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Tree-Ring Analysis of Timbers from 'The Long House', 62 Strand Street, Sandwich, Kent

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Summary

Ten samples were taken from oak timbers at these premises for dendrochronological analysis, of these three were later rejected; SND-A02 and SND-A05 have very short ring width-sequences, and SND-A07 has a distorted ring pattern.

Four samples were grouped and combined into a site sequence of 96 rings, SNDASQ02. This site sequence was successfully matched at a first-ring date of AD 1466 and a last-ring date of AD 1561. None of the samples contained within this site chronology had complete sapwood although all had the heartwood/sapwood boundary ring; the average of these gives an estimated felling date range of AD 1562-75 with the actual felling date thought to be c AD 1570.

In addition two further samples were dated individually. Sample SND-A06 was matched at a first-ring date of AD 1484 and a last ring date of AD 1557, with an estimated felling date range of AD 1569-89 and a sample SND-A10 to spanning the period AD 1472-AD 1555. This latter sample does not have the heartwood/sapwood boundary ring and so an estimated felling date range cannot be calculated.

Sample SND-A09 could not be matched and remains undated.

Keywords

Dendrochronology
Standing Buildings

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TREE-RING ANALYSIS OF TIMBERS FROM 'THE LONG HOUSE', 62 STRAND STREET, SANDWICH, KENT

Introduction

This long building, situated on Strand Street (TR 3288 5849; Figs 1 and 2) dates to the late-sixteenth century. This is clear from the detail of its structure and decoration (Pearson 2001). It is of two storeys and attics, with a high-quality front range and plainer, lower rear wing. The front range has four rooms on each floor. Two on the ground and first floors were heated, and three at least of the four chambers are decorated with fine painting or plaster work. Above, lies a single large attic room, roofed with clasped side-purlins, collars, diminishing principals, and curved windbraces. The rear wing seems to have had one large room on each floor; it is roofed by sling-braced trusses of a form which has sometimes been associated with looms for weaving. Problems concerning the origins of the building and the date of a small cellar, sometimes thought to go back to the thirteenth century, as well as with the position of the sixteenth-century entrance, the stair to the main chambers, provision of an original fireplace in the presumed kitchen in the rear wing, and the sixteenth-century circulation pattern around the house, are discussed in Pearson (2001). By the eighteenth century at the latest the cellar (which is here suggested to be an addition to the sixteenth-century building rather than its precursor) and a third fireplace had been added. Later alterations include the addition of a new stair to serve the best rooms in the house. In its sixteenth-century form this is an important and unusual building, and the question of whether it functioned as an ordinary dwelling, or had other purposes, is raised but not resolved.

The Laboratory would like to thank Mr and Mrs Bolt, the owners of the property for allowing us access to their home for sampling. We also thank Sarah Pearson for all her assistance in locating the property and arranging access and for providing Figures 2, 3a, and 3b. She has also produced an additional buildings survey (Pearson 2001), from which the above introduction is taken.

This building was sampled and analysed as part of a project, funded by English Heritage, to establish a master chronology for Kent, covering the later part of the sixteenth century to the present day.

Sampling

A total of ten samples were taken from oak timbers in the attic of these premises, by means of coring. These samples were from purlins, principal rafters, common rafters, and a collar. They were given the code SND-A (for Sandwich, site 'A') and numbered 01-10. The position of all the samples was noted at the time of sampling and has been marked on Figures 3a and 3b. Further details relating to these samples are to be found in Table 1. Samples SND-A02 and SND-A05 were later found to contain too few rings to make analysis worthwhile and so were rejected prior to this. Additionally, sample SND-A07 was badly distorted and was rejected after attempts to measure it proved impossible. Although there are two wings there is strong structural evidence to suggest that they are contemporary (Pearson 2001), and given the time constraints on the sampling, this was concentrated in the front wing, where initial interest had been expressed and the more suitable timbers were to be found.

Analysis and Results

The remaining seven samples were prepared by sanding and polishing and the growth-ring widths of all 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 three of the samples matched and site sequence, SNDASQ01 of 96 rings, was constructed containing these samples at the offsets shown in the bar diagram (Fig 4). This site sequence was successfully matched against the relevant reference chronologies for oak at a first-ring date of AD 1466 and a last-ring date of AD 1561. The evidence for this dating is given by the t-values in Table 2.

Attempts were then made to date the remaining four samples individually. As a result three further samples were successfully dated. SND-A03 was found to match at a first-ring date of AD 1484 and a last ring date of AD 1558. Sample SND-A06 was found to span the period AD 1484–57. The final sample dated in this way was SND-A10, which was matched at a first-ring date of AD 1472 and a last-ring date of AD 1555. The evidence for these dates is given by the t-values in Tables 3-5.

It was then noted that sample SND-A03 matched site sequence SNDASQ01 at the expected offset at a value of t=4.1 and a second site sequence, containing all four samples was constructed (Fig 5). This site sequence was successfully matched against the reference chronologies, again at a first-ring date of AD 1466 and a last-ring date of AD 1561. The evidence for this dating is given by the t-values in Table 6.

The remaining sample could not be matched and is, therefore, undated.

Interpretation

As a result of this analysis six timbers have been successfully dated. Although none of them have complete sapwood it is possible to calculate estimated felling date ranges for five of these by looking at the heartwood/sapwood boundary ring dates and using the usual range of mature oaks in Kent having between 15 and 35 sapwood rings (Pearson 1994, 150). Site sequence SNDASQ02 contains four samples, each with some sapwood. The average heartwood/sapwood boundary ring date, for these four samples, is AD 1540, which gives a felling date within the range of AD 1562-75. Furthermore, two of the samples in this site sequence, SND-A01 and SND-A04, were from timbers that had complete sapwood on them, some of which, due to its much degraded state, was lost in coring. By noting the amount in millimetres of lost sapwood and counting how many rings this amounted to on the sample estimates were made of the number of rings lost, *c* 10 rings for SND-A01 and *c* 25 rings for SND-A04 which would give a felling date for these timbers of *c* AD 1570, consistent with the above range. This is also consistent with the estimated felling date calculated for sample SND-A06. This sample has a heartwood/sapwood boundary ring date of AD 1554, therefore, pointing towards a felling date within the range of AD 1569-79. The final sample dated, SND-A10, does not retain the heartwood/sapwood boundary ring and, therefore, it is not possible to calculate an estimated felling date range for it, except to say that this would be AD 1571-91 at the earliest.

Discussion

This analysis has resulted in five of the timbers, used in the construction of this building, being found to have a felling date of *c* 1570. However, all five samples for which it has been possible to estimate a felling date for have come from timbers in the front wing with this not being possible to do for the one dated sample from the rear wing, SND-A10. This might leave open to suggestion the possibility that the rear wing is not of the same date. In response to this it can be said that, at the time of sampling, it was thought that the timber from which this sample was taken retained the heartwood/sapwood boundary and that this was lost in sampling, along with one or two rings. This would give a felling date for this timber in the second half of the sixteenth century, if not contemporary with those timbers used in the construction of the front wing, then soon after. The contemporaneous status of these two wings is further supported by the building survey carried out by Sarah Pearson. In this Pearson notes that, although the roof structure is completely different in each wing, the rear wing '… has no south wall of its own, and its west wall plate is tenoned into a post, … which is integral to the framing of the front range.'

The *t*-values at which the final site chronology was constructed are lower than would usually be accepted. However, the dates gained are consistent and as outlined above have been checked by individual dating. In addition they match the reference chronologies well. The reference chronologies used to date this building are not only those from the south-east of England but of necessity, also from the Midlands, the west of England, and also Wales. This is due to the acknowledged problem in the paucity of reference material from this period in Kent.

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Figure 1: Street plan of Sandwich to show the location of 'The Long House', 62 Strand Street, Sandwich, Kent

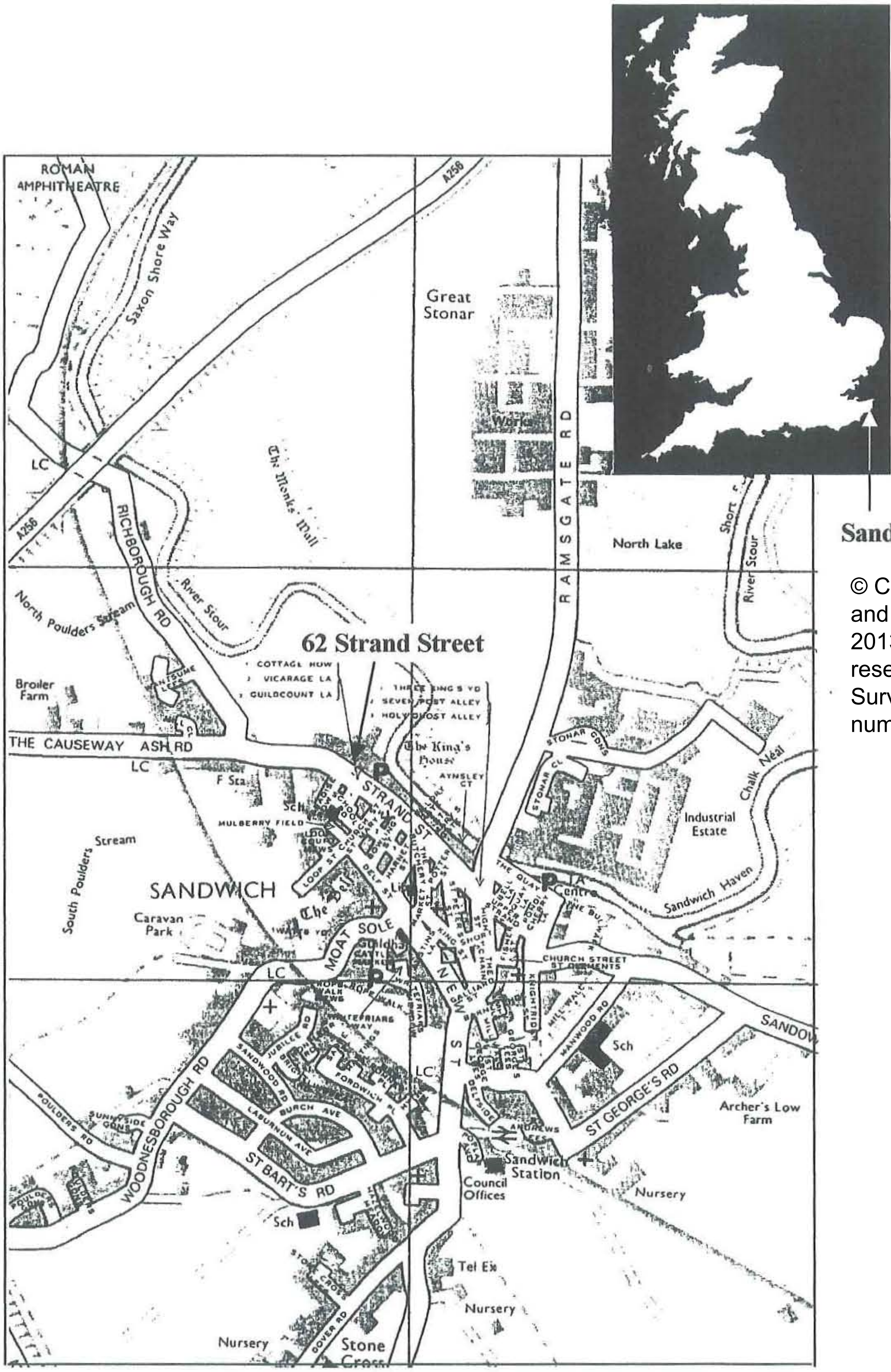


Figure 2: Ground-floor plan of 'The Long House', 62 Strand Street, Sandwich, Kent; drawn by Sarah Pearson

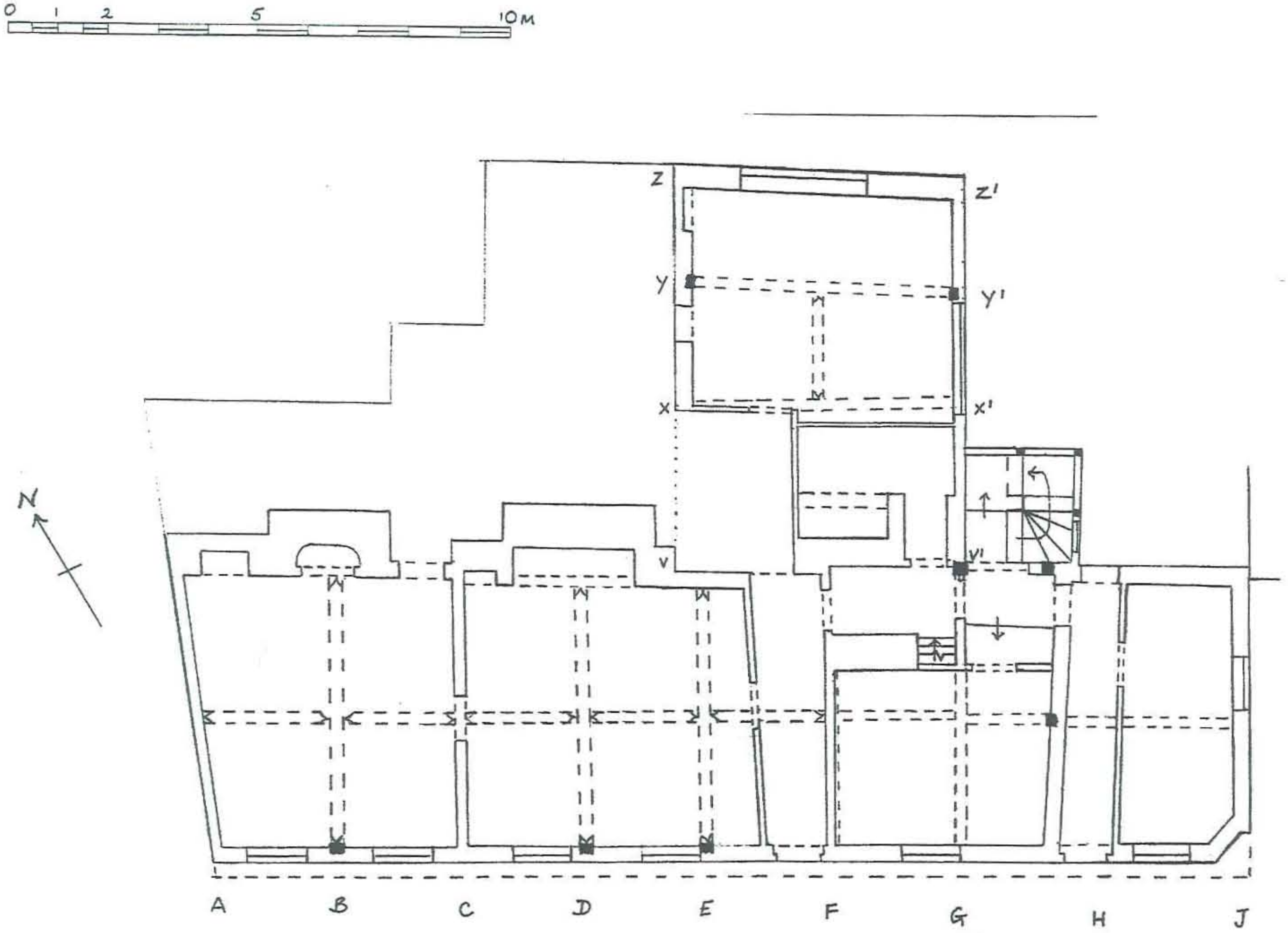
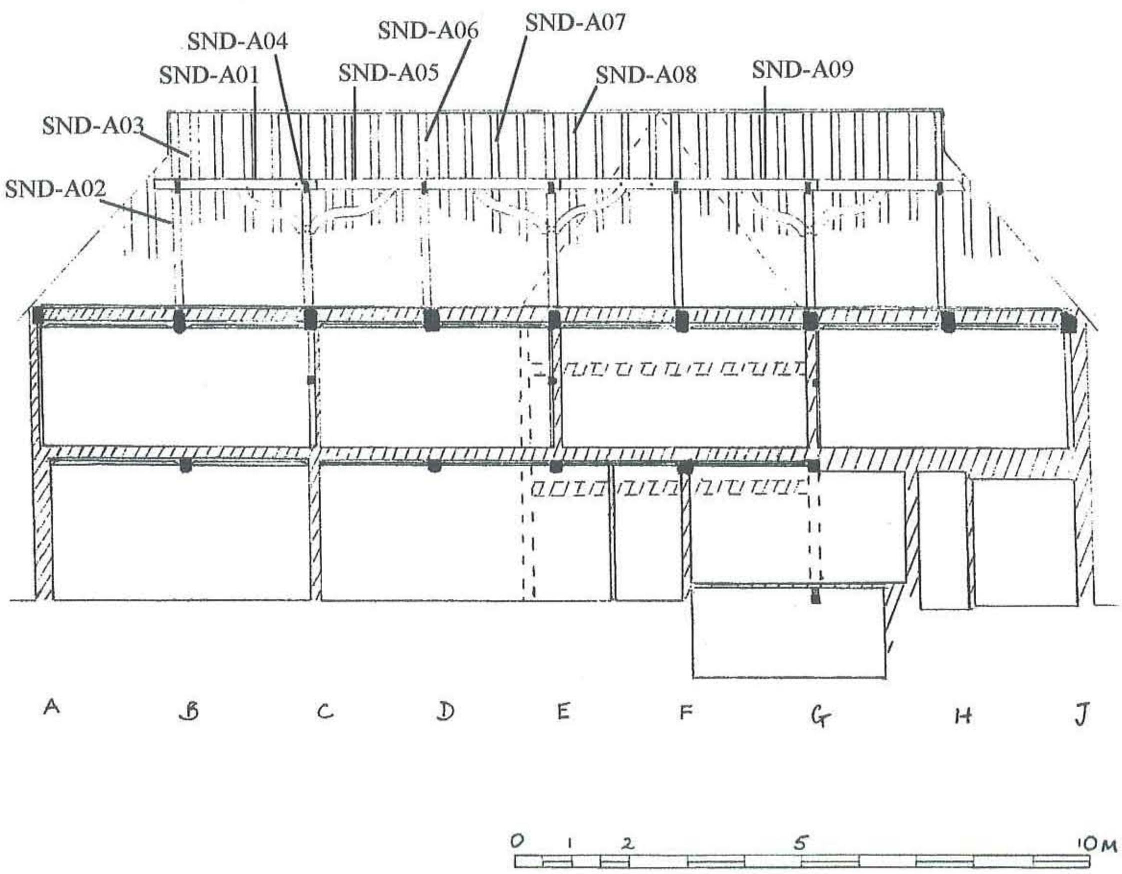


Figure 3a: Long section through front range, from south, showing the location of samples SND-A01-09 with the position of the rear wing indicated by dashed lines and sketch drawing of the rear wing (west wall) showing the location of sample SND-A10; drawn by Sarah Pearson



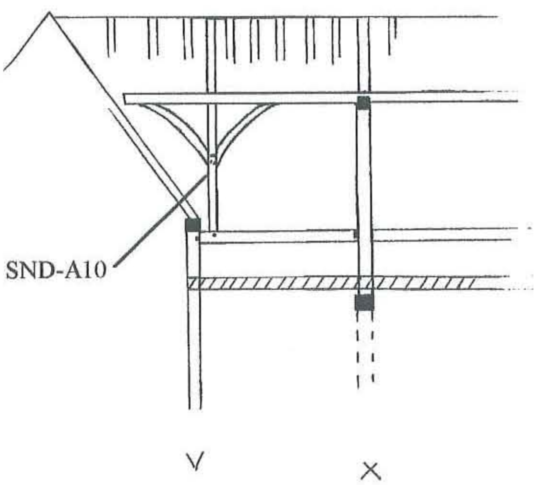


Figure 3b: Sketch section of rear range between V and X showing location of sample SND-A10; drawn by Sarah Pearson

Figure 4: Bar diagram showing the samples in site sequence SNDASQ01

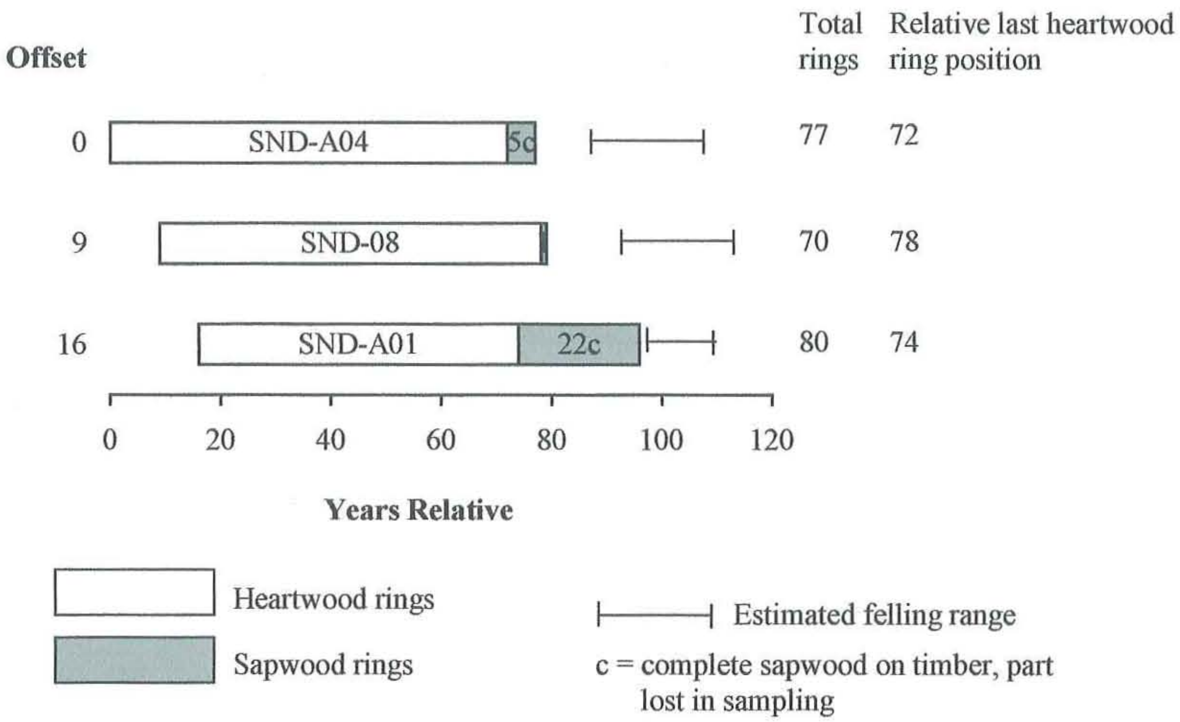


Figure 5: Bar diagram showing the samples in site sequence SNDASQ02

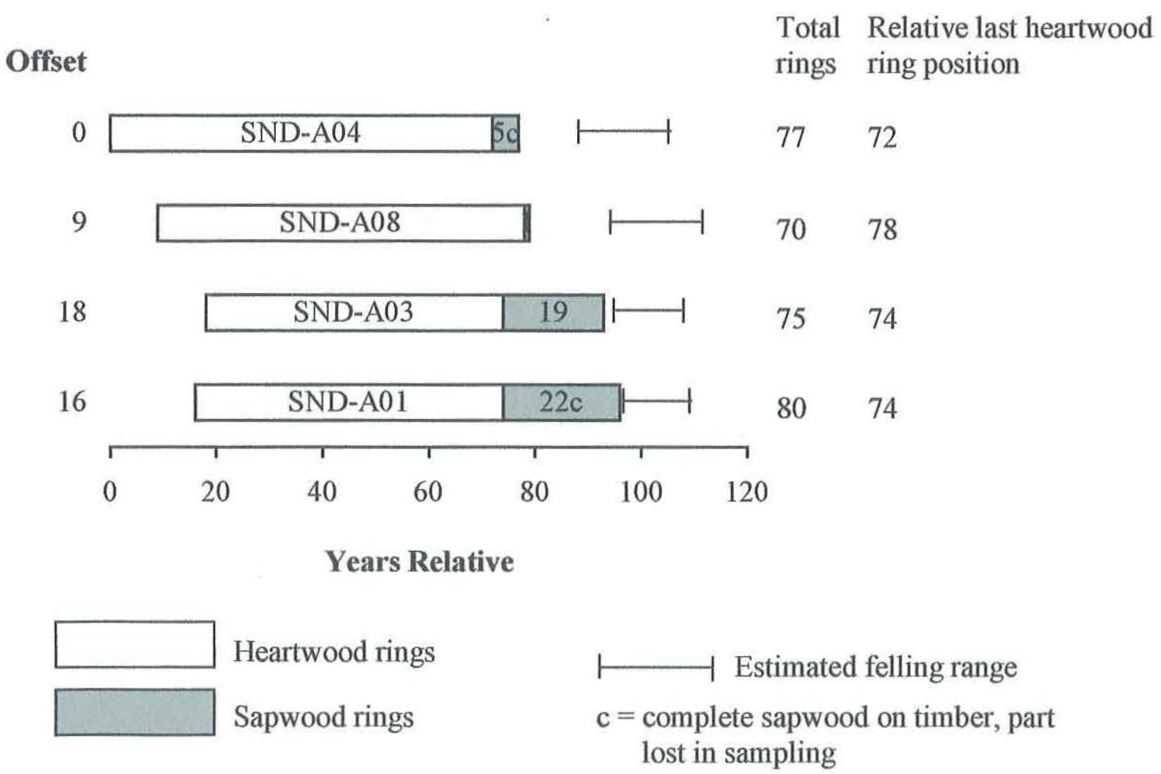


Table 1: Details of tree-ring samples from 'The Long House', 62 Strand Street, Sandwich, Kent

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
SND-A01	Purlin between B and C	80	22c	1482	1539	1561
SND-A02	Principal rafter, B	NM	--	----	----	----
SND-A03	Rafter B1	75	19	1484	1539	1558
SND-A04	Collar, truss C	77	5c	1466	1537	1542
SND-A05	Purlin between C and D	NM	--	----	----	----
SND-A06	Principal rafter D	74	03	1484	1554	1557
SND-A07	Rafter D3	NM	--	----	----	----
SND-A08	Rafter E1	70	01	1475	1543	1544
SND-A09	Purlin between F and G	57	h/s	----	----	----
SND-A10	Principal rafter, rear range, V	84	--	1472	----	1555

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

Table 2: Results of the cross-matching of site sequence SNDASQ01 and relevant reference chronologies when the first-ring date is AD 1466 and last-ring date is AD 1561

Reference chronology	*t*-value	Span of chronology	Reference
England London	5.3	AD 413-1728	Tyers and Groves 1999 unpubl
East Midlands	4.4	AD 882-1981	Laxton and Litton 1988
England	3.9	AD 404-1981	Baillie and Pilcher 1982
Western House, Warborough	5.0	AD 1473-1574	Haddon-Reece *et al* 1990
Hipper Hall, Holymorside, Derbys	5.0	AD 1454-1615	Howard *et al* 1995
Staunton Harold Church pews, Leices	4.8	AD 1508-1661	Howard *et al* 1996
The Manor House, Donington-le-Heath, Leics	4.4	AD 1411-1618	Esling *et al* 1989
Mouseley Bottom, New Mills, Derbys	4.4	AD 1417-1566	Esling *et al* 1990

Table 3: Results of the cross-matching of sample SND-A03 and relevant reference chronologies when the first-ring date is AD 1484 and the last-ring date is AD 1558

Reference chronology	*t*-value	Span of chronology	Reference
Kent	5.3	AD 1158-1540	Laxton and Litton 1989
England London	4.5	AD 413-1728	Tyers and Groves 1999 unpubl
Western England and Wales	3.8	AD 1341-1636	Siebenlist-Kerner 1978
Lacock Abbey, Stable, Wilts	4.6	AD 1448-1546	Esling *et al* 1990
Keyworth barn, Notts	4.5	AD 1451-1628	Laxton *et al* 1984
Ely Cathedral, *ELYQSQ10*	4.2	AD 1466-1610	Howard *et al* 1992 unpubl
Brewhouse Yard Museum, Notts	4.1	AD 1445-1551	Howard *et al* 1994
The Manor House, High Street, Templecombe, Somerset	3.7	AD 1486-1591	Howard *et al* 1997

Table 4: Results of the cross-matching of sample SND-A06 and relevant reference chronologies when the first-ring date is AD 1484 and the last-ring date is AD 1557

Reference chronology	*t*-value	Span of chronology	Reference
Southern England and Wales	4.7	AD 1386-1585	Fletcher 1980
Western England and Wales	4.7	AD 1341-1636	Siebenlist-Kerner 1978
England London	4.6	AD 413-1728	Tyers and Groves 1999 unpubl
26 Westgate Street, Glos	4.9	AD 1399-1622	Howard *et al* 1998
Sinai Park, Staffs	4.1	AD 1227-1750	Tyers 1997

Table 5: Results of the cross-matching of sample SND-A10 and relevant reference chronologies when the first-ring date is AD 1472 and the last-ring date is AD 1555

Reference chronology	*t*-value	Span of chronology	Reference
England London	5.3	AD 413-1728	Tyers and Groves 1999 unpubl
Kent	4.7	AD 1158-1540	Laxton and Litton 1989
Southern England	4.1	AD 1083-1589	Bridge 1988
Western England and Wales	3.7	AD 1341-1636	Siebenlist-Kerner 1978
Brewhouse Yard Museum, Notts	4.6	AD 1445-1551	Howard *et al* 1994
Mansfield Woodhouse Priory, Notts	4.1	AD 1432-1579	Howard *et al* 1987
15/19 Station Street, Mansfield Woodhouse, Notts	3.6	AD 1432-1621	Howard *et al* 1997
Home Garth House, Blyth, Notts	3.5	AD 1426-1571	Howard *et al* 1991

Table 6: Results of the cross-matching of site sequence SNDASQ02 and relevant reference chronologies when the first-ring date is AD 1466 and the last-ring date is AD 1561

Reference chronology	*t*-value	Span of chronology	Reference
England London	5.4	AD 413-1728	Tyers and Groves 1999 unpubl
East Midlands	4.5	AD 882-1982	Laxton and Litton 1988
Kent	4.4	AD 1158-1540	Laxton and Litton 1989
Hipper Hall, Holymorside, Derbys	5.1	AD 1478-1632	Howard *et al* 1994
Pye Corner, Moulsford, Oxon	4.9	AD 1340-1558	Alcock *et al* 1991
Keyworth barn, Notts	4.8	AD 1451-1628	Laxton *et al* 1984
The Manor House, Donington-le-Heath, Leics	4.6	AD 1411-1618	Esling *et al* 1989
Ightham Mote, Ivy Hatch, Kent	4.6	AD 1325-1555	Howard *et al* 1995

Data of measured samples – measurements in 0.01 mm units

SND-A01A 80
106 99 84 53 84 84 76 96 125 46 115 52 89 189 233 218 156 120 62 48
52 78 64 54 98 130 133 155 102 127 172 134 126 121 128 133 158 118 36 43
91 82 117 75 81 78 77 63 45 97 139 72 113 134 122 111 192 173 167 152
61 68 37 49 34 56 77 91 102 134 116 130 192 193 184 151 84 155 174 183
SND-A01B 80
94 97 87 62 67 80 89 93 125 47 106 53 102 182 232 214 159 126 62 39
60 81 62 55 94 128 138 151 107 120 176 142 119 126 114 143 148 116 45 33
104 74 115 71 98 65 78 54 58 99 134 72 90 147 105 128 184 153 172 160
69 59 46 37 39 53 64 90 101 128 120 130 198 198 164 133 114 155 184 167
SND-A03A 75
230 302 368 346 295 275 255 197 206 189 243 237 291 253 160 139 137 105 75 107
69 102 132 104 101 121 76 105 135 86 152 156 141 123 144 135 89 109 168 119
127 111 104 107 112 80 52 97 72 81 65 148 115 102 81 98 108 121 104 46
133 60 74 50 43 59 48 60 65 87 99 109 170 150 173
SND-A03B 75
219 304 366 340 293 279 264 195 202 191 245 234 296 272 158 149 135 107 82 105
72 116 119 105 110 121 69 110 134 80 157 154 135 119 155 132 86 103 173 115
131 112 102 104 112 82 64 92 74 77 68 147 118 104 82 96 113 109 108 50
123 64 74 47 45 58 50 56 71 74 114 108 176 165 190
SND-A04A 77
87 143 72 57 54 119 138 99 166 182 96 81 111 146 166 140 139 145 189 219
158 173 114 115 169 83 127 101 196 238 267 246 219 563 271 137 95 102 70 63
69 51 94 82 55 57 63 49 74 104 86 76 64 61 45 50 98 79 120 66
98 129 120 101 84 117 115 93 82 139 95 121 112 75 80 132 123
SND-A04B 77
95 142 82 55 63 113 140 100 165 182 98 74 116 139 161 154 129 139 185 215
167 173 119 118 168 91 118 107 202 235 269 242 228 563 271 142 97 91 73 55
69 48 91 73 62 61 68 42 76 110 85 66 68 56 50 45 100 83 115 69
106 124 123 99 90 105 109 98 80 135 99 119 104 93 77 133 124
SND-A06A 74
224 260 250 268 213 196 229 114 124 178 124 173 297 411 269 280 183 174 112 109
145 197 216 224 221 231 263 206 237 197 159 159 163 167 143 120 74 85 114 95
104 96 83 98 105 114 86 109 88 74 99 123 91 92 89 105 136 157 151 200
164 135 105 98 177 215 203 299 246 224 224 245 218 219
SND-A06B 74
215 228 268 263 206 196 211 119 120 170 123 166 294 404 262 269 182 169 111 101
167 213 213 222 215 229 265 198 243 181 159 158 156 164 137 121 81 82 119 100
101 95 84 95 110 103 80 105 90 86 93 122 98 98 95 105 118 151 156 195
167 139 98 89 173 205 210 268 215 238 224 237 216 218
SND-A08A 70
182 143 102 123 110 119 133 73 86 104 197 211 148 102 182 170 113 215 205 296
333 333 222 182 167 125 118 116 174 133 139 190 205 147 184 125 119 143 113 127
130 133 114 116 110 99 94 158 107 128 84 73 61 67 65 41 56 55 55 53
54 63 50 45 58 63 59 34 125 135

SND-A08B 70
162 147 103 123 103 128 124 76 81 108 185 206 131 117 155 155 102 211 203 296
325 317 234 161 184 134 98 142 177 134 141 184 205 155 164 142 101 154 113 128
130 131 119 108 115 96 97 156 120 99 81 78 63 71 55 47 59 53 52 52
60 63 47 44 61 51 59 49 109 135
SND-A09A 57
188 317 380 475 496 486 323 353 343 296 392 275 267 335 304 303 213 246 235 205
212 221 226 231 205 232 239 179 133 139 249 185 194 191 152 140 171 144 108 158
124 94 116 89 150 121 128 102 91 73 97 67 150 104 91 88 88
SND-A09B 57
199 324 388 488 501 503 340 352 345 319 382 264 256 355 314 305 213 244 234 208
211 222 249 238 210 222 259 184 133 149 235 183 188 193 161 134 178 135 115 161
114 105 106 96 153 130 128 104 92 86 94 79 141 115 94 78 80
SND-A10A 84
131 371 368 472 201 84 68 82 125 162 91 82 60 61 51 53 46 51 60 57
51 147 265 315 374 419 322 144 128 109 66 63 94 94 149 118 175 173 137 113
116 96 118 123 129 129 159 164 74 69 101 91 201 186 183 157 180 119 87 94
82 70 53 81 112 158 124 151 171 203 111 110 103 81 90 128 222 314 194 187
232 260 219 281
SND-A10B 84
146 367 369 472 195 82 68 86 125 159 98 80 75 57 47 66 50 53 75 50
54 143 272 310 387 436 308 158 116 107 68 64 101 82 132 126 205 182 124 127
115 85 132 99 144 137 126 139 108 67 100 89 228 191 195 156 186 121 80 119
81 84 61 76 115 184 121 174 179 207 89 124 103 90 78 136 226 298 174 183
245 279 210 283

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.

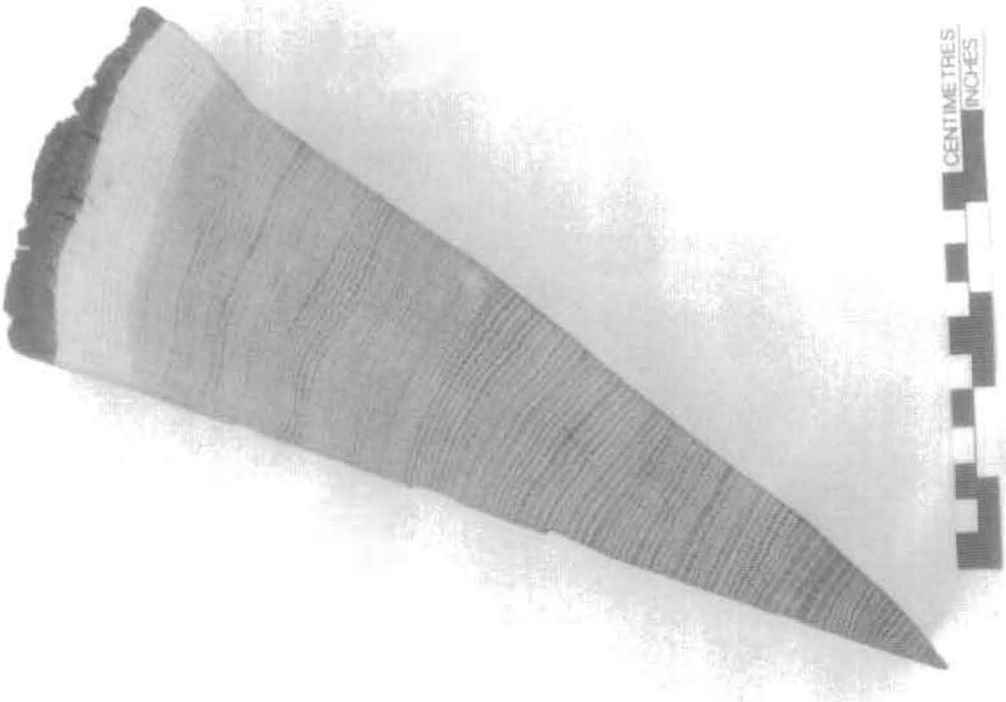


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

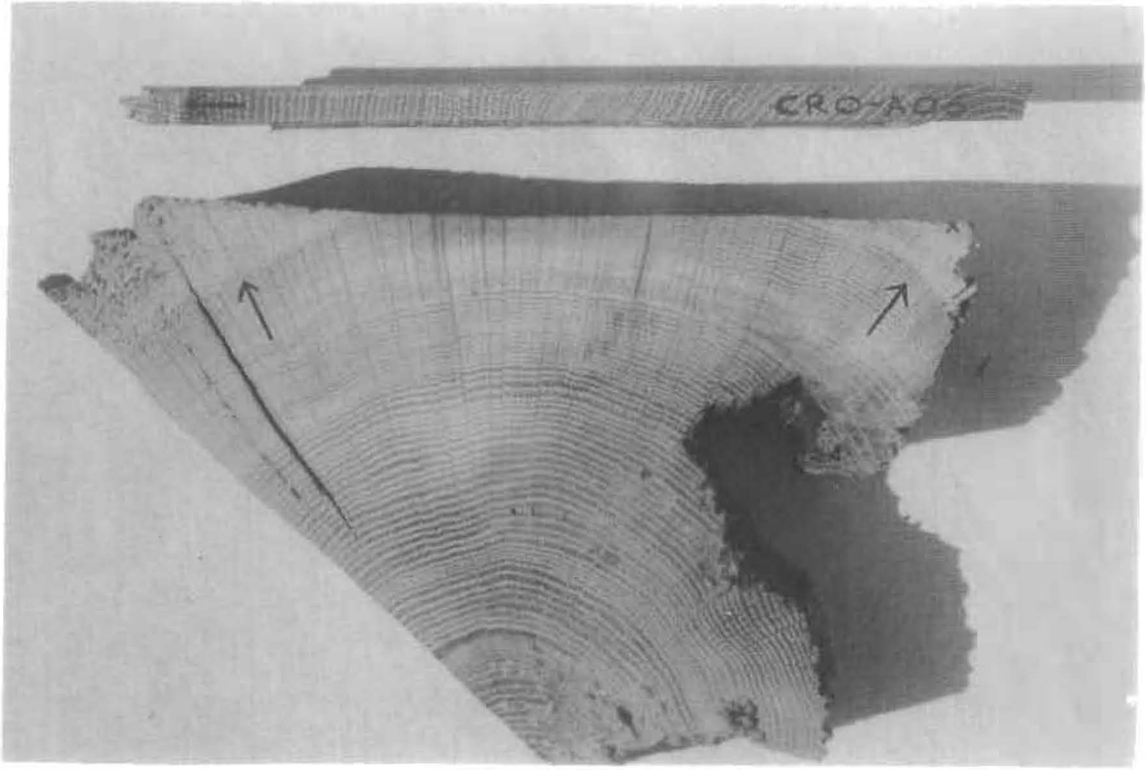


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood: again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

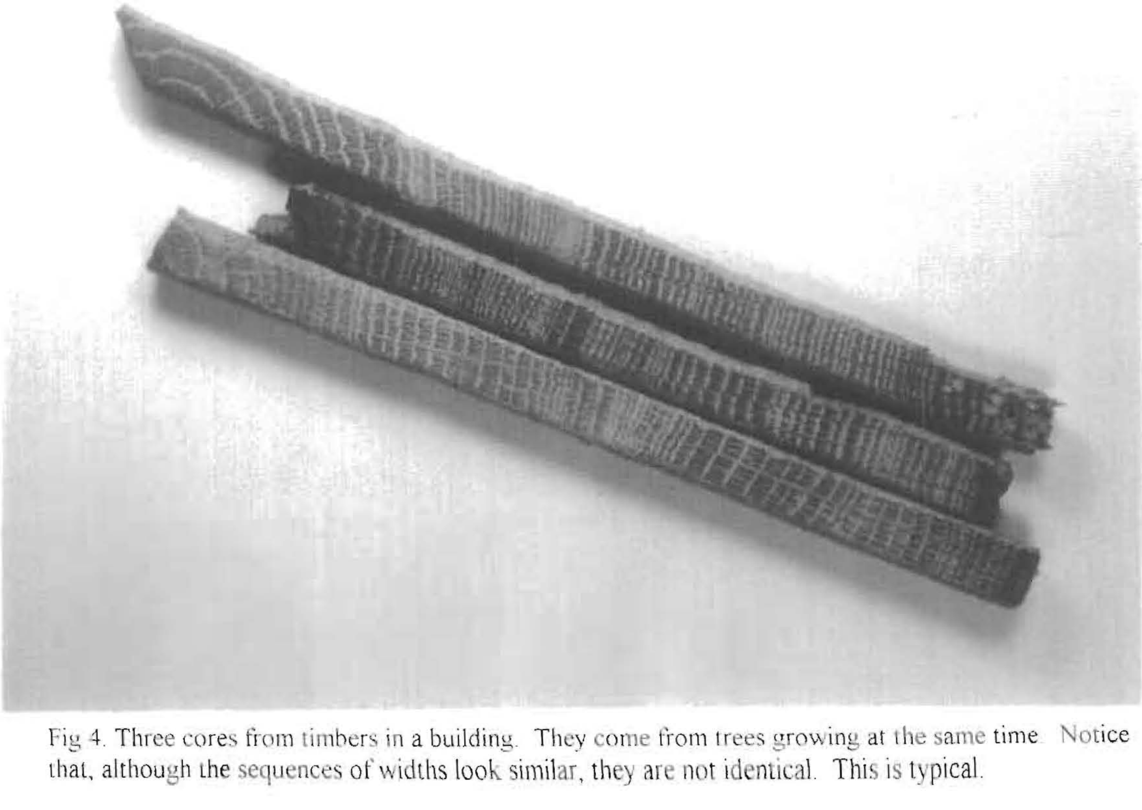


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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.

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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

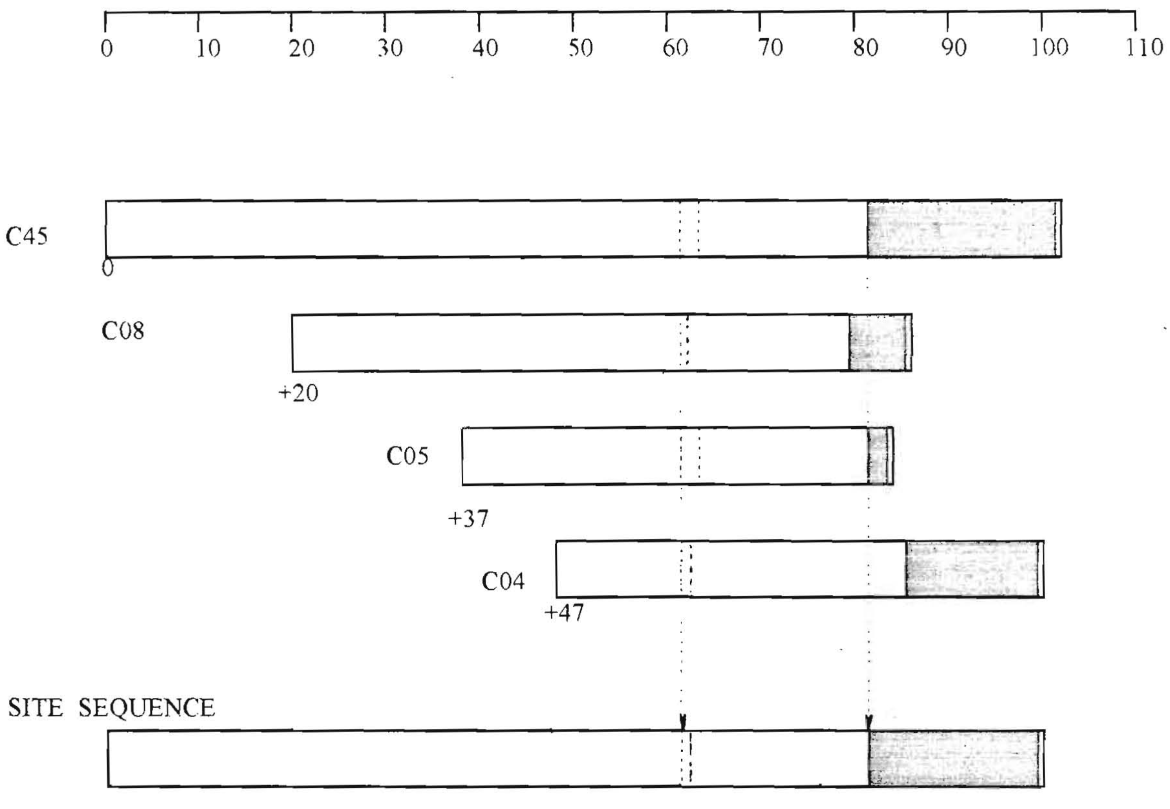


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

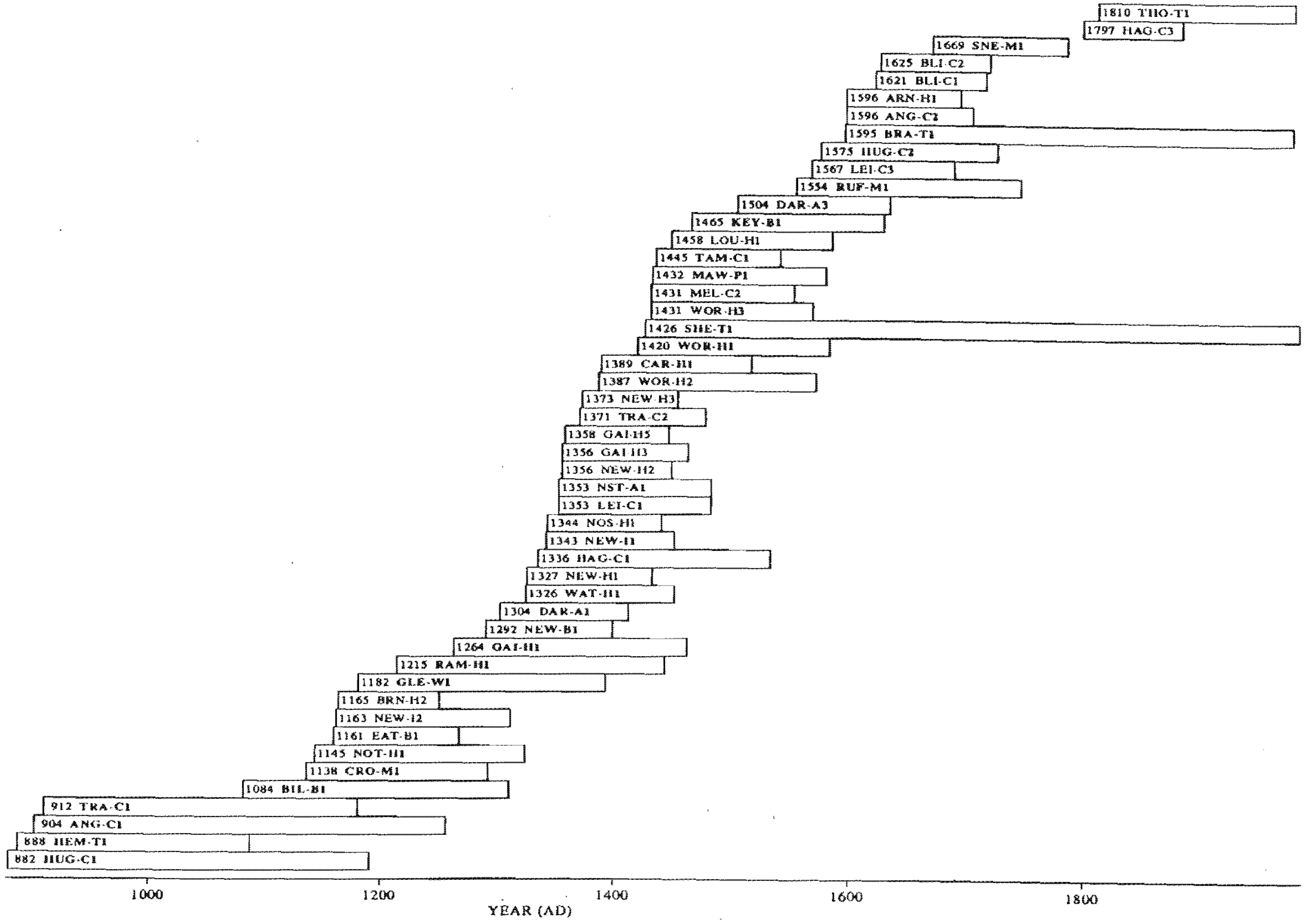
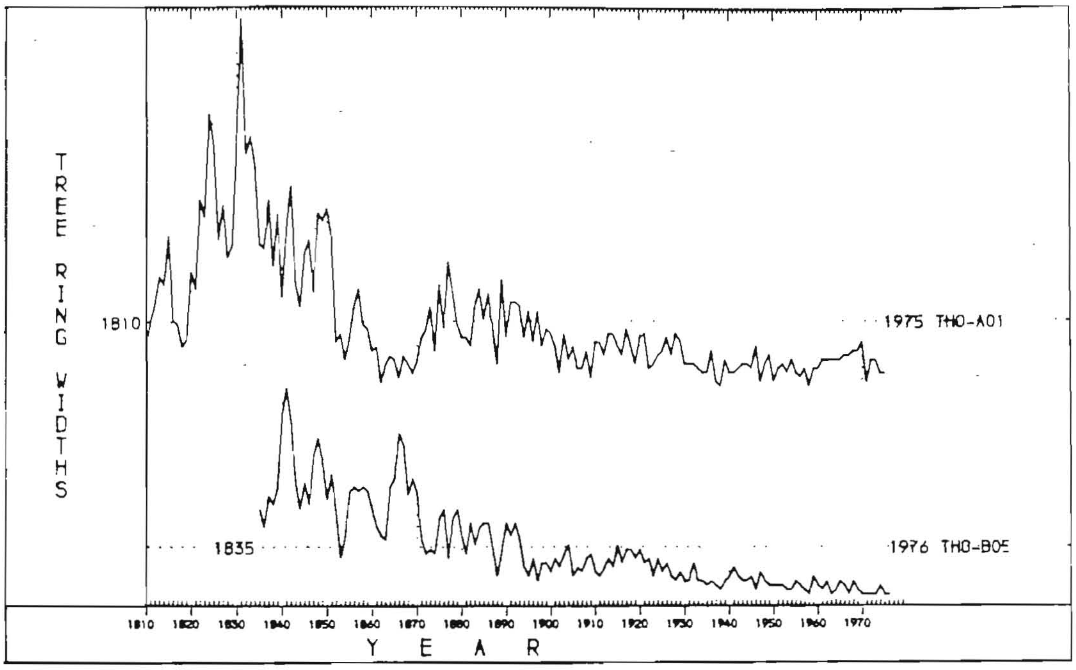


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)



(b)

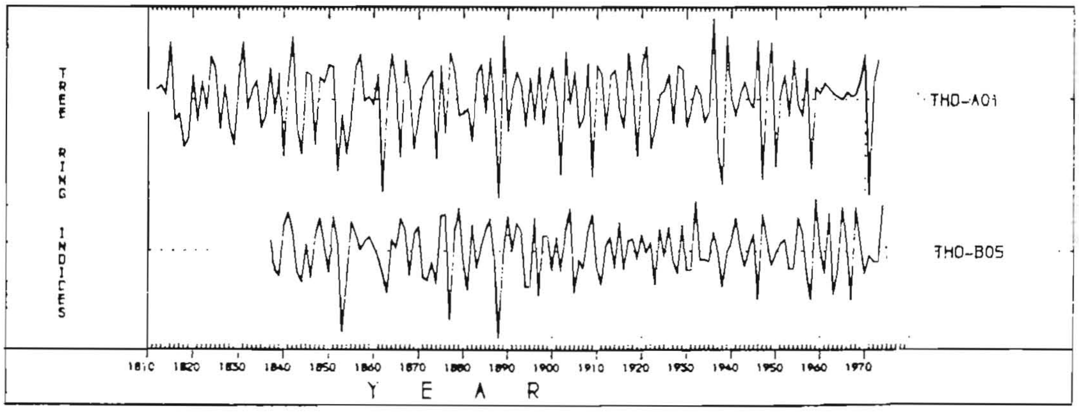


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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