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Tree-Ring Analysis of Timbers from the Standing at the Bucks Head, Debenham, Suffolk

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Summary

Analysis carried out on eight samples from the timbers of this structure resulted in the construction of two site sequences.

The first, of 79 rings, contains two samples and spans the period AD 1507-85. One of the samples is estimated to have been felled in AD 1600-25. An estimated felling date cannot be calculated for the other sample as it does not have the heartwood/sapwood boundary ring.

The second site sequence, of 60 rings, contains two samples, and spans the period AD 1561-1620. Both samples are from trees felled in AD 1620.

Sample KDS-A08 was dated individually to the period AD 1544-1605. This sample has complete sapwood and so that last measured ring date is the felling date of the timber represented.

Keywords
Dendrochronology
Standing Building

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Introduction

At the rear of number 27 High Street, Debenham (TM 173632; Figs 1 and 2) is the former Bucks Inn (to the south), and a theatrical grandstand (to the north). This latter edifice falls into a category of buildings known as Standings (also called scaffold, stage, or gallery); structures used to elevate spectators at sporting events, pageants, plays, hunts, executions, and in gardens. The Debenham Standing was galleried on one side towards the inn-yard and on the other towards the entrance to the Camping Close (an area used for playing sports, or holding church-ales, fairs, pageants, and plays), and so could have been used for viewing a variety of entertainment. The grade II* listed structure is of two-storeys and originally had three bays, although the most western one has since been lost (Fig 3). The main posts to the south are ovolo-moulded, and there are turned balusters to the south (Fig 4) and east (the latter incomplete) and plain balustrading to the north. The upper floor was open, with a hand-rail at mid-height and the ground floor may also have been open. There is evidence for an axial partition on both floors. The original roof has been lost.

This is a rare and possibly unique survival of a grandstand associated with innyard entertainment and is thought to date to the late sixteenth or early seventeenth century.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage as part of their training programme in dendrochronology, and also to provide a precise date for its construction.

The Laboratory would like to thank David and Gillian Shacklock, the owners of the building, for allowing sampling to be undertaken and Adrian Gibson for his on-site advice. Thanks are also given to Timothy Easton for providing the drawings to illustrate this report and on which to mark the location of samples (Figs 3 and 4).

Sampling

Eleven core samples were taken from oak (*Quercus* spp.) timbers at this building, from posts, rails, wall plates, a tiebeam, and a brace. All of these sampled timbers, except the brace, were thought to be part of the original structure. The brace is obviously a later insertion but it was sampled in the hope that it could provide dating evidence for this later work. Each sample was given the code SDS-A (for Suffolk, Debenham Standing, site A) and numbered 01-11. The position of all samples was noted at the time of sampling and has been marked on Figures 3 and 4. Further details relating to the samples are recorded in Table 1.

Analysis and Results

At this stage it was seen that samples SDS-A06, SDS-A07, and SDS-A09 had too few rings for successful dating and so they were not measured. The remaining eight samples were prepared by sanding and polishing and their growth-ring widths were measured; the data of these measurements are given at the end of the report. The growth-ring widths of the samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a least value of t=4.5 four of the samples had formed two groups. Two samples matched and site sequence SDSASQ01, of 79 rings, was constructed containing these samples at the offsets shown in the bar diagram (Fig 5). This site sequence was successfully matched against the relevant reference chronologies for oak at a first-ring date of AD 1507 and a last-ring date of AD 1585. The evidence for this dating is given by the t-values in Table 2.

Two samples matched and site sequence SDSASQ02, of 100 rings, was constructed containing these samples at the relevant offsets (Fig 5). This site sequence was compared with the reference chronologies but although a tentative match was noted, the t-values were not high. Both samples in this site sequence have a band of very narrow growth rings, and it was thought that this might be interfering with the matching against the reference chronologies. To combat this the site sequence was edited by removing the first 40 years worth of growth. This reduced site sequence, now only of 60 rings, was again compared with the reference chronologies, where it was found to match at a first-ring date of AD 1561 and a last-ring date of AD 1620. The evidence for this date is given by the t-values in Table 3.

Attempts were then made to date the remaining samples individually. This resulted in sample SDS-A08 being matched at a first-ring date of AD 1544 and a last-ring date of AD 1605. The evidence for this dating is given by the t-values in Table 4.

Interpretation

Analysis of samples from the building here has resulted in the production of two dated site chronology and an individually dated sample. Site chronology, SDSASQ01, contains two samples and spans the period AD 1507-1585. Only one of the samples, SDS-A04, has the heartwood/sapwood boundary ring. This allows the calculation of an estimated felling date for the timber represented to within the range AD 1600-25. The other sample, SDS-A03, does not have this ring and so a felling date cannot be calculated except to say that, with a last measured ring date of AD 1563, this is estimated to be AD 1579 at the earliest.

Site chronology, SDSASQ02, contains two samples and spans the period AD 1561-1620. Both of the samples making up this site chronology have complete sapwood and the last-ring date of AD 1620, the felling date of the timbers represented.

Sample SDS-A08 was dated to a first-ring date of AD 1544 and a last-ring date of AD 1605. This sample has complete sapwood and so the last-ring date of AD 1605 is the felling date of the timber represented.

Felling date ranges have been calculated using the estimate that 95% of mature oaks from this area have between 15-40 sapwood rings.

Discussion

Following analysis by tree-ring dating it has been possible to obtain dates for five of the timbers of the Standing at Debenham. One of the wall plates was felled in AD 1605, two posts in AD 1620, and one of the rails was felled AD 1600-25, a felling date range consistent with a felling of either AD 1605 or AD 1620. A second rail was felled at the earliest in AD 1579, indicating that again it could have been felled in AD 1605 or AD 1620, although this timber could equally represent a different felling.

Prior to the tree-ring analysis being undertaken, this building was thought to date to the late-sixteenth century or early seventeenth century. Although the dating of four, and possibly five, of its timbers to the early seventeenth century shows that the Standing was in use at this time it is also now clear that the structure contains timber from more than one felling. Thus the dendrochronological dates cannot be used to indicate a precise date of construction and/or repairs as too few timbers are dated. There are a number of possible reasons for the different felling dates. The timber felled in AD 1605 might represent the use of a single stockpiled timber, indicate the date of the original construction, or perhaps even be a repair to an earlier structure. The two timbers felled in AD 1620 could indicate the construction date of the structure or again represent repairs to an existing structure.

One final point of interest concerning the timbers used in the construction of this building is that a number of the samples show evidence for a single major growth suppression event, causing a sudden rapid decrease in growth rate. This event manifests itself as a band of very narrow growth rings that gradually increase in width as the trees slowly recover their previous levels of growth.

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Table 1: Details of tree-ring samples from timbers of the Standing at the Bucks Head, Debenham, Suffolk

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
SDS-A01	South post, truss 2	60 (+1st 40 years removed)	17C	1561	1603	1620
SDS-A02	North post, truss 2	51	--	----	----	----
SDS-A03	South rail, trusses 1-2	48	--	1516	----	1563
SDS-A04	North rail, trusses 2-3	79	h/s	1507	1585	1585
SDS-A05	South post, truss 1	60 (+1st 34 years removed)	19C	1567	1548	1620
SDS-A06	North rail, trusses 1-2	NM	--	----	----	----
SDS-A07	South rail, trusses 2-3	NM	--	----	----	----
SDS-A08	North wall plate, trusses 2-3	63	13C	1543	1592	1605
SDS-A09	South wall plate, trusses 1-2	NM	--	----	----	----
SDS-A10	Tiebeam, truss 2	51	15C	----	----	----
SDS-A11	North brace, truss 2 (later)	58	h/s	----	----	----

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample, last measured ring is the felling date
NM = not measured

Table 2: Results of the cross-matching of site sequence SDSASQ01 and relevant reference chronologies when the first-ring date is AD 1507 and the last-ring date is AD 1585

Reference chronology	*t*-value	Span of chronology	Reference
England London	4.9	AD 413-1728	Tyers 1999 unpubl
East Midlands	4.8	AD 882-1981	Laxton and Litton 1988
England	4.7	AD 401-1981	Baillie and Pilcher 1982 unpubl
Ely Cathedral, Cambs ELYQSQ10	5.7	AD 1466-1610	Howard *et al* 1992 unpubl
Spring House Farm, Walton, Derbys	5.6	AD 1445-1632	Howard *et al* 1995a
Mansfield Woodfield Priory, Notts	5.6	AD 1432-1579	Howard *et al* 1987
Sinai Park, Staffs	5.5	AD 1227-1750	Tyers 1997
26 Westgate Street, Gloucester, Glos	5.1	AD 1399-1622	Howard *et al* 1998
Western House, Warborough	5.1	AD 1473-1574	Haddon-Reece *et al* 1990
Mouseley Bottom, New Mills, Derbys	5.0	AD 1417-1566	Esling *et al* 1990

Table 3: Results of the cross-matching of site sequence SDSASQ02 and relevant reference chronologies when the first-ring date is AD 1561 and the last ring date is AD 1620

Reference chronology	t-value	Span of chronology	Reference
England London	5.1	AD 413-1728	Tyers 1999 unpubl
East Midlands	4.2	AD 882-1981	Laxton and Litton 1988
Abbey Road barrels, Barking, London	8.3	AD 1314-1599	Tyers 2001a unpubl
Beeleigh Abbey, nr Maldon, Essex	7.2	AD 1511-1623	Tyers 2001b unpubl.
England East Anglia Region	6.6	AD 781-1899	Tyers and Groves 2001 unpubl
Corpus Christi (Cupboard Drawers), Oxon	6.0	AD 1478-1604	Fletcher nd unpubl
Essex County	6.0	AD 878-1622	Tyers 1997 unpubl

Table 4: Results of the cross-matching of sample SDS-A08 and relevant reference chronologies when the first-ring date is AD 1544 and the last-ring date is AD 1605

Reference chronology	t-value	Span of chronology	Reference
England London	4.1	AD 413-1728	Tyers 1999 unpubl
Stowmarket Church Spire, Suffolk	7.6	AD 1542-1693	Howard *et al* 1994
Ely Cathedral, Cambs ELYQSQ10	5.2	AD 1466-1610	Howard *et al* 1992 unpubl
Upper House Farm, Nuffield, Oxon	5.0	AD 1431-1627	Haddon-Reece *et al* 1990
15/19 Station Street, Mansfield Woodhouse, Notts	5.0	AD 1546-1660	Howard *et al* 1997
26 Westgate Street, Gloucester, Glos	4.5	AD 1399-1622	Howard *et al* 1998
Rose Farm, Mapledurham, Oxon	4.4	AD 1543-1613	Haddon-Reece *et al* 1990
Saltby Church bell-frame, Saltby, Leics	4.0	AD 1446-1625	Howard *et al* 1995b

Figure 1: Map showing the location of Debenham, Suffolk

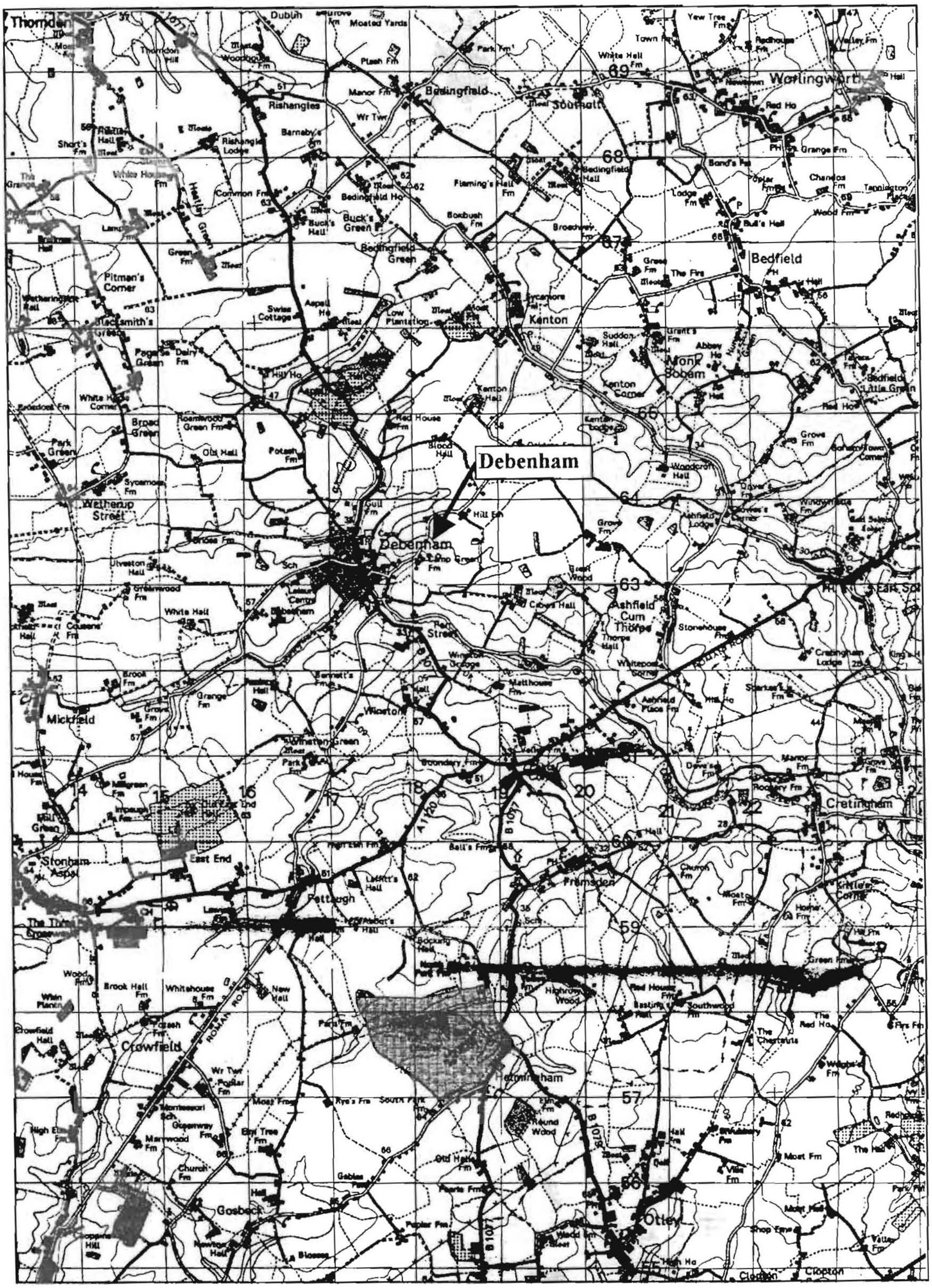

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Figure 2:

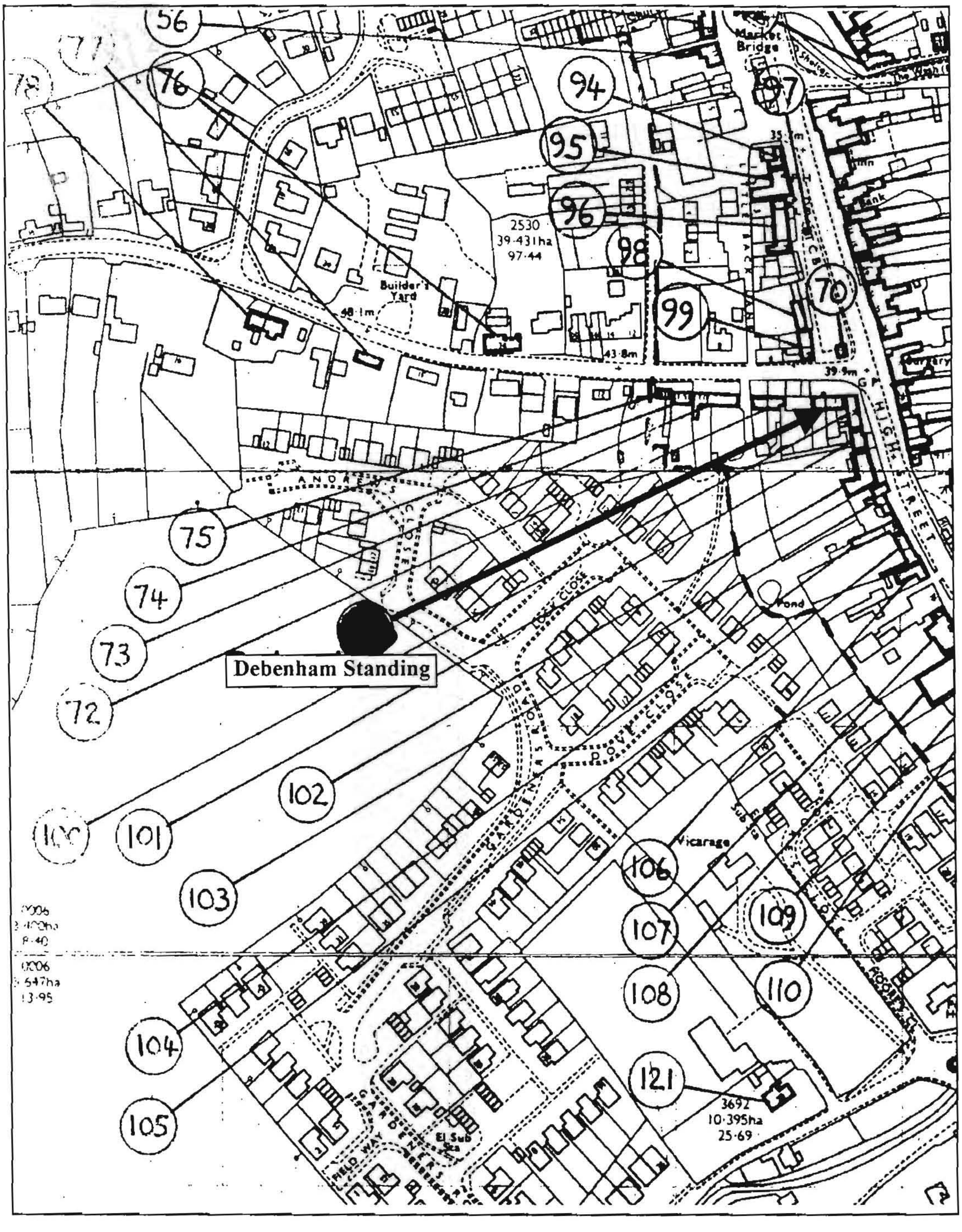

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Figure 3: The Standing at The Bucks Head, Debenham, Suffolk, showing the location of samples SDS-A02, SDS-A04, SDS-A06, SDS-A08, and SDS-A10-A11, (supplied by Timothy Easton)

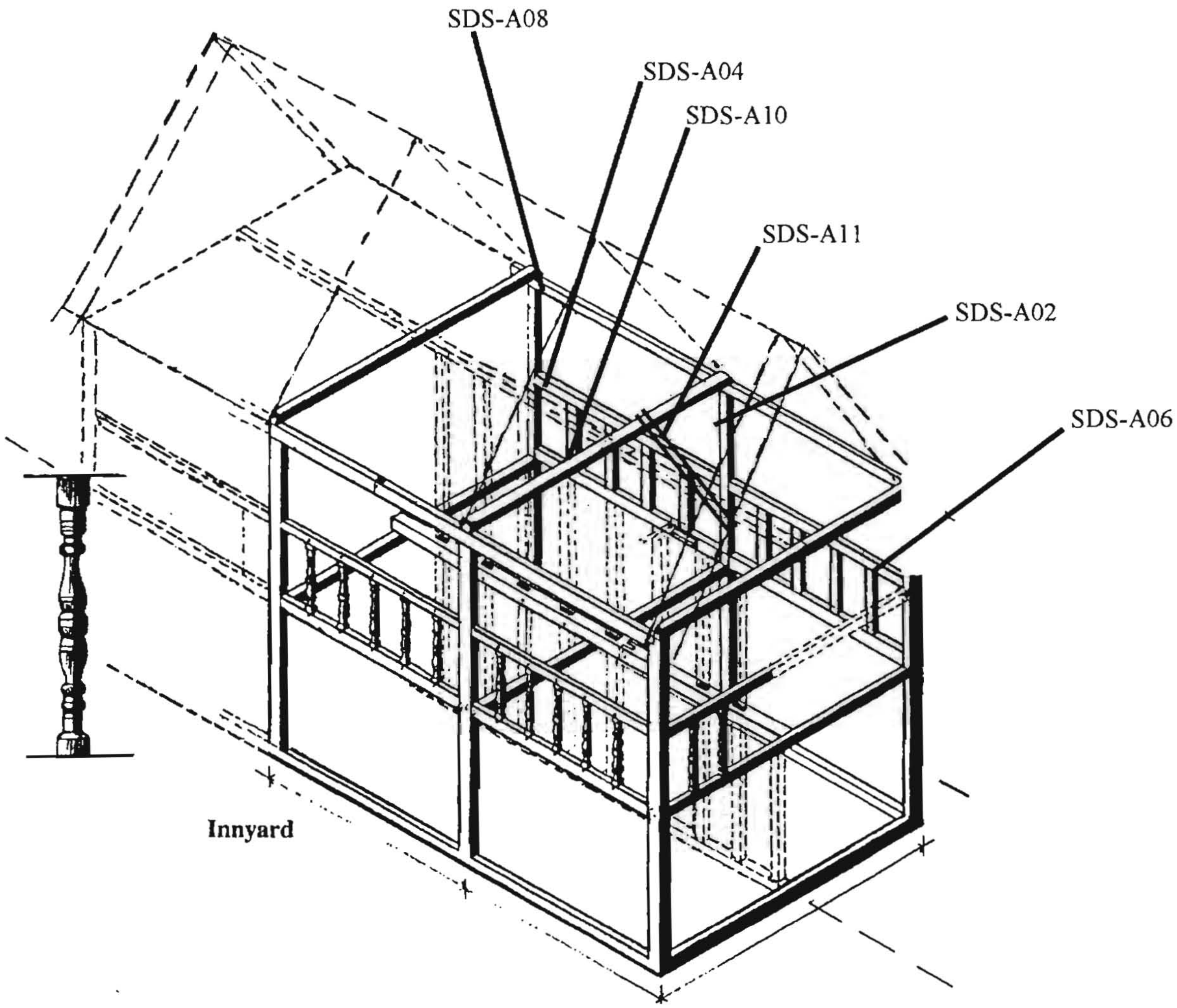


Figure 4: Debenham Standing, Front Elevation, showing the location of samples SDS-A01, SDS-A03, SDS-A05, SDS-A07, and SDS-A09 (supplied by Timothy Easton)

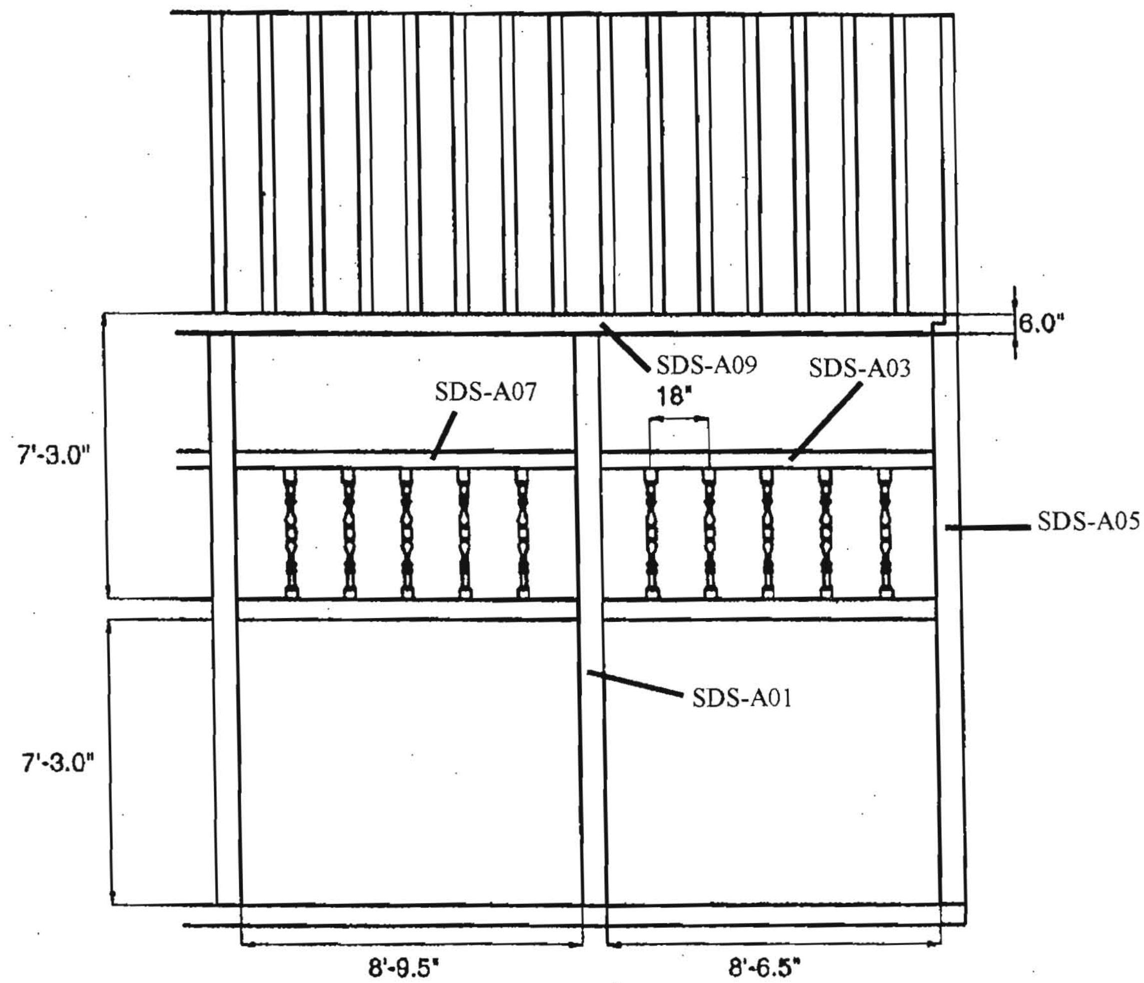
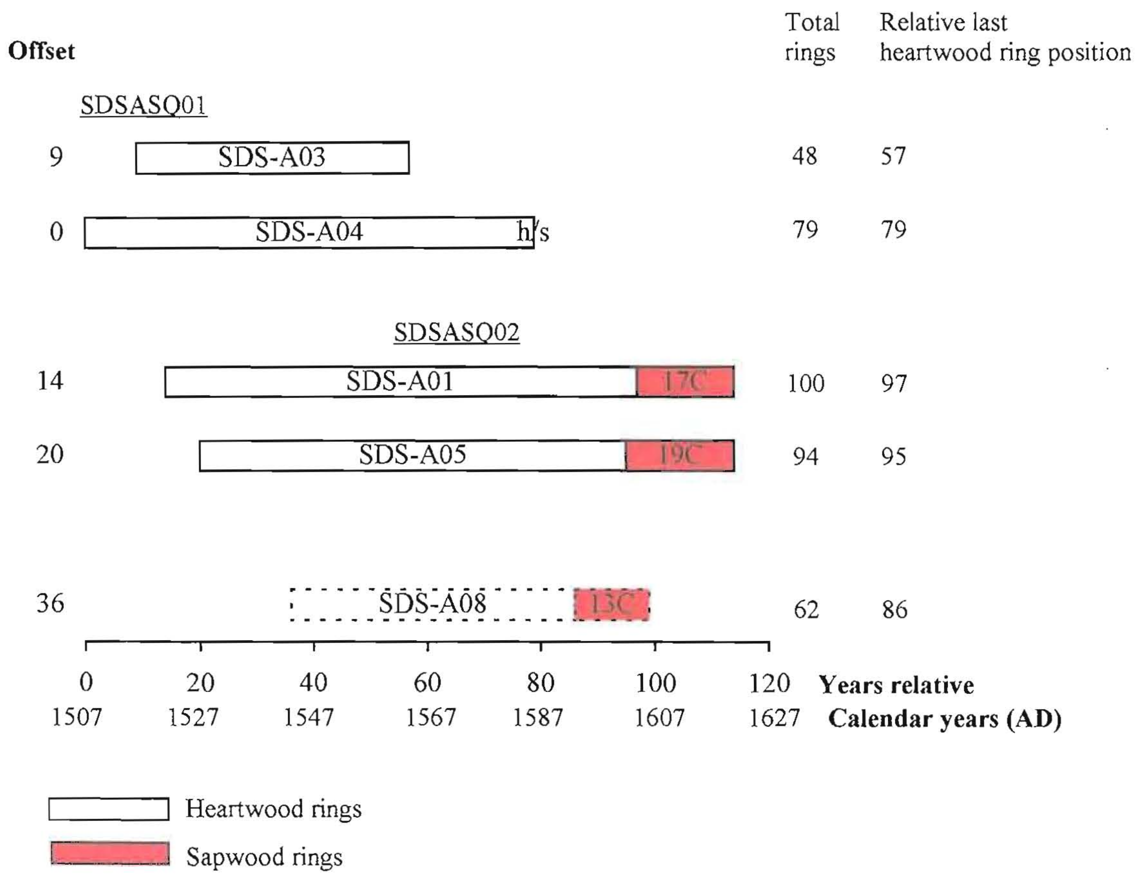


Figure 5: Bar diagram of samples in site sequences SDSASQ01 and SDSASQ02, and showing their relative position against sample SDS-A08 (dashed lines)



C = complete sapwood retained on sample, last ring is the felling date

Data of measured samples – measurements in 0.01mm units

SDS-A01A 100
(184 222 295 182 138 108 138 176 263 205 425 366 352 266 417 352 347 257 281 67
55 68 62 61 75 75 93 106 94 101 126 112 135 109 128 99 98 138 158 141)
204 233 192 277 264 188 211 276 264 257 223 201 188 152 125 111 112 96 124 194
108 117 122 129 142 142 137 133 135 99 110 144 134 161 151 153 152 144 132 153
130 147 140 160 147 197 141 124 137 128 131 125 138 99 88 81 113 104 92 74
SDS-A01B 100
(189 225 290 189 136 104 124 179 251 203 416 372 342 266 449 360 353 249 302 66
42 69 56 60 77 71 96 111 89 96 133 112 106 105 121 101 102 133 164 141)
202 228 190 270 266 181 216 271 247 260 219 205 188 149 129 105 115 95 127 192
104 120 122 122 143 143 141 134 129 100 108 140 146 170 142 153 145 145 127 153
140 143 143 175 154 178 142 120 136 136 123 128 134 95 86 88 108 104 98 81
SDS-A02A 51
406 575 546 317 365 415 495 532 451 469 476 504 341 306 390 457 396 417 395 275
270 236 278 284 287 301 278 204 213 263 189 204 166 183 217 175 170 200 159 217
196 191 152 186 203 183 137 132 185 199 208
SDS-A02B 51
374 550 510 410 373 405 512 508 438 456 479 514 351 285 395 430 406 412 408 243
267 230 273 277 284 289 270 204 204 284 182 207 165 183 205 178 169 186 165 223
189 177 162 189 195 162 171 148 192 189 215
SDS-A03A 48
169 153 295 204 166 145 222 239 197 193 212 144 227 315 212 370 215 247 186 247
233 219 164 194 184 139 68 179 125 172 97 73 152 191 168 177 144 176 190 219
148 94 81 106 129 170 146 128
SDS-A03B 48
173 154 298 197 166 151 214 237 195 187 210 135 222 294 220 356 215 251 181 219
235 230 150 196 168 144 68 169 127 171 102 74 141 193 159 187 147 165 194 212
148 99 72 112 138 155 161 114
SDS-A04A 79
212 184 197 148 260 367 358 235 259 238 92 166 132 125 114 153 187 148 103 141
205 215 259 117 182 178 247 211 255 225 209 165 170 193 134 62 135 146 143 83
82 149 189 135 209 133 137 147 161 124 108 94 101 126 138 131 112 100 78 47
49 35 64 88 63 54 83 68 80 70 45 56 44 48 54 62 87 116 48
SDS-A04B 79
219 180 185 155 260 369 348 238 259 245 94 159 132 128 107 156 192 146 110 146
198 223 236 121 195 176 242 213 247 217 214 179 170 177 134 62 145 118 130 93
69 164 191 135 204 127 146 140 159 126 115 87 98 130 131 152 130 105 76 51
34 53 59 94 58 56 60 65 80 77 46 53 48 48 54 69 82 122 60
SDS-A05A 94
(176 242 237 156 234 138 215 183 236 209 235 215 224 70 62 55 75 93 123 141
36 58 53 60 106 132 127 102 129 110 124 115 121 131) 136 191 136 161 166 144
182 267 211 223 193 184 135 120 115 126 114 104 132 164 127 140 161 186 228 199
145 179 183 140 217 176 179 262 180 217 221 281 179 180 134 133 147 145 128 219
153 144 137 137 109 135 134 114 111 94 115 117 100 154
SDS-A05B 94
(158 242 232 157 228 145 210 182 251 198 249 206 229 68 62 57 77 96 116 122
38 53 55 62 108 121 135 103 121 107 129 126 111 130) 129 213 136 153 168 140
191 269 187 224 195 196 136 129 111 104 91 87 124 178 127 105 128 167 184 202
160 158 192 133 191 189 176 280 167 214 221 272 184 184 118 143 160 150 131 202
161 145 144 132 106 132 135 111 115 94 111 124 99 154
SDS-A08A 62
370 302 394 274 160 285 351 261 269 147 257 253 487 225 296 234 238 359 334 364
187 156 146 167 170 248 306 253 316 130 152 121 122 153 120 95 111 135 117 45
64 84 62 60 53 48 61 64 98 68 90 107 92 101 94 103 79 104 70 67
71 80

SDS-A08B 63
373 288 361 271 182 268 347 255 267 152 254 266 494 228 271 239 227 362 347 387
190 155 148 167 167 248 309 262 316 124 158 123 120 148 124 98 110 136 123 52
60 89 59 63 48 50 63 67 94 74 89 119 83 109 77 93 95 94 79 60
56 43 64
SDS-A10A 51
91 132 195 211 261 283 213 205 215 232 257 234 235 61 68 67 60 70 76 115
62 58 70 102 83 103 170 194 193 209 138 147 163 159 155 200 143 132 132 211
154 228 226 172 154 165 149 190 224 156 151
SDS-A10B 51
69 138 191 201 271 276 201 225 214 233 263 222 253 48 75 67 69 61 71 113
64 61 71 99 85 103 166 202 184 217 137 147 163 169 144 196 152 132 125 175
150 232 232 164 153 177 168 169 207 180 154
SDS-A11A 58
153 270 232 338 342 374 322 221 253 206 274 283 273 304 234 210 193 185 229 266
203 219 184 232 174 262 290 242 140 177 158 238 263 191 172 140 242 244 207 263
173 230 174 164 221 139 183 170 185 195 148 213 209 142 178 128 168 165
SDS-A11B 58
155 273 230 369 300 399 311 198 272 207 287 266 311 287 240 213 197 191 231 268
196 235 186 246 182 270 289 243 148 176 156 236 268 191 179 138 236 244 209 263
175 224 173 162 216 143 179 180 178 185 154 208 214 134 168 137 160 154

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 University of 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.

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 determined by counting back from the outside ring, which grew in 1976.

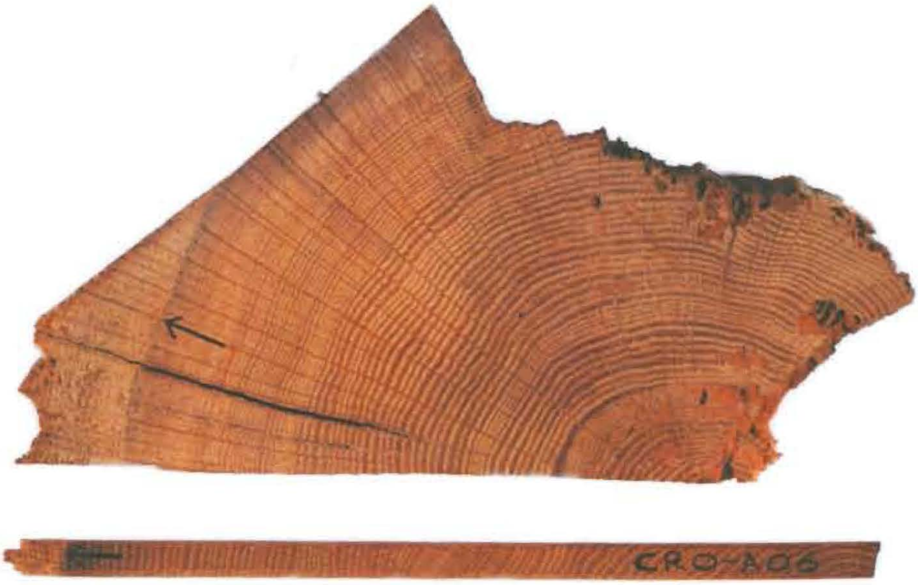


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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 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.

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 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.

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 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 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 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 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 *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

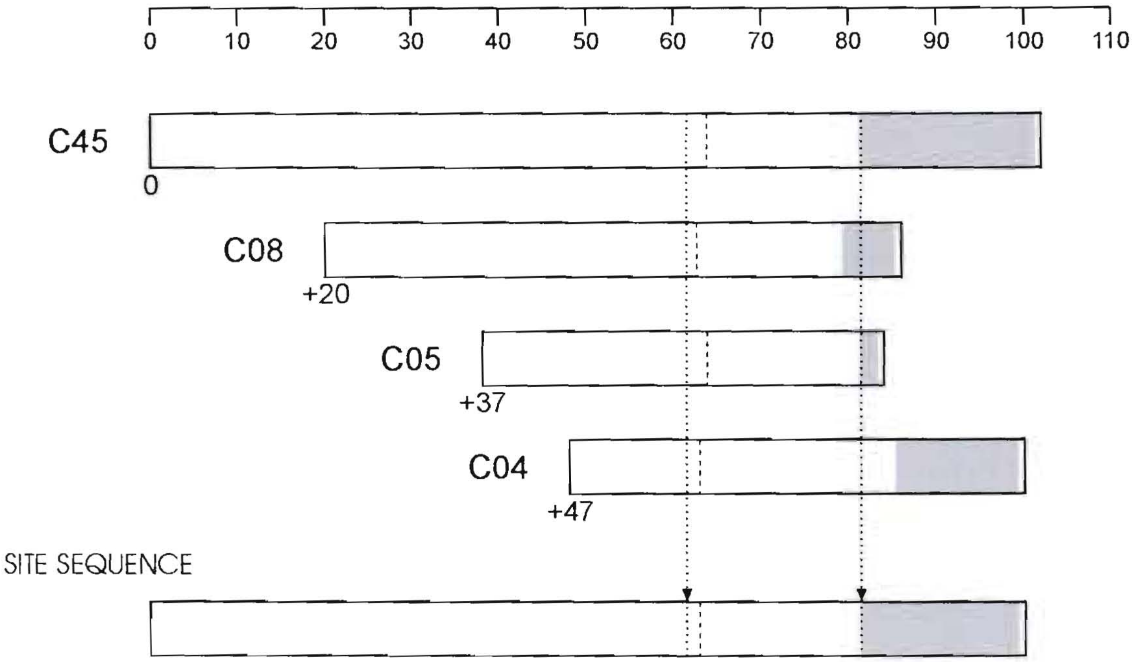


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

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 phenomena 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.

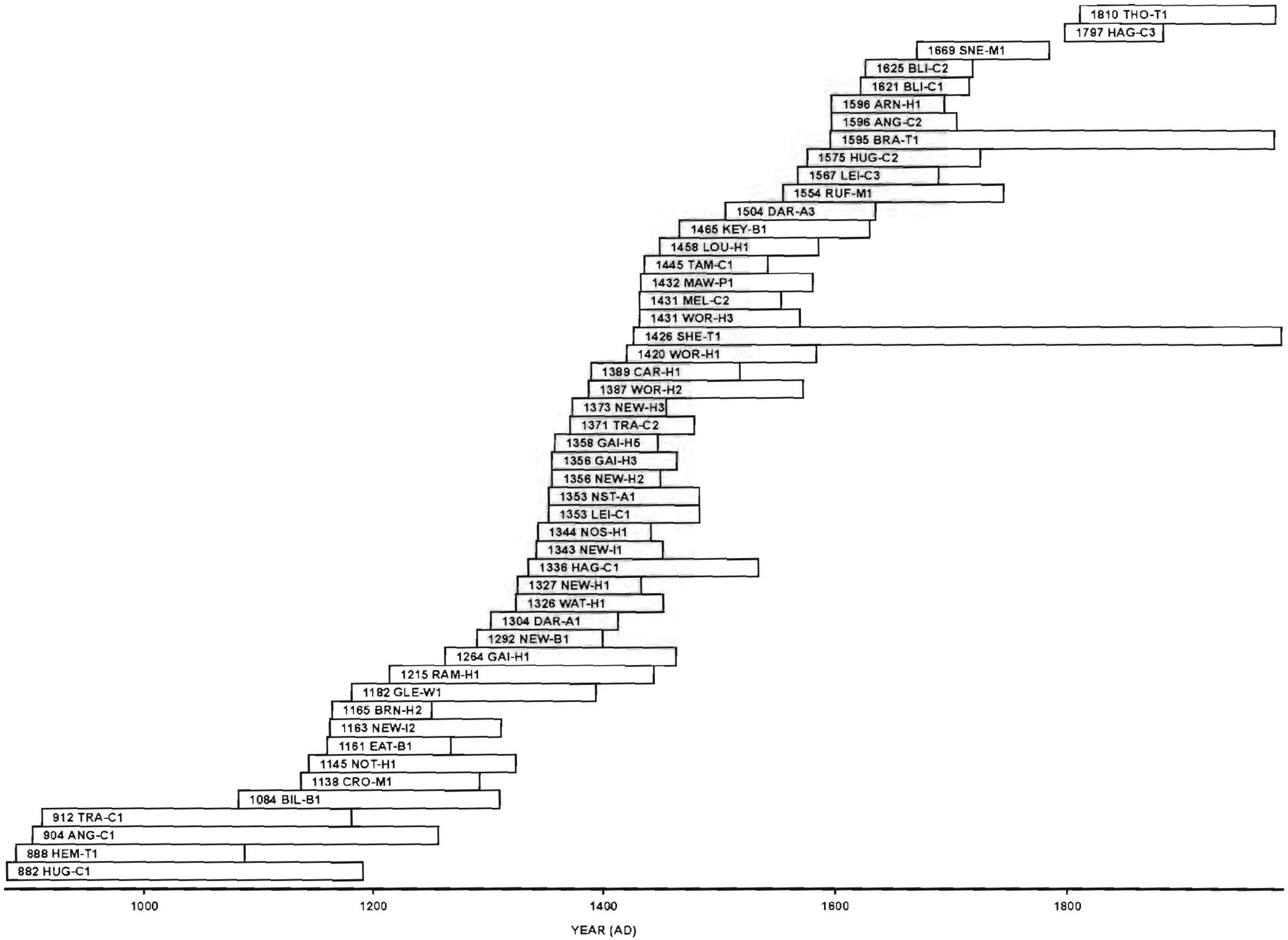
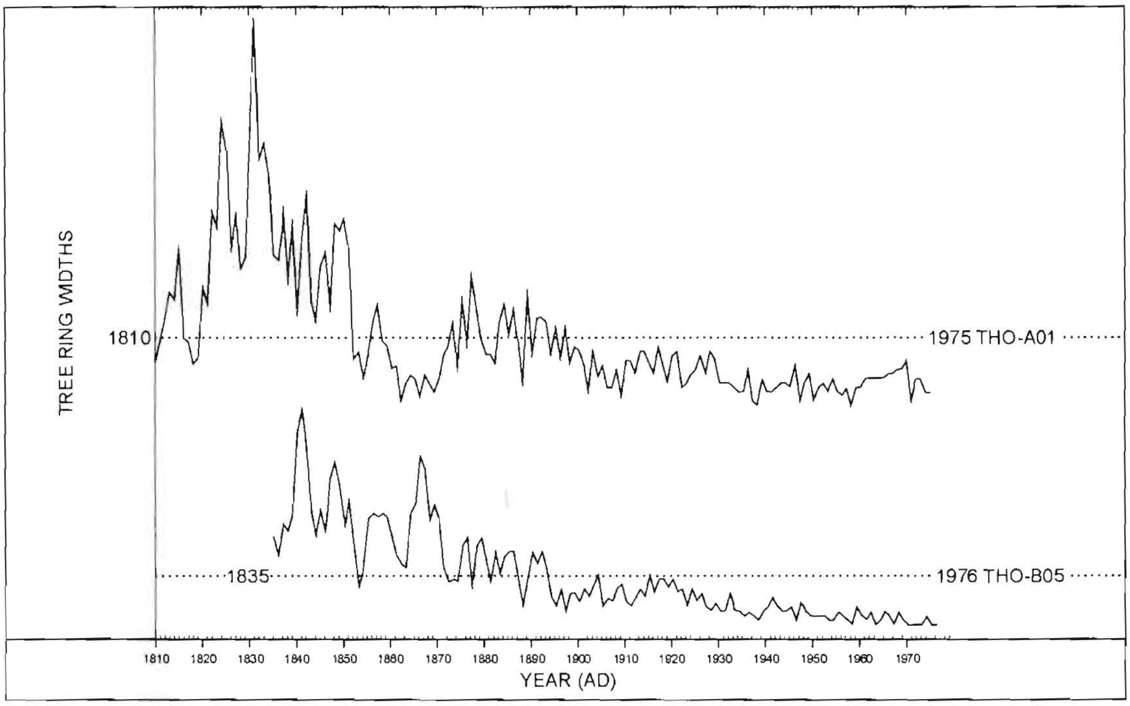


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

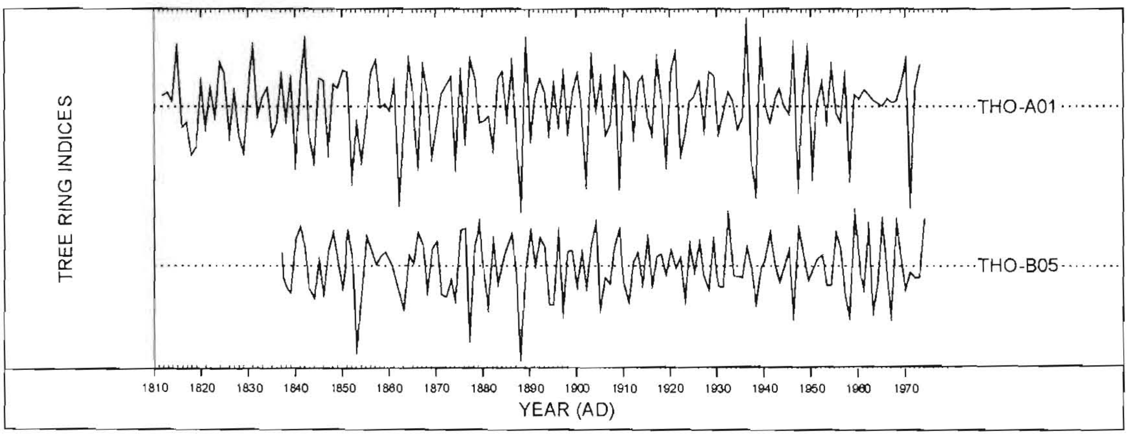


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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