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TREE-RING ANALYSIS OF TIMBERS FROM THE ARCHDEACON OF EXETER'S HOUSE, PALACE GATE, EXETER

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Summary

Analysis was undertaken of samples from fourteen oak beams in the roof of the Archdeacon of Exeter's House, Exeter. This resulted in the production of a single site chronology of 219 rings spanning the period AD 1186-1404. Interpretation of the heartwood/sapwood boundaries on the dated samples indicates that the timbers have an estimated felling date in the range AD 1415-1440.

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Introduction

This complex multi-phase building lies adjacent to Exeter Cathedral Close (SX 921924, see Fig 1) and is traditionally believed to have been the residence of the Archdeacon of Exeter. From the late-nineteenth century to 1997 it was occupied by the Presentation of Mary Convent and used as a school. The building has recently been sold and is undergoing conversion to domestic dwellings.

Hidden by traces of seventeenth- and eighteenth-century work, and extensive nineteenth- and early twentieth-century repairs and alteration are the remains of a medieval open hall with another medieval wing off-set to its south. A site map is provided in Figure 2, with plans of the building being shown in Figure 3. Although the wing and hall are now extensively sub-divided and floored-in the roofs survive largely intact.

While the roof of the southern wing consists of plain principal rafter trusses, the roof of the Hall is more highly decorated. The Hall roof consists of seven arch-braced trusses with collars carrying double purlins forming six bays, each bay having an intermediate arch-brace truss; the intermediate trusses do not have collars, but continue into the semicircular coved upper section of the roof.

The roof is notable for its "short principal" construction in which the principal rafters of the main trusses rise only to the collars. Above the level of the collars is a separate truss construction of smaller scantling, also with arch braces (here called cove braces) and upper collars. The arch braces of the main and intermediate trusses are highly ornamented with mouldings (and originally also with carvings). Each brace is composed of two parts: in the main trusses the lower braces sprang from stone corbels set in the side walls (which are now obscured or removed); the upper braces extend from purlin level to the centre line of the roof. The intermediate trusses are fitted onto the central common rafter truss of each bay, and spring from ashlar pieces above the cornice. An illustration of each type of truss is given in Figure 4.

In its long section (see Fig 5) the roof has two sets of wind-braces. A lower set of slightly curved braces spring from the feet of the principal rafters to meet the intermediate arch-braces where they are crossed by the lower purlin. In the upper set of wind-braces, slightly curved members spring from the intermediate arch-braces where they are crossed by the upper purlin and rise to meet the principal rafters at crown purlin level.

The roof as a whole is notable for its decoration. The main trusses have decorative open-work spandrels, a detail being shown in Figure 6. There were also a quantity of high quality pendant bosses and cusps (not surviving). These were found on the intermediate trusses where the upper part of the arch-braces meet the cove-braces and where wind-braces meet the purlins.

Sampling and analysis by tree-ring dating was commissioned by English Heritage. The purpose of this was to establish with greater precision the construction date of the roof which in general terms was believed to date from the later-fifteenth century or possibly from the very early-sixteenth century. It was considered that the dating of this roof would inform and assist in the management of this site as it undergoes alteration. Furthermore, the dating of the Archdeacon's House would also help in a comparative study programme of a small group of highly similar buildings in and around Exeter, and further refine the dating of these on stylistic grounds.

The Laboratory would like to take this opportunity to thank Stuart Blaylock of Exeter Archaeology for his considerable help in the sampling of this building, for his assistance with the site description given above and for the provision of the plans and other illustrations used in this report. We would also like to acknowledge the co-operation and help of Will Gannon of TOC's Ltd, the site owner and developer, and that of Marcus Burwood, site manager for Barclay Construction Management.

Sampling

A total of fourteen different oak timbers within the roof were sampled by coring, there being no timbers available from the lower walls or floors of the building. Each sample was given the code EXT-A (for Exeter site "A") and numbered 01 - 14. The positions of the cores were recorded at the time of sampling on drawings provided by Stuart Blaylock, reproduced in this report as Figure 7. The trusses have been numbered from site-south to north (in reality south-west to north-east). Where members are made up of more than one piece (the arch-braces for example) they are further described, ie upper or lower sections. Details of the samples are given in Table 1.

Analysis and dating

The fourteen samples obtained from this building were prepared by sanding and polishing and their growth-ring widths measured. A number of timbers required two or more cores to obtain the optimum number of growth rings. Thus some of the readings of the same sample have different numbers of rings, sample EXT-A01A/B/C, for example. The data of the measurements of the samples is given at the end of the report.

All fourteen samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a value of t=4.5 a single group composed of twelve samples formed, cross-matching as shown in the bar diagram, Figure 8. The ring widths from these twelve samples were combined at their suggested relative offsets to form EXTASQ01, a site chronology of 219 rings. Site chronology EXTASQ01 was successfully cross-matched with a series of relevant reference chronologies for oak, giving it a first ring date of AD 1186 and a last measured ring date of AD 1404. Evidence for this date is given in the t-values of Table 2.

Taking the heartwood/sapwood boundary on those samples in the site chronology where it exists, the average last heartwood ring date is AD 1400. The usual 95% confidence limits for sapwood on mature oaks from this part of England is in the range 15 to 40 rings. This would give the timbers represented by these samples an estimated felling date in the range AD 1415 - 1440.

Site chronology EXTASQ01 was compared with the two remaining ungrouped samples, but there was no further satisfactory cross-matching. Each of the two remaining ungrouped samples was compared individually with the reference chronologies. There was, however, no satisfactory cross-matching and these samples must therefore remain undated.

Conclusion

From the tree-ring dating it would appear that the roof of the Archdeacon's House dates from the early to mid fifteenth century. It is, therefore, slightly earlier than expected and its dating will thus help refine the relative dating of other similar buildings in and around Exeter.

Two samples, EXT-A01 and EXT-A07, remain undated although they both have a sufficient number of rings for satisfactory analysis. Neither of them show growth rings with any particular problem, such as complacent or narrow rings, that might make dating difficult.

The dating of material from this building has produced a long and well replicated chronology spanning the period AD 1186 - 1404. This chronology therefore provides an excellent and important reference chronology for an area where dating is currently particularly difficult. The Archdeacon's House has provided another example of a well replicated data set from a Devon building with ecclesiastical associations. This may suggest that future work attempting to provide a strong county specific chronology could usefully focus on similar buildings.

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Table 1: Details of tree-ring samples from the Archdeacon of Exeter's House, Exeter

Sample no.	Sample location	Total rings	Sapwood rings*	First measured ring date	Last heartwood ring date	Last measured ring date
EXT-A01	East archbrace (upper part), truss I	88	h/s	------	------	------
EXT-A02	East archbrace (lower part), truss I	100	h/s	AD 1300	1399	1399
EXT-A03	East archbrace (lower part), truss II	148	no h/s	AD 1202	------	1349
EXT-A04	West mid-rib (lower part), bay V	158	no h/s	AD 1186	------	1343
EXT-A05	West archbrace (lower part), truss VI	143	h/s	AD 1257	1399	1399
EXT-A06	West mid-rib (lower part), bay VI	130	h/s	AD 1269	1398	1398
EXT-A07	West lower purlin, truss VI - VII	138	no h/s	------	------	------
EXT-A08	West principal rafter, truss VI	141	no h/s	AD 1253	------	1393
EXT-A09	West mid-rib (upper part), bay V	200	h/s	AD 1203	1400	1400
EXT-A10	West archbrace (upper part), truss V	155	no h/s	AD 1240	------	1394
EXT-A11	West principal rafter, truss IV	133	h/s	AD 1271	1404	1404
EXT-A12	East archbrace (upper part), truss IV	104	no h/s	AD 1244	------	1347
EXT-A13	East upper purlin, truss V - VI	75	no h/s	AD 1315	------	1389
EXT-A14	East archbrace (lower part), truss VI	82	h/s	AD 1323	1404	1404

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

Table 2: Results of the cross-matching of site chronology EXTASQ01 and relevant reference chronologies when first ring date is AD 1186 and last measured ring date is AD 1404

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 - 1981	4.8	(Laxton and Litton 1988)
MGB-E01	AD 401 - 1981	8.1	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 - 1589	6.8	(Bridge 1988)
Worcester Cathedral, Worcester, Worcs	AD 1181 - 1291	7.1	(Howard *et al* 1995)
Chichester Cathedral, Sussex	AD 1173 - 1295	6.1	(Howard *et al* 1992)
Reading, Berks	AD 1160 - 1407	5.2	(Groves *et al* 1997)
Mercers Hall, Glos	AD 1289 - 1541	5.6	(Howard *et al* 1997)
Ware Priory, Herts	AD 1223 - 1416	6.3	(Howard *et al* 1998 forthcoming)

Figure 1: Map to show general location of Archdeacon of Exeter's House

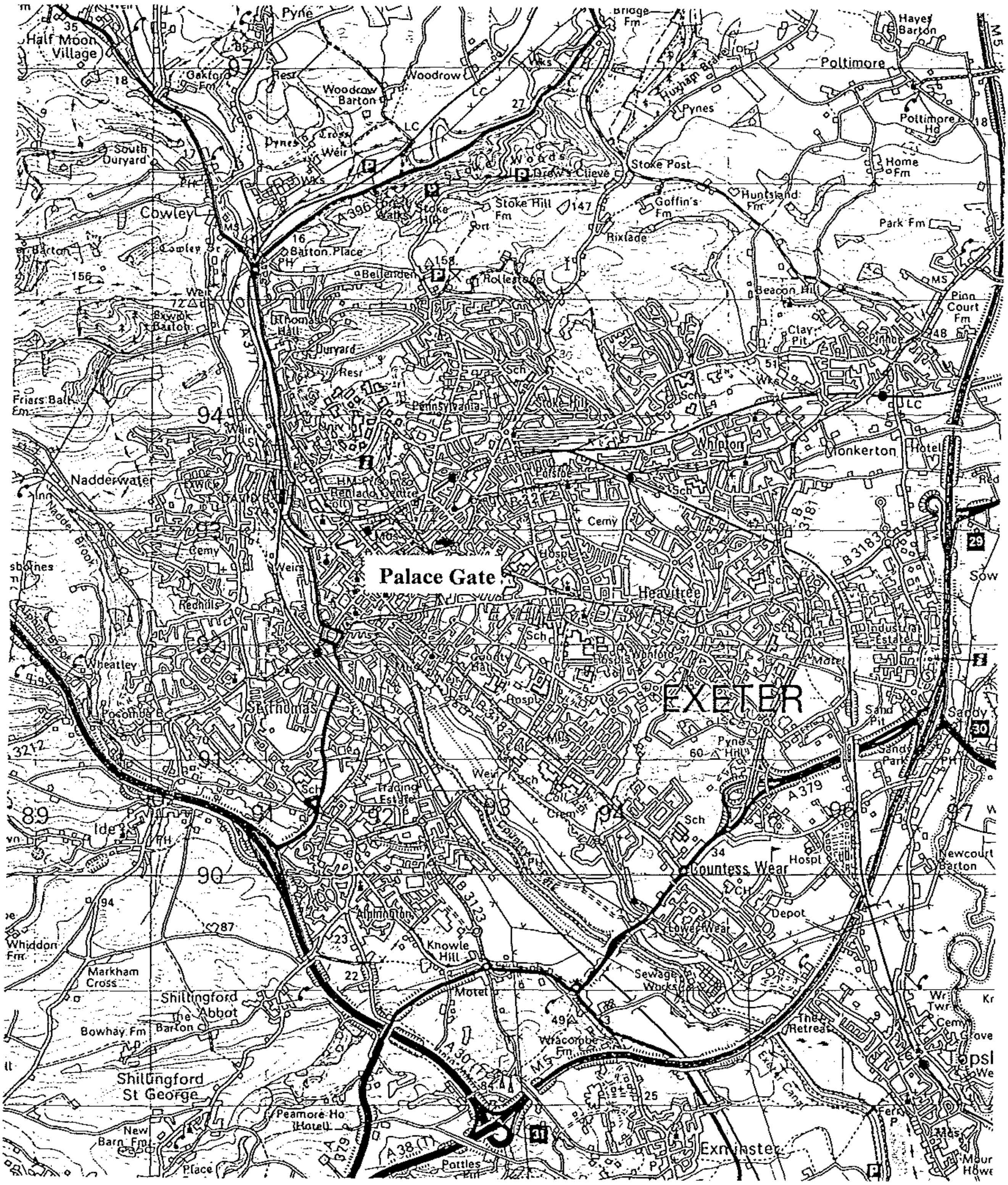


Figure 2: Site map to show detailed location of Archdeacon of Exeter's House (site marked in solid black)

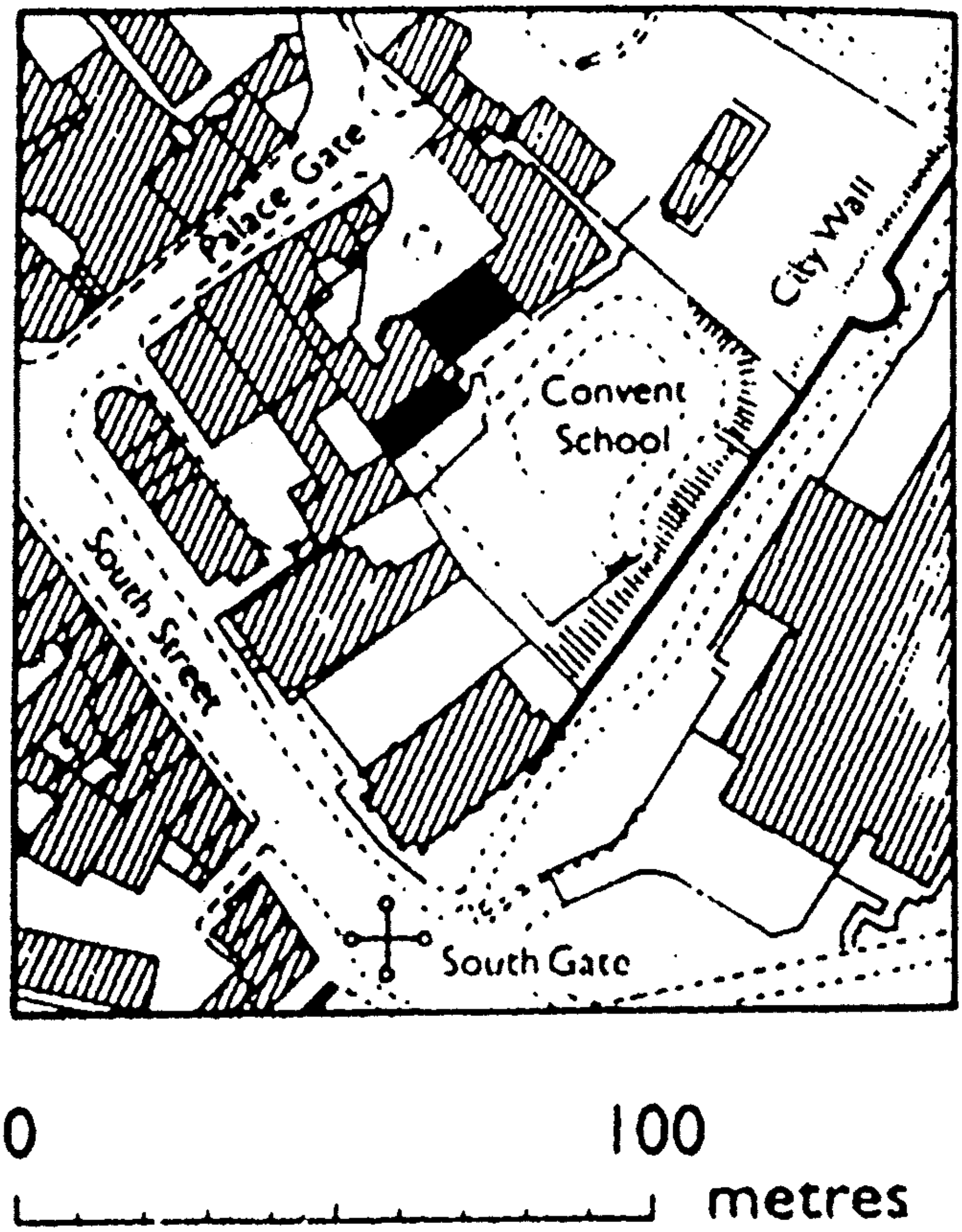


Figure 3: Plan of Hall and Southern wing of Archdeacon of Exeter's House

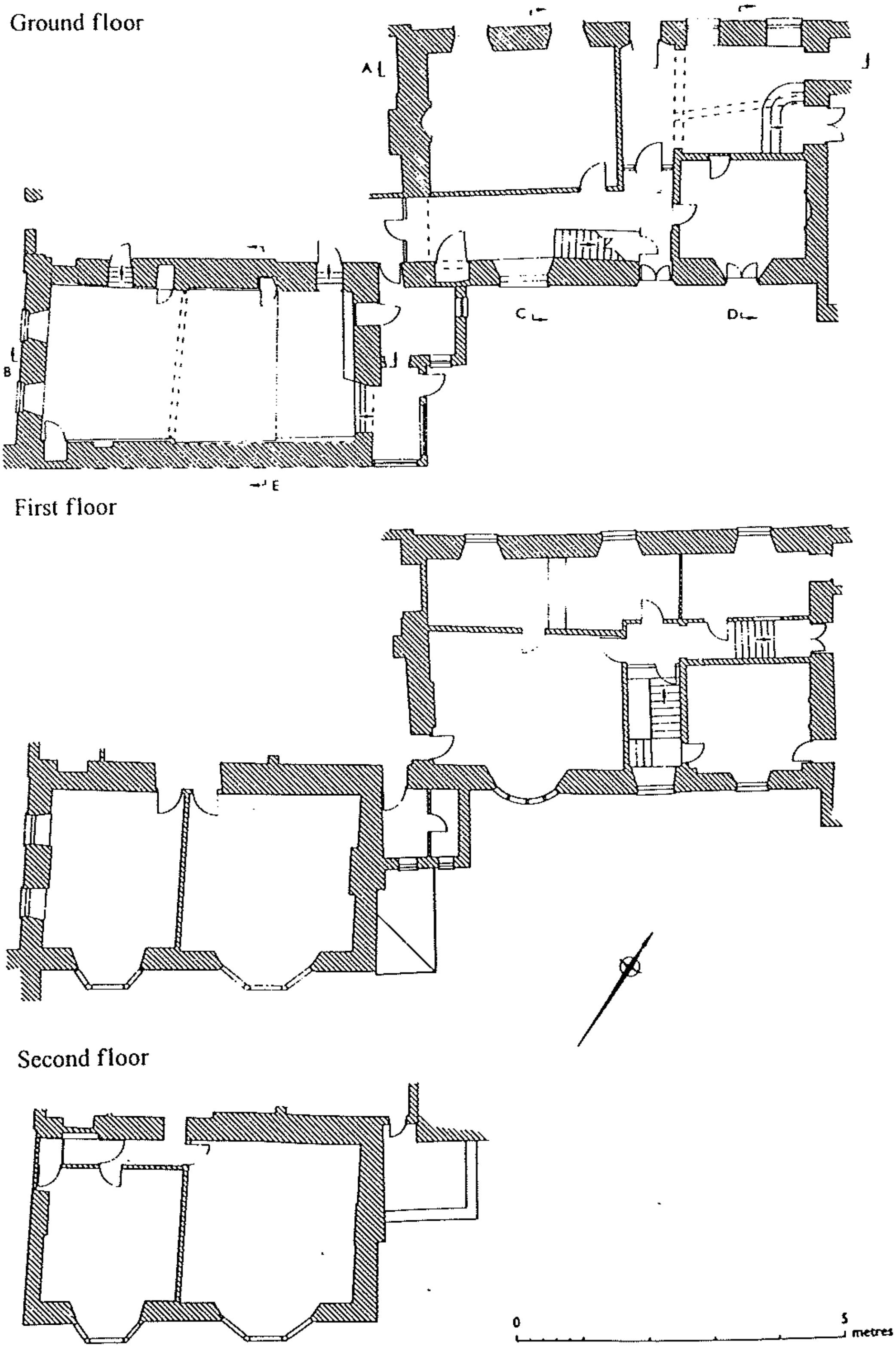
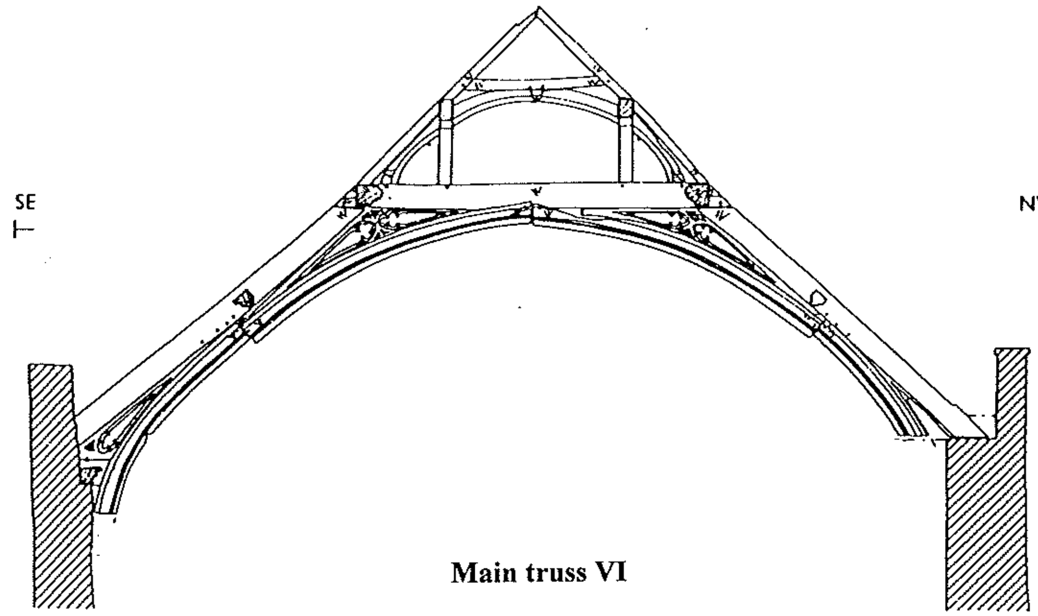
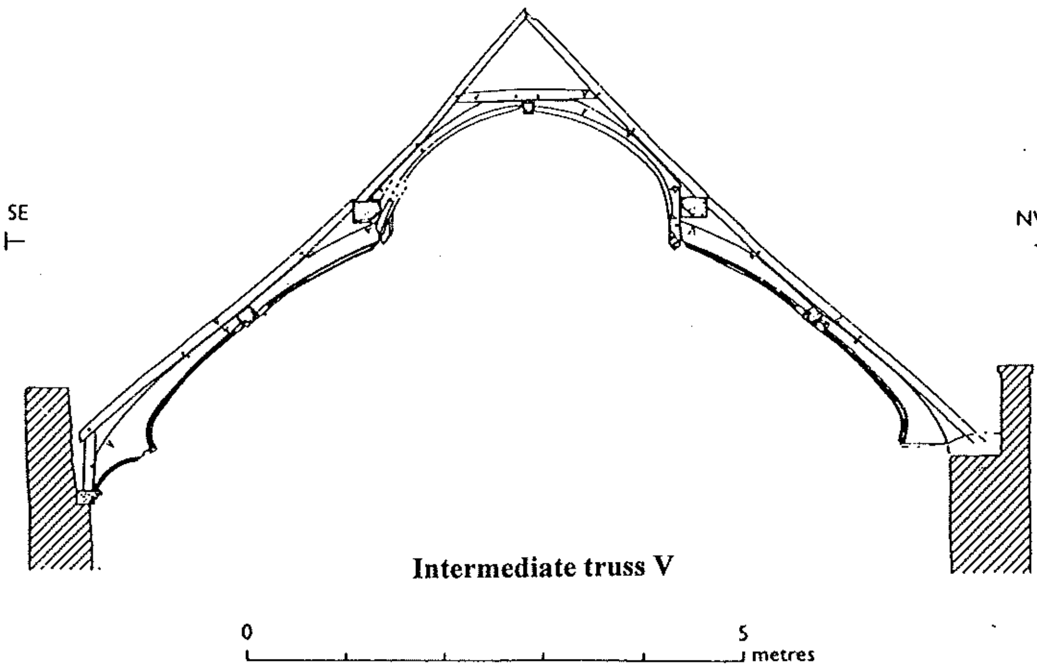


Figure 4: Illustration of truss types



Main truss VI



Intermediate truss V

Figure 5: Long section of Hall viewed from south-east
(bosses and cusps not shown)

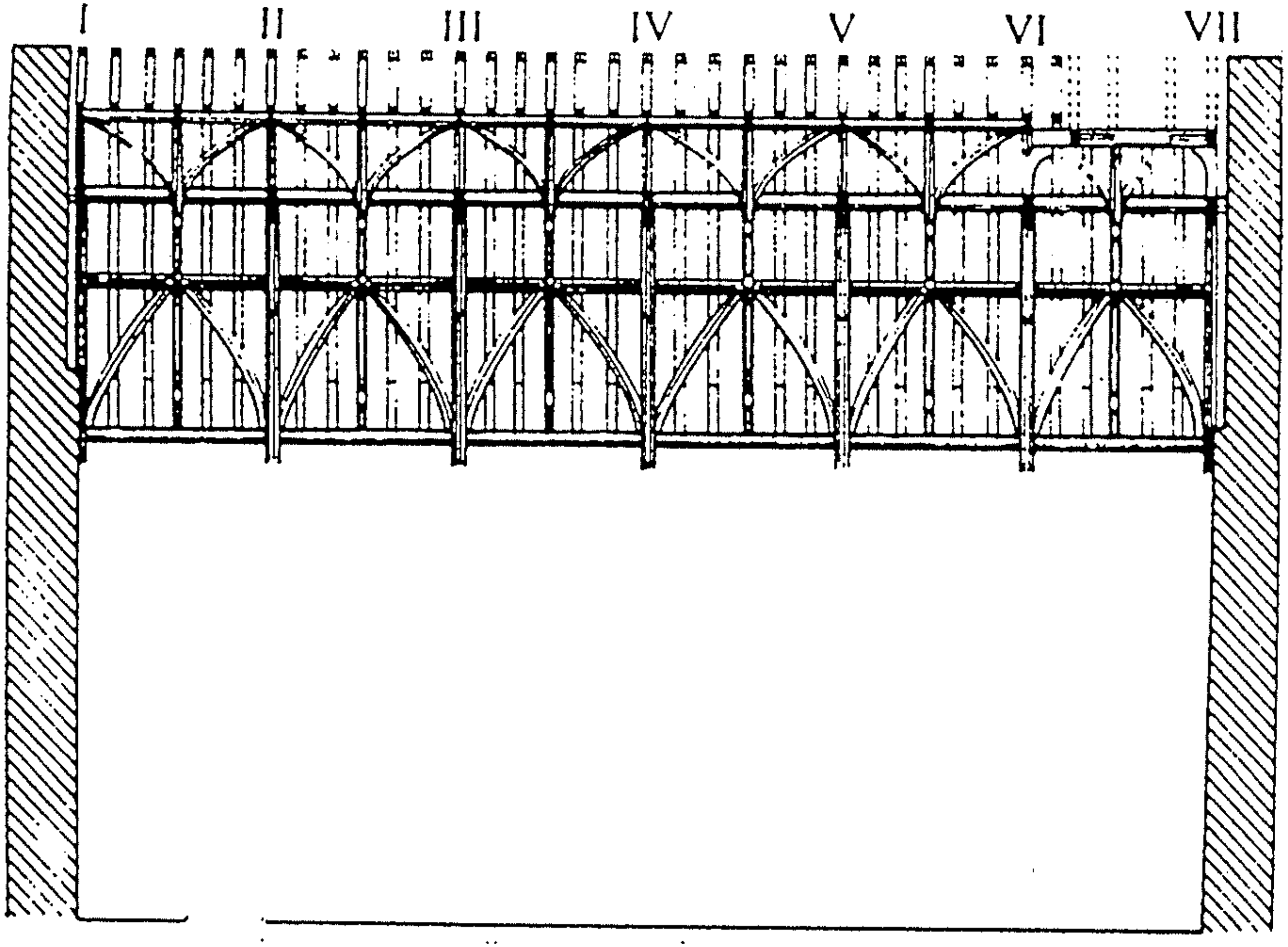


Figure 6: Detail of decorative open-work spandrel of main truss

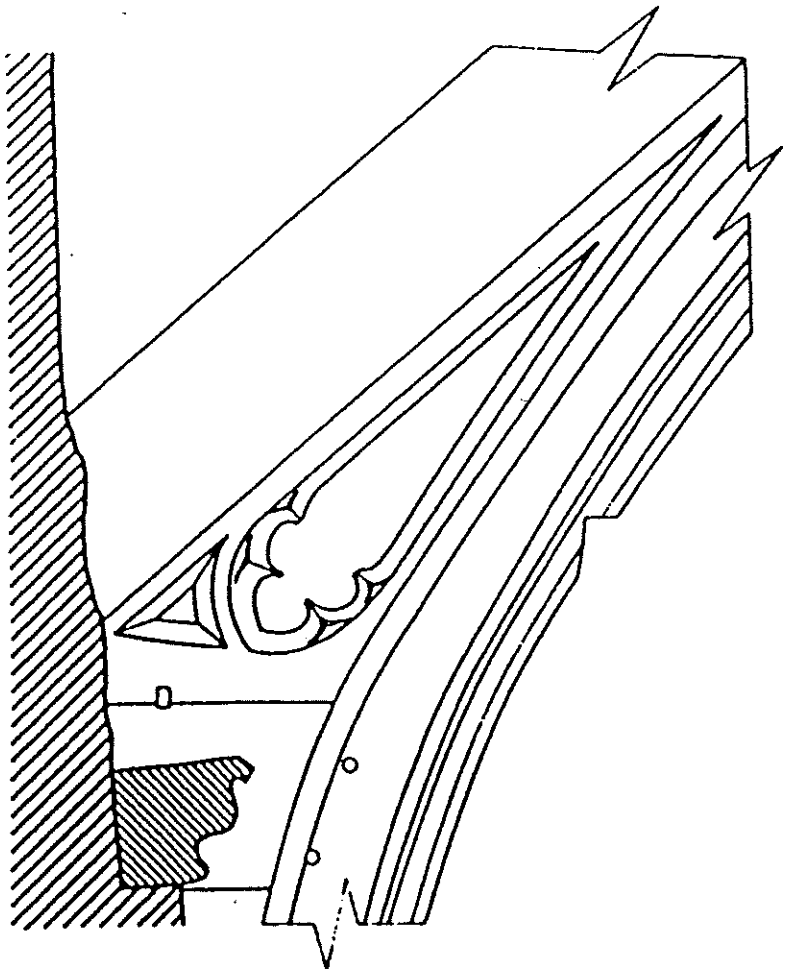


Figure 7: plan of Hall roof to show sample locations

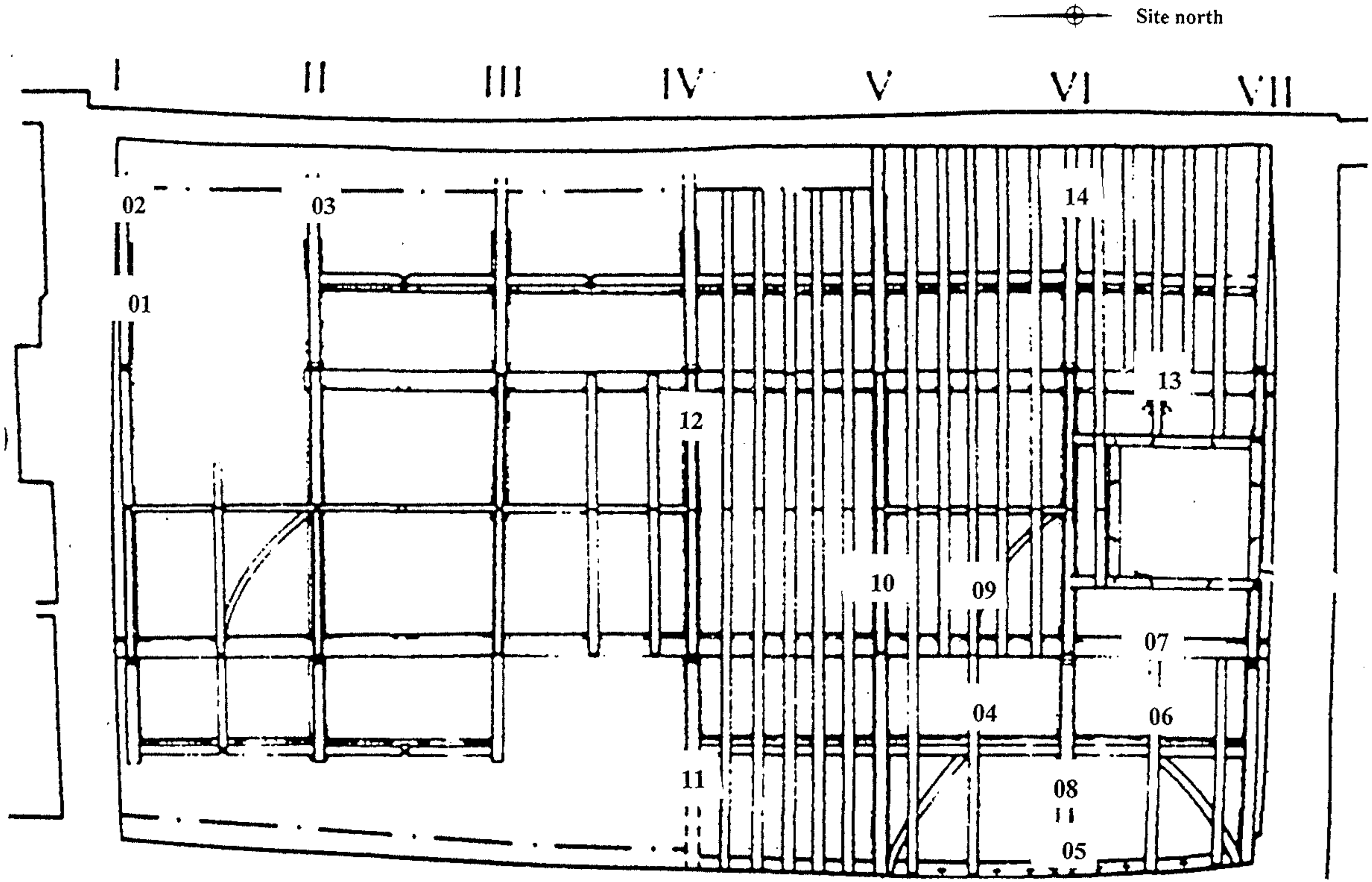
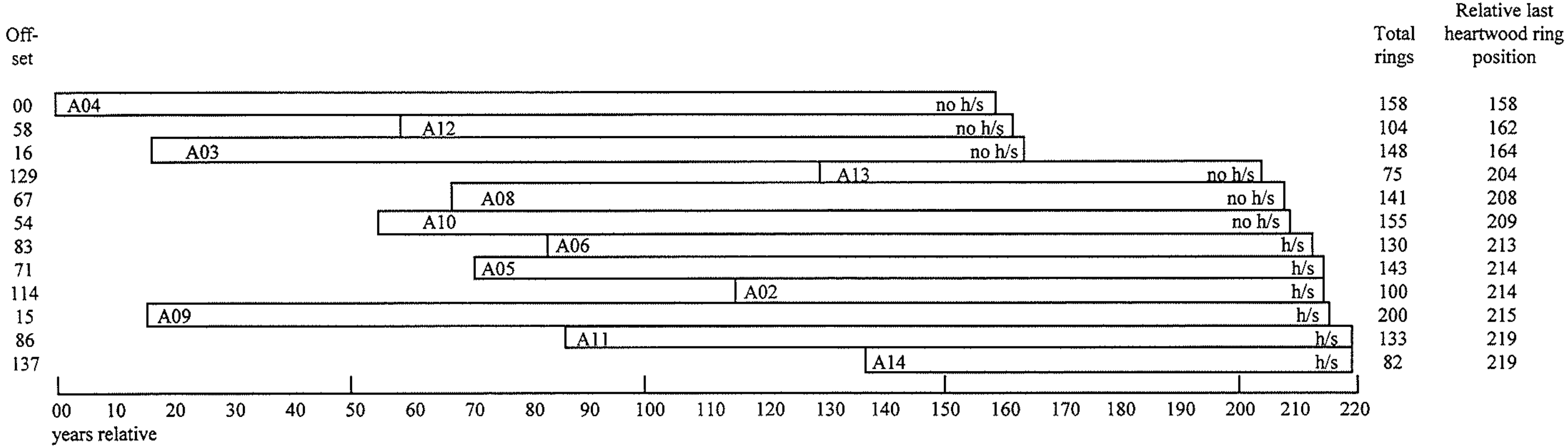


Figure 8: Bar diagram of samples in site chronology EXTASQ01



White bar = heartwood rings
h/s = the heartwood/sapwood boundary is the last ring on the sample

Data of measured samples - measurements in 0.01mm units

EXT-A01A 88
121 135 105 108 122 174 233 182 235 222 208 176 146 70 73 74 116 181 162 173
143 202 118 114 108 88 119 129 172 188 161 133 94 126 239 298 239 280 252 208
160 112 122 144 173 281 278 321 203 229 257 154 180 255 242 223 151 210 215 202
274 230 255 199 203 258 252 185 176 230 217 194 223 184 232 304 239 200 168 171
202 188 264 234 338 269 232 270
EXT-A01B 61
155 168 188 165 133 100 114 236 299 243 269 240 214 182 94 118 157 171 283 292
316 218 229 252 157 200 247 222 214 178 212 209 226 282 227 257 197 208 260 256
196 167 229 214 182 201 202 218 316 239 199 174 176 198 185 275 226 346 259 226
285
EXT-A01C 48
190 144 156 231 196 201 140 106 148 294 306 303 356 275 251 204 179 114 206 274
377 281 370 240 324 332 244 257 267 324 329 193 279 297 381 322 255 288 342 377
309 373 262 247 358 254 252 246
EXT-A02A 100
126 197 250 251 207 168 142 189 205 254 185 137 98 93 98 112 116 113 82 71
70 76 100 128 87 72 70 75 148 108 78 81 62 56 62 60 46 52 62 85
84 66 94 88 103 149 101 83 77 89 77 82 65 105 107 92 71 128 82 103
78 129 213 285 354 240 252 223 154 81 130 95 69 90 85 91 101 79 74 120
150 118 163 138 123 176 116 92 80 79 67 90 62 64 72 60 78 90 104 121
EXT-A02B 100
141 191 251 254 212 164 134 191 207 253 194 133 105 103 88 128 115 118 82 82
71 87 98 138 89 74 79 85 127 116 60 70 56 65 62 66 51 61 88 92
90 67 94 83 107 149 106 81 75 84 82 82 49 99 105 88 86 135 95 100
89 111 202 264 307 222 249 228 152 91 138 90 75 90 94 96 98 84 85 124
139 128 165 156 135 163 112 98 76 81 75 83 66 72 67 75 76 75 112 127
EXT-A02C 60
143 151 94 68 71 92 132 157 115 89 80 110 144 133 47 42 101 227 302 175
310 231 299 220 169 173 201 326 113 90 67 108 105 98 107 190 112 88 60 68
148 297 350 205 222 203 146 91 116 68 78 86 98 104 117 114 148 161 192 158
EXT-A03A 148
237 157 142 114 92 70 98 132 105 84 61 134 92 89 102 218 217 215 145 175
180 187 179 120 203 189 216 228 180 198 199 200 128 208 144 219 210 156 225 91
144 179 214 122 135 194 140 160 102 133 106 158 80 149 106 115 150 154 135 121
118 114 111 135 152 124 157 88 95 112 78 138 91 86 80 63 84 77 93 90
141 129 109 165 252 116 90 102 132 143 141 183 129 124 175 127 145 125 93 101
102 83 83 76 130 111 112 98 160 109 124 114 94 77 70 94 77 99 91 155
149 85 80 80 76 74 88 68 88 92 118 57 55 120 67 75 92 127 111 138
109 92 104 97 117 130 112 132
EXT-A03B 101
221 151 140 114 93 62 91 136 104 88 56 128 91 97 98 221 214 205 159 192
189 184 174 128 216 176 232 224 178 193 187 192 131 196 146 215 196 140 234 91
151 181 209 121 156 185 113 140 108 115 103 158 83 144 108 105 152 157 137 127
122 102 121 133 154 116 152 107 108 101 85 142 82 85 82 66 78 78 96 88
142 133 108 163 251 116 93 96 138 139 148 179 127 115 171 131 148 117 91 94
91
EXT-A03C 93
84 102 95 100 134 86 77 62 69 85 74 77 94 78 76 41 50 57 70 74
56 64 110 120 69 52 70 46 72 65 87 75 96 77 98 64 62 101 100 98
110 108 113 84 94 97 58 100 128 108 123 118 126 131 104 156 115 103 98 97
102 136 94 78 74 86 71 86 72 79 118 83 69 100 111 132 99 135 98 115
109 94 133 76 105 92 109 119 147 141 158 133 174
EXT-A04A 158
233 112 49 108 97 112 162 222 361 208 225 210 126 235 254 353 187 161 62 67
73 62 148 167 144 146 143 216 109 158 139 173 146 139 119 123 123 101 101 145
213 98 346 216 319 219 144 177 138 209 102 231 181 129 194 135 137 463 261 146

154 191 105 109 97 113 85 95 125 162 88 78 162 111 98 83 116 113 174 158
180 95 93 86 111 156 72 173 169 108 77 73 100 86 112 142 167 244 136 117
118 95 62 74 139 139 169 177 125 79 132 119 136 102 82 77 109 86 89 97
137 120 130 117 125 116 86 106 79 107 105 134 102 89 80 108 84 103 78 101
101 152 120 108 132 90 129 110 124 114 76 121 118 161 140 158 117 117
EXT-A04B 158
220 114 44 98 103 112 161 236 352 218 209 221 127 246 273 353 184 169 68 73
71 56 161 170 144 151 151 217 117 152 133 170 158 128 126 122 121 92 112 141
206 96 343 214 316 214 146 168 148 207 93 240 177 124 191 137 140 453 254 130
147 192 112 105 93 114 83 101 122 174 93 79 158 109 91 84 115 124 174 164
173 97 87 89 101 161 67 175 174 109 80 70 98 86 110 139 168 244 129 118
114 96 63 73 137 137 176 161 126 88 128 134 132 98 80 88 97 91 83 103
133 123 130 119 127 107 95 86 85 100 108 135 105 89 104 113 85 103 79 97
106 147 124 113 127 86 133 111 105 123 80 111 116 163 153 144 120 129
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64 49 46 44 62 44 38 45 40 42 43 38 24 33 46 44 52 49 56 50
57 46 51 69 61 69 68 77 71 107 92 59 67 77 86 69 92 72 68 80
128 180 67 62 93 136 128 124 117 63 61 73 84 126 96 60 68 74 52 46
70 63 65 73 98 139 151 93 90 80 114 102 87 68 66 61 110 108 114 99
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58 54 84 75 80 88 91 99 92 96 106 96 109 116 119 91 79 63 61 69
54 71 85
EXT-A05B 143
79 55 35 39 59 52 34 47 41 43 29 43 29 40 41 44 53 43 51 54
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84 123 144 116 87 102 92 84 111 73 74 91 95 55 65 58 122 116 107 106
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64 63 79 76 76 94 86 100 91 88 109 92 91 123 125 83 74 65 64 68
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121 128 212 94 156 120 151 106 127 129 126 104 81 140 125 107 112 128 126 76
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86 130 141 99 106 88 82 86 102 72 64 39 58 56 43 46 38 33 53 51
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144 107 114 134 144 126 91 114 83 120 110 114 118 167 140 72 45 42 109 82
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring..

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the University of Nottingham Tree-Ring dating Laboratory

1. ***Inspecting the Building and Sampling the Timbers.*** Together with a building historian we inspect the timbers in a building to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings. Similarly the core has just over 100 rings.

   To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8 to 10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

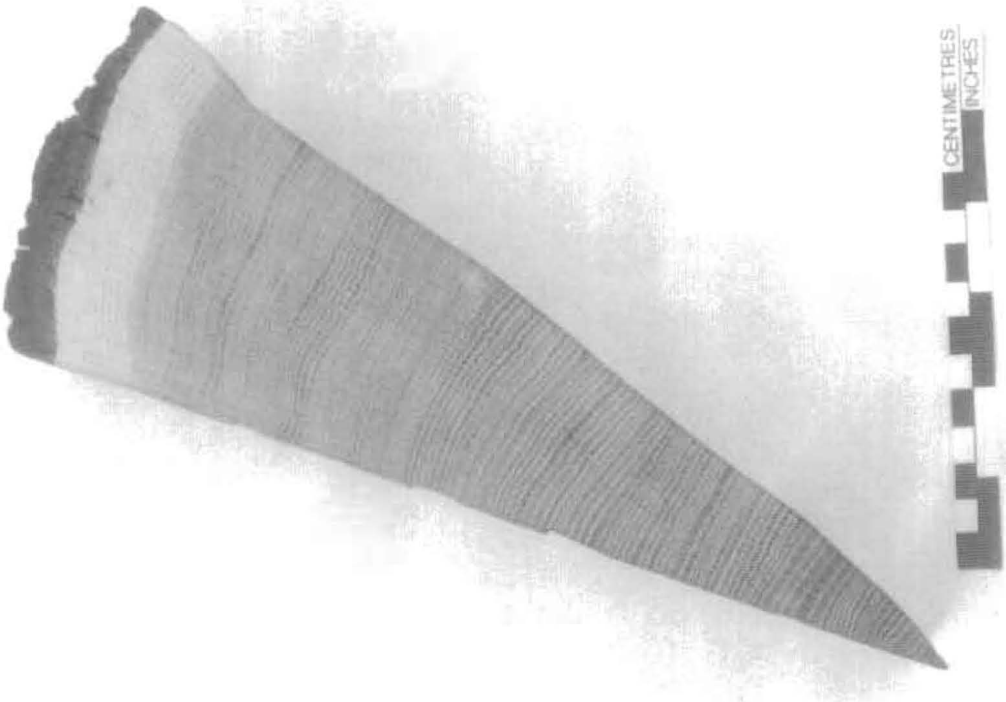

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

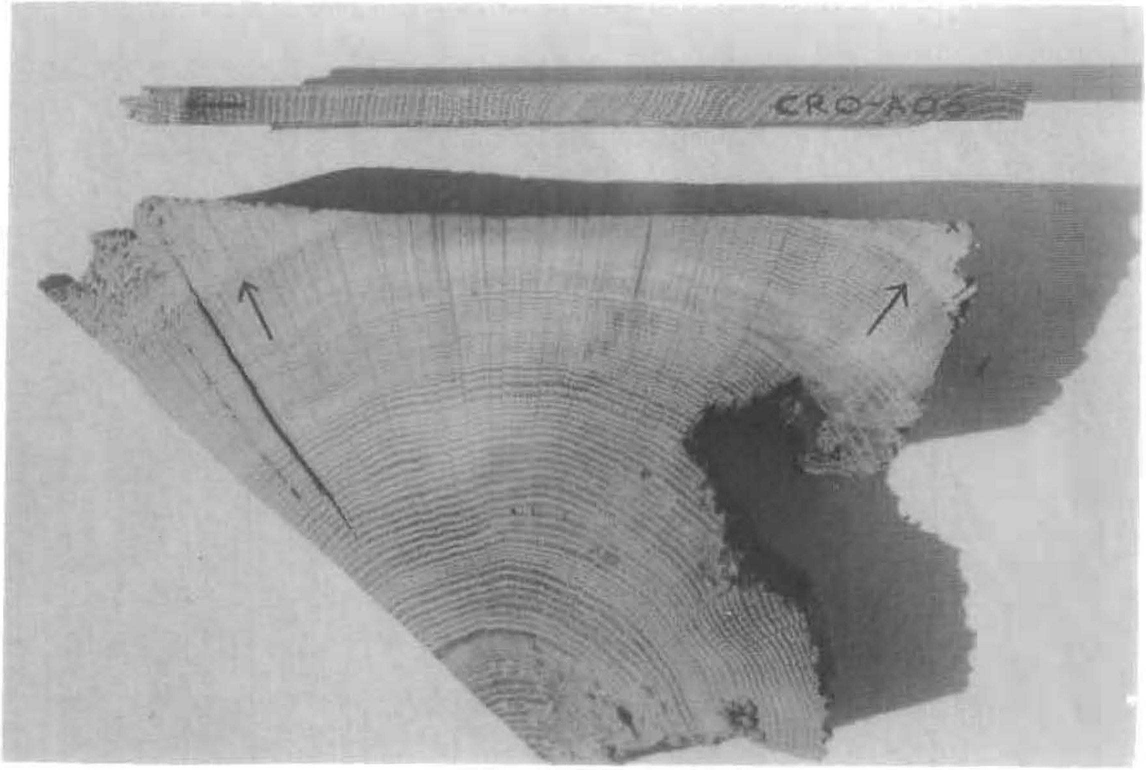

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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

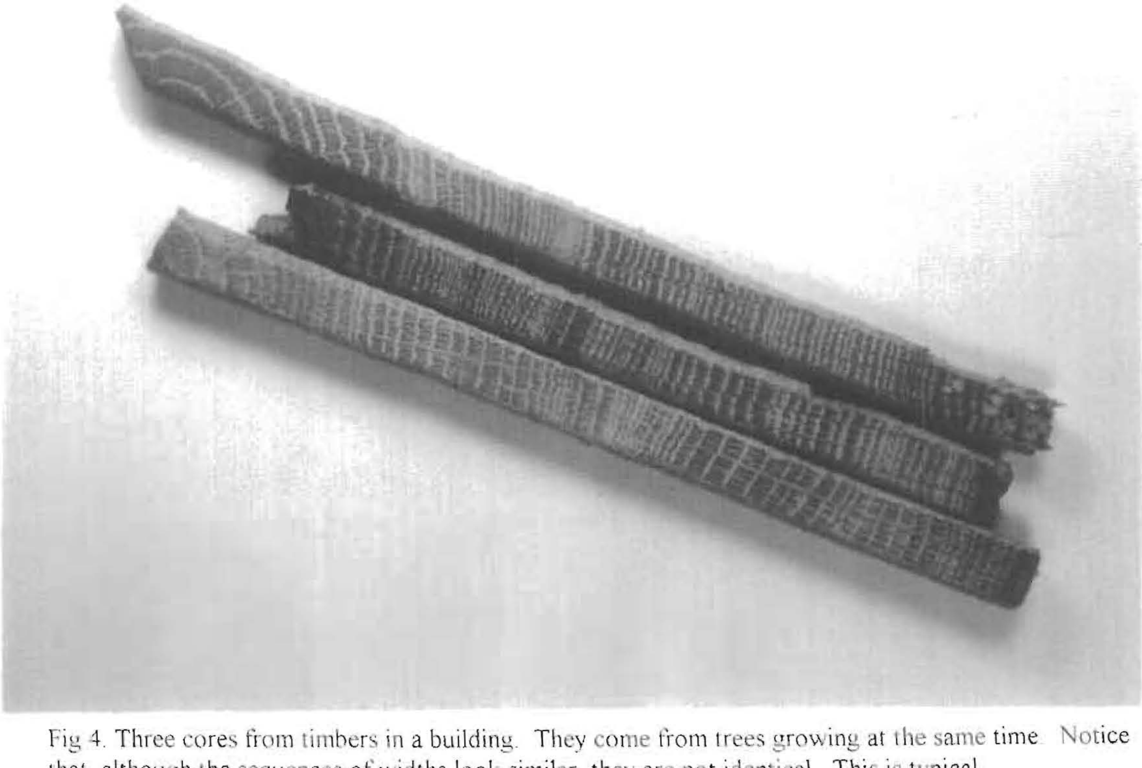

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost This can be difficult as these outer rings are often very soft (see below on sapwood) Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspecton of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards.
The Laboratory is insured with the CBA.

2. ***Measuring Ring Widths.*** Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples.*** Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum t-value among the t-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a t-value of at least 4.5, and preferably 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

   This is illustrated in Fig 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN- C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the t-value between C45 and C08 is 5.6 and is the maximum between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

4. ***Estimating the Felling Date.*** If the bark is present on a sample, then the date of its last ring is the date of the felling of its tree. Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases. The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely for these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

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

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

More precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 40 years later we would have estimated without this observation.

T-value/Offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

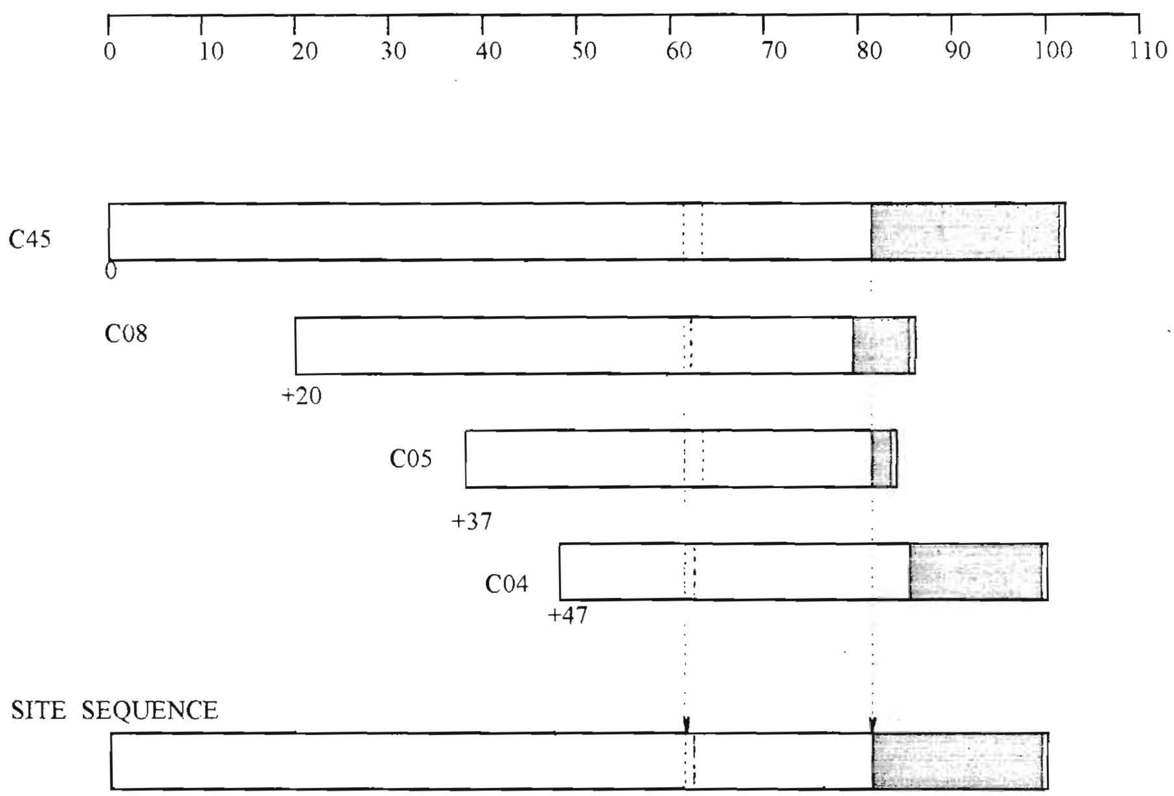

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t-values*.
The *t-value offset* matrix contains the maximum t-values below the diagonal and the offsets above it.
Thus, the maximum t-value between C08 and C45 occurs at the offset of +20 rings and the t-value is then 5.6.
The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

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

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

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ*, and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed for this.

6. ***Master Chronological Sequences.*** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton 1988b, but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988a). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. ***Ring-width Indices.*** Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988b) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

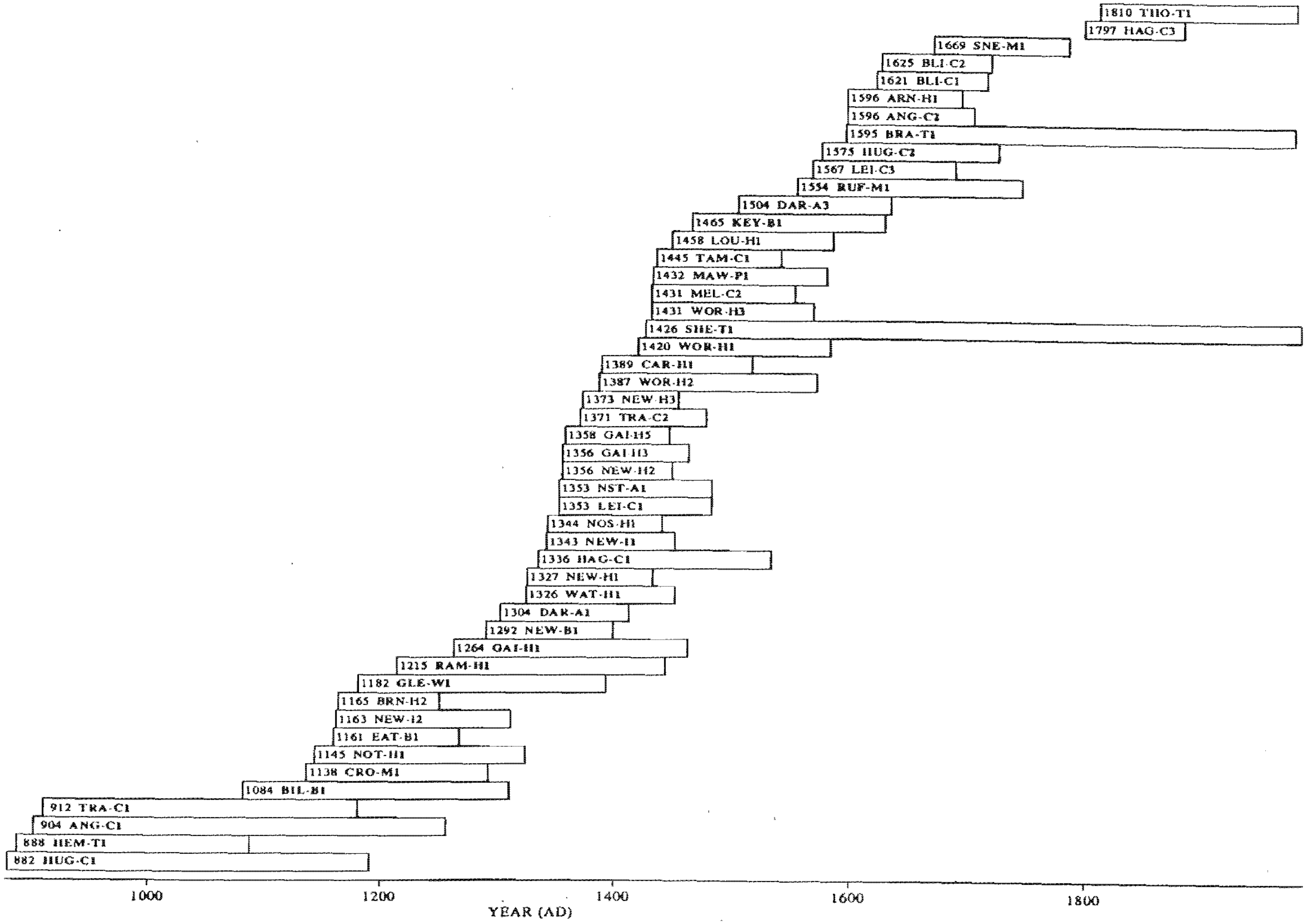

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

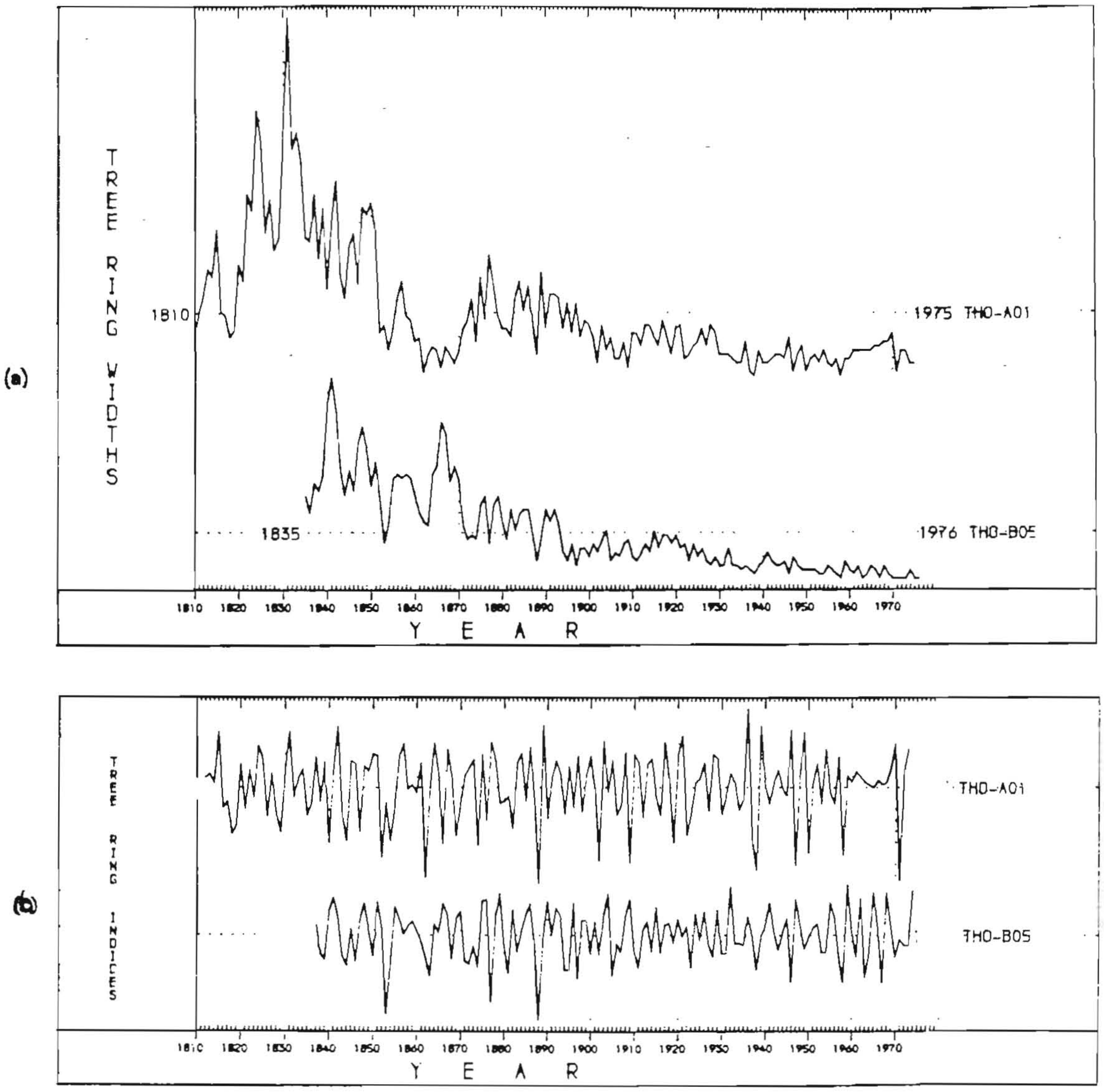

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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