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Tree-Ring Analysis of Timbers from Prudhoe Castle Gates, Prudhoe, Northumberland

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Summary

Thirteen samples were obtained from the structure of these gates; three of these were discarded prior to analysis due to their short ring-width sequences. The analysis carried out on the remaining ten cores resulted in the production of a single site sequence.

Site sequence PRUASQ01 is of 127 rings and contains ten samples. It was successfully matched at a first-ring date of AD 1318 and a last-ring date of AD 1444. Of these samples only one, PRU-A04, has the heartwood/sapwood boundary ring, which suggests a felling date for the timber represented to within the range AD 1459-84. Although an estimated felling date range cannot be calculated for any of the other samples, they all have last ring dates earlier than that of PRU-A04. The earliest any of the trees represented by these samples could have been felled is AD 1425 (PRU-A08), and they all could have been felled at the same time as PRU-A04, especially as they are likely to have come from the same tree, or trees grown in the same locality, as PRU-A04.

The date previously suggested for these gates, on the basis of the carpentry used in their construction and on stylistic grounds, was mid-fourteenth century. Tree-ring analysis has dated the felling of one of the trees used in its manufacture to AD 1459-84, with it being highly probable that most of the other samples have a similar felling date. Construction of these gates is likely to have been at or shortly after the felling date, in the second half of the fifteenth century, over 100 years later than previously thought.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM PRUDHOE CASTLE GATES, PRUDHOE, NORTHUMBERLAND

Introduction

Prudhoe Castle, (Fig 1; NZ 092 634) is first mentioned in the historical records late in the twelfth century but archaeological investigations have shown evidence for a defended enclosure from the mid-eleventh century. The early reference concerns the unsuccessful sieges of AD 1173 and AD 1174 by William the Lion against Prudhoe and Odinel d'Umfraville. Prudhoe had been in the hands of the Umfraville family since Robert d'Umfraville was granted the barony by Henry I. Throughout the thirteenth century the castle underwent considerable rebuilding and improvements. After the death of Gilbert III in AD 1381, his widow married Henry Percy, Earl of Northumberland, and when she died in AD 1398 Prudhoe passed to the Percy family. Henry V took possession of Prudhoe in AD 1403 and in AD 1415 it was granted to the Duke of Bedford, before being restored to the second Earl of Northumberland in AD 1445. Although it was always occupied, the castle fell into a worse state of disrepair during the seventeenth century and by the end of the eighteenth century its condition was so bad in parts that the southeast corner of the keep had collapsed. During the early part of the nineteenth century the Duke of Northumberland embarked on repairs and re-organisation of the castle. The outer wall and great tower were repaired and ruins within the enclosing walls removed. Further repairs were carried out in 1912, and in 1966 Prudhoe came into the guardianship of the Ministry of Public Building and Works. The site is now managed by English Heritage (Saunders 1993).

The gates under investigation here are from the castle's main gateway. They were removed and dismantled in *c* 1980 and are at present awaiting repair and rehanging. Both gates are 'portcullis braced with ledges dovetailed to the hanging and opening stiles. The curved top member of the frame is pegged into the stiles. The frame is covered with flat boards in the front, with moulded ribs covering the joints of the boards.' (Geddes 1989 unpubl). A wicket, made from three ledges across the back, has been inserted in the left gate; this work was probably carried out during the restorations by the Duke of Northumberland in the nineteenth century. On the basis of the carpentry used in its construction these gates have been dated to about mid-fourteenth century (Geddes 1989 unpubl).

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was hoped that dendrochronology would further elucidate the dating made on stylistic and other grounds with the result that a better understanding of the gates and the castle in general would be gained.

The Laboratory would like to thank David Sherlock and Martin Roberts of English Heritage for their assistance and for arranging access to the site.

Sampling

Thirteen core samples were taken from the oak beams making up these gates. The cores were taken using a 15mm diameter corer attached to an electric drill and the resulting holes filled with dowels, which were stained. Each sample was given the code PRU-A (for Prudhoe Castle) and numbered 01-13. The positions of samples PRU-A01-A12 were noted at the time of sampling and have been marked on Figures 2 and 3. With the left gate, which had been previously dismantled, this was done by comparing the timber with the drawings to identify which piece was being sampled. This was possible in all cases but PRU-A13 which could not be identified with total confidence and so is simply marked unknown location. Further details relating to the samples are recorded in Table 1. No sapwood could be found on any of the timber used in the construction of these gates and only one beam appeared to have the heartwood/sapwood boundary.

Analysis and Results

At this stage three of the samples were discarded as having too few rings to make successful dating a possibility. The remaining ten samples were prepared by sanding and polishing and their growth-ring widths 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 all ten samples had grouped and site sequence PRUASQ01 of 127 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 1318 and a last-ring date of AD 1444. The evidence for this dating is given by the t-values in Table 2.

Interpretation

Analysis of samples from the oak gates from the gatehouse at Prudhoe Castle has resulted in the production of a single site chronology. Site chronology, PRUASQ01, contained ten samples and spanned the period AD 1318-AD 1444. Only sample PRU-A04 has the heartwood/sapwood boundary ring, dated to AD 1444. This can be used to calculate an estimated felling date for the timber represented, to within the range AD 1459-84. With this ring absent from all of the other nine samples it has not been possible to calculate felling date ranges for them. However, the earliest any of them could have been felled is AD 1425 (PRU-A08) and they all have last measured ring dates earlier than that of PRU-A04. Therefore, it is possible that they also came from timbers felled sometime between AD 1459 and AD 1484. The felling date range is calculated using the estimate that 95% of mature oak trees from this area have 15-40 sapwood rings.

Discussion

Following analysis by tree-ring dating it has been possible to obtain dates for ten of the samples taken from the oak gates. One of these is estimated to have been felled some time between AD 1459-84. Although it is not possible to calculate a similar felling date range for the other nine samples their last measured ring dates mean they could have also been felled at this time. The level at which many of these samples match each other is very high, with many matching at a value of t=9 and above (Fig 5). It is possible that these gates are actually made up out of only a couple of trees, in which case this lends weight to the conjecture that the other samples are from trees with the same felling date as PRU-A04. It can be seen when the samples are studied that all except samples PRU-A02 and PRU-A12 have a very distinctive ring pattern with bands of narrower rings. The fact that PRU-A02 and PRU-A12 do not have these rings may account for the lower value at which these two samples match the rest of them and does not necessarily mean that they are not from the same group of trees.

The carpentry used in the construction of these gates has been carefully investigated and a date around the middle of the fourteenth century suggested (Geddes 1989 unpubl). Although a felling date range has been calculated for only one of the timbers used, it is highly probable that all samples are taken from wood cut from the same or adjacent trees and that the felling date range of AD 1459-84 can be applied to them also, with the gates being constructed at that time or shortly after, more than 100 years later than originally thought, when the castle was in the possession of the second Earl of Northumberland.

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Table 1: Details of tree-ring samples from Prudhoe Castle Gates, Prudhoe, Northumberland

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
PRU-A01	Post 3, between rails 3 and 4, right gate	97	--	1318	----	1414
PRU-A02	Rail 4 (from top), right gate	76	--	1352	----	1427
PRU-A03	Rail 11 (from top), right gate	NM	--	----	----	----
PRU-A04	Rail 3 (from top), right gate	82	h/s	1363	1444	1444
PRU-A05	Rail 2 (from top), right gate	87	--	1331	----	1417
PRU-A06	Rail 7 (from top), right gate	NM	--	----	----	----
PRU-A07	Rail 1(from top), right gate	NM	--	----	----	----
PRU-A08	Rail 2 (from top), left gate	81	--	1329	----	1409
PRU-A09	Post 1, above rail 1, left gate	106	--	1330	----	1435
PRU-A10	Post 3, between rails 1 and 2, left gate	89	--	1352	----	1440
PRU-A11	Rail 3 (from top), left gate	76	--	1365	----	1440
PRU-A12	Rail 1 (from top), left gate	72	--	1364	----	1435
PRU-A13	Unknown	63	--	1348	----	1410

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

Table 2: Results of the cross-matching of site sequence PRUASQ01 and relevant reference chronologies when the first-ring date is AD 1318 and the last-ring date is AD 1444

Reference chronology	t-value	Span of chronology	Reference
England	5.0	AD 404-1981	Baillie and Pilcher 1982 unpubl
East Midlands	4.0	AD 882-1981	Laxton and Litton 1988
Kepier Hospital, Durham, Tyne and Wear	7.6	AD 1304-1522	Howard *et al* 1996
Seaton Holme, Easington, Durham, Tyne and Wear	6.6	AD 1375-1489	Howard *et al* 1988 unpubl
North Transept, Durham Cathedral, Durham, Tyne and Wear	6.4	AD 1320-1457	Howard *et al* 1992
The Hallgarth, HM Prison, Durham, Tyne and Wear	6.2	AD 1349-1464	Howard *et al* 1992
Choir Roof, Durham Cathedral, Durham, Tyne and Wear	5.8	AD 1346-1458	Howard *et al* 1992
Hitchins Onset, Scaleby, Carlisle, Cumbria	5.6	AD 1364-1491	Howard *et al* 1997
Witton Hall (barn), Witton Gilbert, Tyne and Wear	5.0	AD 1342-1441	Howard *et al* 1996

Figure 1: Map showing the location of Prudhoe Castle, Prudhoe, Northumberland

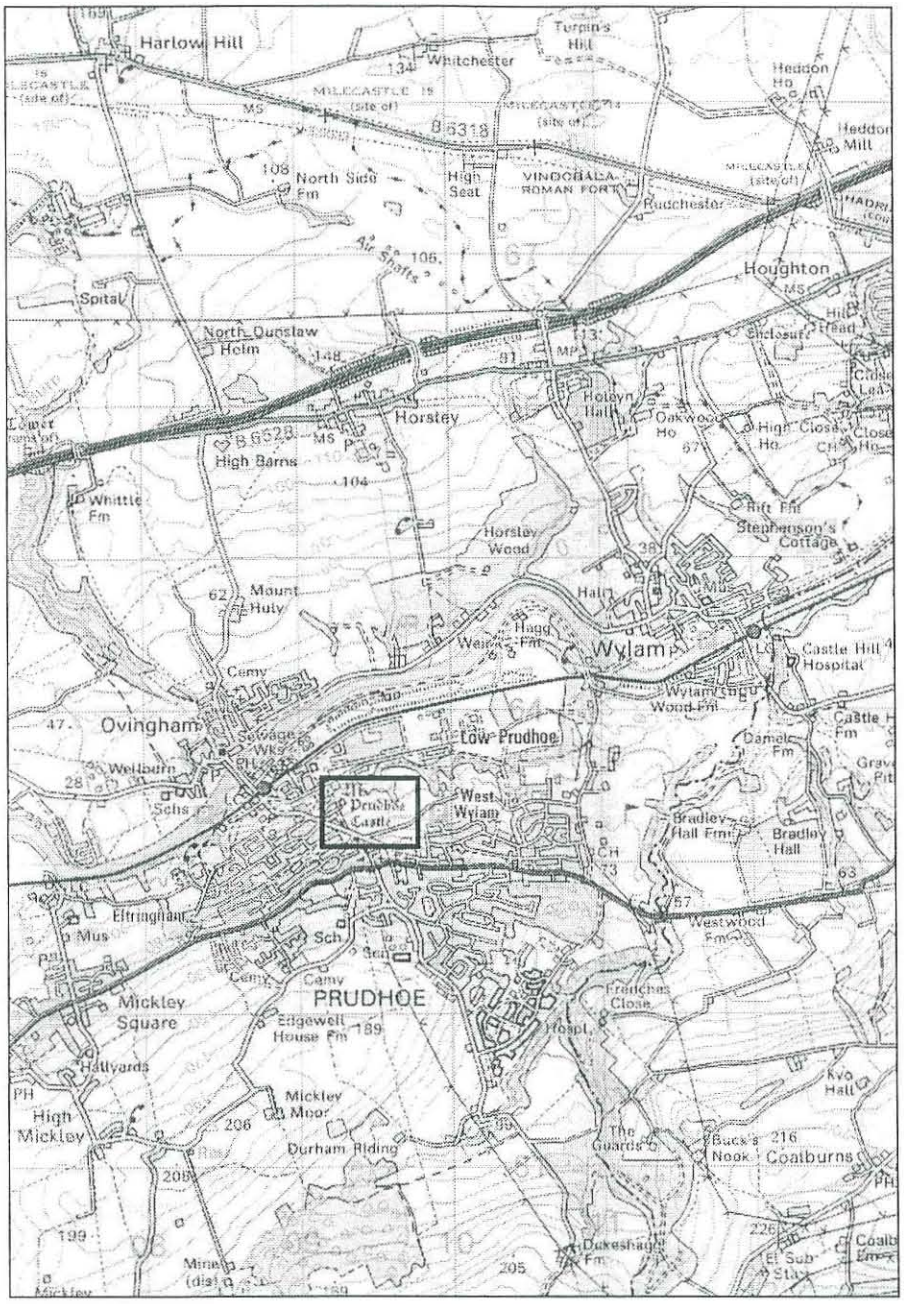

Figure 2: Prudhoe Castle, the Gatehouse Right Gate, showing the location of samples PRU-A01-A07, drawn by M Fenton, English Heritage

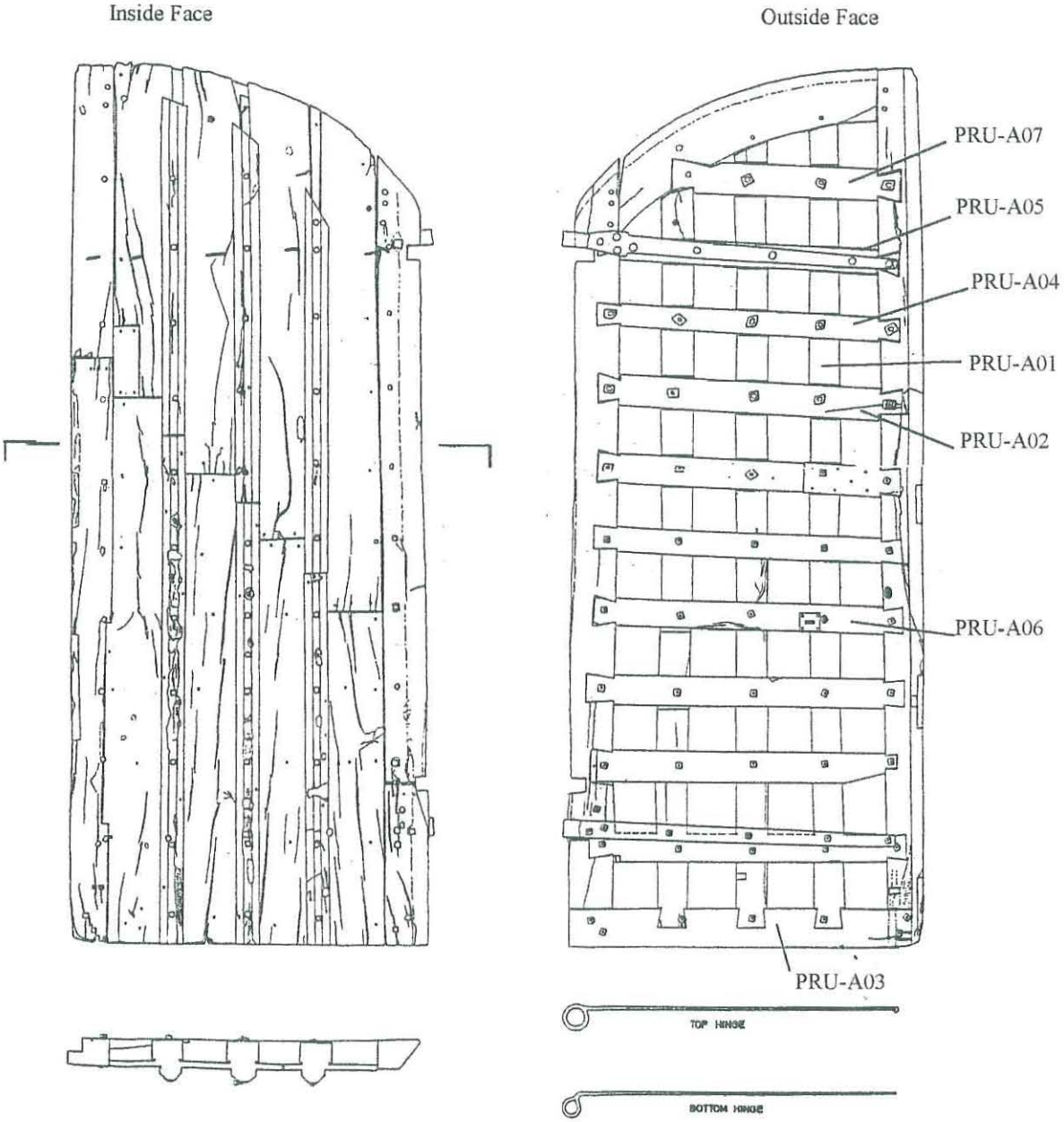

Figure 3: Prudhoe Castle, the Gatehouse Left Gate, showing the location of samples PRU-A08-A12, M Fenton, English Heritage

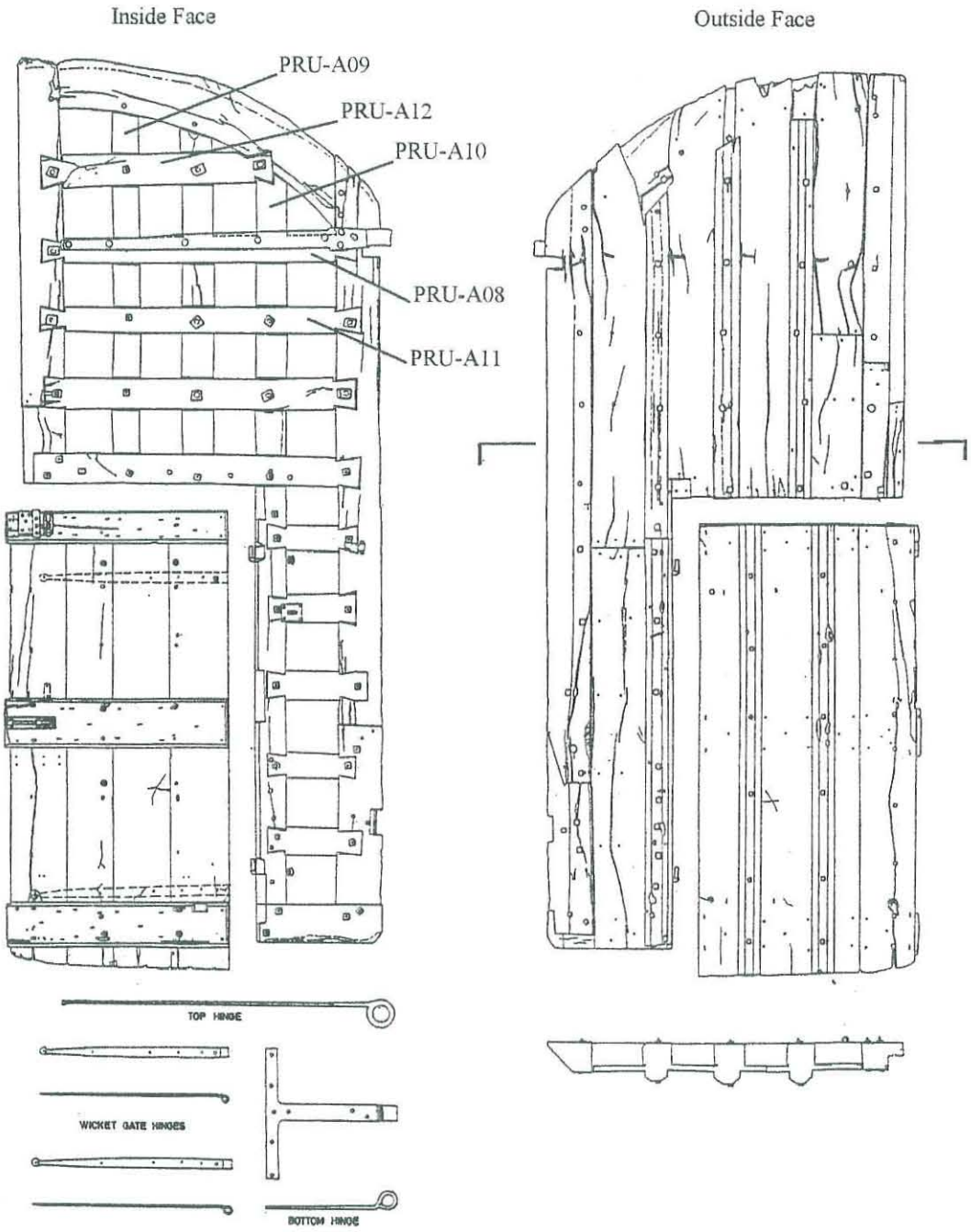

Figure 4: Bar diagram of samples in site sequence PRUASQ01

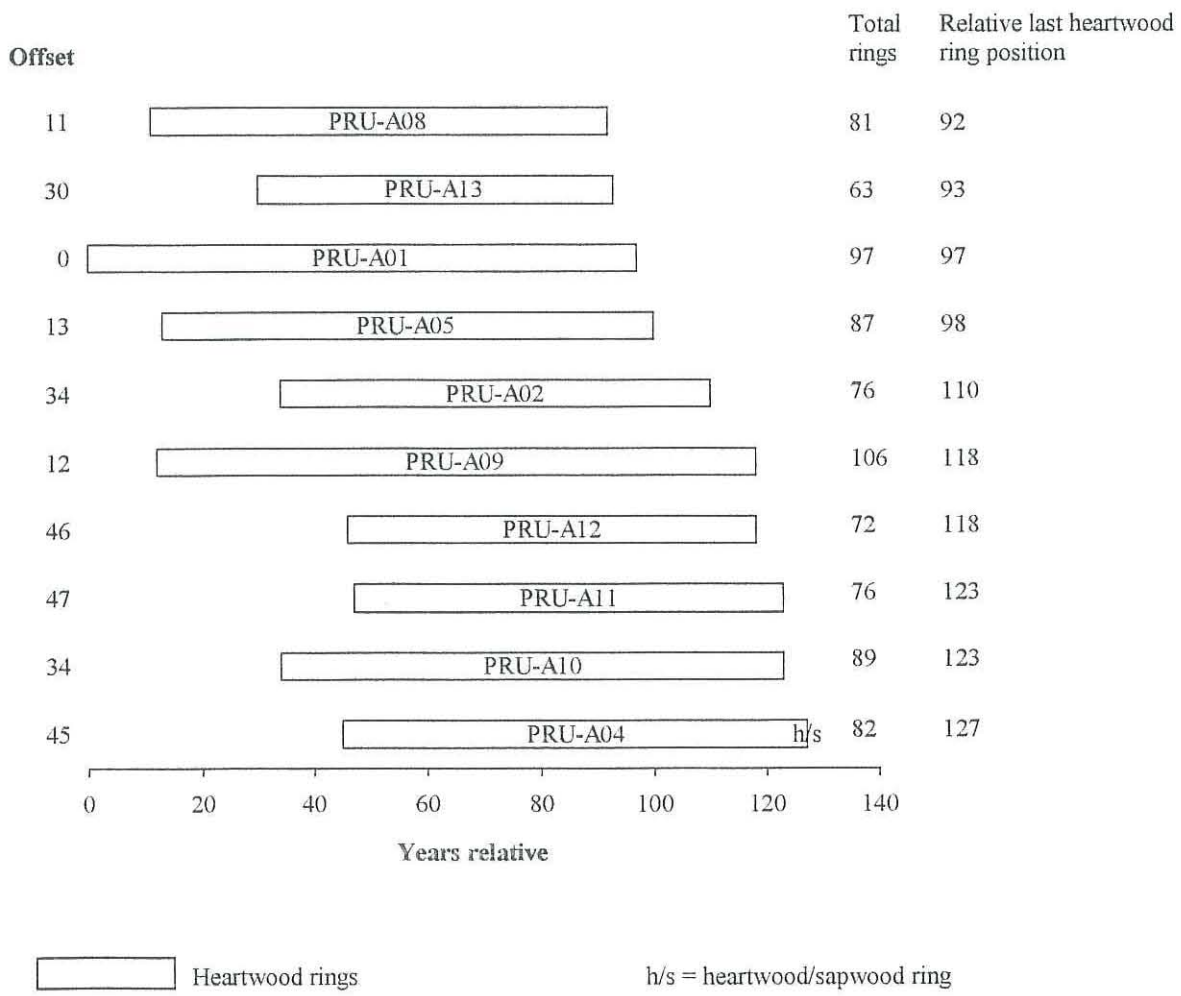

Figure 5: Diagram to show the *t*-values when the samples are cross-matched against themselves, the very high matches which could suggest the samples are from the same tree are in bold (offset above stars, *t*-values below)

***	A01	A02	A04	A05	A08	A09	A10	A11	A12	A13
A01	***	-13	13	-13	-11	-12	-34	-26	11	-30
A02	3.0	***	-11	21	23	22	00	-13	-12	4
A04	2.4	5.2	***	32	5	33	11	-2	-1	-25
A05	**10.6**	3.7	**10.6**	***	2	1	-21	-26	-33	-17
A08	**12.1**	3.6	2.5	**12.8**	***	-1	-23	-15	-10	-19
A09	**9.5**	3.8	**9.0**	**9.2**	**10.2**	***	-22	-35	-34	-18
A10	**9.4**	4.5	**9.6**	**9.4**	**10.0**	**8.1**	***	-13	-12	4
A11	2.5	3.7	**11.1**	1.8	3.2	**11.7**	**11.3**	***	1	-11
A12	3.1	2.8	3.8	2.4	1.8	4.9	3.6	3.8	***	00
A13	**9.0**	3.1	2.6	**12.4**	**7.9**	**8.9**	6.1	1.4	2.2	***

Data of measured samples – measurements in 0.01mm units

PRU-A01A 97
376 301 205 142 124 150 120 119 150 202 262 327 317 269 217 182 182 167 203 130
128 164 121 147 178 130 98 132 130 163 176 197 147 139 150 147 157 137 150 120
122 148 105 101 72 119 125 126 105 121 115 86 104 134 116 116 103 95 91 85
84 111 93 75 98 83 98 87 99 138 125 93 75 89 102 73 108 102 129 96
102 97 113 92 70 116 101 107 78 114 142 161 151 154 182 159 135
PRU-A01B 97
377 300 192 129 107 146 116 116 195 199 268 320 321 276 221 191 170 174 189 132
135 161 120 154 179 121 101 131 126 161 175 200 142 140 150 140 153 135 148 115
124 156 101 103 60 125 140 116 112 118 119 85 101 130 119 115 97 104 83 79
93 115 97 79 99 80 97 87 96 135 119 87 82 79 103 84 96 98 120 107
103 99 112 89 74 122 100 109 77 109 142 162 147 174 163 162 132
PRU-A02A 62
173 306 320 286 241 179 178 214 173 214 239 253 255 265 223 225 215 289 236 235
278 266 294 206 197 142 130 138 172 197 58 59 88 99 142 184 188 160 126 236
206 240 258 248 283 173 174 243 277 205 134 272 227 222 235 260 258 285 286 235
289 223
PRU-A02B 68
154 172 214 270 276 310 217 207 173 239 195 235 283 262 251 162 173 132 142 167
188 196 72 47 97 90 125 176 150 126 106 165 156 160 204 206 260 156 185 253
308 188 142 272 241 254 217 237 242 277 274 260 278 226 188 240 190 212 242 141
247 257 218 203 242 201 150 117
PRU-A04A 82
94 123 149 110 125 98 98 94 95 98 93 79 87 69 52 62 63 69 78 85
68 87 81 103 116 117 116 92 129 131 132 135 154 169 131 131 134 161 137 100
160 148 152 135 198 237 282 297 292 239 247 175 186 176 211 203 121 157 204 229
190 195 142 114 137 167 229 187 147 208 114 138 127 143 137 136 109 136 122 119
108 117
PRU-A04B 82
93 126 144 112 130 90 103 95 94 104 89 85 84 59 61 62 68 73 71 80
74 87 80 97 119 101 117 92 119 138 126 142 138 170 126 129 136 165 132 104
162 154 144 135 202 235 277 297 291 234 251 164 189 174 211 204 125 151 208 227
190 191 151 106 143 164 224 188 145 212 112 141 128 154 131 138 108 136 139 104
112 110
PRU-A05A 87
308 243 200 169 157 247 125 111 140 153 166 179 109 80 95 96 115 156 169 104
101 110 88 101 135 138 125 103 129 90 114 62 130 141 143 113 113 105 99 113
112 104 110 120 144 106 93 97 123 118 129 134 107 145 116 138 176 151 138 102
127 134 123 130 124 158 113 114 114 152 133 109 159 132 124 103 173 201 228 260
234 215 203 183 177 151 170
PRU-A05B 87
308 242 200 167 161 224 130 113 140 140 167 181 119 88 95 113 127 148 165 106
106 94 105 99 124 131 130 112 130 97 99 68 124 146 142 112 110 96 96 104
117 103 118 130 134 113 95 101 111 130 128 127 101 145 125 148 174 150 135 111
113 138 127 123 133 158 114 115 115 147 132 105 162 118 123 113 170 194 239 266
232 218 207 184 175 165 200
PRU-A08A 81
322 338 283 200 196 166 201 218 114 101 126 108 110 166 138 112 129 127 138 164
180 134 134 136 133 154 152 147 138 114 128 91 115 66 120 148 130 105 111 100
91 93 114 96 115 107 115 82 62 79 96 88 79 92 66 101 88 124 157 142
130 99 127 126 121 146 123 139 128 107 117 148 118 88 158 110 131 112 203 246
154

PRU-A08B 81
332 332 288 201 192 167 205 212 116 99 125 110 109 168 138 106 134 130 137 161
174 143 131 127 136 147 157 149 134 115 127 92 110 76 118 147 131 105 115 112
89 94 98 98 117 114 105 76 78 74 107 80 78 101 58 102 85 120 167 143
120 97 127 127 124 140 127 143 118 110 119 143 124 86 156 109 126 120 190 264
149
PRU-A09A 106
232 174 175 133 174 144 151 93 106 128 127 145 184 124 88 124 114 125 111 152
133 113 116 99 105 95 95 116 94 111 87 87 47 102 102 112 76 86 81 71
94 84 107 99 103 88 67 74 63 68 69 62 67 69 78 63 100 126 99 106
83 88 91 89 104 102 133 105 114 110 160 115 99 164 128 116 80 171 195 190
227 212 204 169 147 173 136 142 159 111 148 184 187 188 180 149 99 114 121 162
141 134 146 99 74 57
PRU-A09B 106
232 173 178 147 171 158 157 90 112 99 126 115 180 123 94 112 112 120 108 140
137 125 118 90 104 90 100 116 99 118 79 82 48 100 107 102 77 83 80 77
92 88 99 104 90 91 72 66 61 71 77 60 70 61 82 65 102 120 103 106
80 97 91 94 106 95 136 111 108 122 157 112 99 176 128 120 77 162 214 179
237 211 211 159 157 169 126 142 157 120 149 184 188 175 181 140 94 118 116 160
142 145 144 98 68 52
PRU-A10A 89
120 146 135 148 147 135 124 168 113 130 81 152 128 125 141 126 122 92 93 112
100 91 96 114 85 76 105 114 104 72 98 64 100 90 96 166 154 137 105 121
129 111 136 142 187 125 117 123 162 115 102 166 155 137 137 211 172 259 252 267
230 213 183 168 138 173 212 127 158 188 201 171 183 147 104 136 156 200 148 165
177 114 147 131 143 121 162 89 139
PRU-A10B 89
117 144 136 144 144 146 127 171 110 135 86 145 124 130 133 122 121 105 92 115
99 101 99 110 82 83 96 117 103 77 103 66 104 88 103 162 163 136 94 125
131 110 132 136 185 127 115 117 164 116 98 165 150 127 138 208 182 256 251 269
242 210 180 171 139 177 206 111 152 202 187 177 191 157 96 136 154 201 148 175
175 109 158 131 143 122 152 100 136
PRU-A11A 62
114 105 107 86 89 95 92 84 113 88 111 69 68 61 85 72 71 104 72 100
86 97 152 114 109 92 108 132 124 150 129 171 120 111 136 148 142 108 202 158
164 122 274 333 363 409 335 301 289 234 225 175 176 239 136 222 274 279 261 280
211 110
PRU-A11B 73
83 94 105 115 105 132 94 118 76 66 75 73 82 61 108 71 97 88 92 157
115 101 86 120 131 107 145 137 150 114 104 128 148 144 101 194 158 154 107 229
245 277 322 325 317 268 208 261 204 201 222 144 230 282 273 250 251 206 118 151
177 260 203 177 232 156 233 187 165 175 174 73 103
PRU-A12A 72
215 205 268 268 207 208 206 175 193 191 278 228 121 137 82 158 173 174 170 240
180 139 139 119 117 130 98 127 131 175 142 143 181 119 120 104 128 116 123 203
230 214 181 147 140 115 130 133 107 96 88 113 86 106 142 82 152 138 116 152
181 130 79 86 105 109 96 97 117 127 97 80
PRU-A12B 72
217 204 265 270 217 196 204 176 191 193 268 204 119 143 86 156 176 180 155 243
187 131 139 128 109 128 113 143 125 159 166 116 172 127 111 95 139 111 131 206
244 200 180 159 135 117 143 129 110 108 89 100 80 115 139 87 151 135 133 150
176 136 95 71 104 120 86 102 119 121 101 96
PRU-A13A 63
138 160 111 107 128 95 99 89 110 88 90 90 80 77 45 80 90 100 83 85
75 65 77 77 74 66 62 64 54 46 46 57 64 67 66 62 76 72 73 105
99 93 90 93 109 112 122 116 142 101 111 107 127 112 100 157 136 157 134 194
220 240 217

PRU-A13B 63
135 158 113 111 127 98 101 83 106 92 87 92 77 82 41 75 93 99 77 97
70 69 76 71 72 67 59 67 46 51 53 53 65 62 60 58 71 78 79 105
95 92 90 99 120 111 123 131 136 101 115 115 131 116 94 153 138 152 130 192
219 242 196

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.

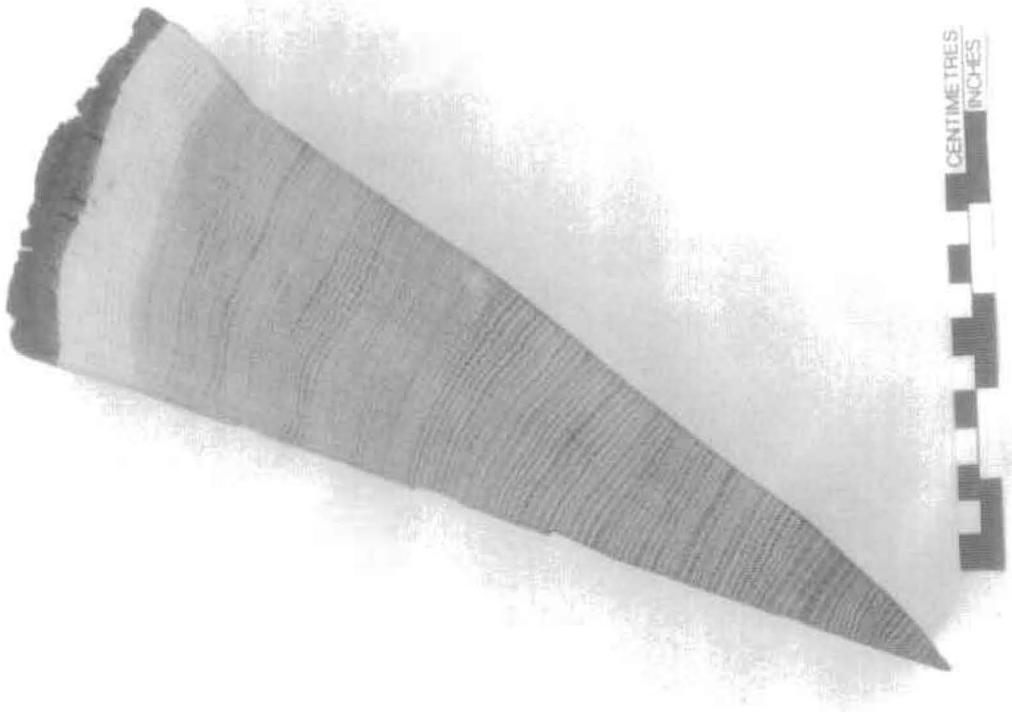

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

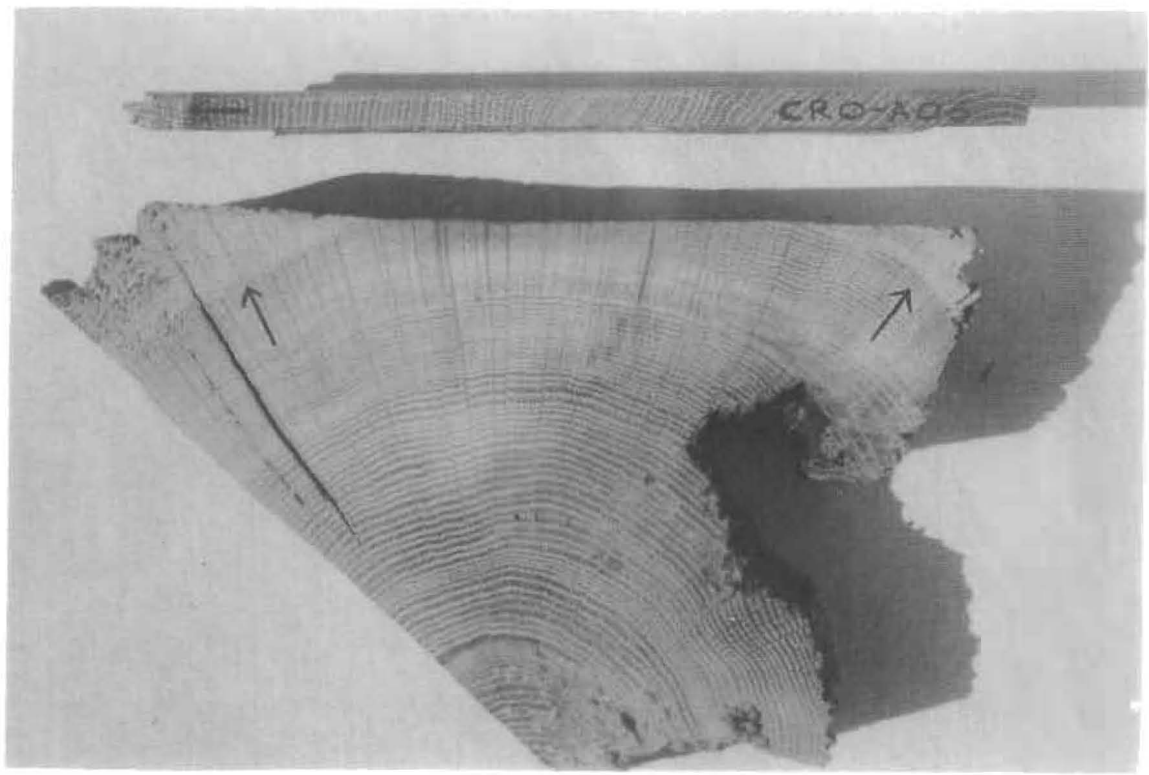

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

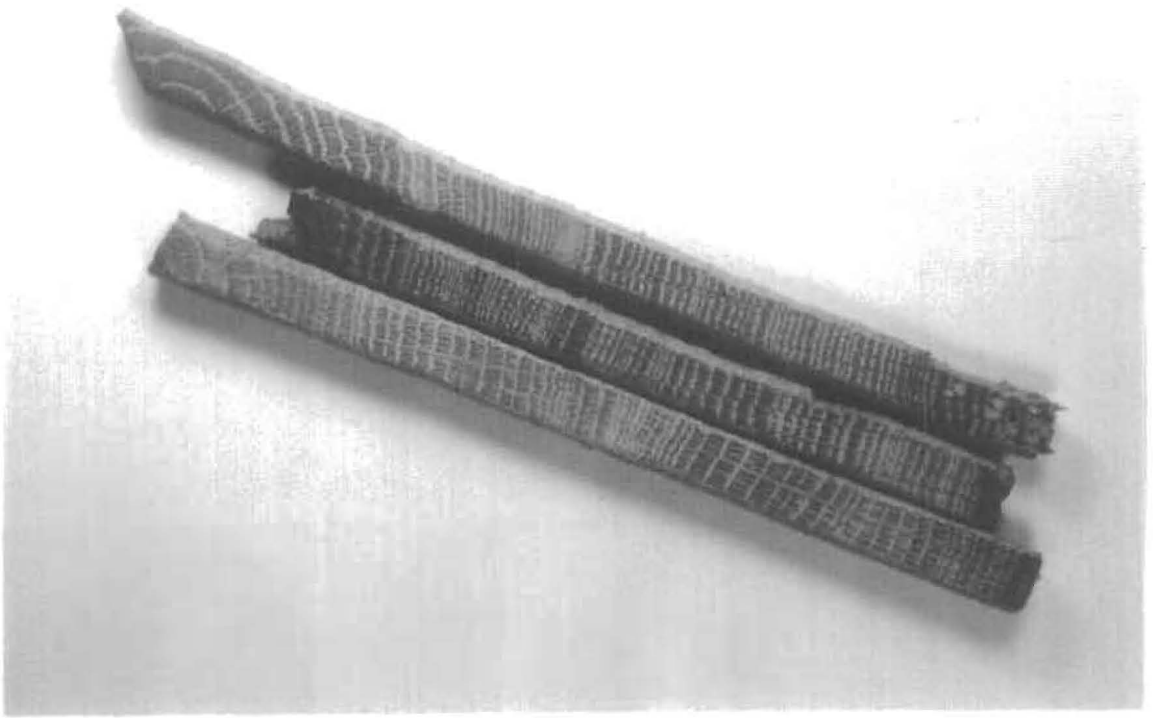

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

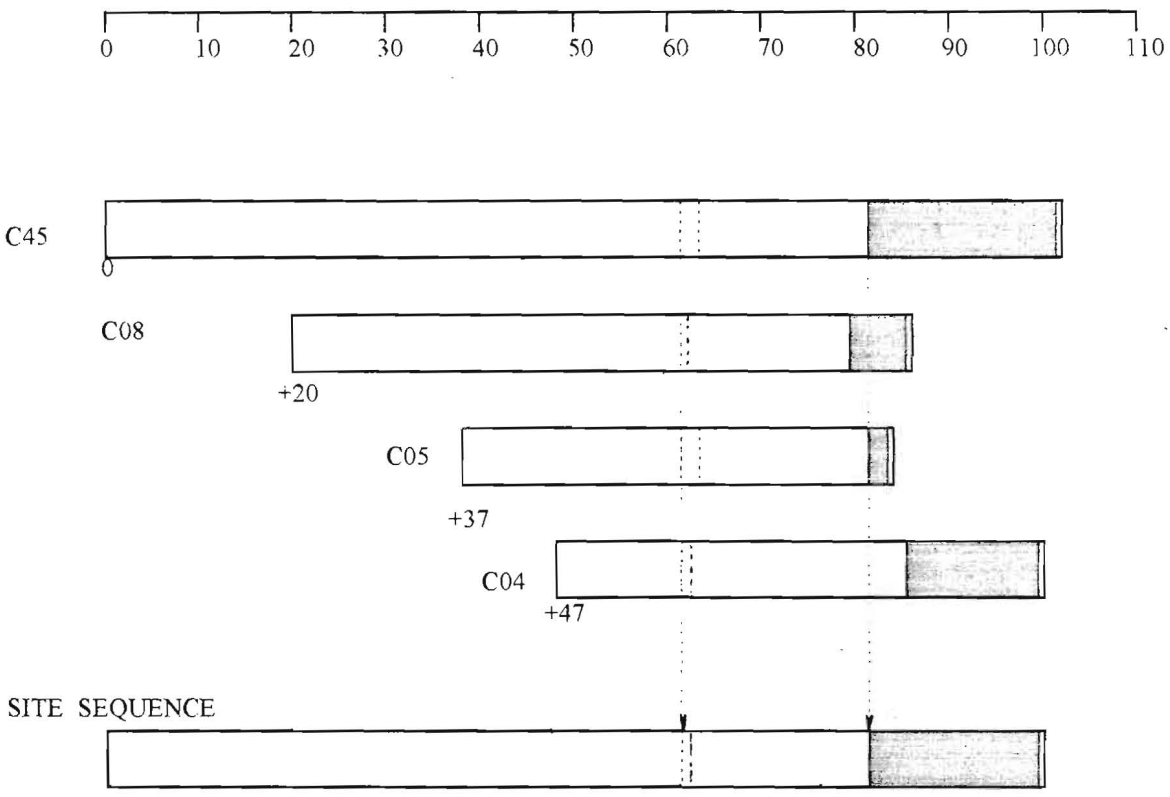

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

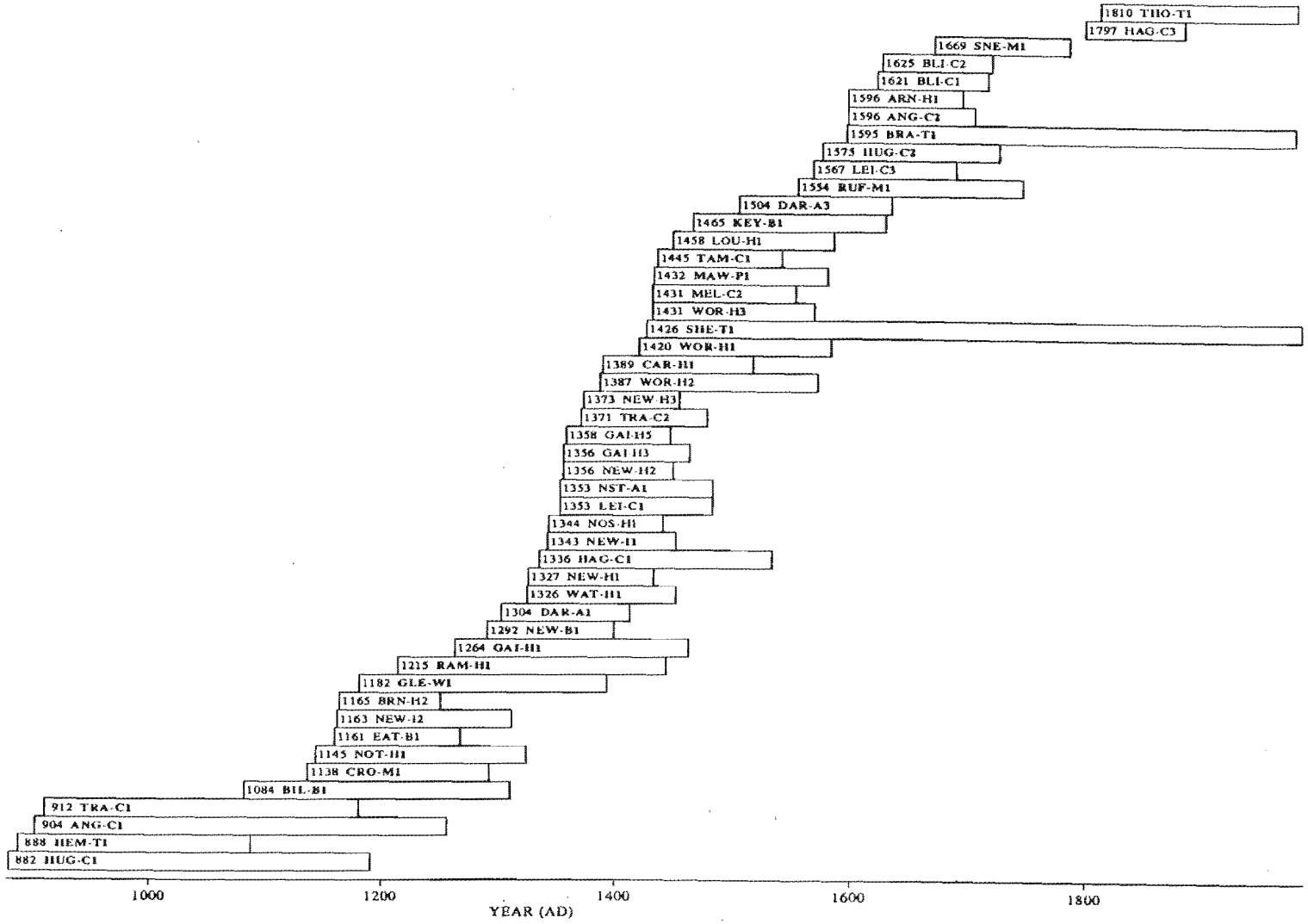

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

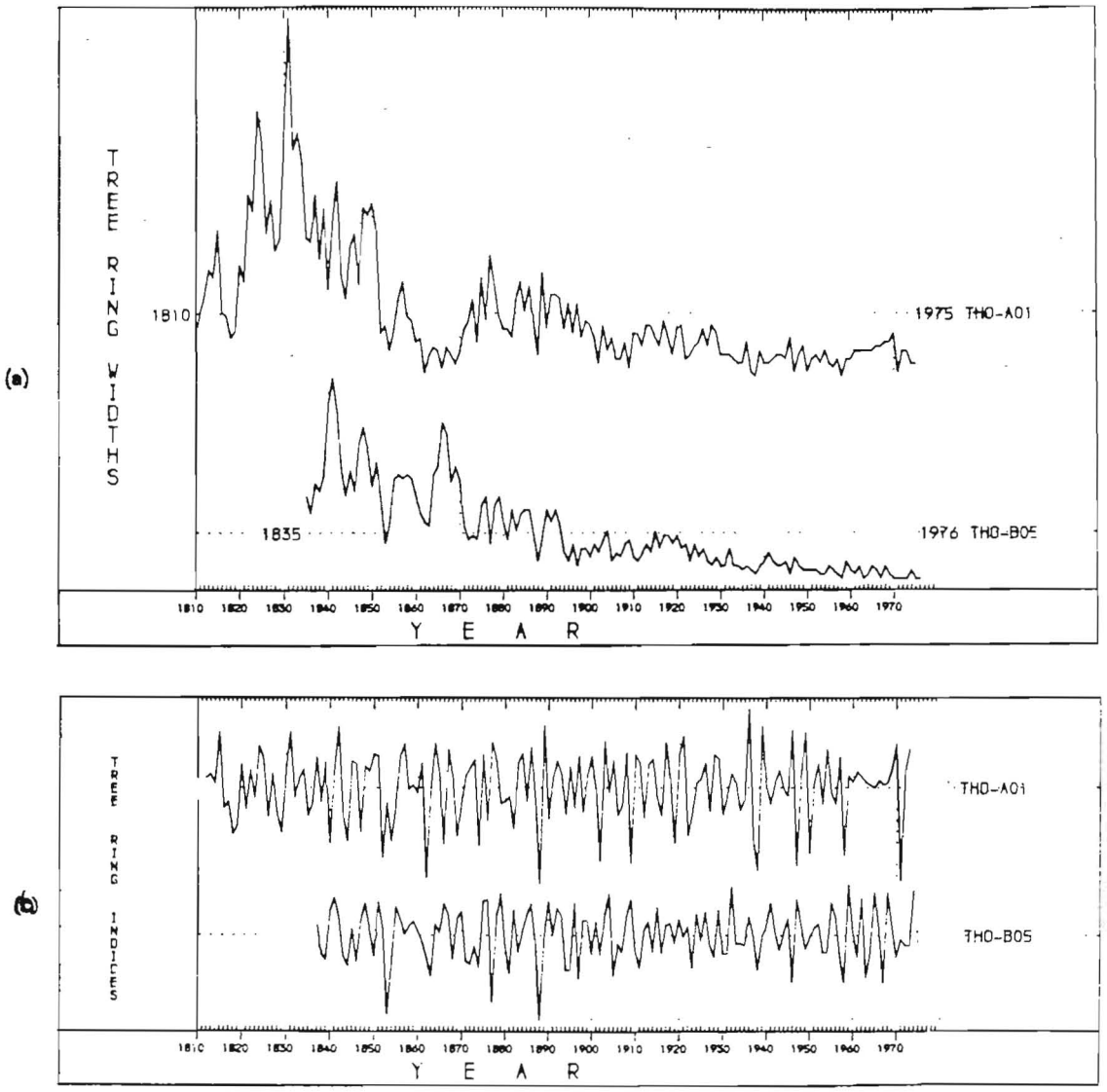

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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