RESEARCH DEPARTMENT REPORT SERIES no. 56-2010 ISSN 1749-8775

THE CHURCH OF ALL SAINTS, RAVENSTONE, NEAR OLNEY, BUCKINGHAMSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

ARCHAEOLOGICAL
SCIENCE

ENGLISH HERITAGE

Research Department Report Series 56-2010

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NGR: SP8505650894

ISSN 1749-8775

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SUMMARY

Analysis of 11 samples from the bellframe and eight from other beams within the west tower of the Church of All Saints, Ravenstone, indicates that timbers with different felling dates are present. The earliest material detected is a beam of a partial, lower, floor frame, which has an estimated felling date in the range AD 1149–74. It is likely that one upper beam, supporting the floor of the winding chamber, was felled in the period the AD 1176–1201, while another upper beam was felled in the period AD 1193–1228. Hence it is possible that these two timbers share a single felling date some time in the period AD 1193–1201. Given that the tower is not believed to have been built until the mid-thirteenth century, it is possible that these are reused timbers. The timbers of the bellframe have an estimated felling date in the period AD 1651–76.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank the Church Warden, Mrs Ann Adams, for her unfailing cooperation and considerable help with this programme of analysis. The Laboratory would also like to thank Richard Peats, English Heritage's Historic Buildings and Areas Advisor, for his help and advice prior to sampling, and Dr Peter Marshall, Scientific Dating Coordinator, also of English Heritage, for providing background material. Finally, we would like to thank Cathy Tyers of the Sheffield Dendrochronology Laboratory for her considerable help in dating some of the samples reported upon here.

ARCHIVE LOCATION

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DATE OF INVESTIGATION

2010

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INTRODUCTION

According to its listing description (http://lbonline.english-heritage.org.uk/), the parish church of All Saints, Ravenstone (SP8505650894, Figs 1 and 2), was founded in the eleventh century, the three-bay nave possibly having remains of this date. An arcade was added to the south side of the nave in the late-twelfth century, and a tower to its west end in the mid-thirteenth century. The south aisle was widened in the fourteenth century, a chancel of two bays, with a south chapel, being added at about this time as well. The nave was given a clerestory in the fifteenth century at which time the original roof may have been replaced by one with a lower pitch. Although the nave roof was again replaced, that to the south aisle retains its fifteenth-century framing of moulded principal rafters supported on south side by curved braces springing from embattled and moulded wooden corbels. Intermediate principals and purlins are chamfered and stopped. The south aisle chapel retains its seventeenth-century roof of moulded main beams.

The tower (Fig 3), at the west end of the church, and of particular concern to this report, presents a three-stage structure, with double lancet windows to the upper stage, below a shallow-pitched pyramidal roof. The tower also has a west-facing single-lancet window to its lowest stage.

Within, to its lower levels, the tower contains a first-floor frame comprising two substantial, parallel, north–south beams, upon which are laid a few broad but thin, and otherwise unsupported, planks to form a partial floor (Fig 4). The western of these two north–south beams is supported at either end by a stone corbel projecting from the wall, but both ends of the eastern beam are set fully within the tower walls. These timbers are believed to be potentially of some antiquity but possibly not original, as they cut across the middle of the single-lancet west window of the tower. This partial floor is reached by a dog-leg staircase.

The internal opening of the window to the west wall of the tower is splayed and retains two sets of timbers. Each set comprise six beams placed one behind the other in the thickness of the wall, the top set forming the lintels to the window opening, with a further six timbers set in a similar fashion, to the middle of the opening (Fig 5). Two of the upper lintels appear to have redundant mortices in them and the timbers may thus be reused in their present positions.

A wooden ladder rises steeply from the partial floor frame to the clock or winding chamber above. The floor of this chamber, formed of modern, probably late-twentieth century softwood joists and tongue-and-groove boards, is again supported by two full-length north–south beams (an east beam and a west beam), their ends set in the walls, and by the stub remains of a third, 'middle', beam, extant in the south wall only (Fig 6). A fourth, larger, north–south beam is also found here, set close to the east wall but at a slightly lower level. It appears to act in isolation and offers no support to the floor frame of the winding chamber.

The ceiling of the winding chamber comprises four north–south beams, the ends of which are set in the tower walls. These beams also form the sub-structure of the bellframe above. The bellframe (Fig 7) has three parallel pits, aligned north–south, with a fourth east–west pit at its north end (Fig 8). The trusses of the frame may be described as inverted double jack-braced type, having sills, long heads, outward braces from sill to head, and jack braces from sill to braces and from braces to head, a form categorised as type 6E (long-headed frames without centre posts) in Pickford's classification (Pickford 1993). All the timbers of the bellframe appear integral to each other, being jointed and pegged, and show no evidence for the reuse of older timbers or the insertion of later repairs.

SAMPLING

Sampling and analysis by tree-ring dating of the timbers within the tower was requested by Richard Peats, English Heritage's Historic Buildings and Areas Advisor, to inform statutory advice relating to a programme of works being undertaken.

Thus, from the oak timbers available, a total of 20 samples was obtained by coring, each sample being given the code RVS-A (for Ravenstone, site 'A') and numbered 01–20. Twelve timbers, RVS-A01–A12, were obtained from the bellframe, with a further four samples, RVS-A13–A16, being obtained from suitable main floor beams. A final four samples, RVS-A17–A20, were obtained from the lintels (the upper beams) of the west window opening. While other timbers were in theory possibly available for sampling, all were either unsuitable, in having fewer than the 54 rings necessary for reliable tree-ring analysis (eg the ceiling beams of the winding chamber or the middle beams of the west window opening), or were inaccessible (eg the inner lintels and beams of the west window).

Where possible, the positions of these samples are marked on drawings made or photographs taken at the time of sampling. These are reproduced here as Figure 3 and Figures 9 and 10. Details of the samples are given in Table 1. In this table all the trusses and the individual timbers have been identified and numbered from either north to south or east to west as appropriate (see Fig 8).

ANALYSIS

Each of the 20 samples obtained was prepared by sanding and polishing. It was seen at this time that one sample, RVS-A01, had fewer than 54 rings, the minimum required for reliable dating, and it was rejected from this programme of analysis. The annual rings widths of the remaining 19 samples were measured, however, the data of these measurements being given at the end of this report. The data of these 19 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). At a minimum value of t=5.8, three groups, comprising 14 measured samples in total, could be formed, the samples cross-matching with each other at the offset position shown in the bar diagrams, Figures 11a–c. The samples of each group were combined at their respective offset positions to form site chronologies RVSASQ01–03, of 10, 2, and 2 samples, with overall lengths of 121, 90, and 55 rings, respectively.

Each of the three site chronologies was then compared with an extensive series of reference chronologies for oak. This process indicated a satisfactory cross-match and date for site chronology RVSASQ01, with a first-ring date of AD 1523 and a last measured ring date of AD 1643, and also for site chronology RVSASQ02, with a first-ring date of AD 1089 and a last measured ring date of AD 1178. The evidence for this dating is given in the *t*-values of Tables 2 and 3. There was no satisfactory cross-matching, and hence no date, indicated for site chronology RVSASQ03.

The remaining five measured but ungrouped samples were also compared individually with a full series of reference chronologies, this indicating a cross-match and date for sample RVS-A15 only, giving it a first-ring date of AD 1003 and a last-ring date of AD 1136. The evidence for this date is given in the *t*-values of Table 4.

This analysis may be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
RVSASQ01	10	121	AD 1523–1643
RVSASQ02	2	90	AD 1089–1178
RVSASQ03	2	55	undated
RVS-A15	1	134	AD 1003–1136
ungrouped	4	---	undated
unmeasured	1	---	---

INTERPRETATION

The bellframe – site chronology RVSASQ01

None of the 10 dated samples in site chronology RVSASQ01 retains complete sapwood, and it is thus not possible to reliably indicate a precise felling date for any of the timbers represented. Eight of the samples, however, do retain some sapwood, or at least the heartwood/sapwood boundary. It may be seen from Table 1 and the bar diagram, Figure 11a, that this boundary has a remarkably narrow five-year variation, from relative position 112, AD 1634, on samples RVS-A09 and A12, to relative position 116, AD 1638, on samples RVS-A03 and A05. Such consistency in the position of the heartwood/sapwood boundary is indicative of timbers representing a single programme of felling, with all the trees being cut at the same, or very similar, time.

The average date of the heartwood/sapwood boundary, on the eight dated samples where it exists, is AD 1636. Using a 95% confidence interval of 15–40 years for the sapwood rings the trees might have had would give the timbers represented an estimated felling date in the range AD 1651–76.

The upper floor beams – site chronology RVSASQ02

Site chronology RVSASQ02 comprises samples RVS-A13 and A14 from the upper east and upper middle beams, which support the floor of the winding chamber. Neither of these two samples retains complete sapwood, and it is again not possible to reliably indicate a precise felling date for either of the timbers. Both samples, however, retain the heartwood/sapwood boundary. It may be seen from Table 1 and the bar diagram, Figure 11b, that this boundary has a wider range than those of the bellframe, varying from relative position 73, AD 1161, on sample RVS-A13, to relative position 88, AD 1178, on sample RVS-A14.

Taking the samples and the timbers they represent individually, and applying the usual 95% confidence interval of 15–40 sapwood rings to each of them, would give the tree represented by RVS-A13 an estimated felling date in the range AD 1176 –1201, and that represented by RVS-A14 an estimated felling date in the range AD 1193–1228. Thus, while it may be seen that the two timbers do share a possible single felling date some time in the period AD 1193–1201, it is equally possible that they were felled at slightly different times.

The window lintels – site chronology RVSASQ03

Site chronology RVSASQ03 comprises samples RVS-A17 and A20 from the lintels of the tower's west window. This site chronology is undated and it is thus not possible to determine a likely felling date range of the trees represented. However, although undated, given that the relative position of the heartwood/sapwood boundary varies by only one ring (Fig 11c), it is probable that the timbers represented were felled at the same time as each other. Indeed, given that the samples cross-match with each other with a very high value of t=18.8, it is almost certain that the timbers are derived from the same tree, a probability made more likely by the fact that both timbers are unlikely to be more than 1 metre long, and are quartered, and would thus be easy to produce from a single baulk of wood.

The lower floor beams – sample RVS-A15

Sample RVS-A15 is taken from the lower east beam of the partial floor frame. This sample has a heartwood/sapwood boundary date of AD 1134. Using the same sapwood estimate as above, 15–40 rings, would give the timber represented an estimated felling date in the range AD 1149–74.

CONCLUSION

Analysis of 19 measured samples from a series of different timbers in the west tower of the Church of All Saints has resulted in the production of three site chronologies, two of which can be dated, accounting for 14 samples, and dated a further single sample individually. Interpretation of the sapwood on the dated samples shows that timbers felled at different times are to be found here.

The earliest material detected in this programme of analysis is represented by the east beam of the partial, lower, floor frame, which has an estimated felling date in the range AD 1149–74. It is likely that one of the upper beams supporting the floor of the winding chamber was felled in the period the AD 1176–1201, while the other was felled in the period AD 1193–1228. Hence it is possible that these two timbers share a single felling date some time in the period AD 1193–1201.

Given the early likely felling dates for these floor timbers, and that there is no clear evidence of disturbance to the stonework where their ends fit in to the tower walls (as might be expected were they later insertions), it would appear possible that these timbers are in fact integral to the construction of the tower. The lower floor beams may cut across the west window at the level of its middle beams by design, the window thus lighting both the ground-floor room and a possible first-floor room. However, given that the timbers are each potentially felled at different times, and that the tower is not believed to have been built till the mid-thirteenth century, it is quite likely that they are reused in the construction of the tower.

The latest phase of felling detected in this analysis is represented by the bellframe, the timbers of which have an estimated felling date, and hence likely construction date, in the range AD 1651–76. Several of the samples from the bellframe cross-match each other particularly well, with a number of t-values exceeding 10.0, and some in excess of t=17.0 and t=18.0. Such high values are indicative of timbers potentially being derived from a single tree. Given that the members of the bellframe are short lengths of timber, nothing in excess of 1.25m, and quite thin, approximately 0.1m, it would be perfectly possible for a good carpenter to achieve this.

The source woodland for the timbers dated here cannot be identified precisely by dendrochronology (eg Bridge 2000), but it seems probable that they are relatively local, and certainly of the region. As may be seen from Tables 2–4, site sequence RVSASQ01 appears to match more widely than either RVSASQ02 or RVS-A15, but this phenomenon is quite common with seventeenth century material. Site sequence RVSASQ02 and RVS-A15 both match particularly well with a series of reference chronologies from London but it should be noted that the area exploited for timber for use in London was extensive.

Four measured samples, RVS-A02, A16, A18, and A19, remain ungrouped and undated. None of these samples show any specific anatomical problems, such as compressed or distorted rings, which might make cross-matching and dating difficult. Two of the samples, RVS-A18 and A19, do, however, have low numbers of rings, and this may cause difficulties, although, as seen here with samples RVS-A17 and A20, such short series can cross-match.

Sample RVS-A02 is from the frame head of truss 1 of the bellframe. It may be of interest to note that this timber, along with the timber represented by unmeasured sample RVS-A01 (the frame head of truss 4), is longer than all the other timbers of the bellframe. It is perhaps possible that these two timbers are from different sources making them, in effect, 'singletons', such samples being more difficult to date than those which are part of a well-replicated site chronology.

The final undated sample, RVS-A16, is from the west beam of the lower, partial, floor frame. Given that this timber is supported on corbels at either end, it is more likely to be a later insertion, perhaps a replacement of an original timber, of a different date, and thus, again, a singleton.

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TABLES

Table 1: Details of tree-ring samples from the Church of All Saints, Ravenstone, Buckinghamshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Bellframe						
RVS-A01	Frame head, truss 4	nm	---	------	------	------
RVS-A02	Frame head, truss 1	71	h/s	------	------	------
RVS-A03	North brace, truss 6	93	h/s	1546	1638	1638
RVS-A04	Frame head, truss 6	81	no h/s	1523	------	1603
RVS-A05	South brace, truss 6	103	h/s	1536	1638	1638
RVS-A06	Frame head, truss 5	54	no h/s	1536	------	1589
RVS-A07	North brace, truss 7	99	h/s	1538	1636	1636
RVS-A08	South brace, truss 7	79	6	1565	1637	1643
RVS-A09	Frame head, truss 7	78	4	1561	1634	1638
RVS-A10	South brace, truss 4	101	h/s	1535	1635	1635
RVS-A11	Sill beam, truss 5	107	h/s	1529	1635	1635
RVS-A12	North brace, truss 4	86	h/s	1549	1634	1634
Floors						
RVS-A13	Upper east beam	73	h/s	1089	1161	1161
RVS-A14	Upper middle beam	75	2	1104	1176	1178
RVS-A15	Lower east beam	134	2	1003	1134	1136
RVS-A16	Lower west beam	82	2	------	------	------
Lintels						
RVS-A17	Upper lintel 1	55	h/s	------	------	------
RVS-A18	Upper lintel 2	56	h/s	------	------	------
RVS-A19	Upper lintel 3	54	h/s	------	------	------
RVS-A20	Upper lintel 4	54	h/s	------	------	------

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

Table 2: Results of the cross-matching of site sequence RVSASQ01 and relevant reference chronologies when first ring date is AD 1523 and last ring date is AD 1643

Reference chronology	Span of chronology	*t*-value	
Upwich, Droitwich, Worcestershire	AD 1454–1651	7.6	Groves and Hillam 1997
Chapter House roof, Worcester Cathedral	AD 1558–1660	6.4	Arnold *et al* 2004
East Midlands Master Chronology	AD 882–1981	5.9	Laxton and Litton 1988
Flore's House, Oakham, Rutland	AD 1408 –1591	5.9	Hurford *et al* 2008
De Grey Mausoleum, Flitton, Beds	AD 1510–1726	5.8	Arnold *et al* 2003
Cressing Temple farmhouse, Essex	AD 1514–1608	5.8	Tyers 1995
Swarkstone Hall, Swarkstone, Derbys	AD 1484–1675	5.7	Arnold and Howard forthcoming
Church of St Nicholas, Bringhurst, Leics	AD 1502–1687	5.6	Arnold *et al* 2005

Table 3: Results of the cross-matching of site sequence RVSASQ02 and relevant reference chronologies when first ring date is AD 1089 and last ring date is AD 1178

Reference chronology	Span of chronology	*t*-value	
Essex county	AD 663–1899	6.4	Tyers pers comm 2004
Winchester Round Table, Hampshire	AD 1041–1211	6.2	Barefoot and Haddon-Reece pers comm
Fleet Valley, City of London	AD 745–1316	5.8	Tyers and Hibberd 1993
Billingsgate, City of London	AD 611–1243	5.5	Tyers pers comm 1997
Fennings Wharf, Southwark, London	AD 802–1435	5.4	Tyers 2001
Swan Lane, City of London	AD 938–1192	5.2	Groves and Hillam 1987
Adisham reredos, Kent	AD 890–1153	5.2	Tyers 1999

Table 4: Results of the cross-matching of site sequence RVS-A15 and relevant reference chronologies when first ring date is AD 1003 and last ring date is AD 1136

Reference chronology	Span of chronology	*t*-value	
Essex county	AD 663–1899	6.3	Tyers pers comm 2004
Adisham reredos, Kent	AD 890–1153	6.2	Tyers 1999
Bull Wharf, City of London	AD 620–1181	6.0	Tyers and Boswijk 1997
Fleet Valley, City of London	AD 745–1316	6.0	Tyers and Hibberd 1993
Bank Street, Tonbridge, Kent	AD 998–1116	6.0	Tyers 2005
Bishops Palace, Hereford	AD 915–1112	5.9	Haddon-Reece *et al* 1989
Vintry, City of London	AD 743–1241	5.9	Hibberd 1992
Hampshire county	AD 443–1972	5.8	Miles 2003

FIGURES

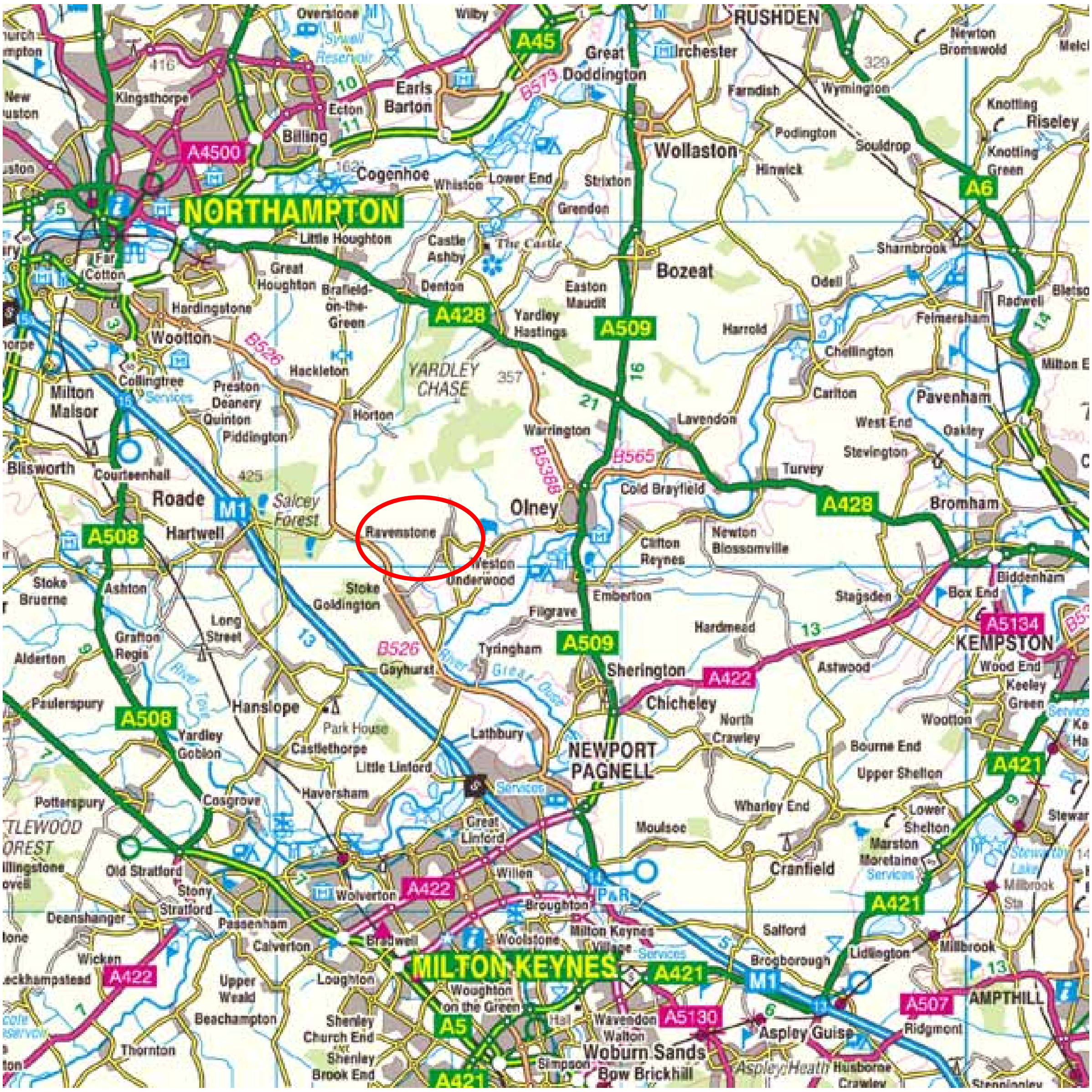


Figure 1: location of Ravenstone (circled)

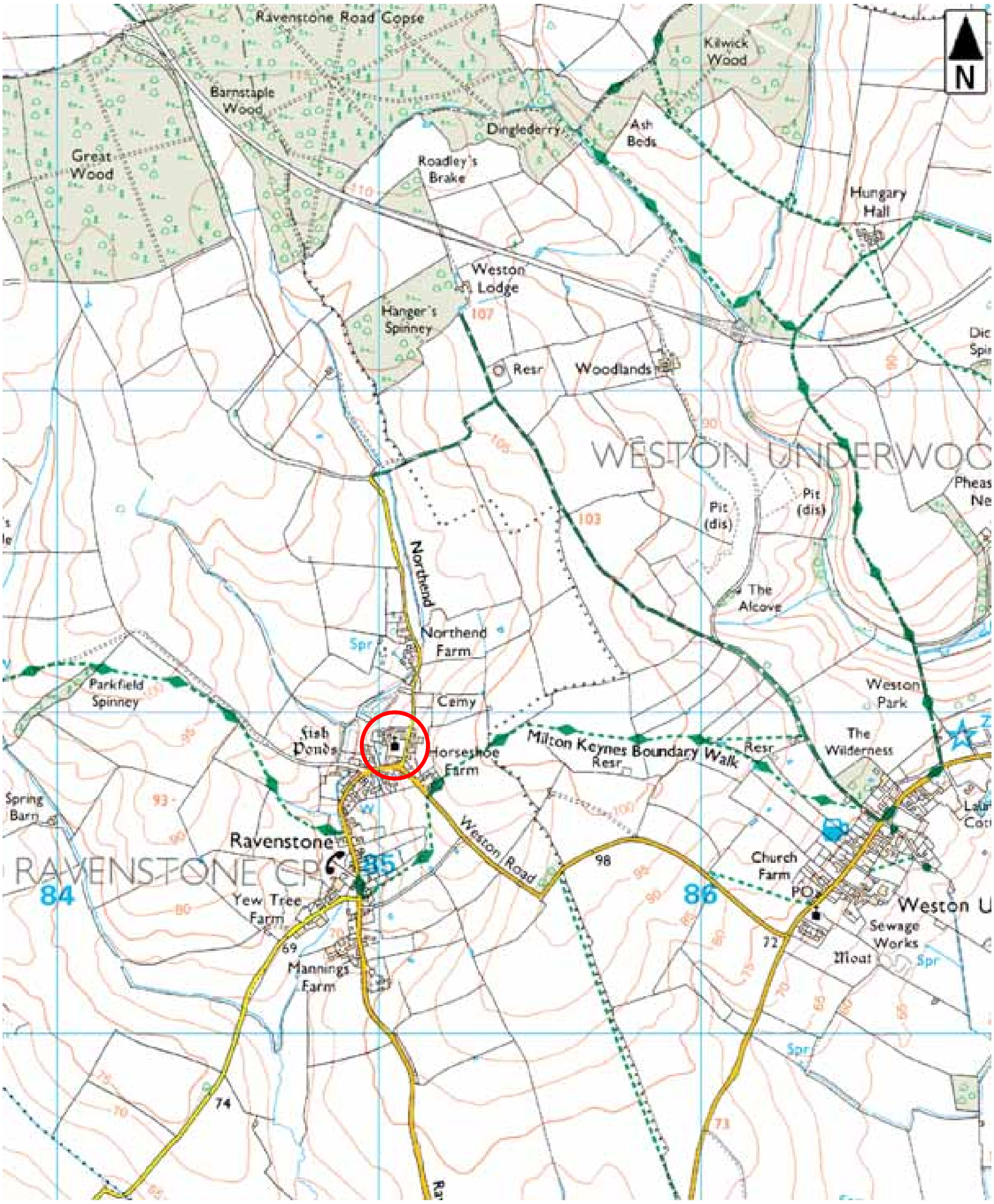


Figure 2: location of All Saints' Church, Ravenstone (circled)

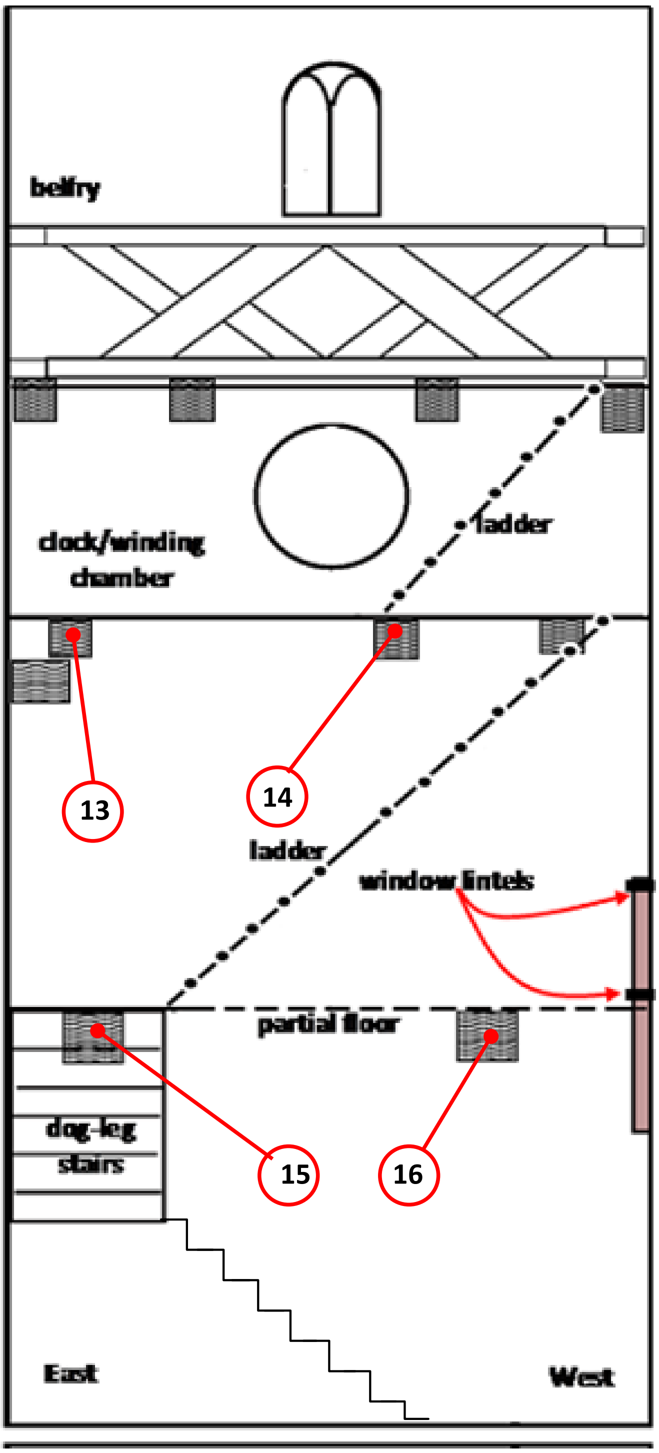


Figure 3: Section through Ravenstone church tower showing different features and some sampled timbers

Figure 4 (top): View, looking up, of the partial lower floor

Figure 5 (bottom): View of the double set of beams to the tower's west window

Figure 6 (top): View of the beams to the floor of the winding chamber

Figure 7 (bottom): The bellframe viewed from the south-east

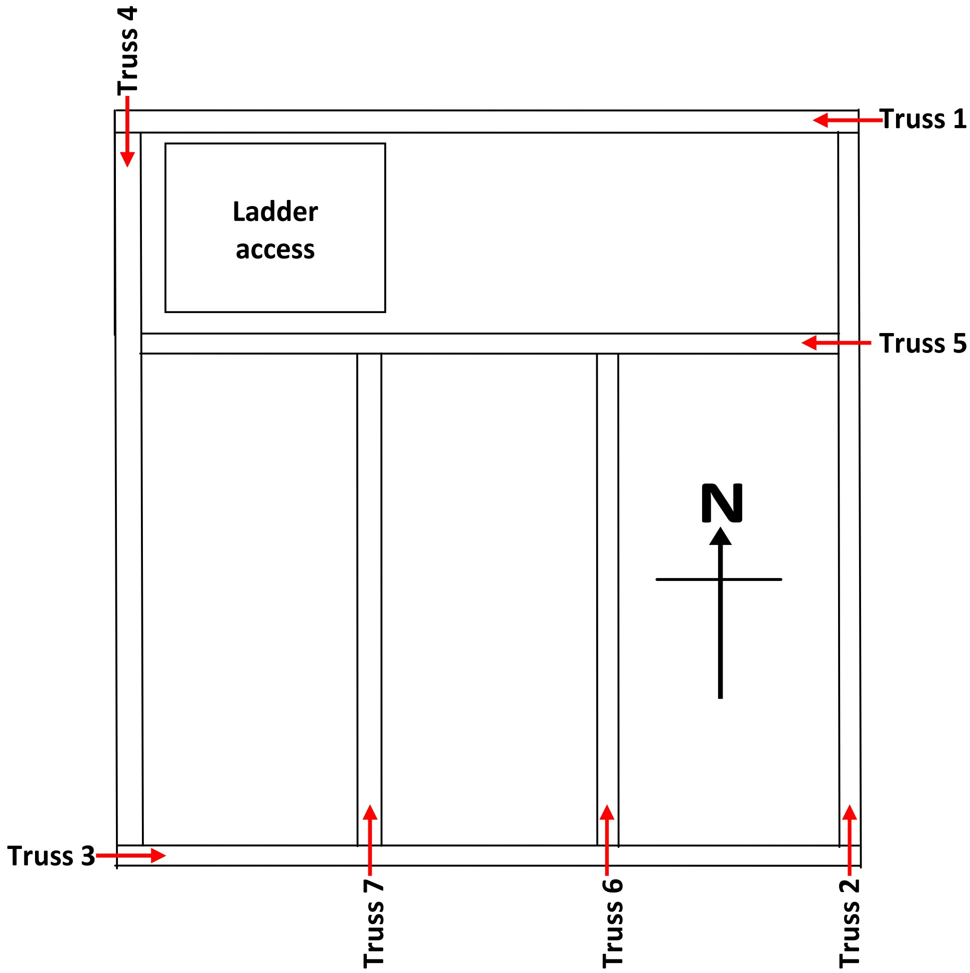


Figure 8: Simple plan of the bellframe

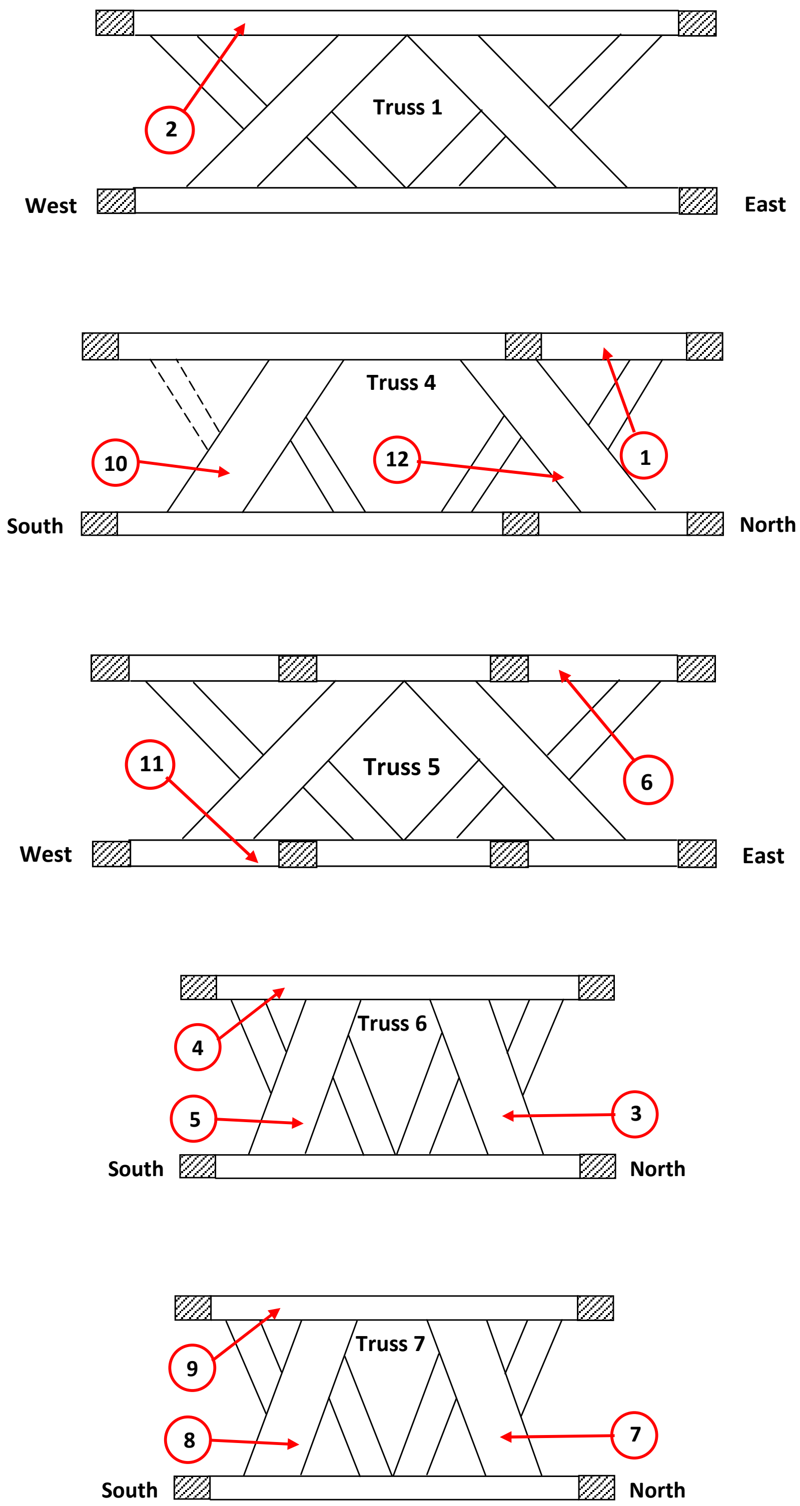
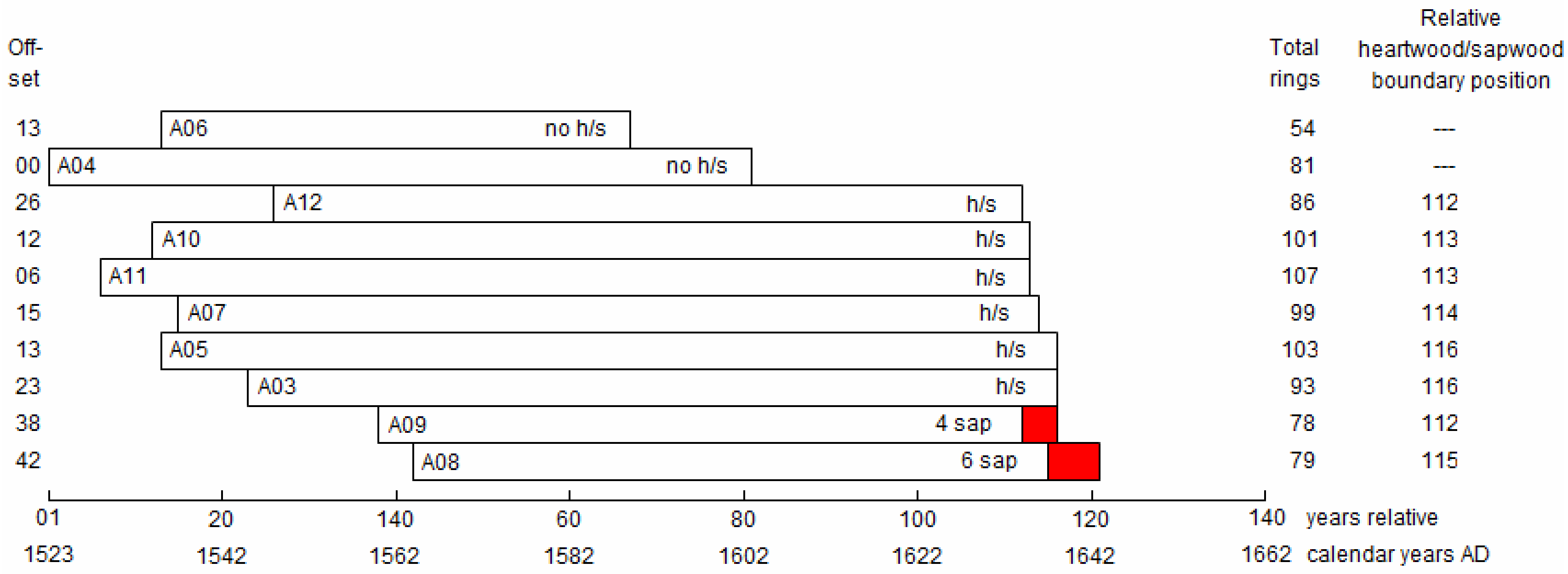


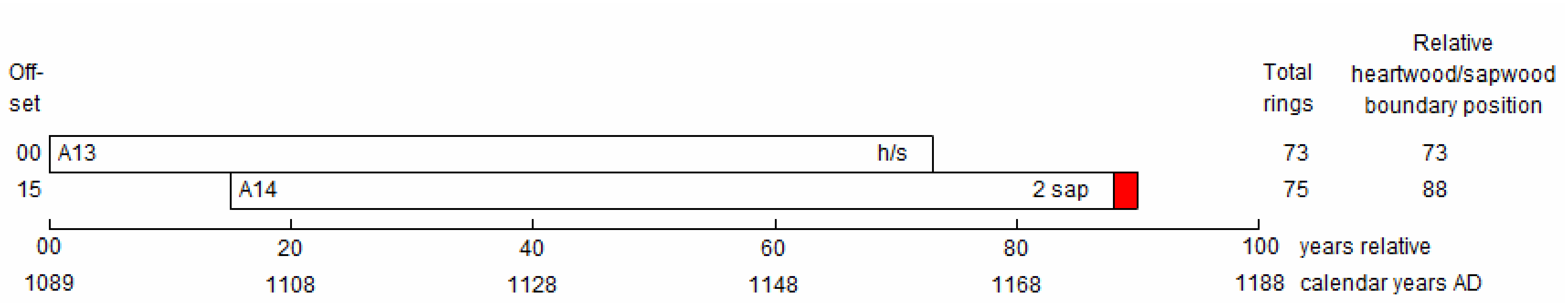
Figure 9: The bellframe trusses to show sampled timbers

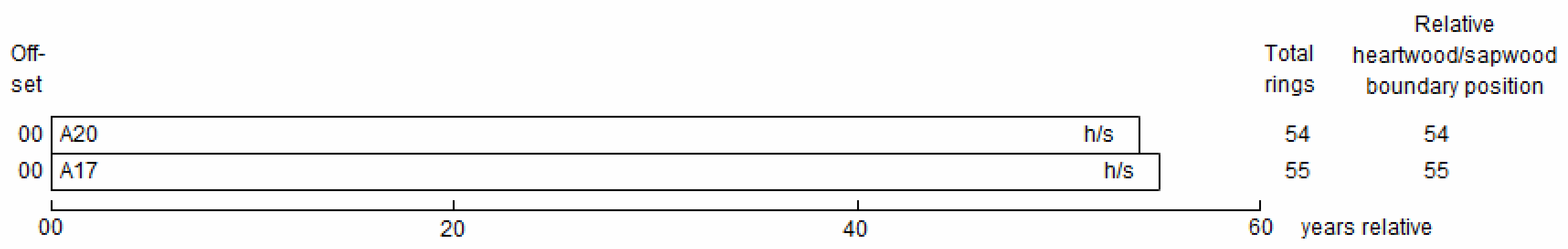
Figure 10: Photograph of the west window lintels to show sampled timbers



White bars [ ] *= heartwood rings, shaded bars* [ ] *= sapwood rings*
h/s = the last ring of the sample is at the heartwood/sapwood boundary (only the sapwood rings are missing)

Figure 11a: Bar diagram of the samples in site chronology RVSASQ01





White bars [ ] = heartwood rings, shaded bars [ ] = sapwood rings
h/s = the last ring of the sample is at the heartwood/sapwood boundary (only the sapwood rings are missing)

Figure 11b (top): Bar diagram of the samples in site chronology RVSASQ02

Figure 11c (bottom): Bar diagram of the samples in site chronology RVSASQ03

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

RVS-A02A 71
179 272 226 203 117 103 119 171 275 228 218 119 145 113 173 212 241 123 82 167
129 129 171 127 145 121 110 185 202 136 145 128 140 121 169 197 144 148 127 107
82 95 126 199 191 219 193 191 177 200 272 226 281 220 156 150 288 278 175 174
188 217 220 245 242 313 297 251 150 134 166
RVS-A02B 71
230 263 218 207 161 139 112 146 265 240 222 121 137 123 172 208 246 103 75 165
121 141 163 131 146 125 104 188 188 153 148 131 137 116 174 181 159 159 108 124
93 91 130 195 168 215 191 171 178 216 284 216 298 204 163 137 251 291 175 149
213 230 212 229 262 324 285 250 158 113 163
RVS-A03A 93
357 563 588 575 280 233 142 225 205 277 141 96 43 45 36 51 65 44 52 55
51 54 68 61 64 73 78 69 70 80 79 90 88 134 215 146 246 208 340 387
350 445 314 211 140 212 96 48 45 62 72 82 84 108 115 115 116 189 141 147
210 172 193 157 229 238 175 313 207 350 342 276 288 250 274 280 231 264 250 288
282 375 394 530 211 319 452 260 219 358 323 267 364
RVS-A03B 93
378 557 573 580 266 234 156 212 195 279 119 105 49 47 41 42 63 49 55 57
50 51 65 65 59 78 72 75 61 82 79 91 95 127 220 141 246 205 328 397
346 457 299 215 132 220 88 47 42 57 96 70 91 101 111 117 122 182 146 143
229 151 203 170 222 242 191 304 218 350 372 268 290 261 282 275 250 278 262 280
305 359 408 540 239 334 425 291 215 393 301 251 37
RVS-A04A 81
415 436 201 318 351 280 224 175 272 219 201 164 277 206 201 195 230 191 173 120
193 163 181 178 187 268 361 188 215 150 209 167 234 137 108 34 40 36 39 47
38 52 46 49 64 93 96 80 90 87 93 85 109 134 179 125 170 293 112 189
139 145 238 216 267 218 199 127 185 89 78 62 69 69 56 70 88 102 101 99
169
RVS-A04B 81
376 440 182 292 372 286 223 179 268 222 218 172 270 194 202 213 177 209 202 164
184 164 190 173 203 254 288 192 199 169 217 168 231 133 97 44 31 36 39 48
38 52 45 46 71 84 95 67 82 79 96 79 116 131 173 136 133 297 120 182
140 137 244 189 258 217 198 123 195 145 68 68 63 73 62 74 79 98 93 108
133
RVS-A05A 103
306 294 242 240 245 243 164 273 255 365 192 278 316 292 256 245 163 252 243 298
164 103 37 49 45 41 53 48 74 66 57 70 96 96 103 138 105 123 116 146
166 195 156 170 269 134 199 202 249 330 288 421 335 300 154 248 104 49 53 68
99 65 88 118 134 117 131 206 164 171 196 161 195 141 190 220 190 323 280 276
318 288 359 321 297 319 305 389 246 285 202 217 306 500 379 610 928 517 305 537
502 358 456
RVS-A05B 103
294 288 264 221 227 247 174 273 261 366 222 272 276 350 273 227 166 246 263 321
177 107 38 44 51 37 51 48 66 73 51 71 94 100 88 144 100 128 121 143
189 183 172 162 264 134 202 210 245 327 290 434 340 222 169 243 123 39 54 65
84 79 79 130 125 145 118 205 170 179 225 164 178 143 193 216 192 341 247 257
325 308 354 320 311 290 313 393 242 295 179 232 298 487 323 657 907 476 305 567
476 357 460
RVS-A06A 54
139 121 119 200 210 201 139 331 375 431 306 413 456 496 446 413 257 341 347 383

261 229 61 30 43 49 58 60 36 52 49 66 81 92 87 142 110 88 85 154
166 177 177 166 286 208 213 216 259 531 415 440 378 403
RVS-A06B 54
142 120 121 189 220 211 140 326 369 428 319 383 488 478 447 407 242 362 341 383
274 233 66 44 52 37 60 63 46 66 49 57 85 82 99 144 104 87 86 159
168 185 155 170 296 200 230 230 261 513 434 427 392 444
RVS-A07A 99
209 202 203 222 145 143 157 168 146 178 222 196 183 139 131 147 167 211 115 96
28 48 57 45 69 60 73 79 63 78 92 94 104 127 104 120 102 132 137 178
137 176 226 139 186 172 196 255 265 337 187 217 119 189 77 43 49 67 86 85
96 111 134 144 133 184 164 137 158 126 180 144 218 219 178 276 170 188 240 217
245 184 196 208 172 185 196 247 213 202 187 302 204 354 465 287 174 285 279
RVS-A07B 99
213 200 200 216 77 159 141 161 141 171 178 216 172 154 111 175 167 192 98 85
50 50 51 50 67 57 76 81 62 69 93 101 99 118 100 120 93 131 151 164
169 170 232 138 182 188 201 254 222 341 177 203 128 173 87 56 39 75 77 93
91 97 150 141 138 227 162 124 169 126 170 151 218 215 188 232 180 192 227 200
240 167 215 198 177 199 188 240 205 221 219 282 178 353 490 275 189 271 285
RVS-A08A 79
67 86 49 77 106 92 115 88 105 102 113 143 144 115 125 198 112 141 135 218
323 299 418 275 289 192 241 129 65 69 76 67 91 101 121 151 137 136 219 208
157 187 170 233 157 189 216 168 249 189 203 189 199 212 152 232 173 148 196 203
232 179 198 237 286 214 253 397 273 223 321 273 205 324 195 211 172 228 285
RVS-A08B 79
89 58 67 82 91 96 114 108 107 90 126 133 156 114 158 158 139 142 136 208
327 292 422 289 283 195 245 116 52 68 73 73 83 108 134 136 131 145 224 215
146 194 167 229 160 187 220 163 215 183 196 194 200 205 167 214 185 149 193 184
244 209 200 232 262 178 319 437 268 212 319 257 226 313 189 218 202 235 229
RVS-A09A 78
39 41 35 46 49 36 57 66 74 81 87 41 68 46 48 60 74 79 107 192
144 164 117 186 225 296 243 154 153 119 162 80 39 52 60 76 53 80 81 87
80 84 117 114 89 131 108 138 95 119 153 126 147 136 107 121 134 127 100 122
121 109 120 146 145 135 149 134 171 107 180 225 225 139 171 202 191 223
RVS-A09B 78
47 42 34 49 51 42 55 66 68 79 89 43 63 45 55 62 68 82 116 189
140 176 136 175 248 302 236 150 153 124 162 67 42 52 60 74 56 75 81 89
85 83 111 113 90 133 107 133 96 122 153 125 151 128 118 117 136 127 94 122
128 114 119 144 135 125 150 133 185 103 179 196 221 153 171 182 157 266
RVS-A10A 101
346 252 220 229 288 325 315 238 406 463 521 365 418 453 394 318 318 193 314 278
262 141 94 34 37 44 50 73 58 62 54 52 65 86 97 88 119 91 109 105
137 128 152 144 155 243 176 243 206 292 410 320 356 256 203 124 172 69 36 35
63 78 85 89 98 96 101 115 233 174 139 259 202 241 144 220 233 146 260 176
195 302 378 328 239 236 228 191 298 248 341 246 260 300 344 198 352 469 352 221
322
RVS-A10B 101
453 243 223 217 297 307 300 243 428 476 535 367 421 448 389 320 310 201 327 264
284 126 86 38 46 48 42 80 56 58 55 54 59 77 97 100 119 97 89 93
137 144 155 134 157 244 172 243 203 309 411 329 356 248 247 130 183 72 34 38
71 74 81 90 101 85 107 114 232 176 147 260 154 219 153 233 258 161 281 171
178 313 366 300 257 215 224 175 287 276 321 260 252 285 345 198 330 464 324 237
301
RVS-A11A 107
494 331 344 411 245 298 297 378 260 273 234 307 278 241 160 218 234 219 177 190
270 324 240 238 169 246 209 222 149 111 81 46 54 56 64 73 61 54 67 92

69 61 64 64 75 66 77 99 122 117 139 223 172 190 173 173 293 230 374 298
267 156 253 144 34 51 37 85 95 115 110 112 98 121 110 132 124 154 171 152
117 168 188 177 198 182 148 222 204 243 167 172 153 156 185 178 171 158 128 132
208 183 194 448 385 258 397
RVS-A11B 107
453 307 362 393 256 315 306 343 280 268 238 292 291 236 173 217 208 209 173 193
252 310 241 239 183 258 204 215 167 109 74 44 56 73 54 60 76 51 67 83
82 68 76 48 79 57 92 88 122 118 131 217 173 193 172 180 277 245 395 285
253 150 238 155 30 52 61 82 90 114 111 118 99 118 108 131 125 164 161 153
115 143 190 182 224 166 183 204 222 223 169 154 166 146 175 188 164 138 125 133
207 180 209 440 382 273 354
RVS-A12A 86
479 354 346 227 280 237 280 155 101 40 43 50 39 66 60 50 70 40 51 84
106 74 99 88 98 95 131 127 160 158 184 235 192 250 182 218 303 276 307 221
211 136 180 53 32 34 67 89 83 95 97 89 108 119 223 148 125 230 199 245
151 277 330 182 269 151 194 257 284 397 213 274 232 198 251 238 307 242 223 263
220 176 305 385 343 258
RVS-A12B 86
486 370 352 233 283 235 275 158 87 47 38 46 43 65 54 59 67 43 53 78
107 71 116 93 98 98 127 127 167 139 171 261 171 253 193 229 302 231 284 216
179 130 172 51 31 41 57 88 87 95 103 82 108 115 214 148 120 186 200 250
193 301 325 184 267 143 186 280 321 372 256 276 248 191 259 248 290 201 240 253
256 183 259 414 345 191
RVS-A13A 73
285 221 288 333 344 355 363 367 429 374 270 357 289 293 372 415 329 281 446 539
455 268 290 260 353 382 396 329 290 258 169 228 227 193 258 182 219 166 101 96
85 110 123 80 72 59 71 59 61 88 73 119 134 74 87 65 62 68 58 52
99 127 178 179 274 227 219 154 192 143 229 265 277
RVS-A13B 73
314 242 277 349 329 368 354 377 404 368 272 343 284 300 381 394 324 285 449 528
487 279 285 261 339 366 391 352 308 280 175 227 229 207 249 200 215 167 113 94
90 110 124 73 76 56 77 61 60 84 74 131 144 77 83 61 61 65 59 49
97 134 180 178 309 257 227 160 202 154 254 235 276
RVS-A14A 75
315 362 297 449 585 493 241 293 446 466 372 406 391 362 301 294 259 210 191 311
338 325 233 146 109 107 225 233 248 233 148 146 121 134 189 158 296 280 111 78
115 94 78 80 73 163 106 123 144 182 191 197 113 102 68 158 139 124 155 175
181 164 127 84 106 155 194 173 150 145 130 147 117 98 169
RVS-A14B 75
313 369 298 449 592 494 247 289 447 471 360 424 378 356 293 294 271 198 191 313
327 335 227 137 116 104 226 249 244 228 160 127 133 140 190 156 299 282 114 96
101 71 69 73 73 170 103 115 160 183 193 183 110 105 71 147 147 123 168 164
177 169 120 92 113 162 193 165 154 145 136 148 128 108 173
RVS-A15A 134
162 197 149 151 185 250 190 94 79 97 121 69 90 161 300 136 166 150 248 279
323 211 137 267 160 217 212 240 134 135 142 165 193 118 256 136 165 149 153 157
152 160 108 98 130 124 188 150 152 145 159 140 204 189 202 251 201 147 143 287
191 239 152 314 269 165 116 82 71 66 81 114 195 211 181 179 152 130 72 129
116 82 152 176 128 204 195 134 121 266 245 234 242 197 176 175 171 180 180 274
294 227 214 230 210 331 229 108 127 173 320 275 216 214 199 193 221 149 183 284
126 159 144 103 76 78 62 150 114 104 85 103 82 95
RVS-A15B 134
145 193 146 158 183 244 199 100 87 96 114 71 96 163 284 186 156 156 246 274
290 212 144 260 170 213 211 243 142 129 145 174 195 121 251 135 176 149 145 154
155 162 93 116 125 114 187 129 164 158 156 145 188 207 208 258 206 141 135 284

199 222 171 308 264 156 127 110 45 65 83 121 188 213 174 161 161 118 87 122
115 87 148 170 129 175 223 110 125 281 248 232 243 194 162 178 171 186 175 268
284 232 238 204 220 355 215 111 124 188 297 284 214 203 199 195 209 160 173 284
100 167 150 110 68 74 75 147 108 96 94 94 80 86
RVS-A16A 82
189 146 134 189 72 104 199 146 155 172 161 76 77 100 120 139 118 127 222 190
189 141 122 162 143 172 85 39 46 50 39 49 56 53 56 93 86 99 96 117
131 129 133 125 78 161 187 161 118 173 262 161 157 307 141 276 181 192 167 206
197 225 169 186 148 191 154 158 272 159 133 199 194 261 235 195 206 246 162 191
167 132
RVS-A16B 82
206 138 134 191 68 112 189 150 152 175 159 74 87 91 126 138 114 124 216 196
196 151 130 167 137 172 74 38 40 44 58 38 61 54 57 100 83 102 98 105
120 135 128 132 77 176 183 150 130 176 236 154 136 300 151 271 189 169 175 206
208 224 159 201 167 175 163 146 252 163 163 201 198 260 251 189 204 258 161 183
163 132
RVS-A17A 55
226 224 163 162 227 253 328 322 263 180 249 317 341 278 224 316 268 249 201 281
351 292 228 151 244 254 185 147 153 172 206 201 204 194 214 149 223 164 84 98
97 242 224 169 104 80 77 130 91 217 111 89 160 159 137
RVS-A17B 55
239 222 152 161 240 248 314 322 254 197 249 323 348 259 234 304 274 244 201 300
323 321 211 164 240 240 190 170 147 203 201 151 202 189 216 144 231 164 97 95
95 233 224 167 111 71 89 123 102 203 95 83 166 159 147
RVS-A18A 56
163 117 83 101 79 91 75 115 108 125 122 109 78 58 62 62 45 77 63 80
64 42 73 46 87 105 73 76 66 75 87 121 52 57 45 62 58 44 39 53
63 46 53 41 34 34 53 72 47 61 66 101 98 91 80 87
RVS-A18B 56
167 120 87 104 85 85 88 105 109 134 114 107 79 63 72 48 48 77 65 76
57 41 75 45 79 107 79 68 63 75 85 109 60 58 43 68 54 44 41 56
57 48 52 38 30 38 48 66 53 67 56 92 89 90 71 90
RVS-A19A 54
400 331 351 174 332 479 360 220 196 247 237 128 216 201 154 147 200 122 190 208
226 203 207 362 457 288 340 364 665 390 287 314 208 188 199 289 210 158 145 219
293 224 253 195 165 172 79 131 138 166 124 163 136 82
RVS-A19B 54
398 355 313 186 328 454 328 258 167 238 233 120 210 197 152 193 163 140 189 194
240 232 277 330 424 307 264 504 575 445 311 285 205 179 211 287 215 152 157 217
287 210 253 196 177 183 118 142 151 161 131 159 141 77
RVS-A20A 54
243 287 177 159 227 257 325 338 270 150 248 314 380 270 283 311 330 236 204 258
331 316 185 152 213 224 173 165 148 185 245 144 208 179 207 147 211 184 81 94
108 211 227 164 121 78 84 119 96 197 68 107 144 161
RVS-A20B 54
234 286 181 165 242 248 340 325 238 166 254 310 363 289 262 330 337 232 202 246
332 310 187 156 213 209 180 155 148 206 224 150 223 188 192 152 211 173 77 87
106 219 225 163 117 98 79 115 97 200 93 93 160 156

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 A1 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 A1, 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 A2 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 8–10 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 A2; it is about 150mm long and 10mm 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 A1: 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 A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: 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 A4: 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 A2. 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 A3).

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 A4). 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 A5 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 A5. 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 A5 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 straightforward 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 (or the last full year before felling, if it was felled in the first three months of the following calendar year, 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 A2, 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 region 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 A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, 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; Miles 1997, 50–5). Hence, provided that 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, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage 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 Figure A6 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 Figure A6. 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 Figure A7. 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

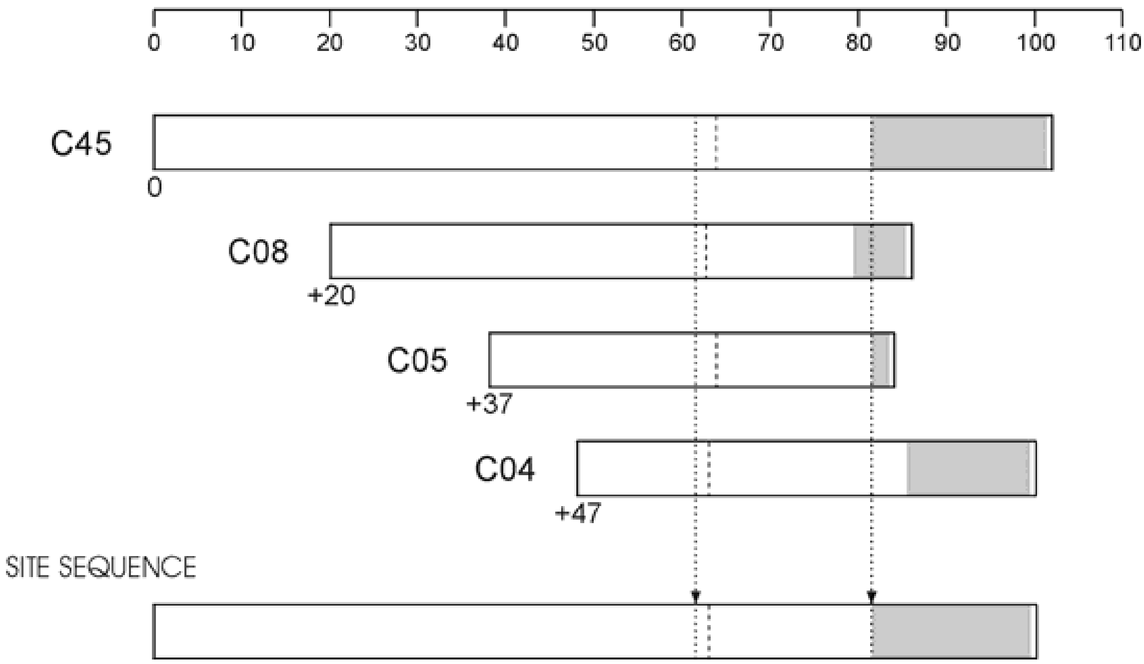


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

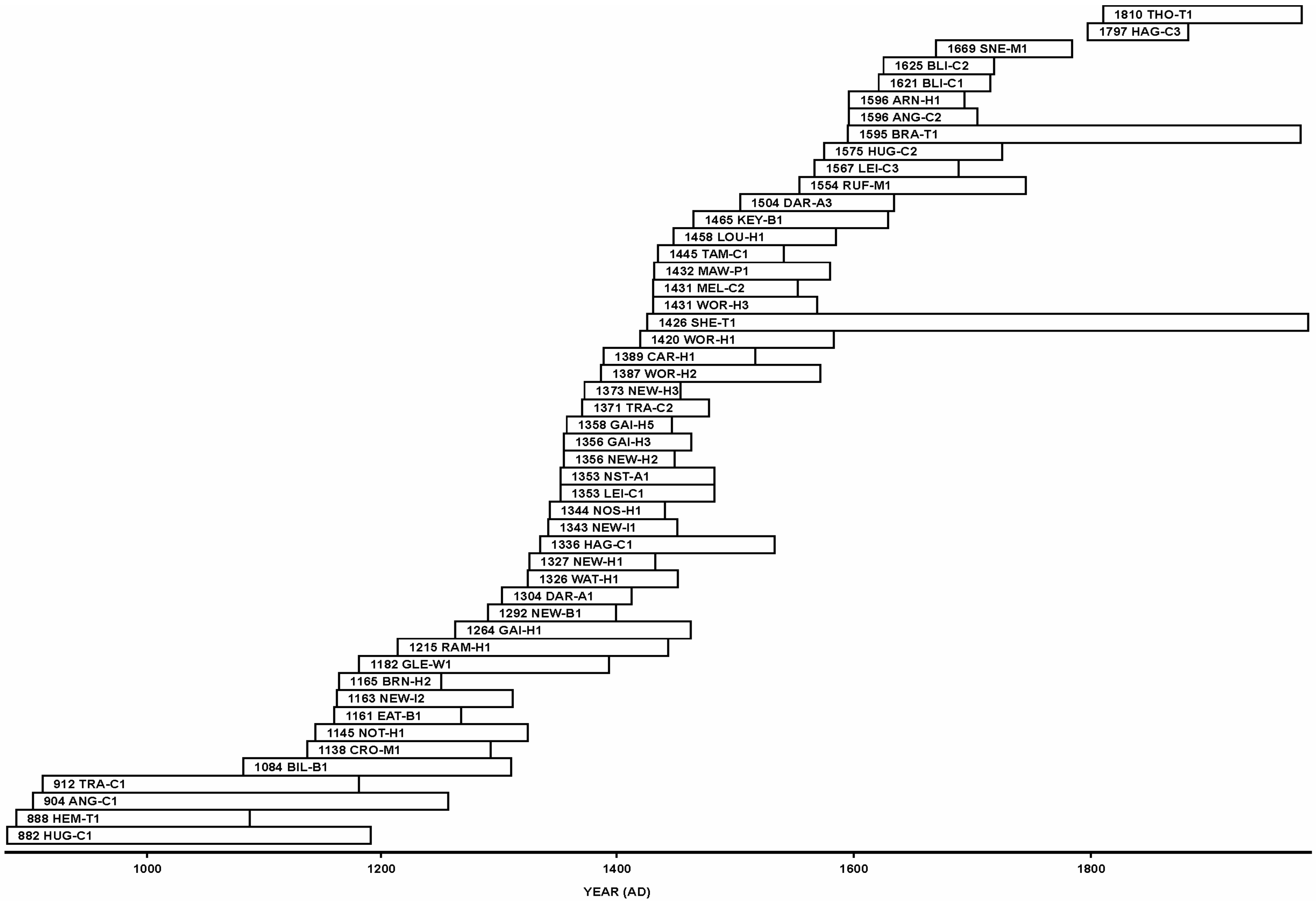
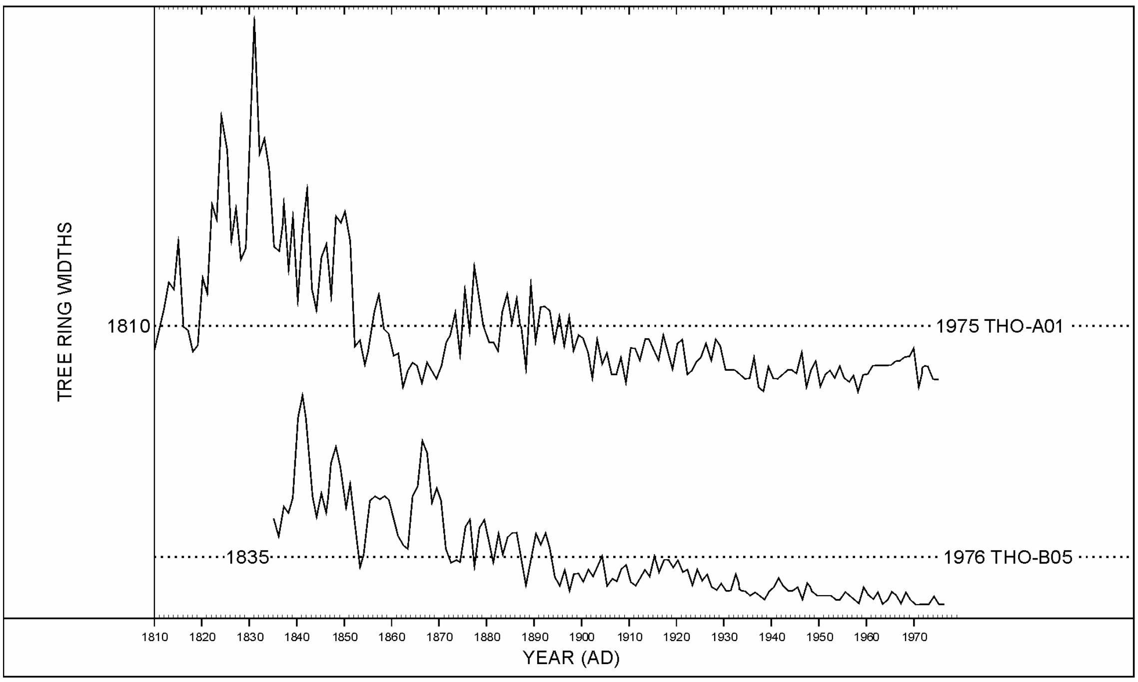


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

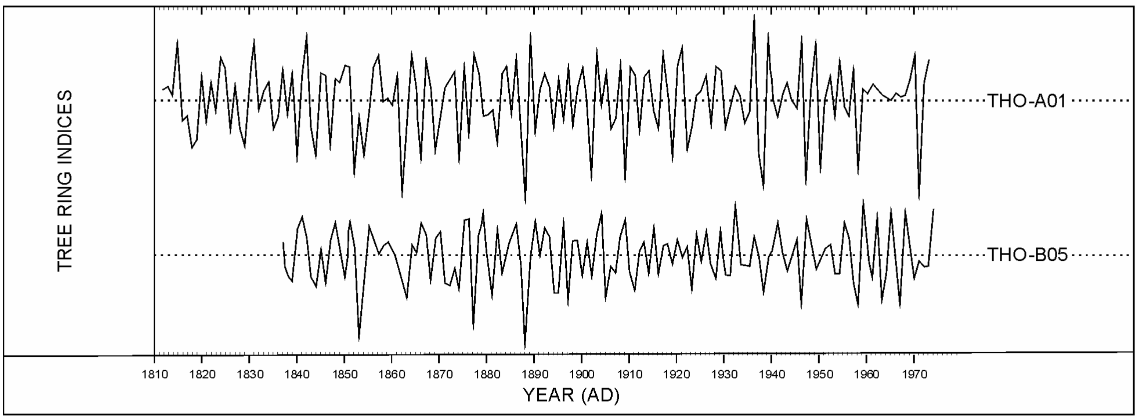


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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 A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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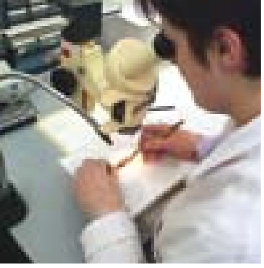 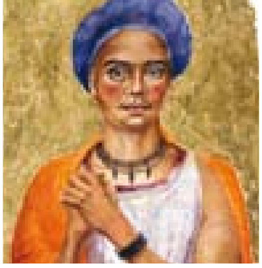    

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