Ancient Monuments Laboratory
Report 61/98

TREE-RING ANALYSIS OF TIMBERS FROM BAY HALL, HALL LANE, BENINGTON, LINCOLNSHIRE

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Summary

Analysis was undertaken of eight samples from Bay Hall, Benington, Lincolnshire. This resulted in the production of a single site chronology of 127 rings spanning the period AD 1591 to 1717. Interpretation of the sapwood indicates that the felling of the timbers represented took place no later than the summer of AD 1717.

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Introduction

Bay Hall (TF 393463, see Fig 1) is a grade II* listed building, on the edge of the village of Benington about four miles east of Boston in Lincolnshire. It is a three-storey red brick rectangular double-pile plan country house believed to have been built about AD 1730. It is believed that the Hall underwent major refurbishment in the mid-eighteenth century, and a two-storeyed service wing was added to the rear, or north side, of the Hall in the early-nineteenth century. A plan of the ground floor, taken from a historic building report by the Royal Commission on the Historical Monuments of England, is provided in Figure 2 (*Giles et al* 1991).

Much of the roof covering is currently missing, and the house stands empty and at risk from dereliction. This structure has been identified as a priority A case on the English Heritage Register of Buildings at Risk (English Heritage 1998). Sampling and analysis by tree-ring dating of timbers of the primary phase of construction only were commissioned by English Heritage. There was no request to sample timbers of the refurbishment phase. The object of this analysis was two-fold. Firstly it was to inform a proposed programme of repair. Secondly the work will contribute to the on-going research programme by the Tree-ring Dating Laboratory to enhance the later part of the East Midlands Master Tree-ring Chronology.

Sampling and analysis

Much of the available oak timber within the body of the Hall consisted of small floor and ceiling joists. From the broken ends of some beams and at other points, such as empty mortises, it was possible to see that most of these timbers had too few rings for satisfactory analysis. Furthermore the joists had been well trimmed and squared with the result that very few of them had even the heartwood/sapwood boundary present. Such timbers were not sampled.

Fortunately the primary roof structure of Bay Hall contained suitable timbers. This roof is not made up of trusses but consists of principal oak beams spanning the width of the Hall, intermediate beams, cross-beams, and trimmer beams. These timbers had sufficient rings and had sapwood.

Each of the eight available oak timbers was sampled by coring. Each sample was given the code BEN-A (for Benington, site "A") and numbered 01 – 08. The positions of the samples were recorded on a plan provided by the architects, J L Moore and Associates, which has been amended to show the timbers and is reproduced in this report as Figure 3. Details of the samples are given in Table 1.

The eight samples obtained were prepared by sanding and their growth-ring widths measured, the data of the measurements being given at the end of the report. Whilst most timbers were sampled with a single core, some timbers required two cores to obtain the inner and outer most rings of the tree. This is represented by the two core samples BEN-A03A/B for example, each of which has a different number of growth-ring measurements.

All the samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), and at a value of t=4.5 all eight cross-matched with each other as shown in the bar diagram, Figure 4. The ring-widths from these eight samples were combined at these relative off-sets to form BENASQ01, a site chronology of 127 rings. Site chronology BENASQ01 was successfully cross-matched with a series of relevant reference chronologies for oak, giving a first ring date of AD 1591 and a last measured ring date of AD 1717.

Evidence for this date is given in the t-values of Table 2. Because of the late date of this chronology there are relatively few reference chronologies available for comparison. For this reason there is only a small number of chronologies listed and they are from further afield than would usually be desirable, Worcester Cathedral for example. They do, however, show consistency and high t-values and the Laboratory is confident that the dating is correct.

Two of the dated samples retain complete sapwood each with a last measured ring date of AD 1717. Under the microscope it is possible to see that on both samples the spring cell growth is complete and that the summer cell growth has commenced. Two other dated samples also retain complete sapwood each with a last measured ring date of AD 1716. Under the microscope it is possible to see that on these two samples the spring cell growth of the following year, AD 1717, has just started. It would therefore appear that the timbers for the principal roof beams were all felled in the spring and summer of AD 1717.

Conclusion

Analysis by dendrochronology of material from this site has indicated that the felling of the timbers sampled took place in AD 1717. This is a few years earlier than the date of AD 1730 suggested by Giles *et al* (1991).

It may be worth noting that, given the high t-values of the cross-match between samples, it is probable that single trees have been split to make two timbers. This is probably the case with timbers represented by samples BEN-A01 and A03, with samples A02 and A06, with A04 and A05, and A07 and A08. The probability of this is enhanced by the fact that, as will be seen from Table 1, each of these pairs of samples is from a similar timber member and, as was noted at the time of sampling, each timber was made of half a tree.

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Table 1: Details of samples from Bay Hall, Hall Lane, Benington, Lincolnshire

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
BEN-A01	North principal beam	90	15C	AD 1628	1702	1717
BEN-A02	East intermediate beam	75	12c	AD 1636	1698	1710
BEN-A03	South principal beam	97	15C	AD 1621	1702	1717
BEN-A04	East central intermediate beam	106	31C	AD 1611	1685	1716
BEN-A05	West central intermediate beam	101	25C	AD 1616	1691	1716
BEN-A06	West intermediate beam	72	h/s	AD 1626	1697	1697
BEN-A07	North trimmer beam	100	h/s	AD 1602	1701	1701
BEN-A08	South trimmer beam	109	h/s	AD 1591	1699	1699

*h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber; all or part lost in sampling
C = complete sapwood retained on sample

Table 2: Results of the cross-matching of site chronology BENASQ01 and relevant reference chronologies when first ring date is AD 1591 and last measured ring date is AD 1717

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	7.4	(Laxton and Litton 1988)
MGB-E01	AD 401 - 1981	3.6	(Baillie and Pilcher 1982 unpubl)
COSBSQ06	AD 1642 - 1734	6.2	(Howard *et al* 1991 unpubl)
Sinai Park, Staffs	AD 1227 - 1750	5.0	(Tyres 1997)
Worcester Cathedral	AD 1597 - 1730	5.8	(Howard *et al* 1995)

Figure 1: Map to show general location of Benington

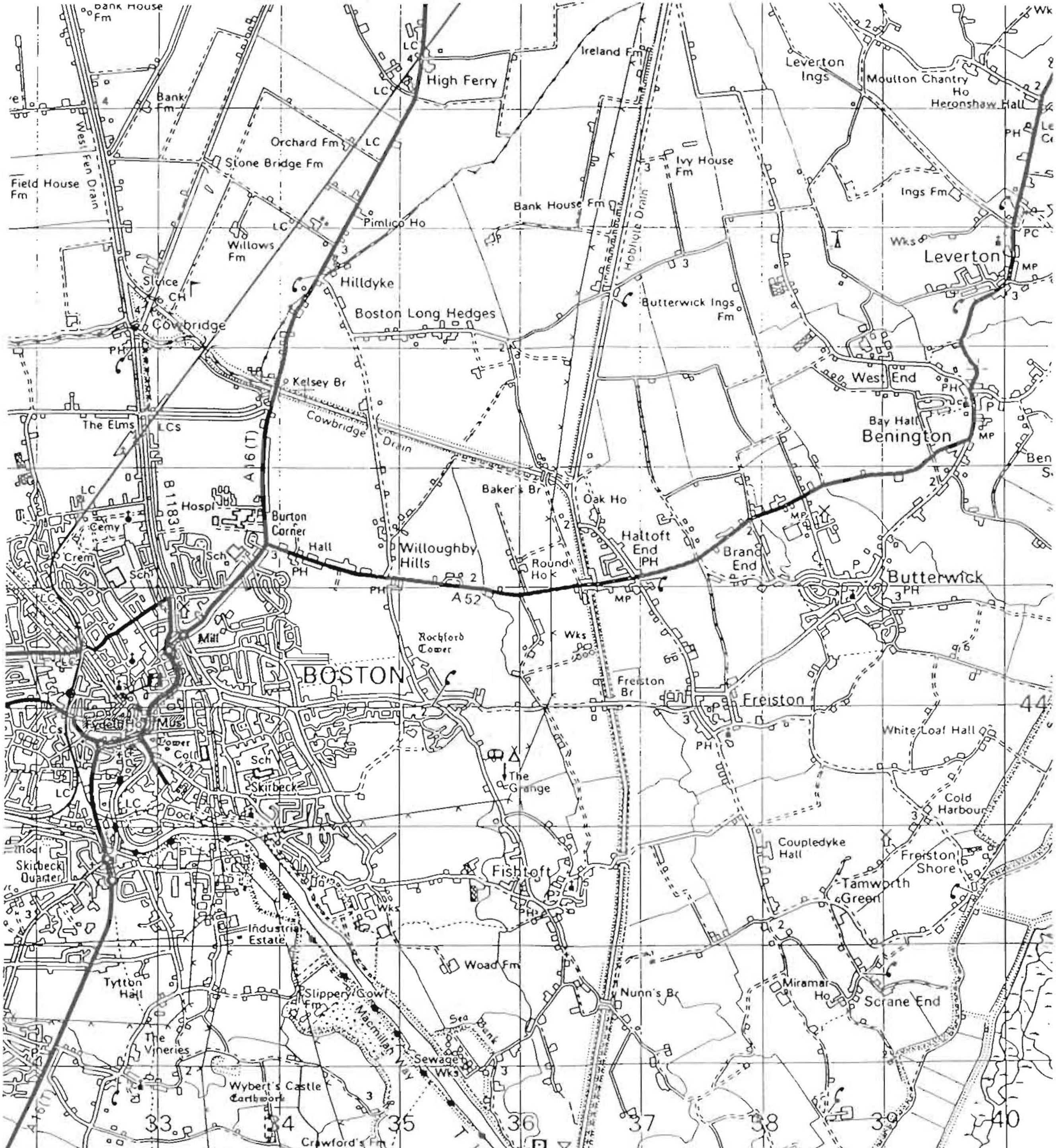
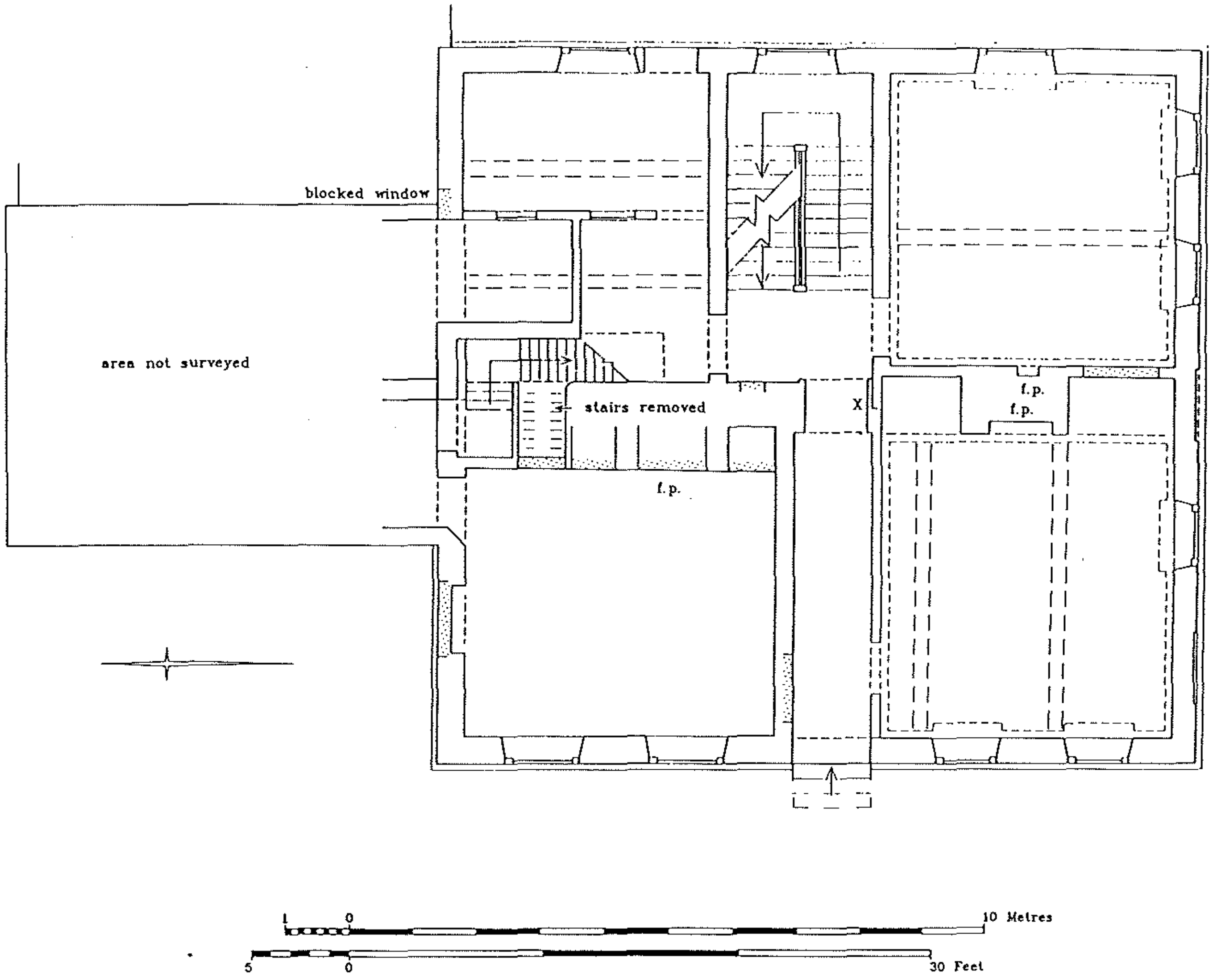


Figure 2: Ground floor plan

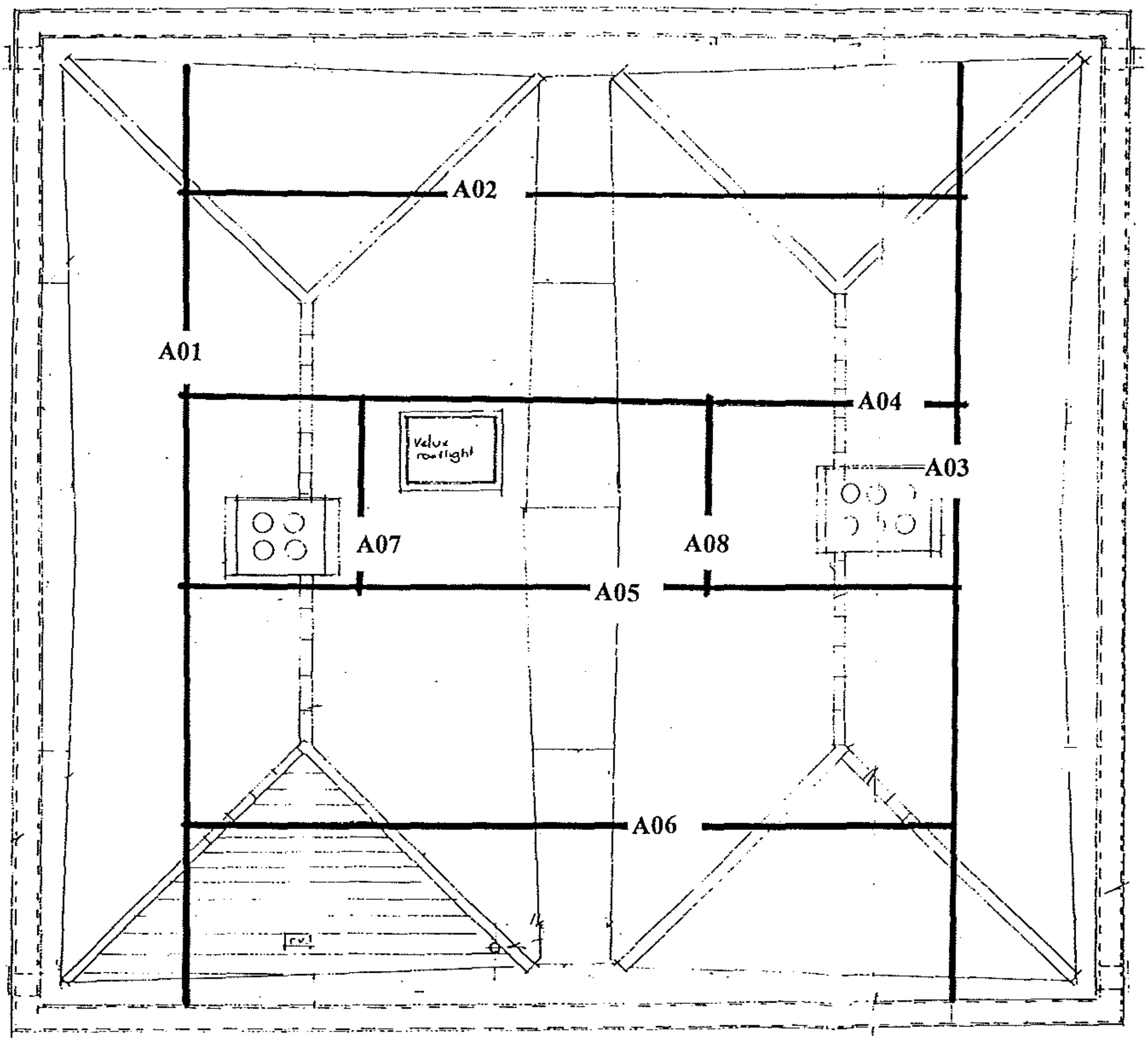


Bay Hall, Benington, Lincolnshire.

Ground floor plan

RCHM
ENGLAND

Figure 3: Plan to show position of samples
(adapted from architects drawings)



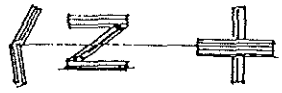
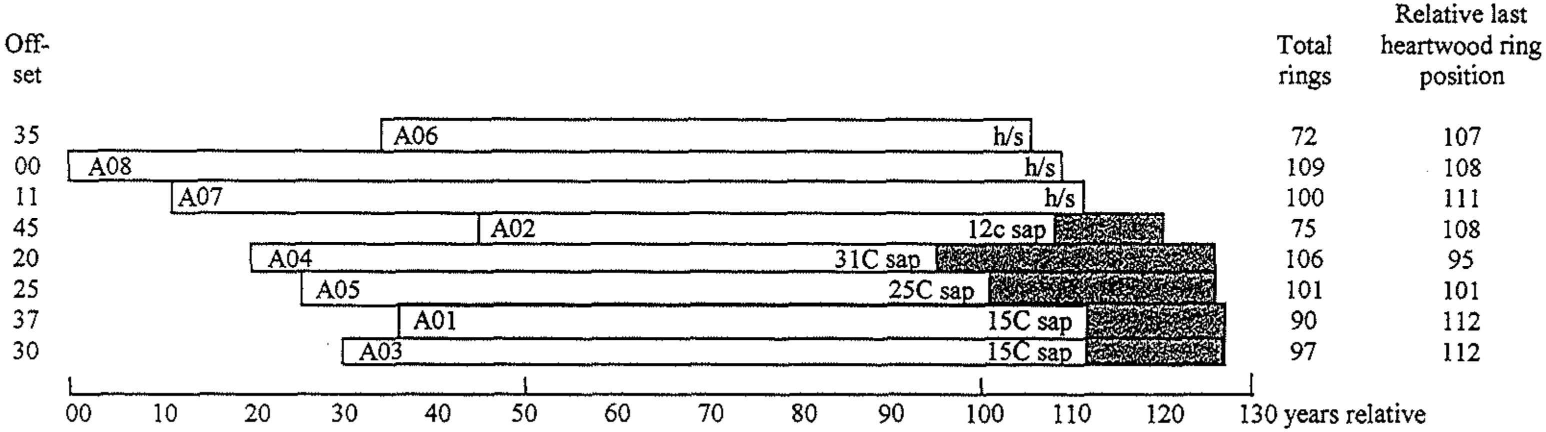


Figure 4: Bar diagram of samples in site chronology BENASQ01



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber; all or part lost in sampling
C = complete sapwood retained on sample

Data of measured samples - measurements in 0.01mm units

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BEN-A01A 90
 386 390 295 340 325 337 232 257 229 209 258 276 306 314 294 279 251 219 240 157
 174 108  88 115 111 112 123 238 205 174 164 108 166 118 100 108 128 103  98 116
 150 141 107 102 138 108  93 105  74 132 159  98 124 125 146  79  80  65  79 106
 117  86  67  98  61  68 109 134  90 129 145 120  89 118  93  94 116  77 129 130
 141 130  75 108 133 130 105  88  76  78
BEN-A01B 90
 384 377 317 343 306 316 218 221 252 199 276 262 315 321 280 272 252 202 244 157
 200 102  90 120 126 112 128 227 220 170 162 110 164 112 105 112 130  96  75 120
 155 136 104 106 138 105  87 116  72 104 176  92 126 120 147 101  77  49  89 119
 133  84  70  91  69  80 119 114 105 126 139 133  88 117  95  92 113  80 122 129
 142 138  72 106 140 130 108  80  72  60
BEN-A02A 75
 198 105 150 138 102 136 188 161 130 140 244 115 219 115 106 121 129  76  67 122
 100 116 111 143 182 151 154 153 159 118 100 155 137 132 150 139 142 188 210 225
 116 259 176 110 197  75 147 102 105 118 150 124 163 104 100 113 155 181 127 128
 203 180 219 183 132 182 141 150 135 103 114 104 196 144 173
BEN-A02B 75
 198 114 159 144 104 140 171 151 132 149 242 121 209 118 106 118 121  78  69 121
  98 120 114 145 193 150 151 150 161 111 102 136 133 134 157 140 143 187 219 215
 120 249 178 104 202  69 148 103 101 120 148 124 164 110  88 118 156 188 120 131
 200 179 214 175 149 176 131 134 144  87 121 109 177 149 222
BEN-A03A 88
 315 194 156 319 433 492 436 363 325 260 370 371 341 243 320 298 215 237 218 222
 239 245 230 216 204 228 192 184 146 105 132 132 112 111 225 193 149 169 125 174
 100  70 134 135 109 139 149 144 133 109 125 161 129 128 133 110 177 177 112 171
 124 148  81  83  85 126 142 142  86 102  99  92 104 145 128 167 157 143 128 109
 132  82 105 156 110 135 144 142
BEN-A03B 85
 261 296 316 304 220 269 268 251 257 260 250 236 200 233 202 235 192 163 174 139
 123 138 234 193 142 146 115 147 106  80 128 130 122 126 163 151 123 106 123 164
 146 149 179 133 187 195 115 177 127 157  82  95  91 143 148 160  70  94 129  71
 102 139 124 126 142 140 117  98 115  78 107 141  94 129 130 144 156  81 112 164
 158 116  70  56  60
BEN-A04A 88
 544 353 369 286 349 402 442 389 248 215 244 218 215 188 143 133 177 143 177 144
 141 132 117 111  96 117  96  64  88 139 160 105 104  99  91 142 106  75  68  46
  70  62  52  50 118 118  75  97  78  83  58  74  94  95  91  64  92  99 155 122
 103 135  78  93  77  50 141 165  68 125  86  99 102  85 100 188 122  97  80  68
  83 105 119  96  79 106 169 173
BEN-A04B 75
 208 159 144 135 223 157 129 112  68  71  70  52  55 132 130  81  98  86  63  64
  70  84  67  91  49  85 102 136 127  94 171  99 113  88  68 149 213  89 156 100
 115 114  86 108 205 134 107  89  65 101  96 134 121  93 121 197 190 184 117 110
  61  79  86  46  74 112 129 119 119 172 157 156  69 102  88
BEN-A05A 101
 322 440 407 435 353 542 541 462 427 470 561 512 409 482 300 384 365 346 228 266
 273 267 203 212 295 271 221 204 181 176 206 142 141 137  97 103  67  57  50 108
 103  44  78  70  65  50  50  45  54  58  36  49  63  75  91  85  96  83  85  59
  48  72  91  48 110  48  92  63  72  47 100  92  95  66  68  67  80  60  85 115
 102 150 153 126 103 103  62  72  85  48  67  95 110 121  67  90 127 130  44  75
  71
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BEN-A05B 101
 300 437 410 426 354 536 538 458 432 459 588 523 414 482 302 371 349 352 232 274
 278 275 213 211 290 286 239 212 182 190 198 143 140 138  88 106  68  51  52 107
 110  69  63  59  73  52  44  49  43  50  38  44  59  90  90  77 104  78  78  69
  44  73  90  45 100  62  91  63  60  65 105  98  93  60  66  55  76  70  89 116
 100 126 153 130  95 110  60  64  91  50  61  99 109 118  79  82 114 126  59  65
  76
BEN-A06A 72
 452 447 363 433 317 360 302 318 184 287 272 206 227 280 236 204 204 188 173 123
 163 121 175 115 115 132 158 113 100 193 139 140 150 150 149 107 114 182 190 145
  96 124 139 133 144 127 144 151 164 165  84 218 190 110 212 110 197 172 124 154
 192 133 157 123 111 113 140 149 123 147 166 197
BEN-A06B 72
 474 454 345 429 344 413 402 345 179 279 288 190 237 273 238 199 201 189 170 125
 154 128 173 129  96 133 160 122 101 181 145 146 149 148 148 104 116 175 195 147
 102 133 140 132 146 138 148 153 171 156  86 215 195 113 199 101 195 167 112 155
 190 149 154 124  96 116 130 159 116 150 174 205
BEN-A07A 100
 255 312 455 269 360 406 398 338 366 258 234 352 347 330 377 326 189 127  93  82
 103 134 124  90  52  72  70  55  63  59 117 100  89  93  79  86 113 106 105  98
  73  67 111 132 209 133 184 104  76  41  46  52  51  87  90  84  96  66 126  87
  70  86  96 102  97  87  99 103  90  93 122 166 159  94  64 123 175 142 158  97
 181 141 113 116 105 123  94  82  63  96  90 119 113 102 120 190 209 170 155 176
BEN-A07B 100
 235 315 396 255 338 410 348 341 375 283 237 358 342 320 382 301 227 140 105  74
 116 128 126  87  61  67  63  58  59  77  91 111  94  82  78  85 105 105 120  95
  56  87 103 126 203 133 184 109  76  57  50  51  58  79  99  59 103  87 111  70
  72  93  91 106  86  95 104 101  80  86 119 162 163  88  72 125 183 154 174 109
 184 142 126 107 121 128 101  76  63  92  92 118 106 111 123 216 197 160 165 186
BEN-A08A 109
 266 273 251 245  76  48  30  23  25  25  52 106 199 286 156 233 262 213 179 155
 134 134 139  85 104 133  91  73  50  46  76  87  81  98  84  59  70  83  70  63
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  56  43  43  42  79  83  74 114  85 123 103 122 149 118 163 130  99 155 122  96
 125 144 141 115  83  44  93  99  90 134  99 156 106  73  69  61  67  65  53  47
  57  48  75  68  71  94 128 120 103
BEN-A08B 109
 269 282 246 244  80  63  31  24  26  25  54 100 202 288 148 214 255 215 173 161
 132 129 140  84 108 127  99  69  47  61  77  80  76  91  73  67  61  88  74  55
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  49  44  56  37  79  83  73 105 103 134 100 111 152 121 162 129 109 148 112 105
 123 154 141 116  79  48  89 100  89 125 108 161 101  69  72  61  66  59  57  45
  48  52  67  76  65  99 115 128 107
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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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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. 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 University of Nottingham Tree-Ring dating Laboratory

1. *Inspecting the Building and Sampling the Timbers.* Together with a building historian we inspect the timbers in a building 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. Similarly the core has just over 100 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.

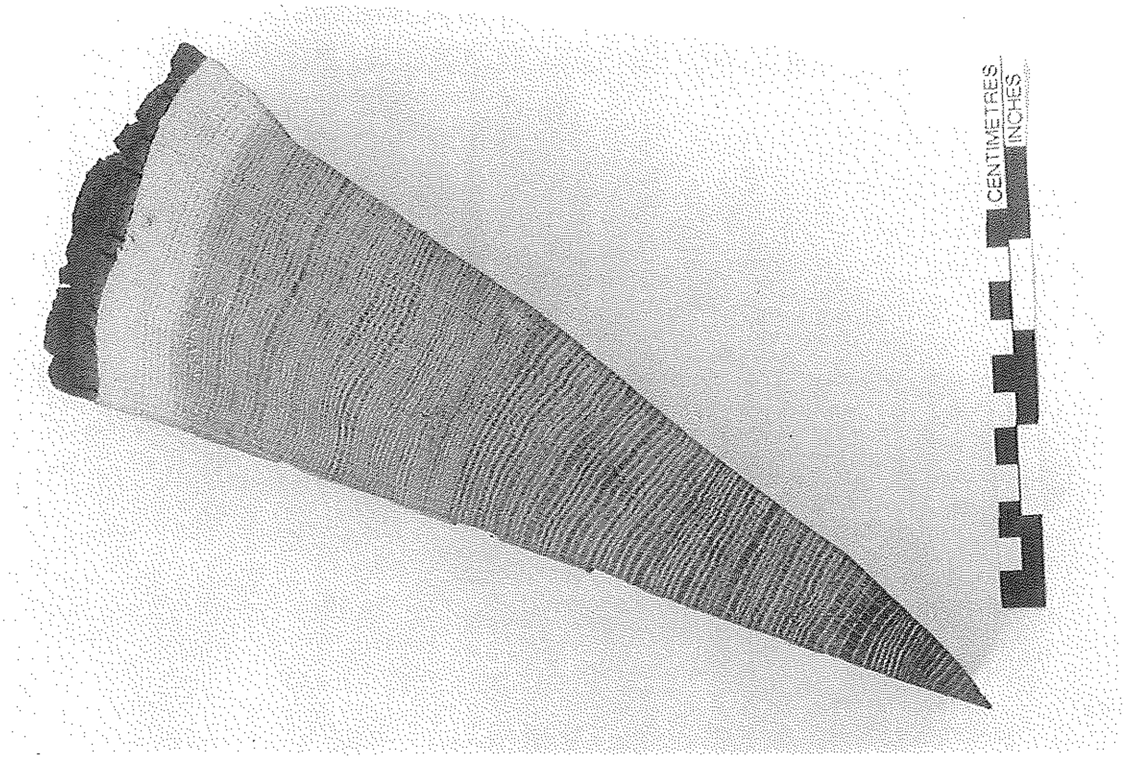

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

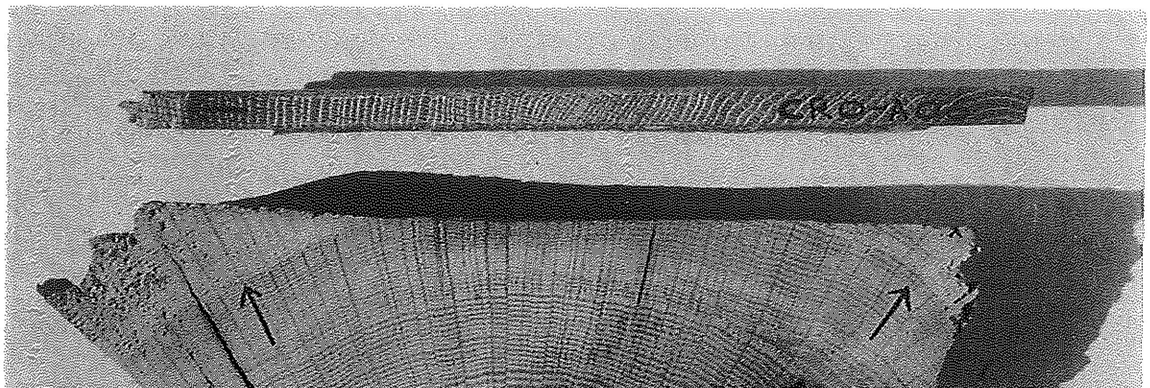

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners; the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

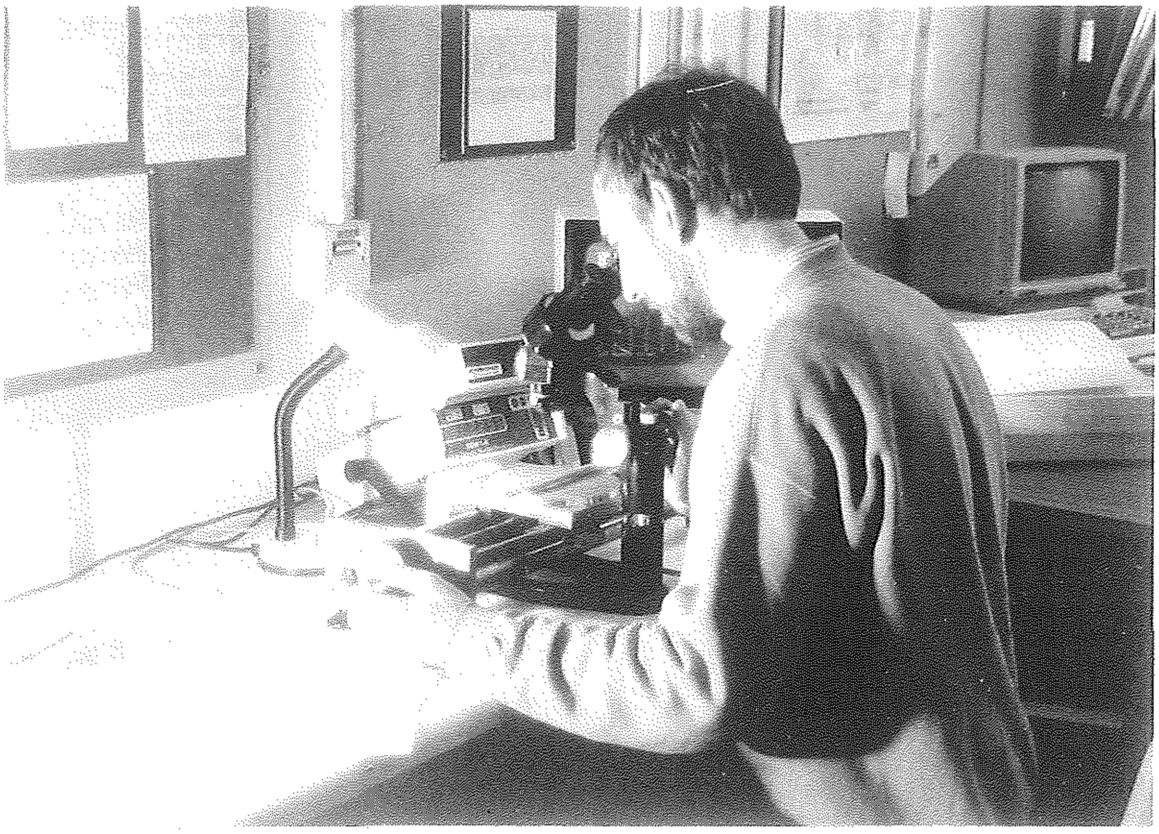

Fig 3. Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

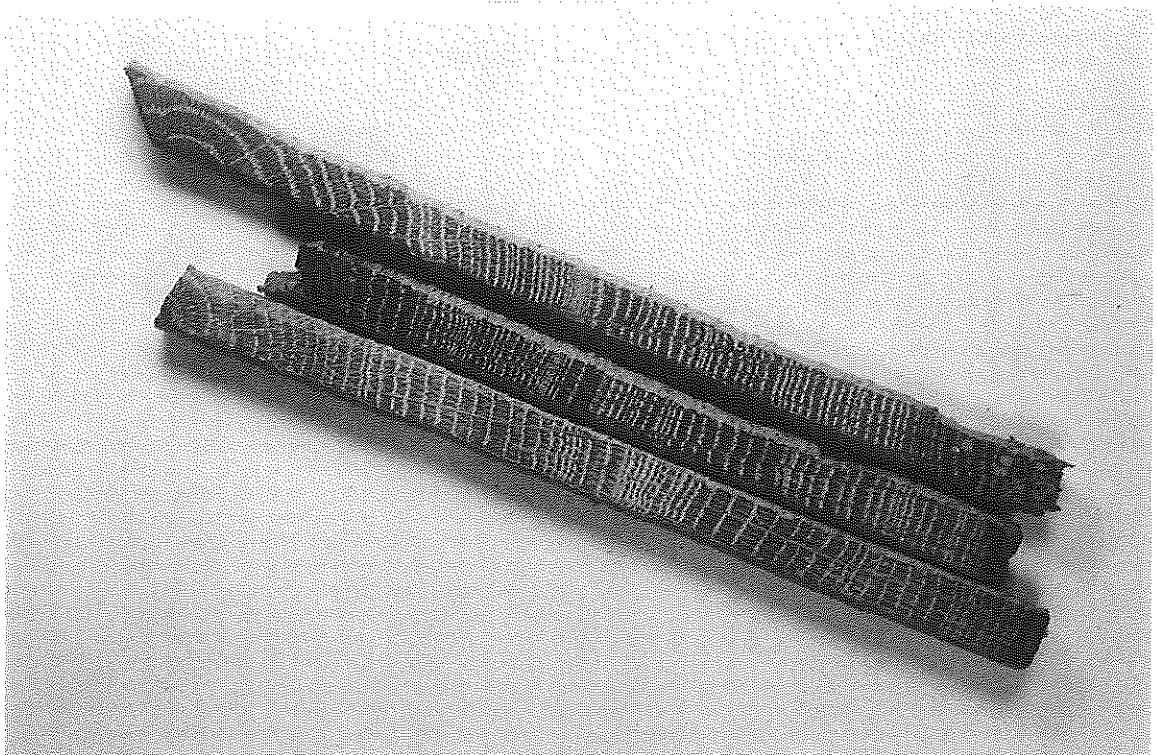

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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. 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 inspecton 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 is insured with the CBA.

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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

   This is illustrated in Fig 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, 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 between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the 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 Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

   Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

   Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

   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. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

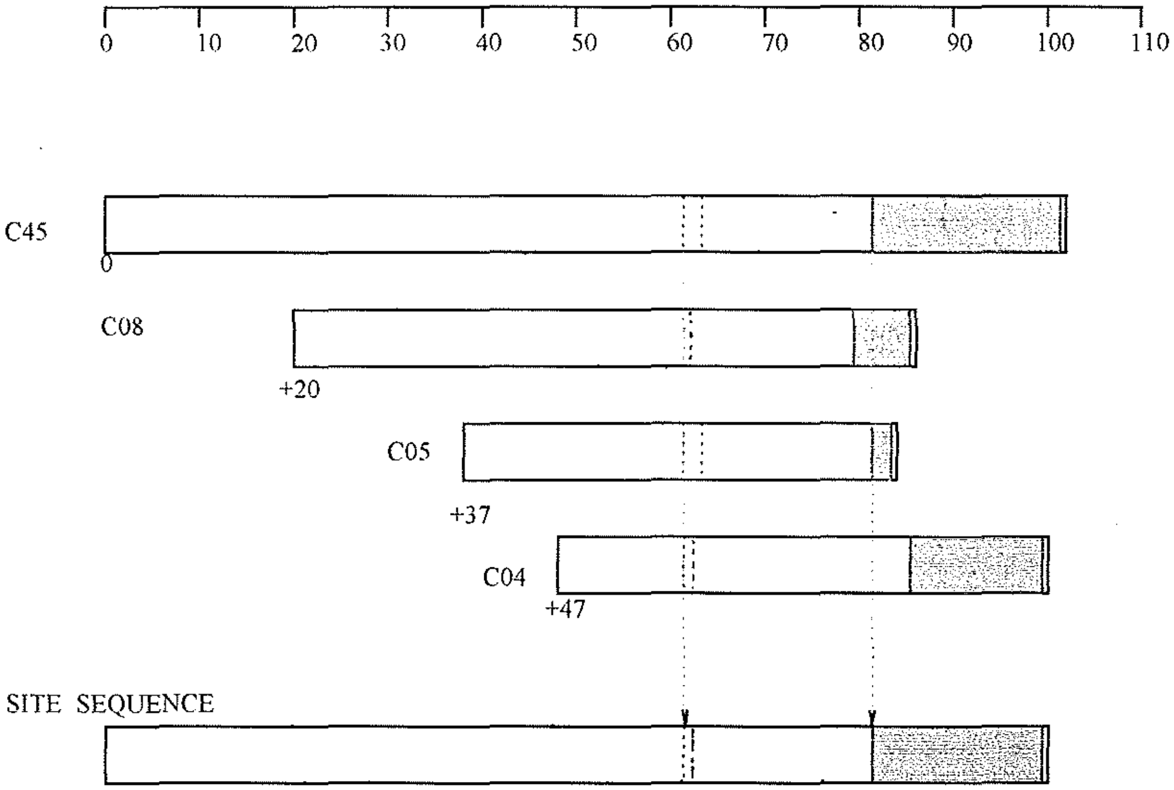

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. *Estimating the Date of Construction.* There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ*, and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 1988b, 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* 1988a). 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 (1988b) 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 (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain. only associated with the common climatic signal and so make cross-matching easier.

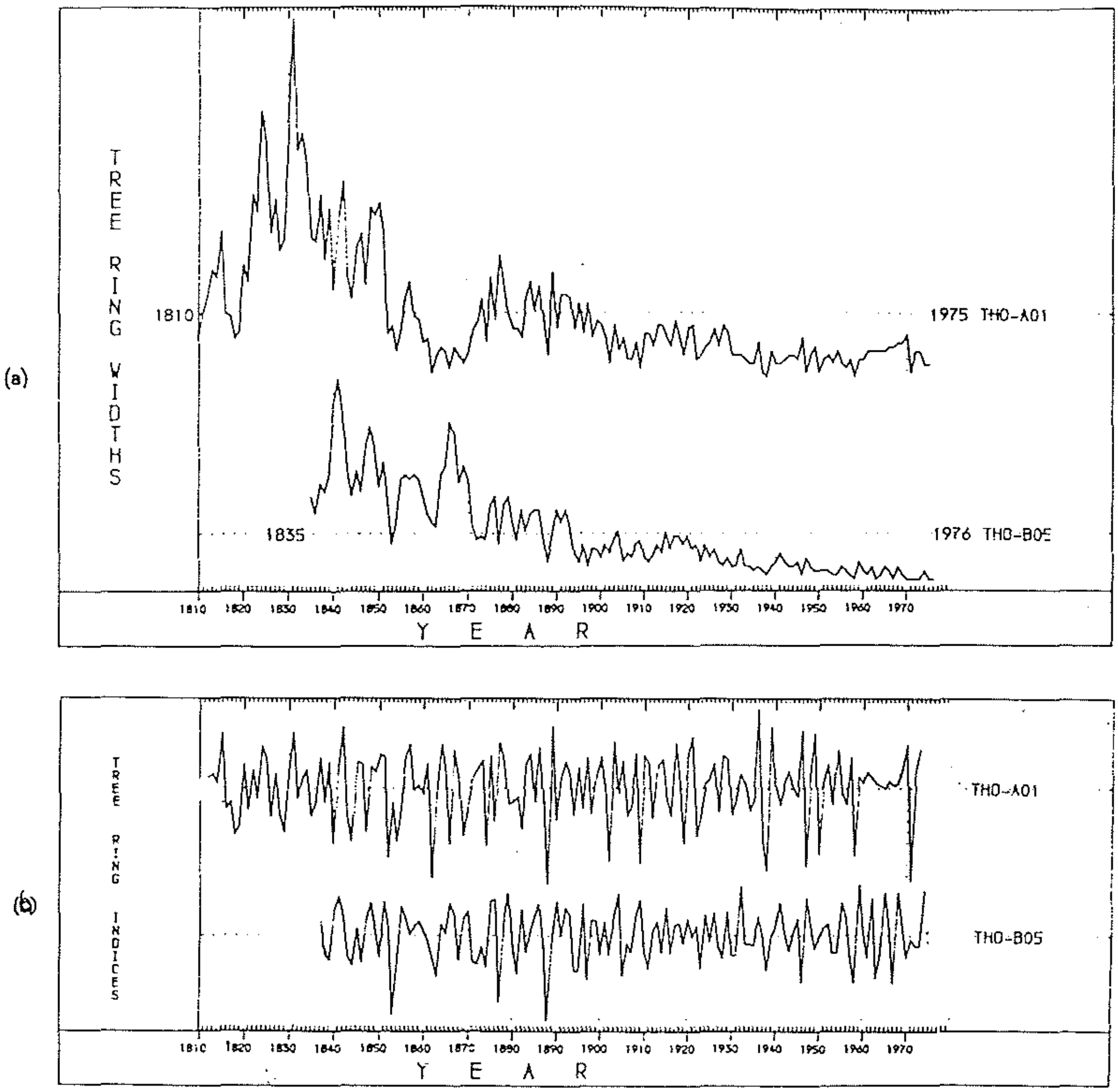

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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