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THE OLD RECTORY, EPWORTH, NORTH LINCOLNSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

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Summary

Dendrochronological analysis was undertaken on samples taken from the roof structure and ceiling beams at this building, resulting in the construction of two site sequences.

Attempts to match these site sequences against the reference material were unsuccessful and both remain undated. However, site sequence ORYASQ02 contains samples from the roof and one ceiling beam, and interpretation of the heartwood/sapwood boundary ring position of these demonstrates that at least one of the ceiling beams is likely to be of the same date as the roof structure.

A sample taken from a principal rafter has been dated individually to the period AD 1623–1704 and the tree from which it was derived is estimated to have been felled within the range AD 1705–18.

Prior to the tree-ring analysis, documentary evidence suggested the Old Rectory was constructed in AD 1709, following a fire that totally destroyed an earlier building on the site. It is now known that the roof of this extant building contains at least one timber felled in AD 1705–18, consistent with a felling of AD 1709.

Keywords

Dendrochronology
Standing Building

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Introduction

The Grade-1 listed Old Rectory is located at Epworth, in the Isle of Axholme, North Lincolnshire (Figs 1 and 2; SE 785 036). It has been operated as a museum by the World Methodist Council since being sold by the Church of England in AD 1954.

In AD 1696, the Rev. Samuel Wesley became rector of St Andrew's Church at Epworth and moved into the Old Rectory with his wife Susanna and their four children. Whilst in Epworth they had several further children, including John and Charles, who went on to become instrumental in the founding and development of the Methodist movement.

During the time that the Wesleys were in residence there were a number of fires at the rectory; it is thought likely that these were not accidents, rather deliberate arson perpetrated by local residents objecting to some of Samuel Wesley's beliefs. The most serious of these occurred in AD 1709, which was said to have totally destroyed the building. The present structure is thought to have been built to replace this. The following description is taken from the Conservation Plan produced by Kate Judge (Judge 2004).

Description (Figs 3–6)

The house was built in AD 1709 and subsequently had two extensions built; one on the east end of the property in the late eighteenth/early-nineteenth century and a later one of AD 1883 on the north-west corner – both now demolished.

The house is of local red-brown brick, in Flemish bond on the south front and in English garden wall bond on the other elevations. The property has a pantile roof, in two ranges with valley gutter, that was re-roofed in AD 1956 with some replacement of roof timbers and tiles. The roof is hipped on the west side and has a concrete coping detail to the east side. The roof structure is a collared rafter roof with pegged butted purlins (Fig 3). The dormers are additions of AD 1956.

The south front is of seven bays, not quite regular, in order to allow for the substantial flue rising from the original kitchen in the south-east corner. The central bay is emphasised by a break forward and is the position of the front door, although the doorcase and door are modern. The elevation has an ovolo-moulded plinth with characteristic chamfered brick quoins. A two brick deep string course articulates the ground from the first floor. A modillioned cornice runs along the south and west fronts of the house. The west and east elevations are each of four uneven bays. The elevations are articulated with 12-pane sash windows (apart from the north) which are principally modern with some slightly earlier survival, although probably none original. Windows are under rubbed-brick arches with originally ashlar sills, mostly now modern with some unsympathetically concrete ones.

The plan is double pile with a central spine wall, two storeys with an attic. On the south side of the house are three rooms. On the ground floor from east to west, the kitchen, entrance hall and another room (use uncertain but possibly the parlour). On the first floor there are three rooms of the same size as those on the ground floor. A spine wall runs east/west through all floors of the property. The staircase in the centre of the property is original with an open well, closed string staircase, a wide corniced handrail, moulded string, heavy turned balusters and square newel posts.

The attic is now divided into a number of rooms, although this plan is probably later and originally the attic is likely to have been much more open, with perhaps one of two divided chambers used by servants.

Acknowledgements

The Laboratory would like to thank Joan Sidaway, museum curator, and all staff at the Old Rectory for their assistance and enthusiasm throughout the duration of the sampling. Thanks are given to Naomi Field of Lindsey Archaeological Services for liaising with David Glew Architect & Surveyor regarding the supply of Figures 4–6.

Thanks are also given to John Meadows of English Heritage Scientific Dating Section and Cathy Tyers of Sheffield University Dendrochronology Laboratory for their advice and assistance throughout the production of this report.

Aims and Objectives

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. It was requested by Dr Diane Green, Historic Buildings Inspector at English Heritage's York office, to inform statutory advice in the context of a proposed programme of refurbishment.

It was hoped that tree-ring analysis of the extant roof and ceiling structures would provide a construction date for the building. Additionally, some of the ceiling beams were thought to be reused and it was hoped that dendrochronology would show whether these were the same date as the roof or of a separate phase. Recent investigations had suggested that some structural timbers may have survived the AD 1709 fire and it was hoped that if these did indeed exist, dendrochronology might be able to identify them.

Sampling

Whilst the roof timbers were readily accessible, the accessible timbers of the ground and first-floor ceiling frames were restricted to the main beams, with no common joists visible. Upon close inspection, these main beams could be seen to be derived from reasonably fast-grown trees. However, as these timbers are quite large it was thought that samples containing enough growth rings to make successful dating of the samples a possibility may be obtained. Within the brief provided by English Heritage, these ceiling beams were described as reused, however, with the exception of one in Bedroom 4 (ORY-A20) obvious signs of reuse were not noted.

A total of 20 samples was taken from timbers of the roof structure and several main ceiling beams on the ground and first floors. Each sample was given the code ORY-A (for The Old Rectory) and numbered 01–20. Samples ORY-A01–13 are from the roof timbers and samples ORY-A14–20 from ceiling beams. The position of samples was noted at the time of sampling and has been marked on Figures 4–7. Further details relating to the samples can be found in Table 1. Trusses were numbered west to east.

Analysis, Results, and Interpretation

At this stage it was noticed that four of the samples taken from the roof and five of the samples from the ceiling beams had too few rings to make secure dating a possibility and these samples were rejected prior to measurement. The remaining 11 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. These samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a least value of t=4.5, eight of the samples had matched to form two groups.

Two samples, both from the roof, matched each other and were combined at the relevant offset positions to form ORYASQ01, a site sequence of 101 rings (Fig 8). Six other samples, five from the roof and one from a ceiling beam, matched each other and were combined at the relevant offset positions to form ORYASQ02, a site sequence of 79 rings (Fig 9). Attempts to date these site sequences by comparing them against a series of relevant reference chronologies for oak were unsuccessful and both remain undated.

The remaining three ungrouped samples were then individually compared against the reference material, resulting in sample ORY-A08, taken from a principal rafter, being matched at a first-ring date of AD 1623 and a last-ring date of AD 1704. This sample has the heartwood/sapwood boundary ring date of AD 1678, which allows an estimated felling date range to be calculated for the timber represented of AD 1705–18, allowing for the fact that the sample has a last measured ring date of AD 1704 and incomplete sapwood. This felling date range has been calculated using the estimate that 95% of mature oak trees from this area have 15–40 sapwood rings.

Discussion

The present building was thought to be a replacement of an earlier building totally destroyed by a fire in AD 1709. However, recent investigations had raised the possibility that some of the timbers from this earlier building may have survived and were incorporated into the present structure.

Tree-ring analysis has only succeeded in dating one timber from the extant roof structure, a principal rafter now thought to have been felled some time within the period AD 1705–18. Although this felling date range is consistent with the documented rebuilding in AD 1709, the dating of a single sample cannot be said to be conclusive evidence for a construction date. All that can be said is that the roof contains at least one timber of this date.

Interpretation of the relative heartwood/sapwood boundary ring positions of the six samples contained within site sequence ORYASQ02 does suggest a single felling for the six timbers represented. This does demonstrate that at least one of the ceiling beams is likely to be of the same date as the roof structure, although unfortunately, it is not possible as yet to say what this date would be. It is unfortunate that the one obviously reused ceiling beam did not match any of the other samples, which would have at least given us a date relative to the rest of the timbers, if not an absolute date.

The fact that the two site sequences do not match each other or the unmatched individual samples does not necessarily mean that they are of different dates. It may be that the trees represented are from different sources, have been subjected to varying management regimes or have responded to environmental forces to a greater or lesser extent, all factors which could have resulted in obviously different growth patterns and thus inhibited grouping.

It is unfortunate that more timbers from this building have not been dated and the reason for this lack of success is unclear. One contributory factor for this poor dating may be the inadequacies of the site sequences. Site chronologies which are relatively short in length or poorly replicated, with only a small number of samples incorporated, are more likely to remain undated. At this site, one of the site sequences (ORYASQ01) is of a satisfactory length (101 rings) but contains only two samples, whereas the other site sequence (ORYASQ02) is quite well replicated, containing six samples, but is only 79 rings long.

Alternatively, it may be that the growth patterns in the trees represented have been influenced by non-climatic factors. Although there is nothing obviously unusual about the growth patterns of the samples, which might suggest a major growth disturbance in the trees represented, it could be that they were subjected to highly localised growing conditions. This may mask the overall climatic signal necessary for successful dating by inhibiting successful matching with available reference chronologies.

Whatever the reason, in this instance dendrochronology has not been able to provide conclusive evidence for a construction date and at present dating and interpretation must remain on stylistic and documentary grounds only.

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Table 1: Details of tree-ring samples from the Old Rectory, Epworth, North Lincolnshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
ORY-A01	South principal rafter, truss 1	NM	--	----	----	----
ORY-A02	North principal rafter, truss 2	48	02	----	----	----
ORY-A03	South principal rafter, truss 2	60	09	----	----	----
ORY-A04	North principal rafter, truss 3	64	18	----	----	----
ORY-A05	North principal rafter, truss 4	101	17C	----	----	----
ORY-A06	North principal rafter, truss 5	64	17	----	----	----
ORY-A07	South principal rafter, truss 5	NM	--	----	----	----
ORY-A08	South principal rafter, truss 6	81	26	1623	1678	1704
ORY-A09	North common rafter 2, bay 1	51	18	----	----	----
ORY-A10	North common rafter 2, bay 4	NM	--	----	----	----
ORY-A11	Mid hip rafter (west end)	62	10	----	----	----
ORY-A12	South hip rafter (west end)	81	02	----	----	----
ORY-A13	Purlin, north side (west end)	NM	--	----	----	----
Ceiling beams						
ORY-A14	Visitor information area	NM	--	----	----	----
ORY-A15	Kitchen	NM	--	----	----	----
ORY-A16	Bedroom 2	NM	--	----	----	----
ORY-A17	Bedroom 3	79	17C	----	----	----
ORY-A18	Bathroom	NM	--	----	----	----
ORY-A19	Bedroom 5	NM	--	----	----	----
ORY-A20	Bedroom 4 – reused	64	13C	----	----	----

*NM = not measured
**C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of sample ORY-A08 and relevant reference chronologies when the first-ring date is AD 1623 and the last-ring date is AD 1704

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	6.6	AD 882–1981	Laxton and Litton 1988
Bolsover Castle (Riding School), Derbys	7.3	AD 1494–1744	Arnold *et al* 2005
Rufford Mill, Notts	6.9	AD 1571–1727	Laxton *et al* 1984
De Grey Mausoleum, Flitton	6.7	AD 1510–1726	Arnold *et al* 2003a
Bolsover Castle (Little Castle), Derbys	6.8	AD 1532–1749	Arnold *et al* 2003b
Bay Hall, Bennington, Lincs	6.8	AD 1591–1717	Howard *et al* 1998
Worcester Cathedral (composite of all samples), Worcs	6.0	AD 1484–1772	Arnold *et al* 2003c
St Giles Church (bellframe), Elkesley, Notts	5.8	AD 1628–1722	Arnold *et al* 2003 unpubl

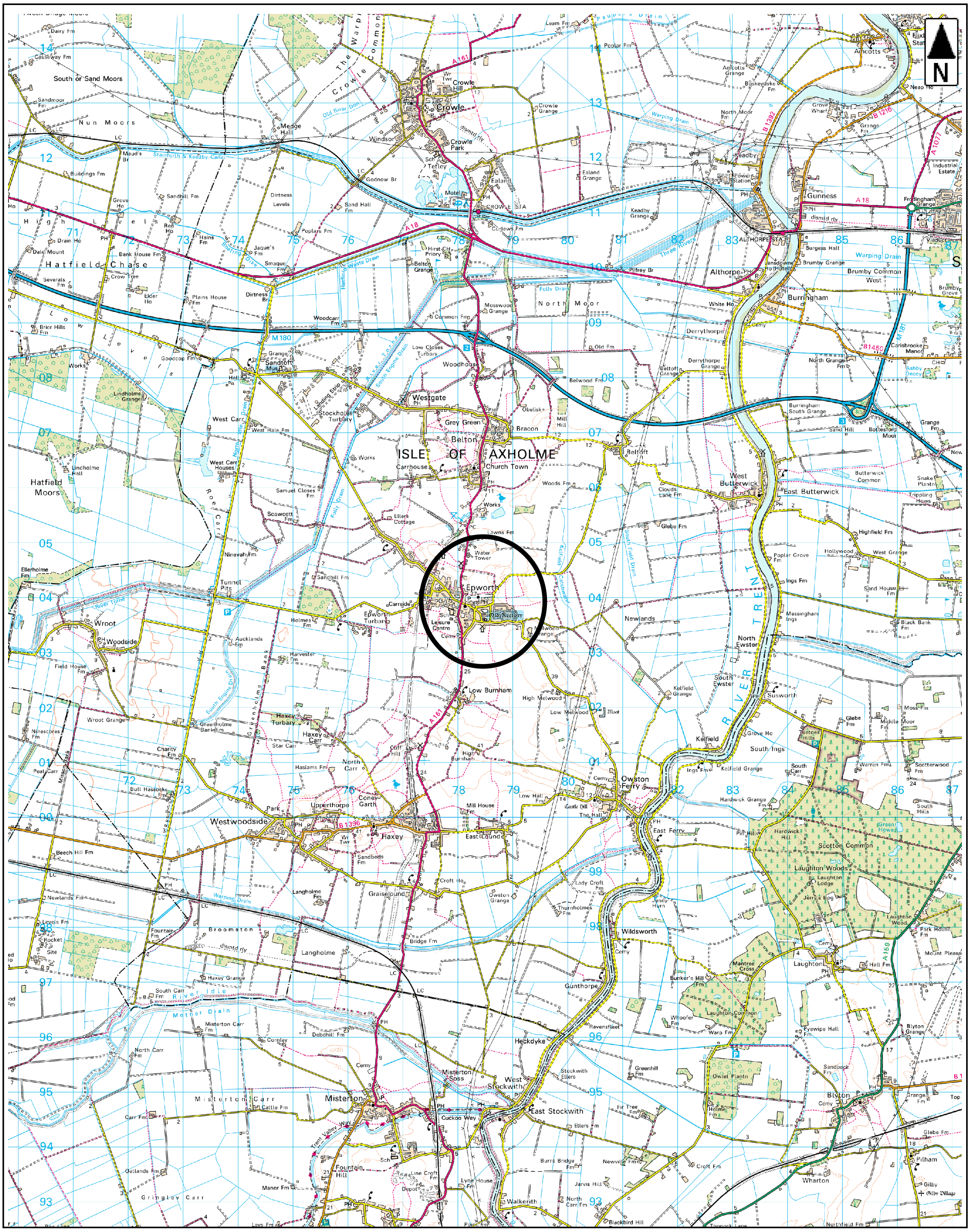


Figure 1: Map to show the general location of Epworth

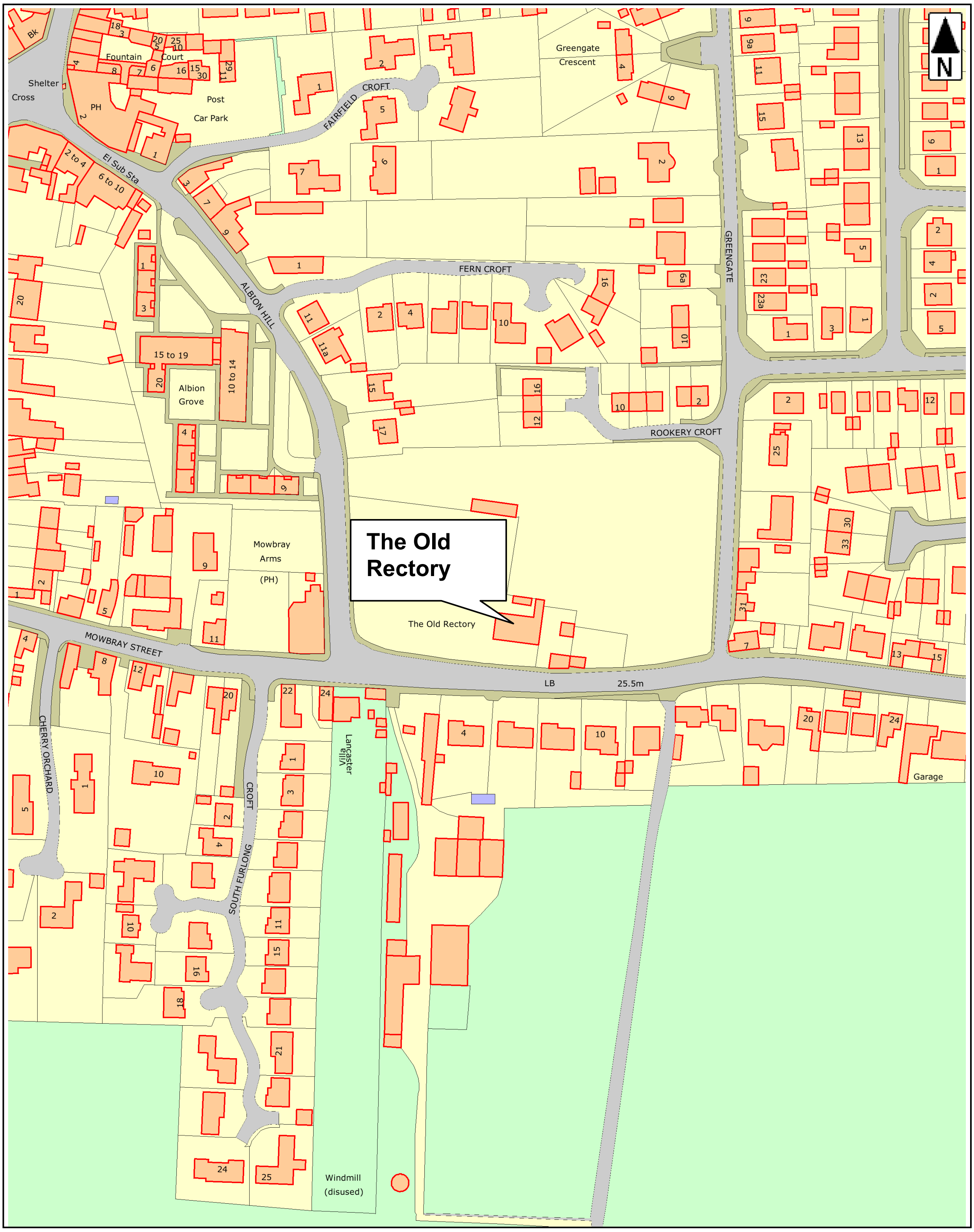


Figure 2: Map to show the location of The Old Rectory

Figure 3: The Old Rectory; roof, looking west

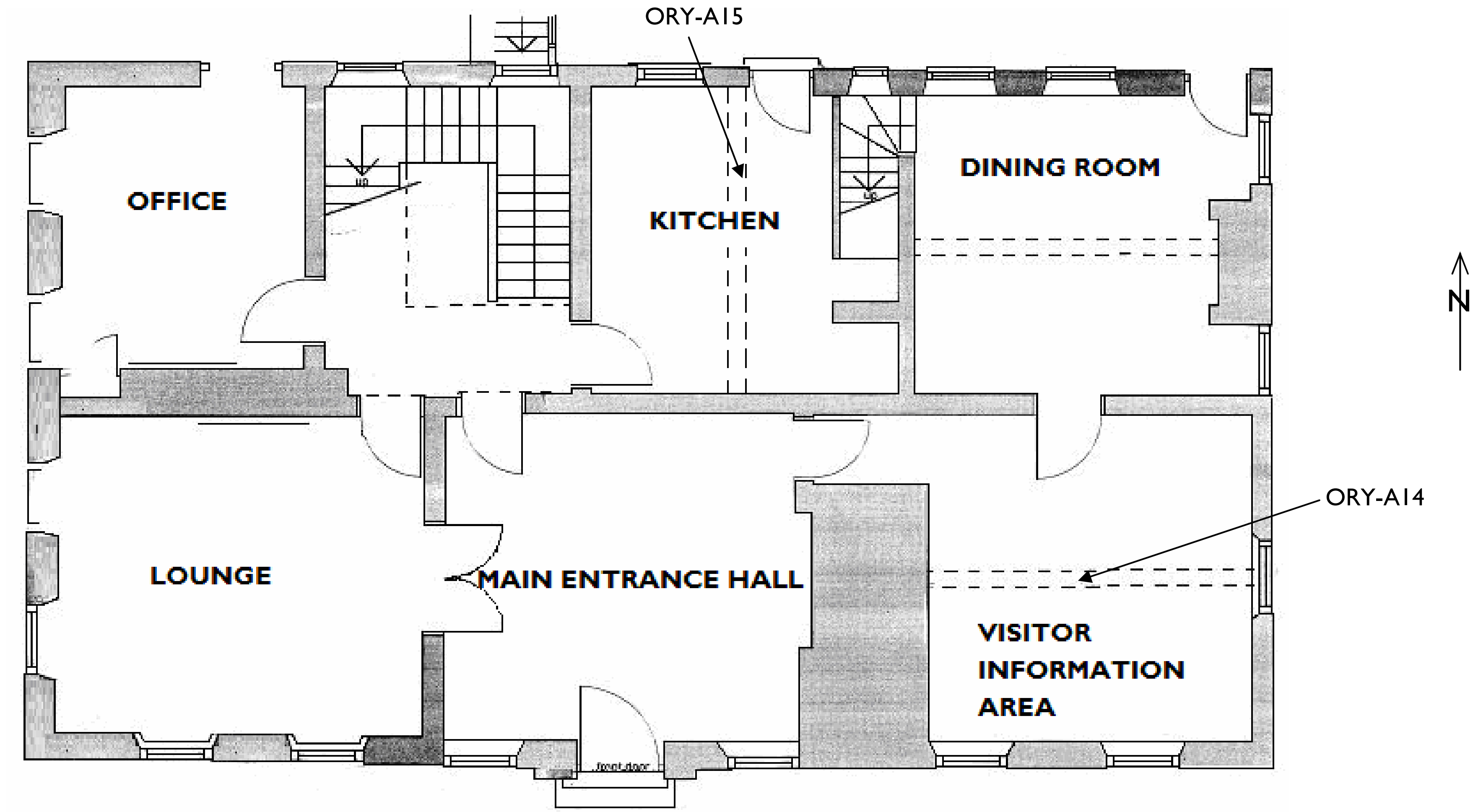


Figure 4: The Old Rectory; Ground-floor plan, showing the location of samples ORY-A14 and ORY-A15 (David Glew Architect & Surveyor)

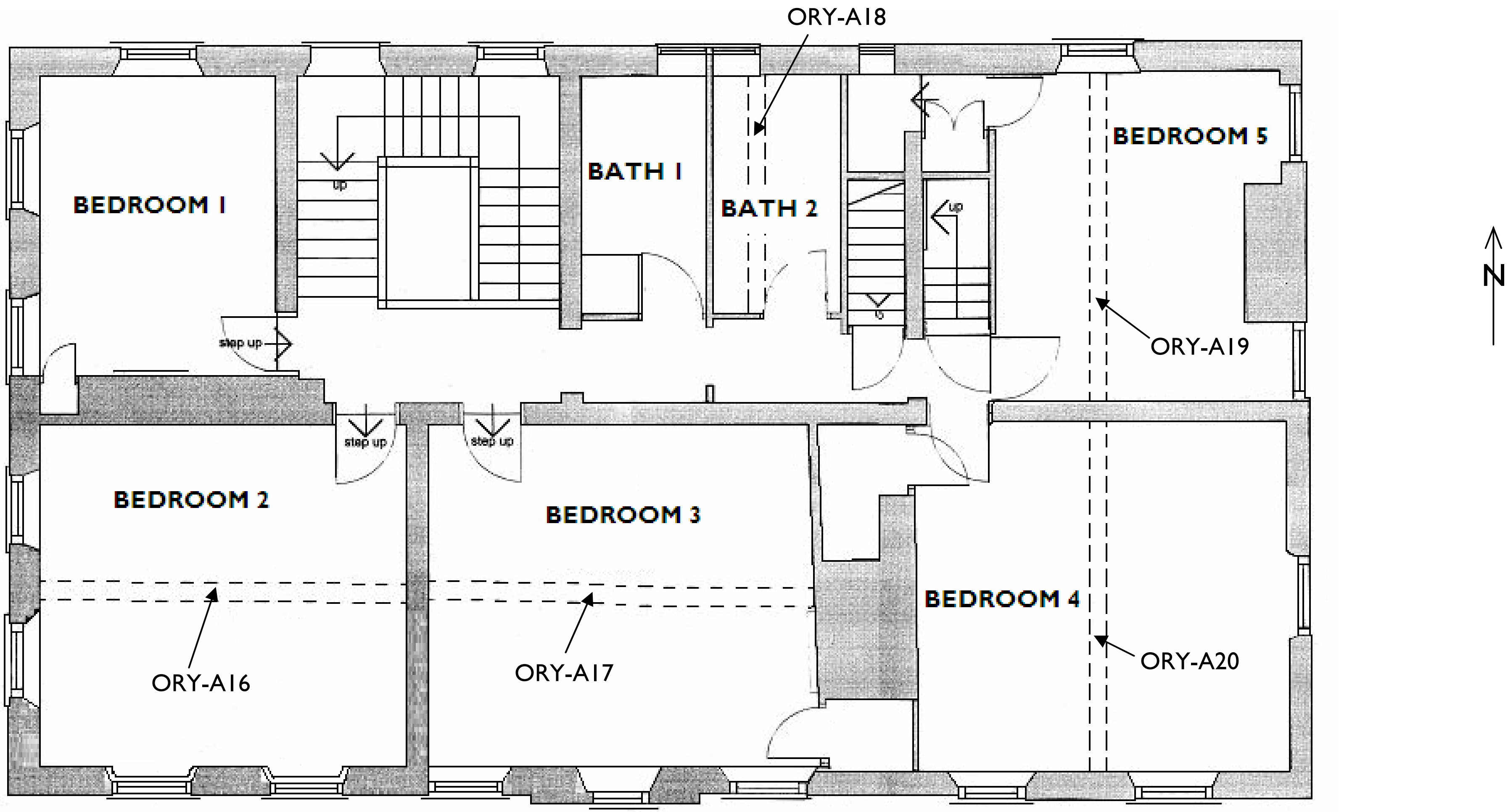


Figure 5: The Old Rectory; First-floor plan, showing the location of samples ORY-A16–20 (David Glew Architect & Surveyor)

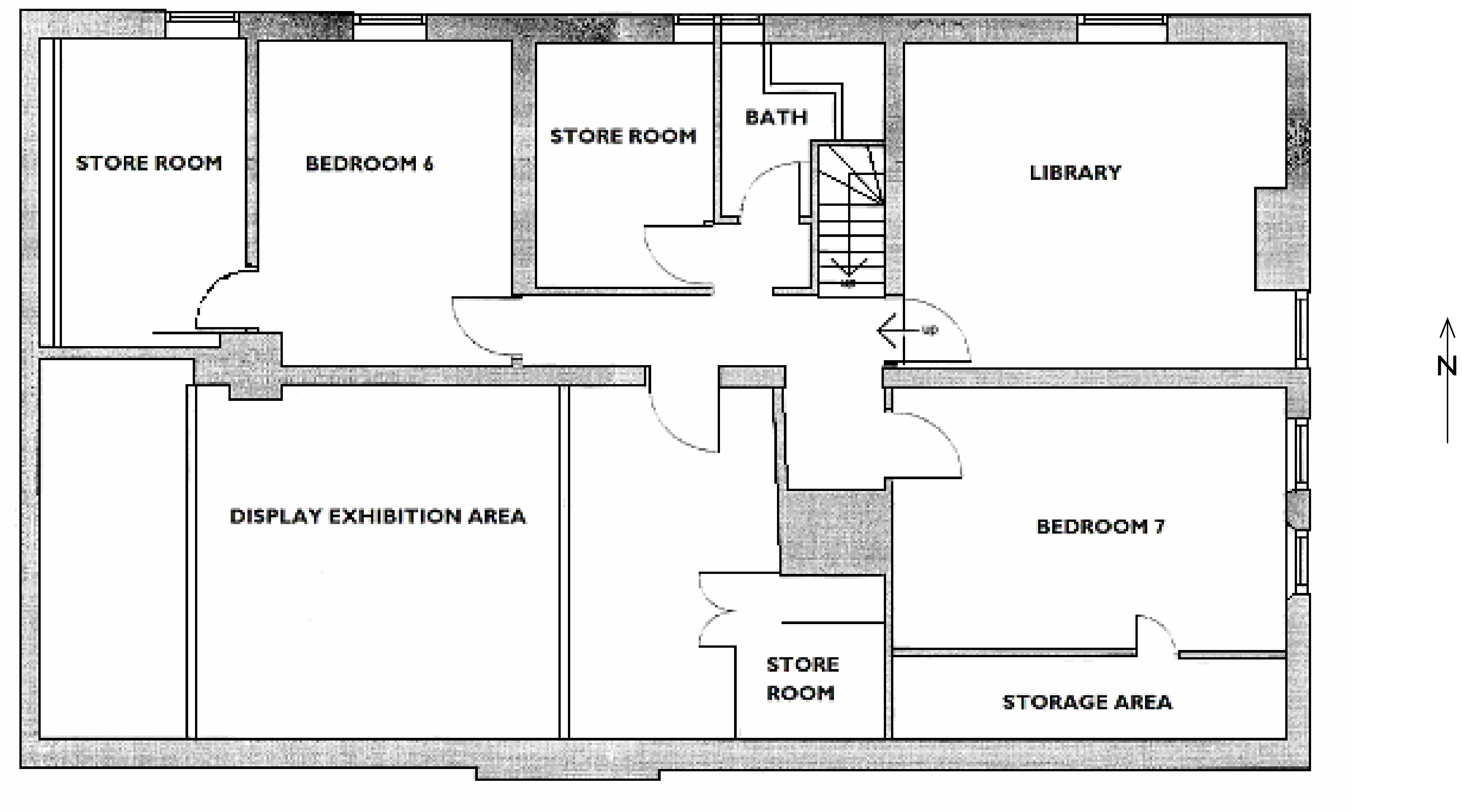


Figure 6: The Old Rectory; Second-floor plan (David Glew Architect & Surveyor)

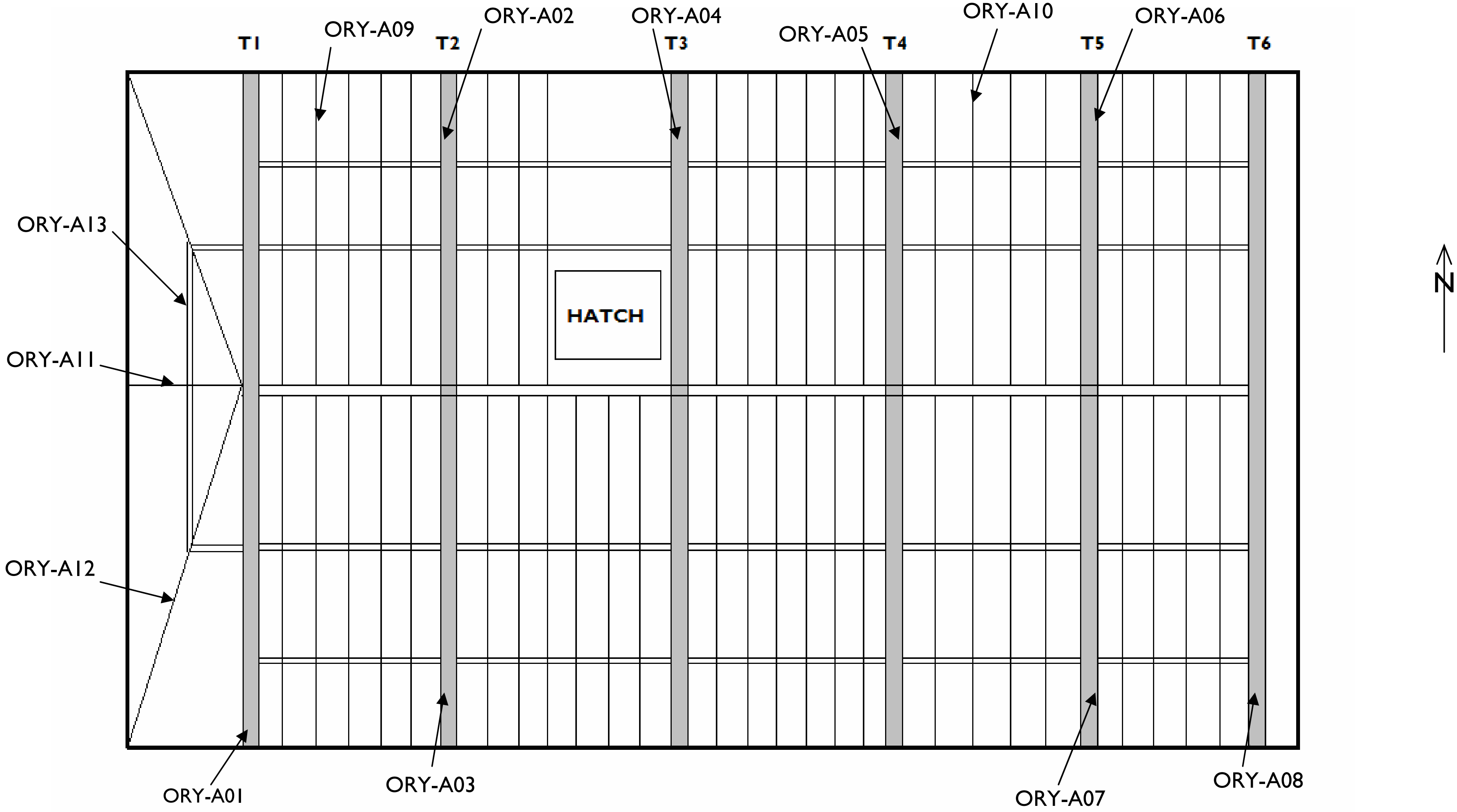
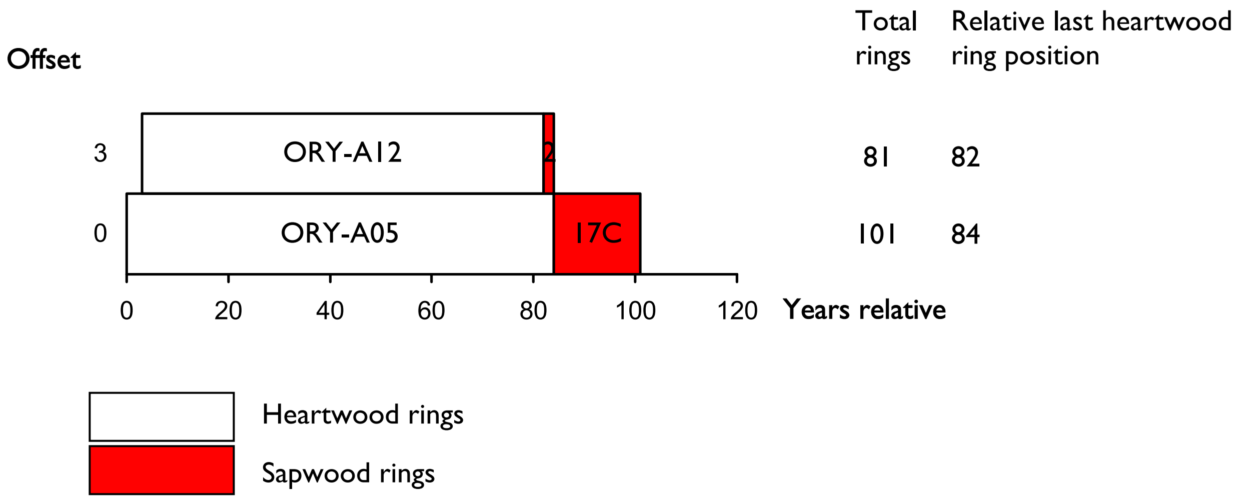
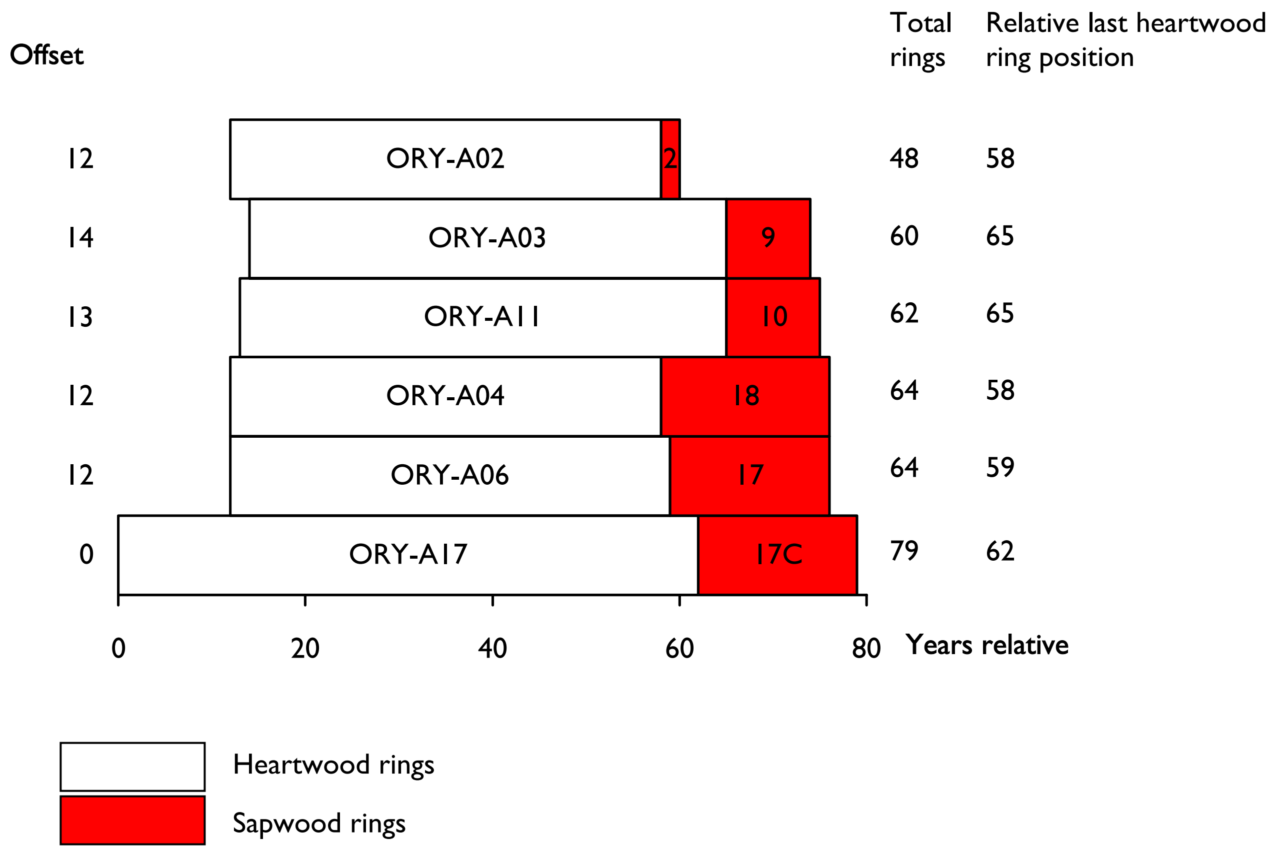


Figure 7: Sketch plan of roof, showing the location of samples ORY-A01–13



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

Figure 8: Bar diagram of samples in undated site sequence ORYASQ01



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

Figure 9: Bar diagram of samples in undated site sequence ORYASQ02

Data of measured samples – measurements in 0.01mm units

ORY-A02A 48
276 202 124 114 74 70 80 67 50 54 85 63 62 56 127 176 107 187 173 291
297 314 351 236 178 177 208 221 259 306 370 300 145 115 223 292 270 277 229 396
271 188 188 161 120 186 192 138
ORY-A02B 48
268 204 130 113 69 73 79 71 60 54 77 70 51 57 119 177 126 179 175 259
288 339 384 229 178 176 222 229 302 301 371 293 144 117 219 297 268 287 226 392
279 181 189 165 121 190 169 153
ORY-A03A 30
93 65 111 161 140 267 189 300 188 127 200 218 213 262 230 182 258 165 128 163
117 89 104 160 151 131 109 123 160 127
ORY-A03B 60
279 207 109 87 88 79 61 78 105 174 257 225 443 620 452 659 457 456 400 465
457 407 382 339 298 383 368 238 312 229 140 102 188 242 183 334 199 339 219 140
187 265 234 222 268 211 237 158 150 153 112 84 111 184 147 152 158 145 181 143
ORY-A04A 47
87 198 205 227 96 91 142 93 102 94 94 118 146 142 190 216 184 235 234 316
265 263 305 242 163 146 165 266 334 262 249 222 116 83 125 214 171 192 178 345
156 166 196 128 94 116 192
ORY-A04B 42
371 297 190 205 213 301 367 296 326 294 130 115 154 254 208 201 207 355 184 159
211 136 97 158 173 164 229 172 174 118 98 74 130 154 164 169 166 132 146 149
134 134
ORY-A05A 101
183 173 247 171 233 311 148 104 135 148 151 92 154 94 77 55 42 42 35 30
35 52 73 141 98 110 104 135 264 314 221 276 402 180 168 144 171 202 201 140
133 97 71 83 90 105 165 196 141 142 109 105 119 136 179 170 201 166 189 158
178 202 199 192 144 198 134 135 204 198 135 117 131 189 117 132 103 90 67 97
109 133 154 176 147 142 146 91 135 147 143 134 170 130 131 213 179 149 181 206
80
ORY-A05B 101
177 173 243 204 286 355 144 92 148 133 155 95 149 96 75 39 51 31 26 29
34 38 59 114 79 114 85 128 253 330 241 270 394 184 179 164 184 237 204 138
139 95 64 82 88 115 161 196 145 130 107 117 122 138 181 167 206 167 195 152
181 199 197 191 146 193 129 137 208 198 130 120 129 194 117 121 112 87 61 117
122 129 153 181 141 151 139 122 125 136 144 137 165 136 137 208 180 143 183 211
73
ORY-A06A 64
111 260 233 258 77 66 93 72 60 45 55 68 97 149 166 184 154 178 145 179
282 201 237 161 112 111 137 120 189 166 177 205 116 159 251 315 241 223 237 301
188 144 214 164 136 176 221 157 210 187 105 87 83 77 122 135 168 169 153 116
105 155 129 95
ORY-A06B 64
77 260 236 247 69 66 82 67 48 41 65 52 73 187 164 182 144 163 132 158
305 216 230 157 126 99 139 115 188 166 179 208 132 140 240 351 267 207 216 305
170 152 222 163 142 187 227 156 208 184 113 86 90 73 120 137 169 146 127 131
107 165 119 106
ORY-A08A 81
81 81 158 240 209 211 147 165 210 208 128 116 74 84 108 76 89 75 60 94
117 103 125 102 140 94 78 81 47 68 50 126 141 83 99 79 74 72 63 98
86 89 67 96 108 120 114 68 52 52 62 74 64 99 142 61 51 87 136 83
44 62 108 101 87 98 69 78 58 81 99 114 149 154 162 129 90 168 105 135
184

ORY-A08B 81
67 89 156 242 234 197 151 152 213 207 129 121 65 84 107 76 89 78 67 95
108 114 117 110 131 96 88 69 49 60 51 140 134 69 90 75 58 87 67 93
87 83 62 78 115 128 105 63 47 53 62 66 64 108 145 56 67 73 145 72
57 64 97 90 100 96 63 74 59 86 101 110 163 158 160 123 88 172 105 140
173
ORY-A09A 51
162 122 134 87 141 144 232 255 216 135 203 196 262 259 251 216 215 178 217 121
178 237 254 175 220 156 247 143 159 163 171 182 196 184 131 165 149 169 136 89
95 124 147 121 81 97 81 100 156 90 107
ORY-A09B 51
148 130 137 87 133 148 234 219 214 140 198 198 261 266 256 213 215 176 219 115
177 239 260 181 221 164 239 151 161 148 180 175 191 193 150 166 138 178 128 85
91 126 149 119 83 98 77 99 157 95 107
ORY-A11A 62
230 500 206 107 79 61 64 47 46 68 99 149 172 258 415 381 475 384 323 319
386 376 455 400 411 401 414 342 257 358 261 160 103 147 200 146 209 221 263 245
188 244 310 239 239 267 167 191 115 150 129 121 121 95 107 129 146 122 155 145
110 140
ORY-A11B 62
209 495 205 114 77 64 63 52 47 60 103 155 172 265 421 395 484 382 316 292
371 374 449 407 411 390 418 386 228 328 245 170 100 142 178 166 207 217 274 241
186 249 289 235 234 273 163 193 115 149 138 115 131 112 101 117 151 107 163 138
118 129
ORY-A12A 81
186 136 423 207 141 177 265 241 126 155 103 51 35 21 25 22 17 33 64 67
94 100 79 104 190 174 123 96 140 162 90 107 127 133 134 136 103 106 98 76
99 127 176 215 273 160 138 134 149 150 321 313 259 189 158 189 176 195 252 203
249 178 196 155 123 221 238 178 162 157 165 126 120 151 75 87 120 143 146 120
135
ORY-A12B 81
138 130 408 204 146 173 226 209 123 154 92 59 40 28 26 21 21 54 86 62
102 102 76 100 193 175 119 85 136 163 95 97 120 148 128 140 106 108 97 77
104 135 176 219 286 151 131 144 145 166 321 335 264 191 156 179 173 201 247 201
246 184 191 153 125 224 245 180 162 174 162 120 116 149 78 92 105 137 136 129
119
ORY-A17A 79
270 296 183 85 126 67 66 117 149 178 261 233 163 196 517 249 116 108 95 128
106 133 161 193 202 233 282 261 232 226 188 204 326 254 282 300 224 198 204 276
277 244 235 263 212 181 253 288 197 193 173 321 204 120 177 132 161 223 217 156
194 150 155 106 102 140 155 210 207 197 142 196 155 154 116 138 147 230 56
ORY-A17B 79
252 318 157 106 140 75 64 111 173 189 258 235 164 196 513 240 122 102 100 129
100 140 153 199 202 233 277 258 229 222 189 206 321 258 276 301 226 199 210 270
280 216 226 249 204 236 271 292 209 201 174 322 202 121 193 119 165 228 219 155
205 152 156 108 121 135 151 208 192 198 140 195 163 150 118 133 154 200 48
ORY-A20A 64
313 454 240 170 355 449 342 338 307 283 192 189 264 204 211 145 260 137 198 135
162 104 91 134 142 196 170 124 122 214 126 321 223 311 131 191 147 85 119 169
134 156 87 220 173 141 156 117 76 136 140 109 204 268 142 171 148 140 298 252
216 191 227 343
ORY-A20B 64
374 400 389 162 376 442 343 333 306 270 193 189 255 199 218 137 270 129 202 135
159 108 90 132 143 200 167 130 121 218 137 311 230 299 129 183 145 74 133 166
140 162 91 228 176 137 152 114 77 129 143 111 202 255 133 171 155 145 299 251
209 200 221 340

APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building*' (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure 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.

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

Figure 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.

Figure 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.

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a *site sequence* of the building being dated and is illustrated in Figure 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig 5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. (Oak boards quite often come from the Baltic and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56)).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. *Estimating the Date of Construction*. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55). Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

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

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

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

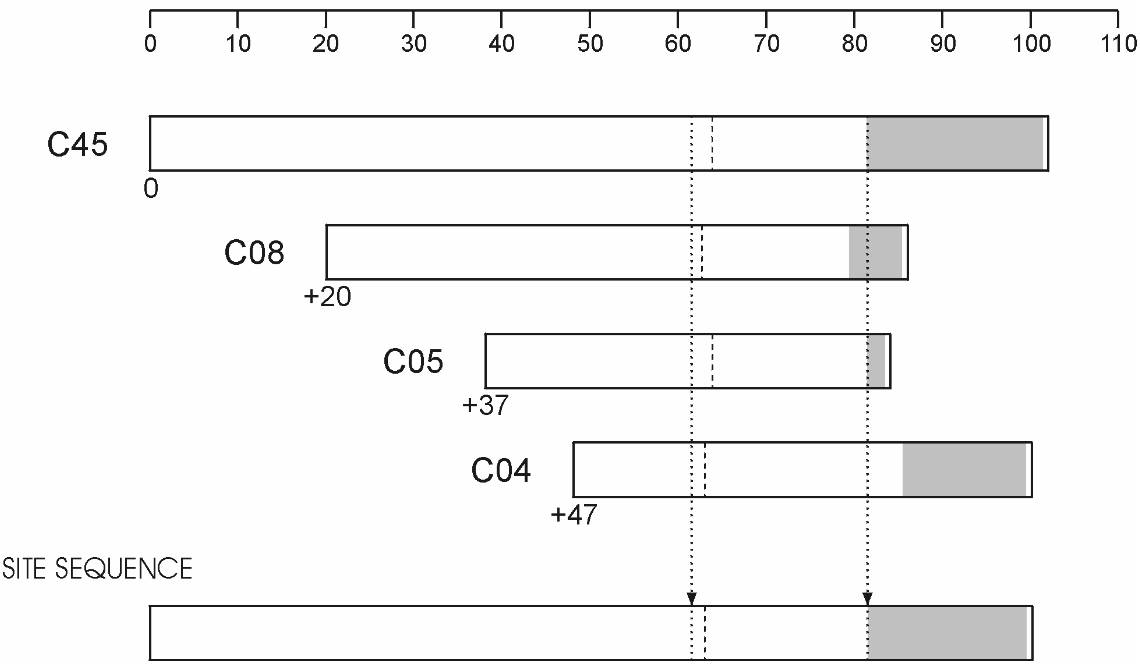


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

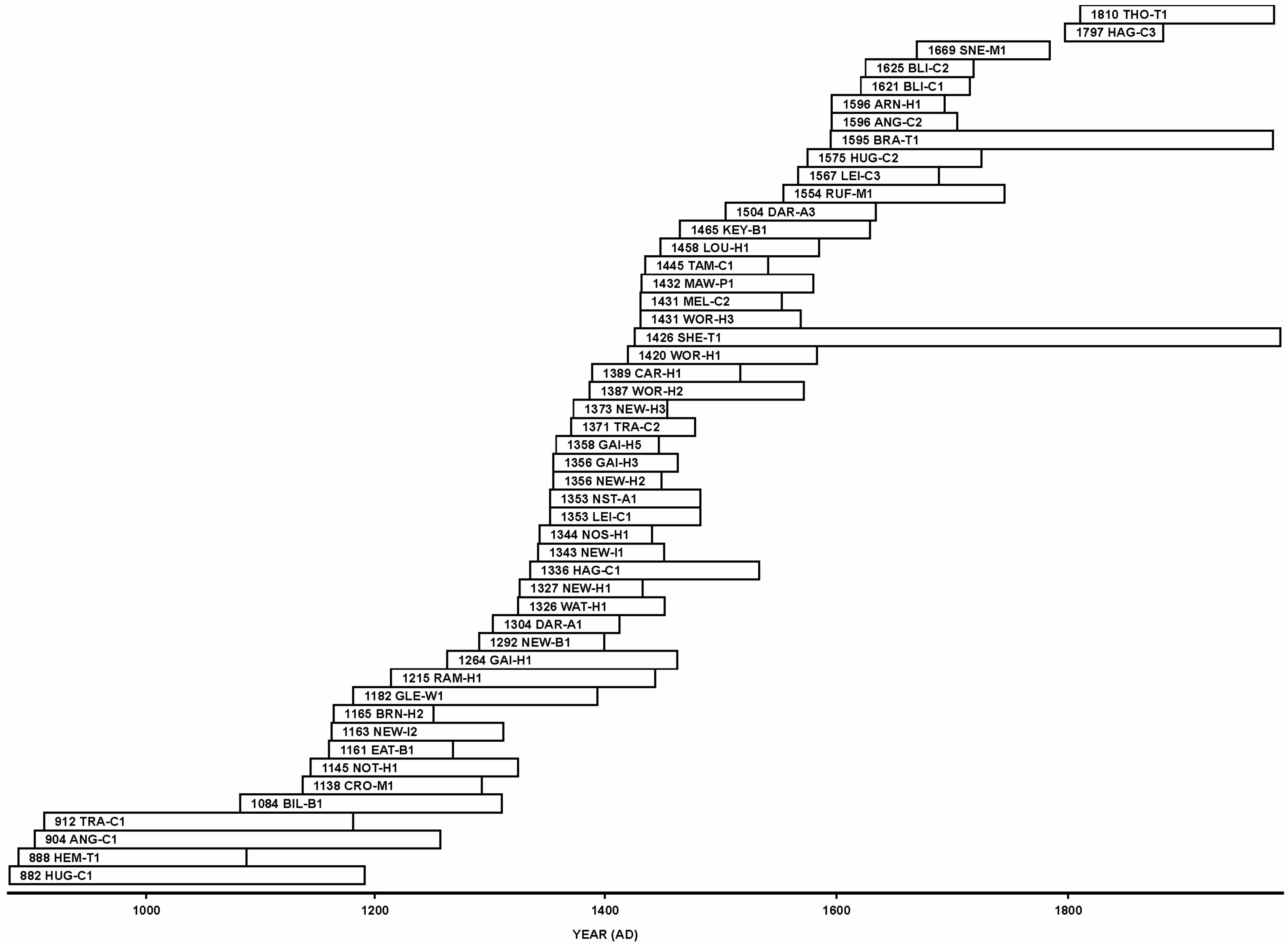
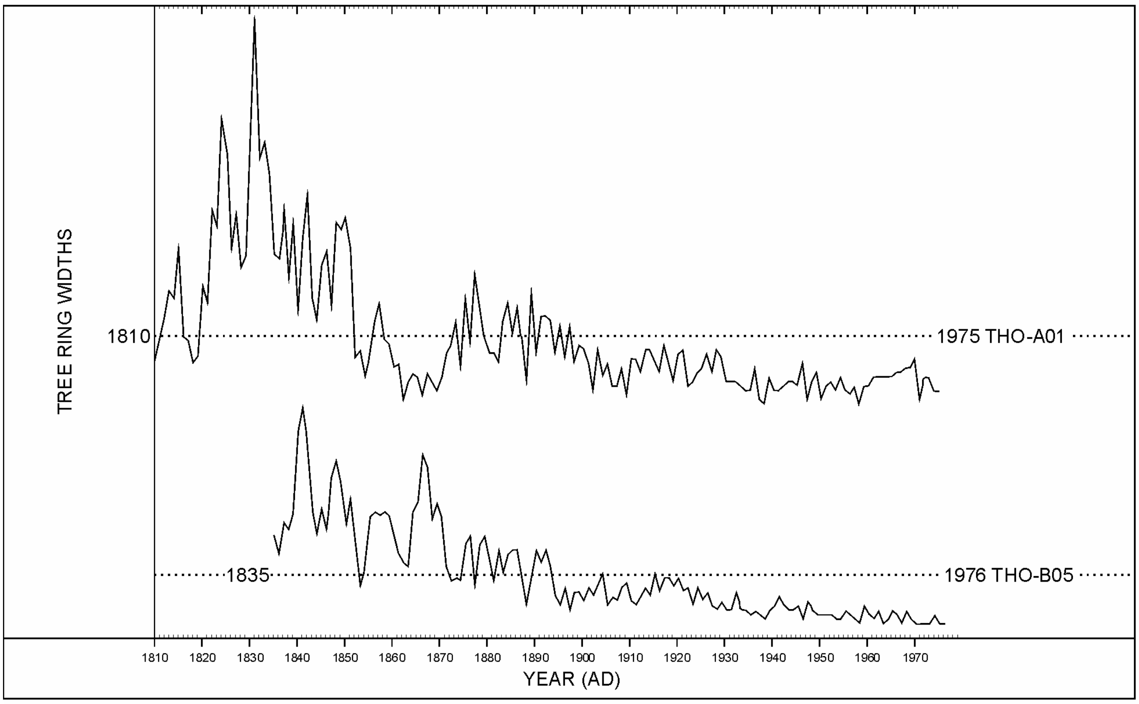


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

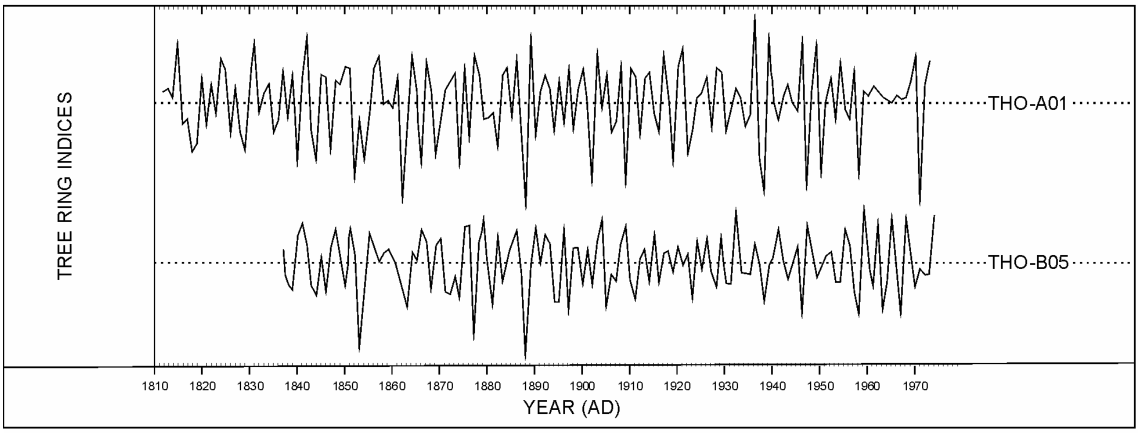


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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

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