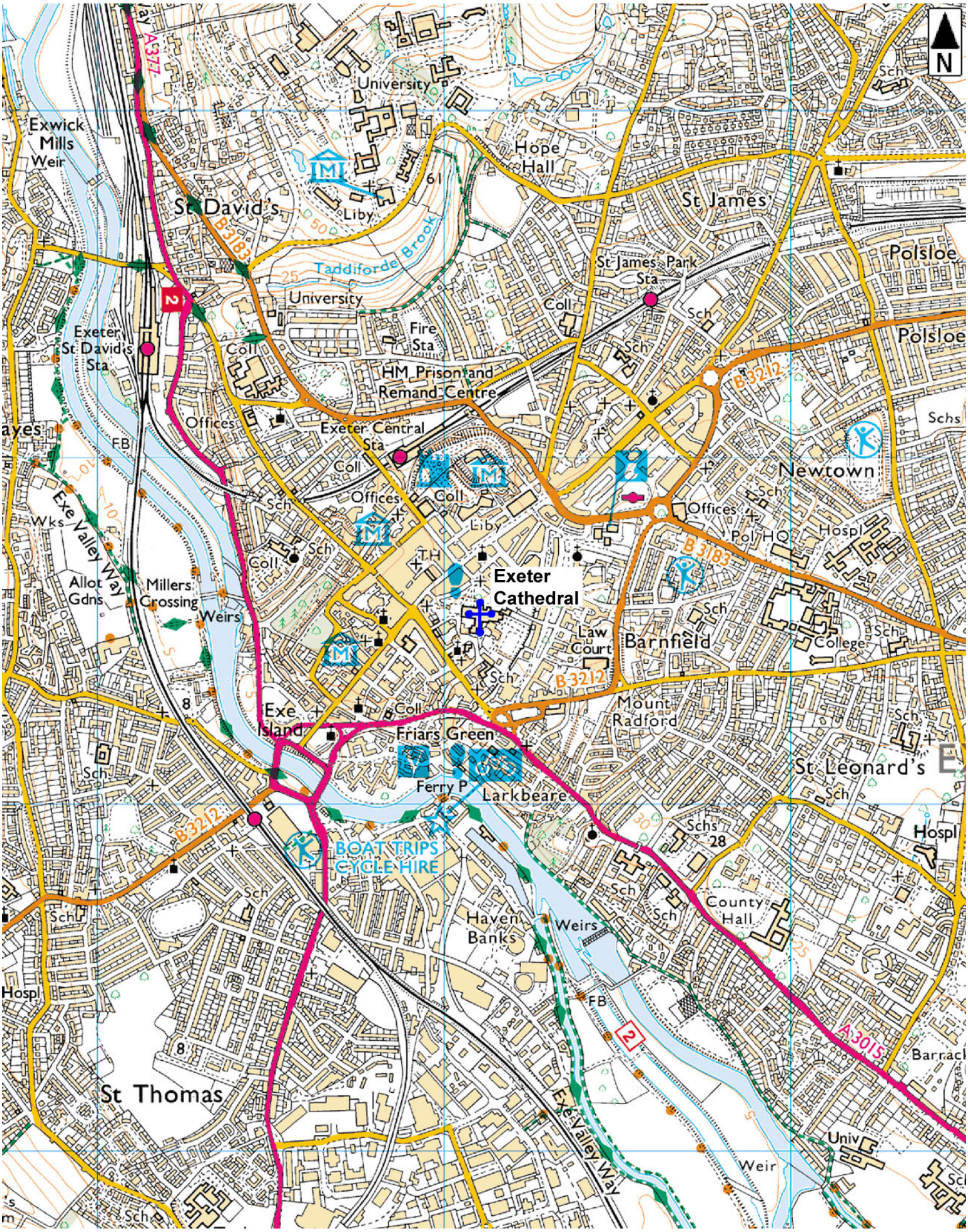


Figure 1: Location map of Exeter Cathedral, as denoted by the dark blue cross in the centre (scale=1:15,000)

Figure 2: Exeter Cathedral from the south east showing the east window

Figure 3: View of the roof timbers of the Chapel of St John the Baptist

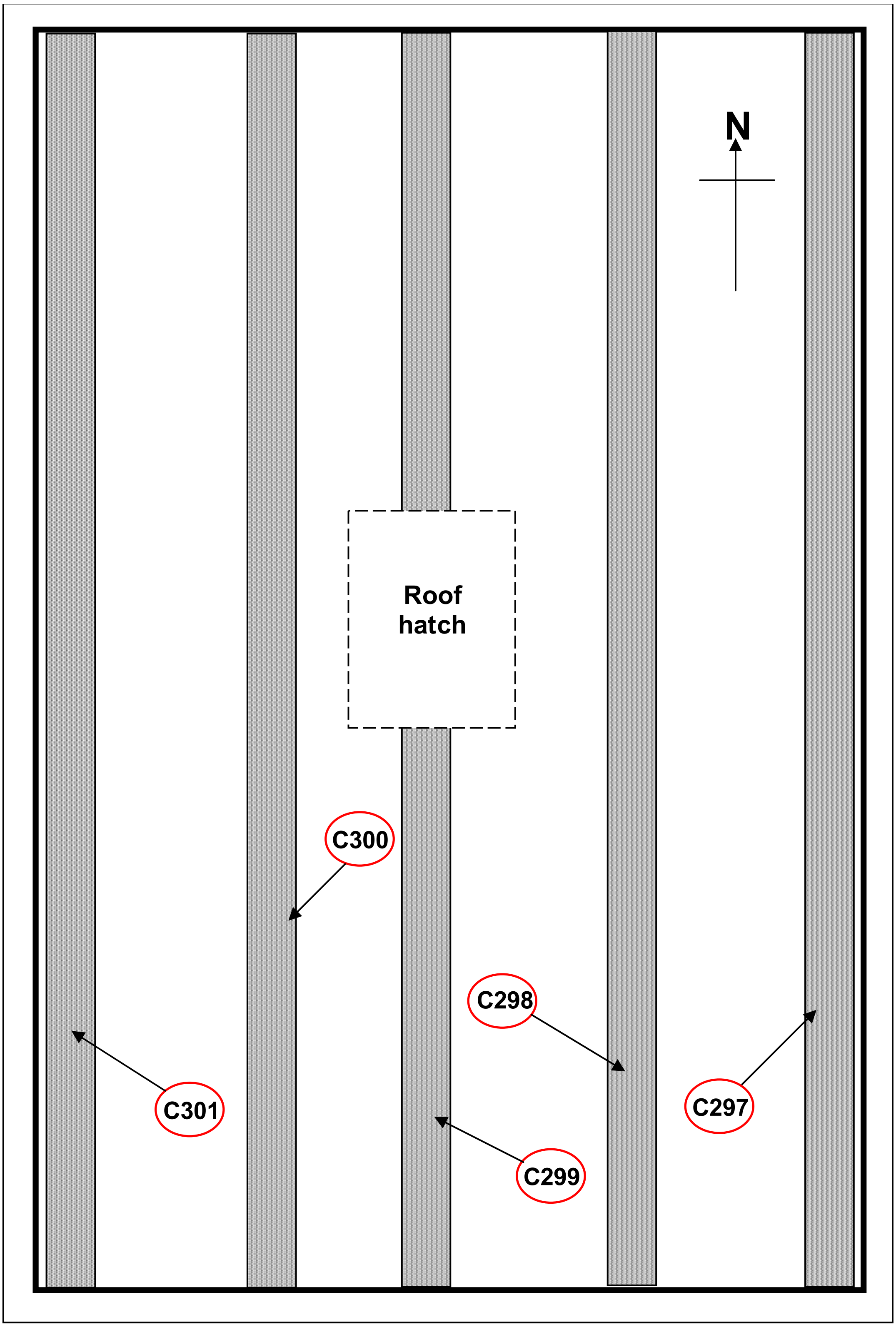
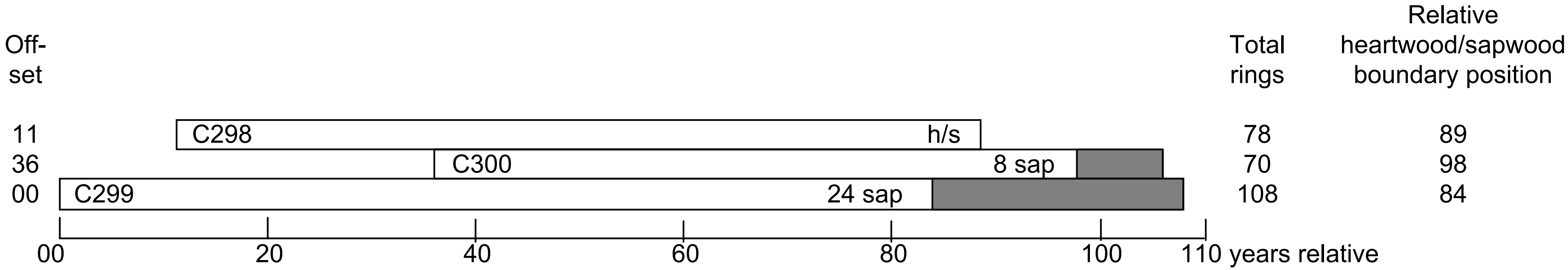


Figure 4: Plan to show sampled timbers from the roof of the Chapel of St John the Baptist



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the samples in site chronology EXTCSQ09

Tree-ring Width Measurements

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EXTC297A 70
 107 174 150 143 138 193 129  98 102 105 114 141 133 115 142 140 126 187
179 143  83  78  76  98  92 111 132 133 141 143 132 173 159 109  95 120 102
73  94 125  82  92 108  74  98 113 118 115  84  80  79 113  84 128 108 107
175 126  82  94 122 165 151 132 265 246 172 150 152 203

EXTC297B 70
  89 171 160 141 131 194 111 121  79  99 124 116 141 115 138 130 133 176
158 145  67  78  71  99  99 110 126 137 133 148 128 180 153 107 101 116  92
79  95 112  76  99 101  84  85 111 126 108  88  74  88 113 110 124 106 118
168 120  88  98 127 157 152 144 269 275 176 144 159 191

EXTC298A 78
 162 170 182 346 213 143 195 137 167 157 145 225 228 276 160 290 251 197
182 255 294 215 166 256 116 157 162 126  88 135 147 105  97 122 105 122 151
174 132  95  86  87 121  96  77  83  97  90  65  82 149 111  63  38 107 130
77 104 114 127  84  64  62  70  75 106 109 107 114  81  92  73  97  91  93
107 100  99

EXTC298B 78
 148 207 197 259 257 160 199 111 144 169 142 222 242 255 157 282 239 209
176 239 289 228 162 263 116 159 159 131  91 144 147 123  85 105 120 111 150
184 134  95  96 102 121 118  63  97  68  86  60  81 150 110  63  48 103 126
91 102 122 129  83  69  61  59  80 105 113 107 108  87  83  76  91  98  91
104 107  95

EXTC299A 108
 267 210 278 191 267 236 240 112 154 190 129 180 197 172 285 254 149 106
131 119 153 154 191 232 303 229 205 189 296 249 263 258 276 206 222 154 181
149 151 120 131 116 135 102  91 146  91  93 122  87  51  52  45  65  59  63
57 102  74  80  47 104  76  57  31 114 133  98  73  66 153 142  55  53  42
38  47  78  63  60  46  34  36  63  88  98  82  75  67  63  78  58  50  45
52  40  44 170  95  73  62  67  55 104  64  80  96 114

EXTC299B 108
 246 213 268 211 237 221 261 109 154 173 120 201 202 169 316 214 153 122
142 126 146 169 193 240 294 247 217 202 291 259 245 265 278 201 220 161 183
153 156 123 134 116 132  99  96 167  94  92 137  81  59  53  42  68  61  67
62  92  84  71  44 110  69  71  28 110 123  96  77  67 159 145  58  51  44
40  55  69  58  68  44  35  40  56  88  98  79  77  69  69  72  50  55  34
53  38  58 180  86  78  59  71  61 104  63  75  85 135

EXTC300A 70
 243 253 216 177 234 266 188 175 236 366 300 235 305 251 190 180 225 392
259 278 353 403 315 243 166 234 258 160  87 180 260 212 203 188 242 189 131
112 108 117 158 190 135 139 121 102 107 137 123 134 113  88  73  66  57  61
66  73  79  67  52 133 135 168 141 201 154 177 163 165

EXTC300B 70
 269 281 204 173 229 273 172 177 268 370 310 244 300 268 184 170 216 366
260 287 354 401 324 237 160 244 262 167  89 178 255 208 196 192 238 186 130
108 105 117 160 186 136 140 125 100 112 139 121 134 127  79  85  65  41  68
61  72  77  75  61 129 145 121 160 207 176 139 126 160

EXTC301A 123
 384 240 356 502 357 321 288 320 306 254 281 165 233 255 276 386 313 272
181 216 192 202 137 182 221 264 235 276 211 199 196 146 244 160 380 425 264
196 228 229 230 183 163 185 312 245 179 204 160 167 160 229 205 188 224  96
80  71 118  92 106  87 109 101 106 108  92  94  75 106  79 143 103  95 119
77  88  91 108  86 100 102 116 148  83  86  88  89  68  68  70  60  88  96
162 121 139  97 104 108  69  70  82 112  94 124  80 159 168 120  85  94  64
91 129 105 151 148 125 131 101  61 114
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EXTC301B 123
 423 225 345 487 358 228 301 336 317 230 297 167 229 278 281 409 312 260
179 214 199 201 125 175 230 238 248 248 220 205 208 146 257 172 376 427 279
199 250 201 253 165 174 194 299 220 166 207 174 160 156 244 200 192 210 108
74  61 120  90 102  76 116 104 110  89 116  70  80  97  73 142 104 101 115
85  74 106  96  87  98 103 126 140  89  83  79  94  71  60  74  76  80  98
155 127 130  98 110  96  73  65  84 109 103 119  83 148 162 110  85  87  70
84 131 106 139 156 133 132  97  67 138
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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 measure 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	

Bar Diagram

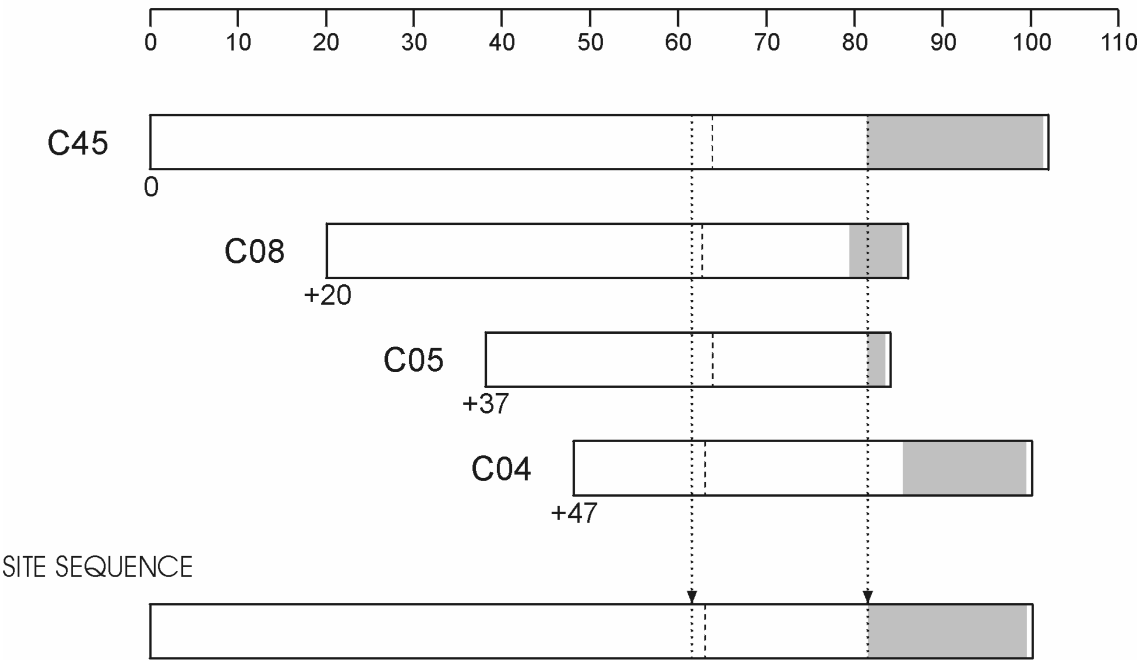


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

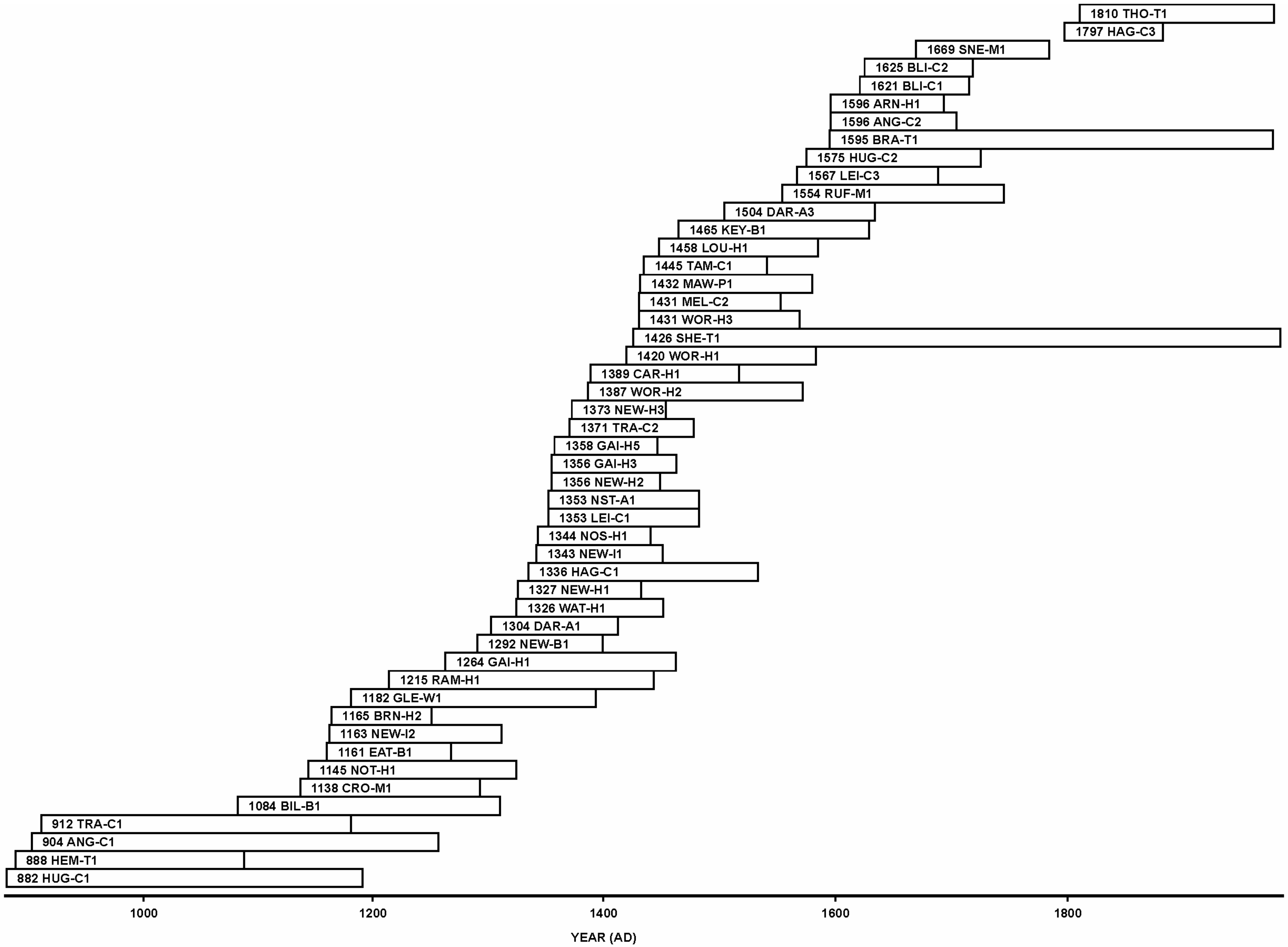
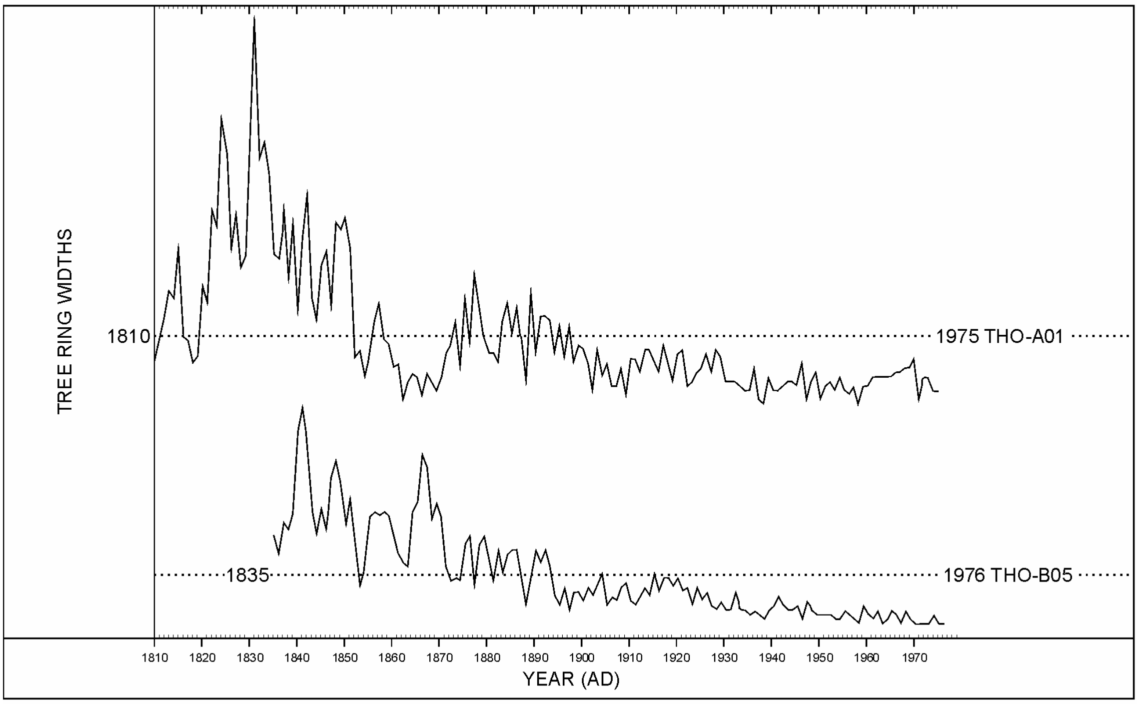


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

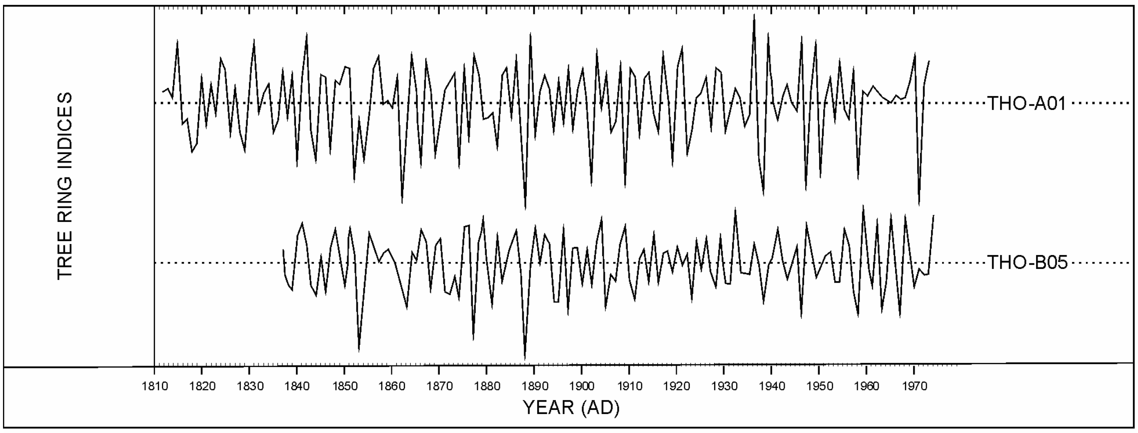


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

REFERENCES

Baillie, M G L, and Pilcher, J R, 1973, A simple cross-dating program for tree-ring research, *Tree-Ring Bulletin*, **33**, 7–14

English Heritage, 1998 *Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates*, London

Hillam, J, Morgan, R A, and Tyers, I, 1987, Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, **3**, 165–85

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95, Nottingham University Tree-Ring Dating Laboratory Results, *Vernacular Architecture*, 15–26

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, **8**, 381–90

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series III

Laxton, R R, and Litton, C D, 1989 Construction of a Kent Master Dendrochronological Sequence for Oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90–8

Laxon, R R, Litton, C D, and Howard, R E, 2001 *Timber; Dendrochronology of Roof Timbers at Lincoln Cathedral*, English Heritage Research Transactions, **7**

Litton, C D, and Zainodin, H J, 1991 Statistical models of Dendrochronology, *J Archaeol Sci*,**18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architecture*, **28**, 40–56

Pearson, S, 1995 *The Medieval Houses of Kent, An Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London