RESEARCH DEPARTMENT REPORT SERIES no. 42-2008 ISSN 1749-8775

CHURCH OF ST NICHOLAS, DEREHAM, NORFOLK

TREE RING ANALYSIS OF TIMBERS FROM THE NORTH TRANSEPT/NORTH CHAPEL AND NAVE ROOFS

SCIENTIFIC DATING REPORT

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ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

Research Department Report Series 42-2008

CHURCH OF ST NICHOLAS, DEREHAM, NORFOLK TREE RING ANALYSIS OF TIMBERS FROM THE NORTH TRANSEPT/NORTH CHAPEL AND NAVE ROOFS

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NGR **TF9869113306**

ISSN 1749-8775

SUMMARY

Dendrochronological analysis was undertaken on samples from the north transept/north chapel and nave roofs.

This resulted in the successful dating of a single site sequence, DERASQ01. This site sequence contains three samples from the north transept/north chapel roof and spans the period AD 1578–1681. Interpretation of the heartwood/sapwood boundary ring suggests felling for at least two, and probably all three, of these timbers in AD 1682–1706. This demonstrates work was being undertaken on this roof at the end of the seventeenth/early-eighteenth century.

A further six site sequences remain undated.

CONTRIBUTORS

Alison Arnold, Robert Howard

ACKNOWLEDGEMENTS

The Laboratory would like to thank Nicholas Warns Architects for their assistance in arranging access and for providing Figure 4. Mr Atthowe, of G F Atthowe, the contractors on site, was helpful in informing us of progress of works and erection of scaffolding. Thanks are also given to the English Heritage Scientific Dating Section and Cathy Tyers of Sheffield University Dendrochronology Laboratory for their advice and assistance throughout the production of this report.

ARCHIVE LOCATION

Historic Environment Record
Norfolk Landscape Archaeology
Union House
Gressenhall
Dereham NR20 4DR

DATE OF INVESTIGATION

2008

CONTACT DETAILS

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CONTENTS

INTRODUCTION

The Grade-I listed parish church of St Nicholas is located on the north side of Church Street in Dereham, Norfolk (Fig 1–3; TF9869113306). It is thought to have its origins in the twelfth century, although the church as seen today is mainly thirteenth century, with some fourteenth- and fifteenth-century additions and insertions.

It is of cruciform plan (Fig 4) with a central tower, nave (Fig 5), chancel, north and south transepts, and sixteenth-century porch. The latter is decorated with carvings and niches, demi-angels and an Annunciation. Within both the north and south transepts are chapels. The south transept is partitioned off from its chapel by a late-fifteenth century screen, which was rescued from the Church of St John in Oxborough after the collapse of its tower. Both the north and south transepts have fine painted ceilings, believed to date to the fifteenth century (Fig 6). To the south of the church is a detached bell tower which is thought to date to the early-sixteenth century. The above description is taken from the buildings Listing Description (www.imagesofengland.co.uk).

SAMPLING

The areas undergoing repairs were the roofs of the nave, the north transept and north chapel to the east of it, and the lantern tower roof. It was hoped that during the re-leading of these roofs it would be possible to gain access to the roof structures beneath for sampling. However, once on site it was found that, although the lead was to be removed, the boards beneath were not. No meaningful access could be gained to the lantern tower timbers, and within the north transept/north chapel roofs access was restricted to those timbers visible in the guttering at the west side of the north transept and the east side of the north chapel. Here the ends of a number of timbers could be seen, but it was not possible to identify what components of the roofs these were, or indeed how they might relate to each other (Fig 7). What could be seen is that there appeared to be two phases of timbers visible in the guttering at the east side of the north chapel (Fig 8). These timbers have been numbered from east to west, with intermediate timbers denoted by 'A'. A total of 17 of these timbers was sampled. Each sample was given the code DER-A (for Dereham) and numbered 01–17 (Table 1).

It was possible to gain access to the nave roof via a hatch at its east end. This roof consists of 34 rafter couples, pegged at the apex and with crossing braces (Fig 9); a number of the frames at the western end appeared to be replacements. Eighteen samples were taken from the timbers of this roof (Fig 9); these are numbered DER-A18–35. Frames have been numbered from east to west. The position of samples was noted at the time of sampling and those from the nave have been marked on Figure 10. Further details relating to all the samples can be found in Table 1.

ANALYSIS AND RESULTS

At this stage it was noticed that one of the samples taken from the north transept roof (DER-A13) had too few rings to make secure dating a possibility and this sample was rejected prior to measurement. The remaining 34 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. All 34 samples were compared with each other by the

Litton/Zainodin grouping procedure (see Appendix), resulting in 23 samples forming eight groups.

North transept/north chapel roof:
Firstly, three samples matched each other and were combined at the relevant offset positions to form DERASQ01, a site sequence of 104 rings (Fig 11). This site sequence was then compared with a large number of relevant reference chronologies for oak where it was found to match at a first-ring date of AD 1578 and a last-measured ring date of AD 1681. The evidence for this dating is given by the *t*-values in Table 2. Two of the samples in DERASQ01 have the heartwood/sapwood boundary ring. In both cases this is AD 1666, allowing an estimated felling date to be calculated for the two timbers represented to within the range AD 1682–1706. This allows for sample DER-A10 to have the last-measured ring date of AD 1681 with incomplete sapwood. The third sample, DER-A12, does not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated, except to say that with a last-measured ring date of AD 1578, this would be estimated to be AD 1594 or later, making it possible that this timber was also felled in AD 1682–1706.

In addition, a number of other small groups were identified. The group individuals were combined at their relevant offset positions to form DERASQ02–DERASQ05 (Figs 12–15) ranging in length from 73 to 154 rings. Comparison of these four site sequences with the reference chronologies proved unsuccessful and all remain undated.

Attempts to date the remaining ungrouped samples by individually comparing them with the reference chronologies proved unsuccessful and these are also undated.

Nave roof:
Analysis of these samples resulted in 11 samples forming three groups. The individuals were combined at their relevant offset positions to form DERASQ06–DERASQ08 (Figs 16–18) ranging in length from 62 to 105 rings. Attempts to date these three site sequences by comparing them against the relevant reference material were unsuccessful and all remain undated.

The ungrouped samples were then individually compared against the reference material, but no consistent match could be found and these also remain undated.

DISCUSSION AND CONCLUSION

It had been hoped that tree-ring analysis would provide secure dating for a number of roofs at this church, thereby aiding in the interpretation of the development of the building. However, despite 35 timbers having been sampled, only three have been successfully dated.

It is now known that at least two (and most likely three) timbers from the north chapel roof were felled in AD 1682–1706. The three dated samples are all from the intermediate, 'A' timbers visible in the guttering on the east side of the roof. It is unfortunate that, as these were the only portion of the timbers visible, it is not possible at present to say exactly what function these beams have, or what their relationship with the rest of the roof timbers is. If these beams were not reused, this dating demonstrates that work was being undertaken on this roof in the late seventeenth/early-eighteenth century.

Although none of the three site sequences constructed from timbers of the nave roof could be dated, it is possible to make some observations about them. One of these, DERASQ06, contains five samples, all with complete sapwood and all with the same end position, demonstrating that all five were felled at the same time. Equally, by looking at the relative heartwood/sapwood boundary ring positions of the four samples making up sequence DERASQ07 and the two contained within DERASQ08, it is possible to say that in both cases each site sequence represents timbers of one felling. However, whether this means that all 11 samples were felled the same time or three separate fellings are represented by these three site sequences cannot be determined.

In the case of both the north transept/north chapel and the nave roofs, the production of multiple site sequences may suggest that timbers from more than one source and/or date have been utilised in their construction rather than a coherent group of trees. Additionally, although there were no obvious signs of growth anomalies noted on these samples, it may be that they have been subject to highly localised growing conditions which might inhibit successful matching against the reference chronologies. Dendrochronological dating in Norfolk is not always as successful as it might be in other parts of England. As a result of these difficulties there is a deficit in reference material from the region with which to cross-match data, a fact which could also have impacted on the dating at this site. This deficit will only be redressed if more buildings are analysed in the region thus providing a localised network of chronologies. This approach has proven successful in other regions where historically difficulties were encountered, such as in Kent, Essex, and Devon; today after sustained and directed research the situation is now improving in these areas and it would be hoped that the same could be achieved in Norfolk in the future.

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TABLES

Table 1: Details of tree-ring samples from St Nicholas' Church

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
North chapel						
DER-A01	East timber 1	61	h/s	----	----	----
DER-A02	East timber 4	139	h/s	----	----	----
DER-A03	East timber 6	122	h/s	----	----	----
DER-A04	East timber 7	57	--	----	----	----
DER-A05	East timber 10	122	--	----	----	----
DER-A06	East timber 11	76	--	----	----	----
DER-A07	East timber 17	83	--	----	----	----
DER-A08	East timber 18	102	h/s	----	----	----
DER-A09	East timber 2(A)	86	--	----	----	----
DER-A10	East timber 10(A)	75	15	1607	1666	1681
DER-A11	East timber 12(A)	61	h/s	1606	1666	1666
DER-A12	East timber 15(A)	77	--	1578	----	1654
North transept						
DER-A13	West timber 5	NM	--	----	----	----
DER-A14	West timber 8	95	--	----	----	----
DER-A15	West timber 9	73	--	----	----	----
DER-A16	West timber 10	101	h/s	----	----	----
DER-A17	West timber 11	66	--	----	----	----

Table 1: Details of tree-ring samples from St Nicholas' Church

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Nave						
DER-A18	South rafter 23	73	04	----	----	----
DER-A19	South rafter 16	58	20	----	----	----
DER-A20	North brace 11	61	02	----	----	----
DER-A21	South rafter 10	66	19C	----	----	----
DER-A22	North brace 10	62	24C	----	----	----
DER-A23	South brace 10	49	13	----	----	----
DER-A24	North brace 6	73	01	----	----	----
DER-A25	South brace 5	58	32	----	----	----
DER-A26	North brace 3	93	25C	----	----	----
DER-A27	South brace 3	105	28C	----	----	----
DER-A28	North brace 2	92	25C	----	----	----
DER-A29	North rafter 1	84	22C	----	----	----
DER-A30	North brace 1	100	24C	----	----	----
DER-A31	South brace 20	50	h/s	----	----	----
DER-A32	South brace 15	51	05	----	----	----
DER-A33	South brace 15	52	07	----	----	----
DER-A34	South rafter 11	51	17	----	----	----
DER-A35	North rafter 5	52	01	----	----	----

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

Table 2: Results of the cross-matching of site sequence DERASQ01 and relevant reference chronologies when the first-ring date is AD 1578 and the last-ring date is AD 1681

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	5.6	AD 882–1981	Laxton and Litton 1988
The Commandery, Worcester	6.5	AD 1569–1655	Arnold and Howard 2006
Hulme Hall, Allostock	6.0	AD 1574–1689	Arnold *et al* 2003a
St Hughs' Choir, Lincoln Cathedral, Lincs	5.7	AD 1575–1724	Laxton *et al* 1984
Staircase House, Stockport, Greater Manchester	5.8	AD 1489–1656	Howard *et al* 2003
Bolsover Castle, (Riding house), Derbys	5.7	AD 1494–1744	Howard *et al* 2005
Teversall Manor, Sutton In Ashfield, Notts	5.6	AD 1487–1632	Arnold *et al* 2003b

FIGURES

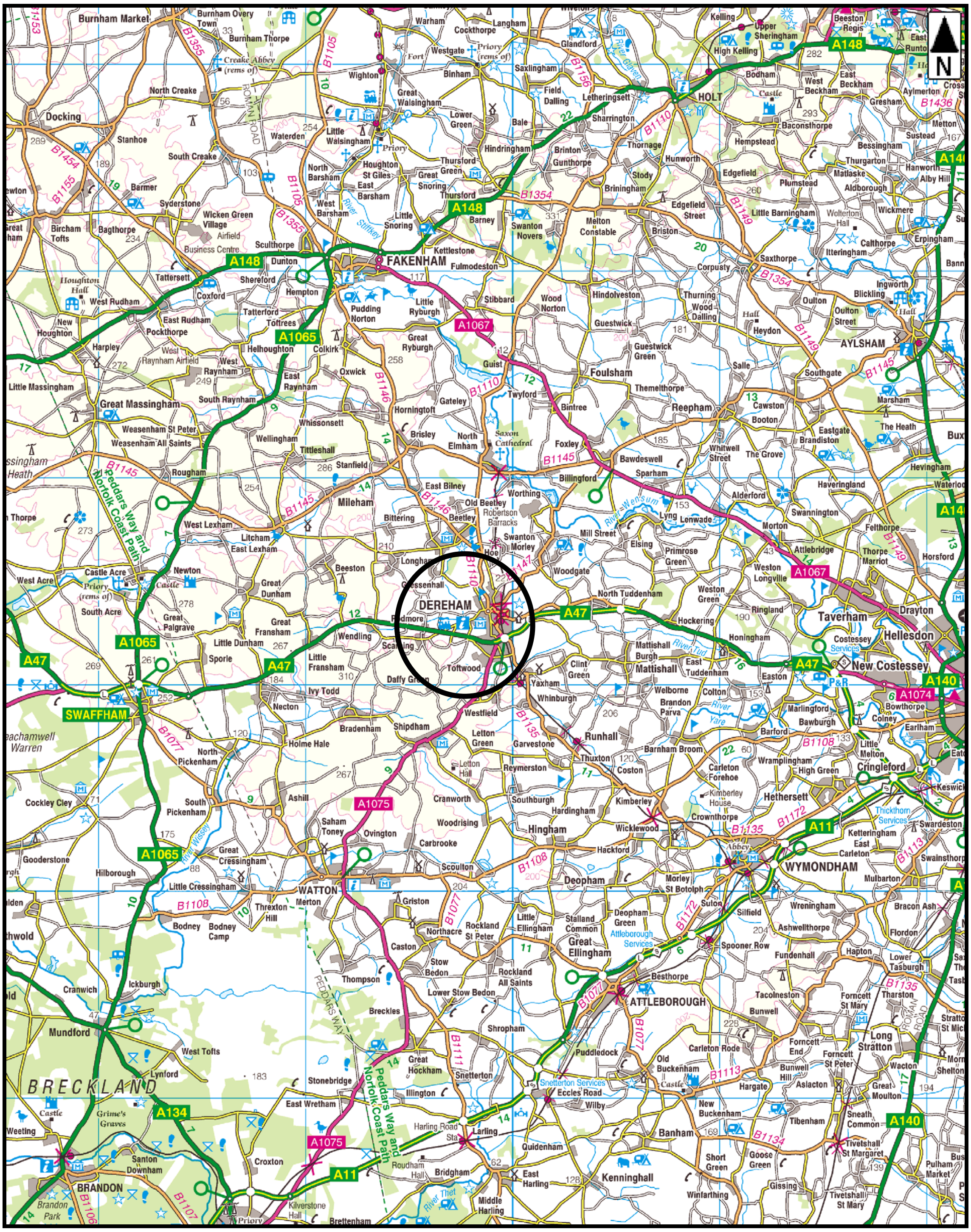


Figure 1: Map to show the location of St Nicholas' Church

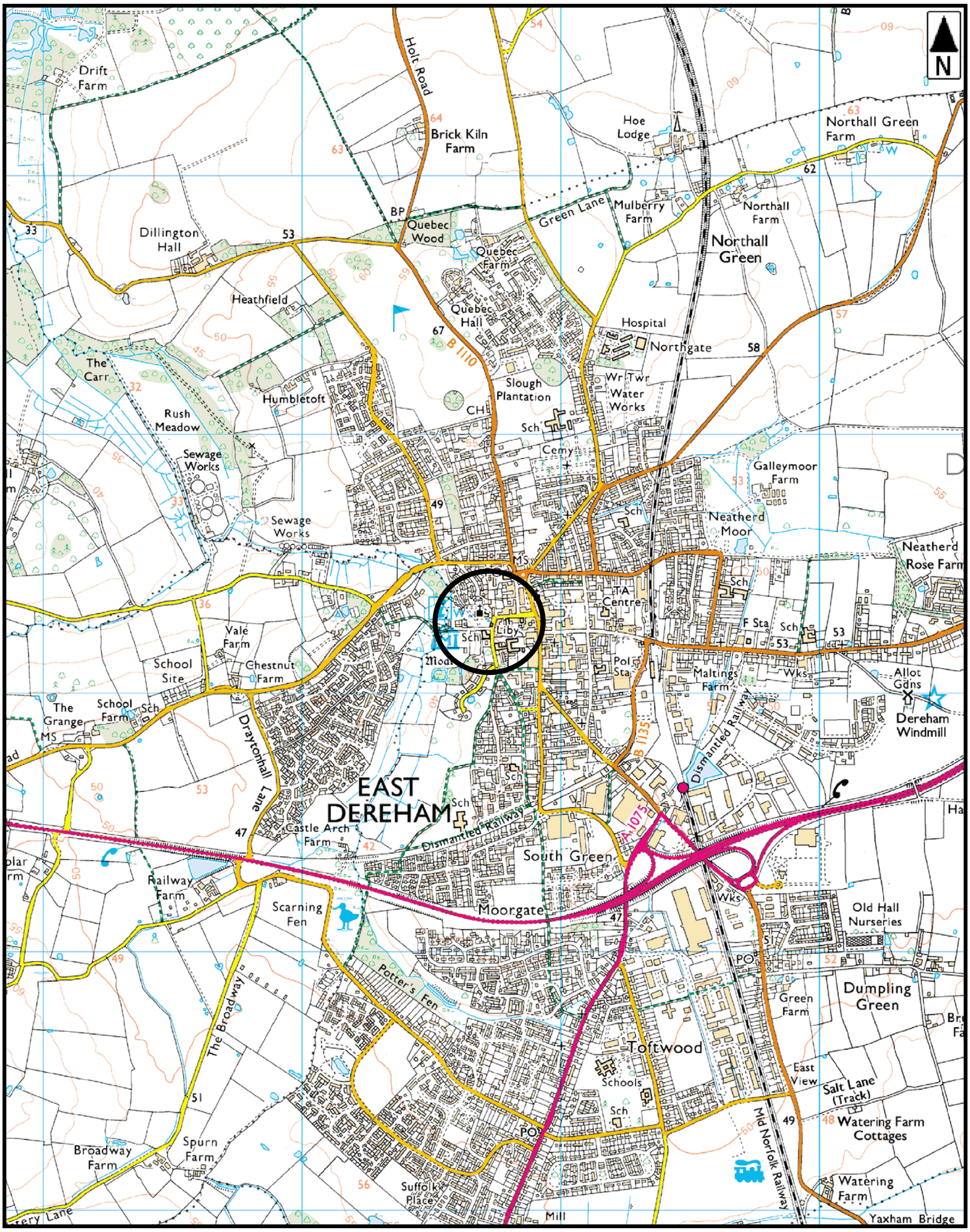


Figure 2: Map of Dereham, with the general location of St Nicholas' Church circled,

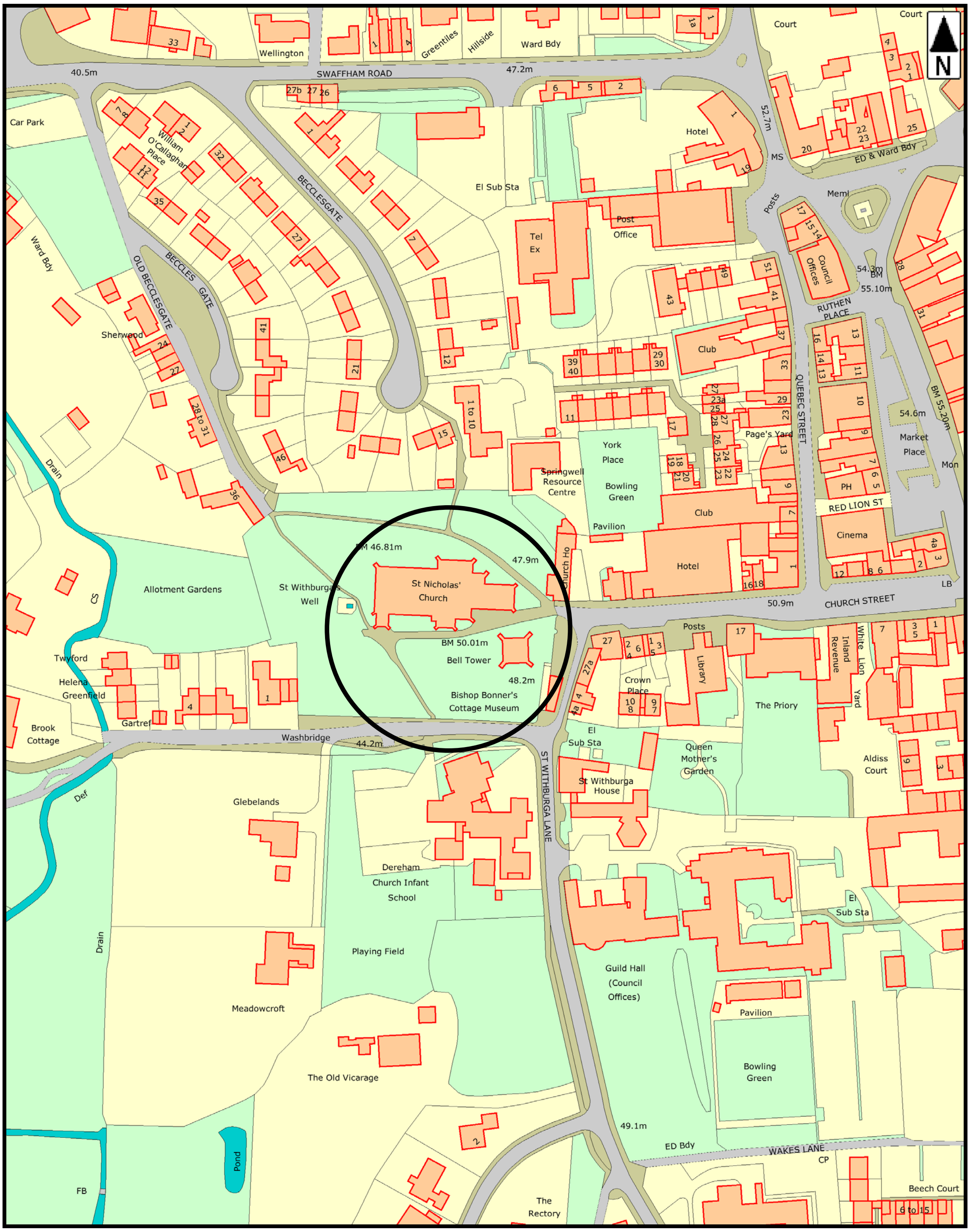


Figure 3: Map to show the location of St Nicholas' Church

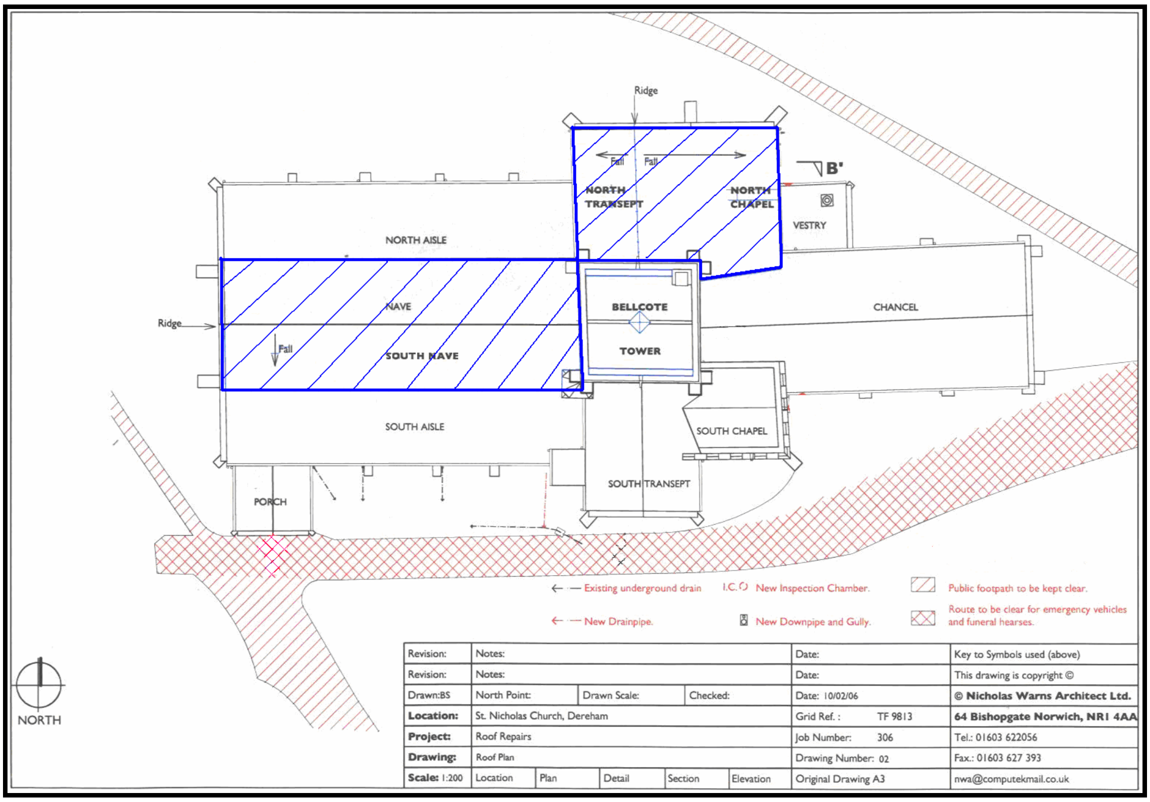


Figure 4: Roof plan of St Nicholas' Church; the sampled areas outlined and hashed in blue (Nicholas Warns Architect Ltd)

Figure 5: The nave ceiling, as viewed from below

Figure 6: North chapel ceiling (as viewed from below) with north transept to the left

Figure 7: North chapel roof, showing ends of timbers

Figure 8: North chapel, exposed timbers, in addition to the main 'joists' are a number of smaller timbers (A)

Figure 9: Nave roof, taken from the east

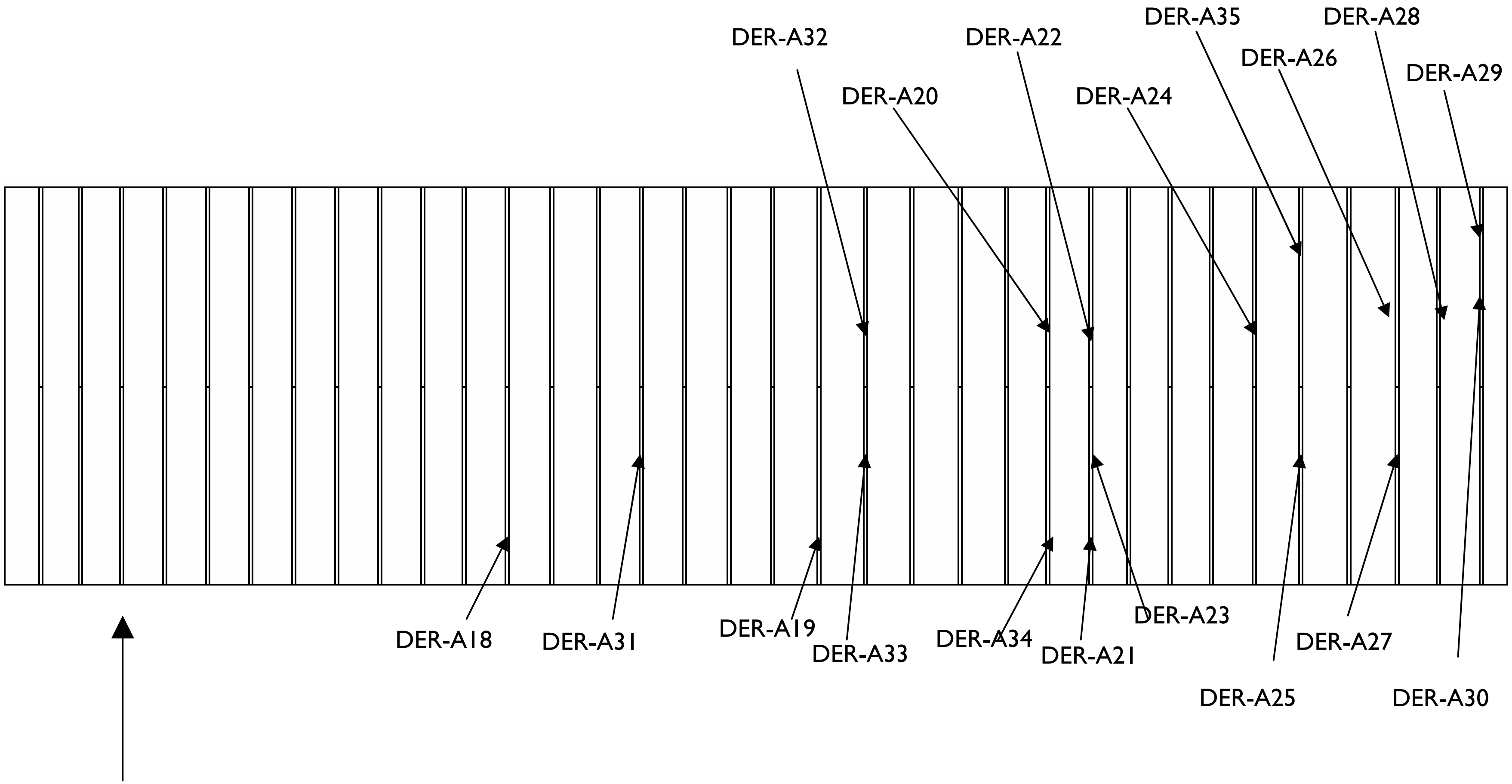
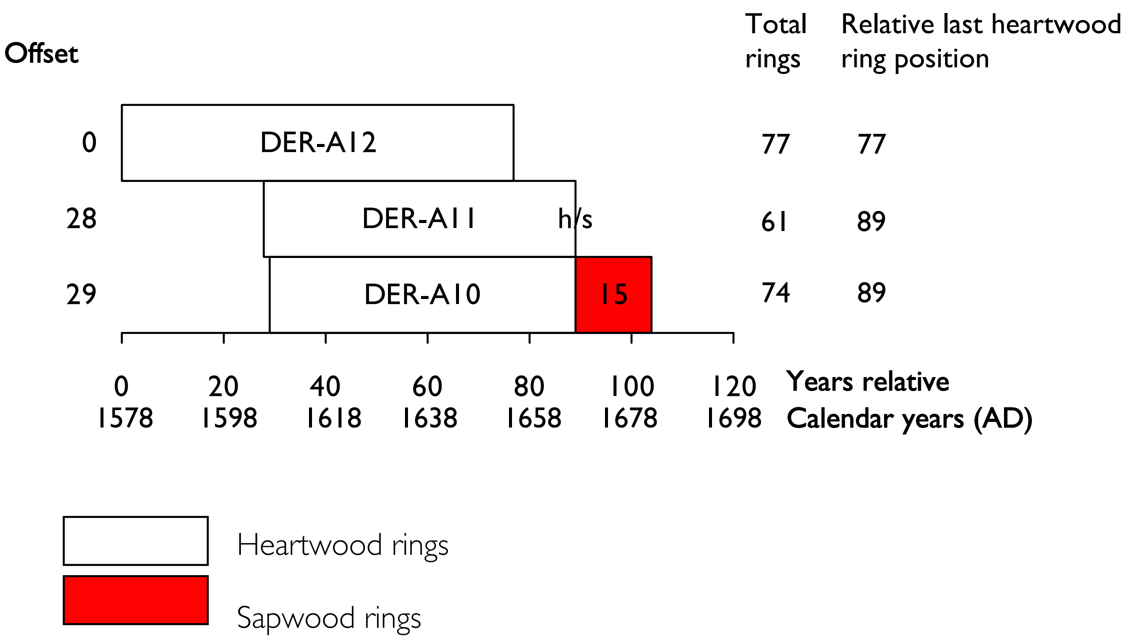
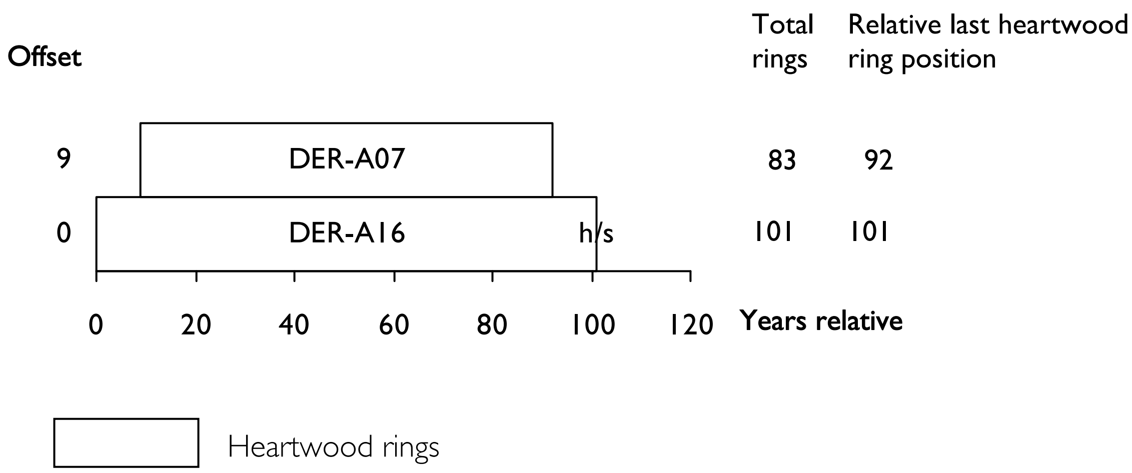


Figure 10: Sketch plan of the nave roof, showing the location of samples



h/s = the heartwood/sapwood boundary is the last-measured ring on the sample.

Figure 11: Bar diagram of samples in site sequence DERASQ01



h/s = the heartwood/sapwood boundary is the last-measured ring on the sample.

Figure 12: Bar diagram of samples in site sequence DERASQ02

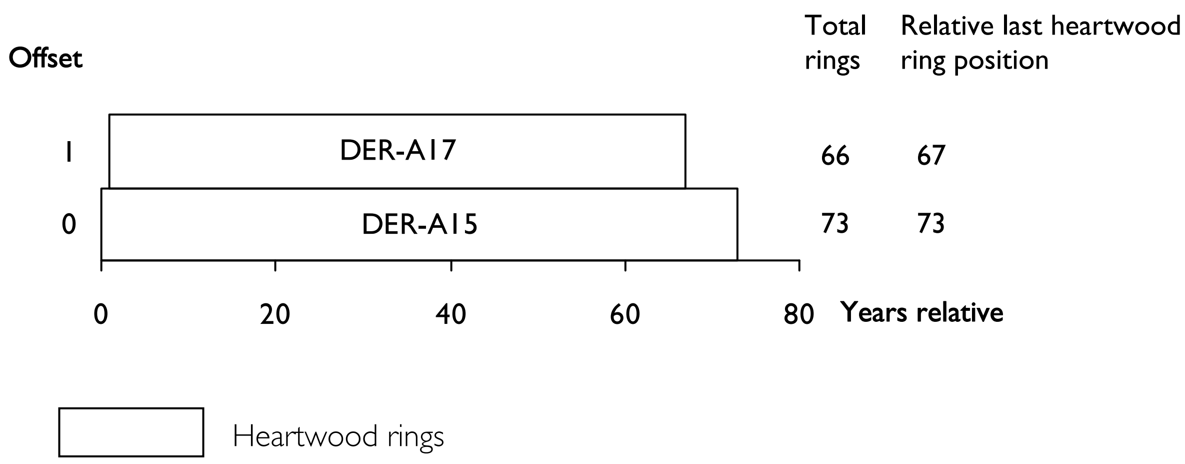
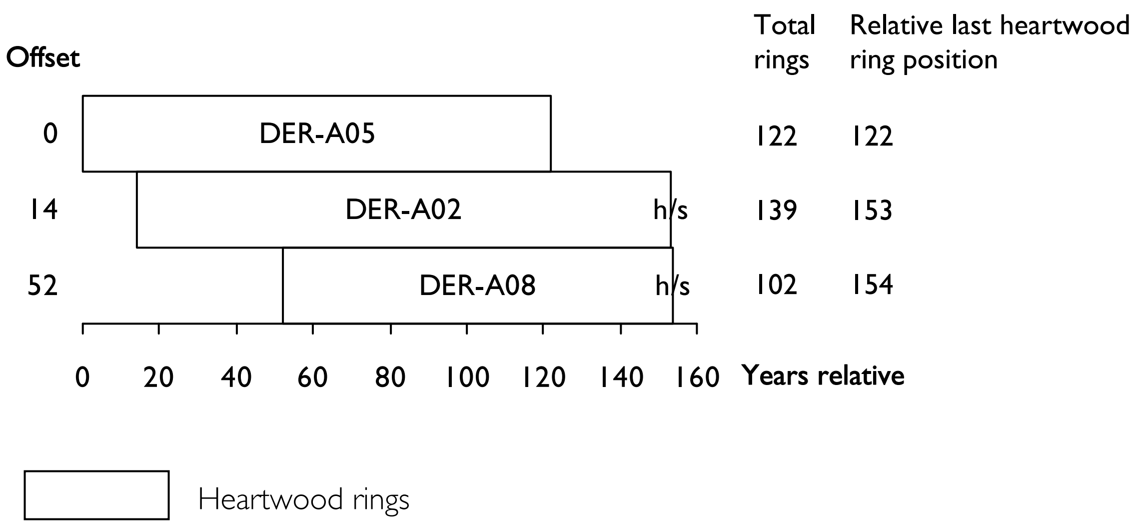
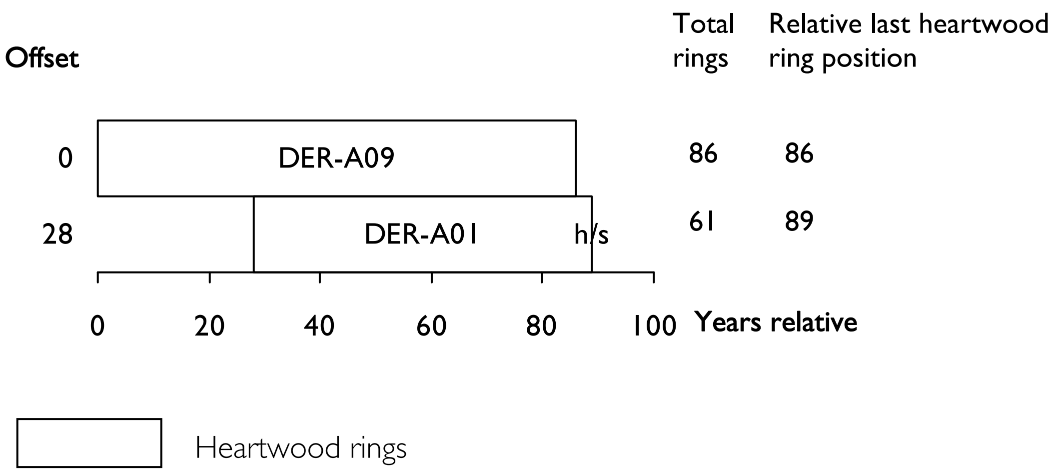


Figure 13: Bar diagram of samples in site sequence DERASQ03



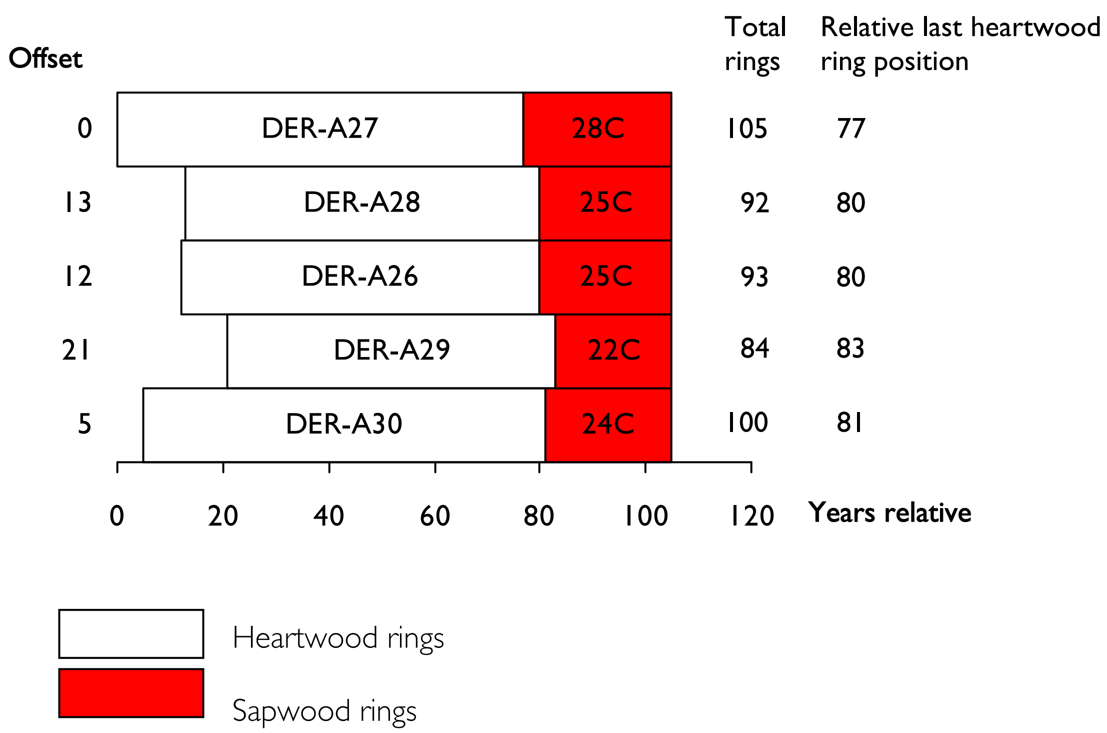
h/s = the heartwood/sapwood boundary is the last-measured ring on the sample.

Figure 14: Bar diagram of samples in site sequence DERASQ04



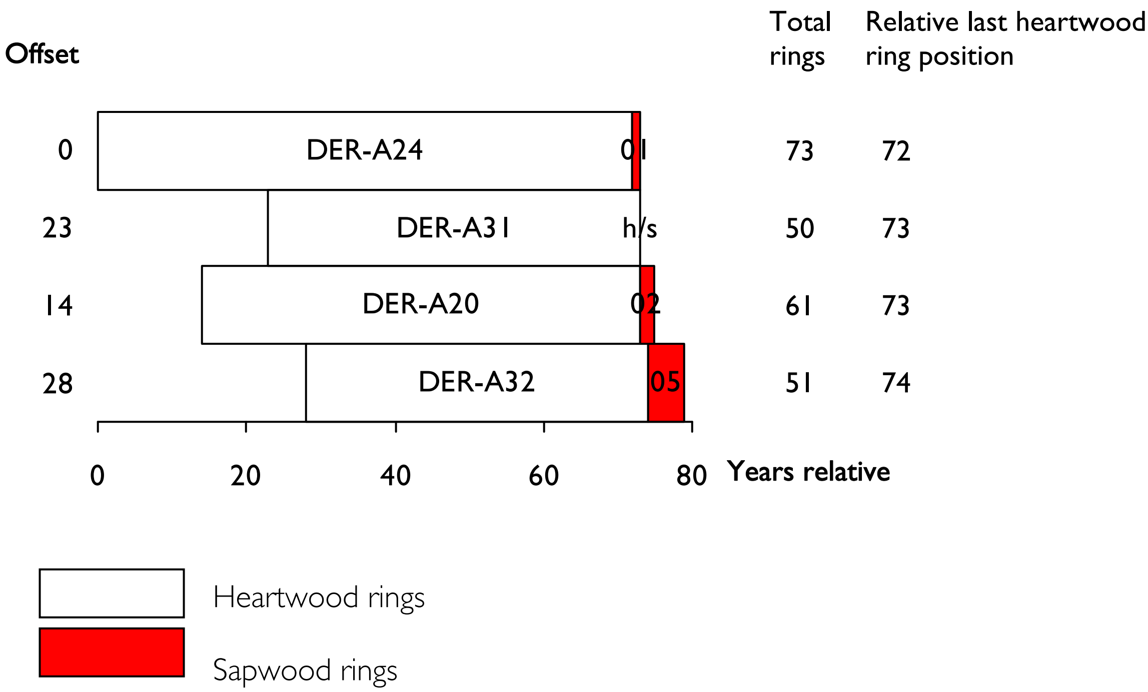
h/s = the heartwood/sapwood boundary is the last-measured ring on the sample.

Figure 15: Bar diagram of samples in site sequence DERASQ05



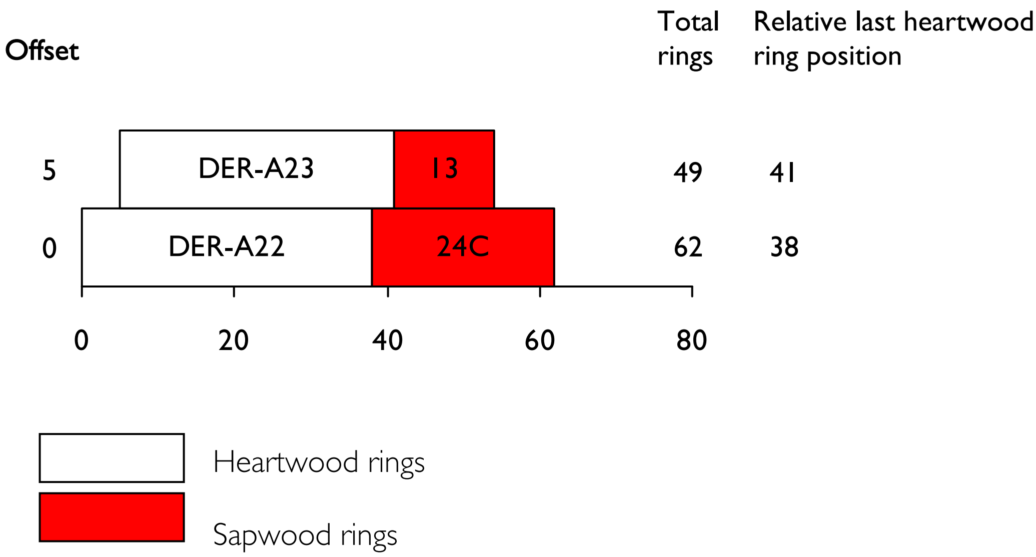
C = complete sapwood retained on sample, last measured ring is the felling date.

Figure 16: Bar diagram of samples in site sequence DERASQ06



h/s = complete sapwood retained on sample, last measured ring is the felling date.

Figure 17: Bar diagram of samples in site sequence DERASQ07



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

Figure 18: Bar diagram of samples in site sequence DERASQ08

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

```
DER-A01A 61
 316 217 194 285 215 154 165 192 189 292 254 254 216 135 194 228 219 208 201 174
 211 179 164 158 205 239 187 195 207 207 161 131 174 170 203 193 137 171 158 130
 149 188 205 160 137 158 176 161 173 100 129 101 149 167 125 133 166 141 110 160
 117
DER-A01B 61
 321 232 198 292 221 149 152 206 195 278 258 250 231 144 201 225 216 209 199 187
 210 176 165 149 211 235 175 216 207 223 172 129 183 167 198 199 142 161 149 140
 144 186 202 165 143 158 175 163 172  95 127 108 144 163 122 138 163 144 116 136
 130
DER-A02A 13
 128  83 127 121  98 106 105  88 109 118  91 103  79  87  98  79  96  81  92 105
 108 118 119 114  89  93 109 111 126 107  90  99 120 113  84 103  97  64  55  63
  46  57 104  88  92  75  92  83  88  70  77  79 103  72  89  88  98  71 103  84
  94  98  85  98 102  93  82  98  79  77  76  68  73  65  59  79  83  80  65  70
  67  64  58  70  84  94  98  76 114  94  86 106  84  78  91  98  73  90  80  91
  89  87  95  68  84  72  91  67  57  70  73  94  93  98 119 107  91  89  81  85
  68  91  87  79  76  89  88  98  81  92  92  97  68  89  75  77  79  87  95
DER-A02B 139
 116  88 118 130 107 123 101  98 109 127 102  98  87  80 102  70  87 102  86 101
 100 108 124 114  93 102 105 114 123 110  99  89 120 111  88 103  99  61  55  65
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DER-A03A 122
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 101  90
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DER-A04A 57
 328 270 137 130 225 223 209  95 104  73  59  83 142 164 222 218 241 260 267 311
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 317 234 270 226 289 187 199 169 264 242 205 160 172 181 172 188 109
DER-A04B 57
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DER-A05B 122
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DER-A06B 76
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  85  92
DER-A08B 102
 342 209 121  96 117 112  95  92  93  69  72  82  88  94  81  92  92  96 115  90
 116 132  98 121  97 117 132 108  97 100  85  93  74  79  73  59  64  85 101  90
  67  56  59  59  60  80  77  84  86  92 127  78  92  99  82  97  98 109 124 139
 109 102 104 111  97  83  99  76  92  87  69  93 109 100 105 110 118 120 103  97
  73  98  79 111  78  94  66 108  97 106  91  94  80 110 101 104  98  93  81 101
  98  72
DER-A09A 86
 117 210 202 142  80  78  67 117 191 238 152 143  66  68 101 184 127  85  74  47
  67  90  86  85  48  48  36  51 110 169 175 199 123  66  87  69  53  55  55  34
  16  26  33  44  59  76  74  78  83  46  49  45  61  80  93  55 114 103  87  50
  65  68  99  68  57  67  72  73 103 137 159 205 119 187 236 203 258 189 213 183
 217 250 142 175 110 129
DER-A09B 86
 112 202 210 142  81  77  76 107 190 247 155 138  64  70  99 183 134  85  65  51
  62  97  89  85  47  46  34  51 101 179 176 201 120  70  86  71  70  62  71  32
  25  19  27  49  64  68  74  69  79  45  58  37  63  91  93  57 109 111  77  50
  70  66  99  70  55  66  75  65 107 135 162 202 123 188 229 205 263 197 204 187
 224 256 135 176 102 115
DER-A10A 75
 135 183 109 116  84 126 166 119  97  85  71 125  82 152 141 140 128  83  53  94
  97 100 162  97  46  49  37  45  38  35  45  40  23  40  38  42  45  49  57  59
  51  72  58  36  59  48  58  84  87  84  69  55  57  44  22  24  45  45  41  50
  58  57  54  67  52  44  41  46  37  26  48  38  40  35  45
DER-A10B 75
 128 163 126 129  75 126 167 120 106 102  63 129  85 145 135 144 115  78  61  94
  91 104 161  98  43  45  39  45  49  37  43  40  29  37  33  40  48  56  46  65
  62  59  60  42  51  47  65  83  83  90  84  57  50  40  30  26  42  42  40  57
  51  56  58  64  56  47  36  46  35  30  56  30  41  31  50
DER-A11A 61
 228 258 221 145 105  82 137 185 153 108 120  98 131  79 119 138 148 106  86  87
 138 143 126 213 157  91  83  89  72  67  50  77  49  38  39  43  26  62  35  65
  84  78 107  79  88  85  90 121 186 177 153 166 144 158  95  47  37  48  63  59
  44
DER-A11B 61
 221 262 231 133 104  86 123 195 144 119 108  74 141  83 116 142 147 104  96  80
 136 144 140 209 161  74  96  80  81  67  46  83  44  35  43  43  26  52  49  63
  78  81 101  82  84  95  82 119 186 175 161 167 143 177  88  43  47  45  58  61
  41
DER-A12A 77
 396 223 314 150 139 171 144 282 213 152  90 132 100 213 198 318 375 368 301 242
 243 225 195 132 104 156 165 120 189 187 130  97 114  79 125 244 149  88 102  83
 130 101 145 132 145 142  78  76  77 109 111 143 101  36  55  39  59  54  37  46
  45  34  42  51  36  46  39  46  56  56  76  66  39  61  66  51  56
DER-A12B 77
 296 222 315 166 143 175 141 288 215 148  97 126  78 217 194 305 351 352 298 241
 246 226 195 134 103 157 167 121 186 183 129  95 118  78 124 244 148  93  94  83
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 135 100 150 131 142 141  81  74  80 102 116 147  97  39  54  38  54  60  33  48
  45  35  41  50  38  43  41  43  59  54  80  68  39  57  66  63  51
DER-A14A 95
 146 161 161 293 303 213 146 116 164 278 212 258 318 240 224 245 224 336 215 300
 334 313 299 390 333 196 205 247 263 241 265 260 205 211 153 160 131 109 136 139
 160 201 219 160 132 190 136 215 193 142 112  97 109 154 123 132  75  82  90  84
  81 103 118 100 111  83  61  78  61  53  34  33  42  55  23  35  39  56  86  76
  70  87  84  78  49  54  46  52  80  71  65  81  85  52  27
DER-A14B 95
 136 157 168 281 309 208 149 119 170 264 222 247 318 243 236 252 223 347 216 285
 336 313 312 385 336 211 207 245 261 253 271 255 204 212 153 159 130 106 135 137
 161 212 191 170 124 192 138 223 189 139 110  99 102 155 133 148  71  72  72  77
  82 108 100 111 111  85  62  78  51  47  39  40  39  43  30  40  41  45  58  83
  67  94  72  79  52  55  43  47  83  76  61  78  87  55  36
DER-A15A 73
 350 508 249 262 295 379 280 274 282 295 413 420 469 317 138 103 159 239 386 307
 161 155 146 148 193 316 378 340 263 226 200 215 159 184 182 155 166 143 180 179
 188 192 172 201 196 253 230 243 164 262 285 358 187 247 181 191 165 140 149 142
 155 133 186 313 174 216 214 218 151 149 120 127  96
DER-A15B 73
 356 498 253 260 298 374 288 283 281 292 436 424 472 330 135 116 161 233 376 301
 161 148 146 148 193 308 368 331 249 219 191 207 153 164 169 146 163 137 185 173
 193 189 181 192 207 245 231 223 175 256 282 363 195 261 173 185 148 147 141 150
 157 126 179 316 177 209 213 213 156 152 108 116 104
DER-A16A 101
 630 503 602 596 460 515 433 562 561 523 513 478 397 391 380 382 286 246 398 402
 317 271 229 259 288 329 237 332 130  68  73 138  88 146 176 182 229 133 104 184
 174 131 114 193 117 122  93 125 204 185 119 152 105  70  67  79  57  93  73 108
 120 122  87 122 173 143 114 109 112  91  83 106 118 109  92 113  98 106  82 154
 122 132 133 111 131 108 162 158 114 170 134 115 126  84  93 141 121 125  91  94
 103
DER-A16B 101
 637 544 574 581 497 517 430 576 553 558 506 442 387 395 388 389 296 247 419 384
 332 275 228 251 302 324 233 333 124  70  77 126 102 143 176 181 224 138  99 185
 182 127 115 189 123 124  91 128 208 183 118 150 107  65  68  78  61  85  71 106
 134 125  89 127 160 138 110 135 103  93  71 105 121 110  90 119 102  99  77 148
 122 129 137 118 132 104 171 146 116 170 135 118 122  88  87 150 121 133  93  96
 139
DER-A17A 66
 231 334 319 298 387 257 302 265 250 362 299 357 318  93  98 121 215 540 448 200
 137 155 167 144 247 313 272 230 226 219 219 197 229 242 242 241 179 233 229 282
 252 228 236 263 444 336 319 209 283 329 438 251 321 250 240 216 173 243 272 244
 216 233 341 231 271 293
DER-A17B 66
 214 337 314 292 394 263 301 261 249 367 291 362 312 111  85 123 202 492 434 200
 129 158 166 146 245 309 274 226 237 203 214 204 232 247 246 239 178 243 228 281
 244 237 228 257 467 336 352 201 288 349 429 255 292 262 226 230 178 245 259 238
 221 236 338 234 272 292
DER-A18A 73
 173 182 118 107 188 210 235 315 174 163 234 214 134  87  98 119 169 184 210 203
 187 126 192 165 245 206 182 237 267 241 243 136 214 181 211 264 299 284 201  90
 108 104 123 152 120 103 145 193 202 167  87  74 163 154  90 133 119 154 188 171
 222 138 112 160 172 171 171 240 236 199 153 184 213
DER-A18B 73
 166 186 115 111 180 208 242 306 171 170 256 206 138  73  85 107 182 213 218 187
 182 112 182 138 236 202 195 222 291 244 255 161 236 176 210 262 290 297 184 110
 112 109 129 172 113 103 152 196 191 175  51  88 148 144  94 119 145 155 198 162
 240 139 110 152 163 180 179 233 230 180 190 166 216
DER-A19A 49
  87 144 319 272 240 208  94 189 258 191 205 196 147 246 242 191 175 254 282 199
 252 220 246 166 176 228 253 212 135 201 218 176 231 182 159 120  97  88 125 170
 181 153 207 124 151 189 127 110 157
DER-A19B 42
 211 297 316 234 214 225 267 191 218 237 243 207 195 196 217 208 214 180 150 136
 120 105 156 209 165 133 193 102 165 192 122 102 160 121 124 107 163 109 144 136
 135  86
DER-A20A 61
 192 155 207 303 256 198 238 273 222 215 340 375 319 333 420 325 204 197 190 234
 301 162 273 236 165 129 210 240 322 236 207 218 181 154 137  78  73  54  97  94
 118  81  96  62  97  83  85  47  70  72 151 133 127 105 107 129  57  46  45  52
  51
DER-A20B 61
 174 155 208 306 252 189 245 275 223 222 331 383 326 333 421 315 200 198 198 231
 291 124 312 235 152 144 207 246 305 239 212 220 182 153 137  73  76  53  97  91
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 113  71  88  69  97  82  95  55  67  76 142 121 134 100 113 119  56  46  67  74
  41
DER-A21A 66
 140  64  19  24  65 139 197 248 184 103  84  68 108 183 273 255 259 227 183 112
  87 103 127 174 230 212 341 168 102 126 265 281 226 243 235 277 160 225 253 139
  85 160 192 226 157 123 207 200 215 199 264 209 168 168 130 167 136 129 199 162
 129 107  93 107  65  71
DER-A21B 66
 158  51  23  24  68 142 212 212 159 105  71  77 102 207 281 257 261 227 178 115
 102  81 122 173 224 211 330 172 102 121 268 295 235 251 239 273 158 225 256 138
  85 154 189 235 164 116 196 192 212 191 255 219 154 172 133 167 144 148 187 162
 125 107 100 103  80  58
DER-A22A 62
 288 291 224 210 307 283 238 269 180 187 229 228 299 185 163 213 182 221 177 230
 305 359 279 210 247 267 338 185 200 216 210 116 136 139 121  95 139 173 177 154
 136  97  98 102  96 152 139 110  89  78  64  63  82  71  47  77  79  67  59  66
  69  89
DER-A22B 62
 302 296 228 217 303 279 240 270 179 184 238 242 293 196 163 224 177 209 174 229
 301 366 285 191 244 274 335 179 211 213 208 129 123 153 113  94 156 183 179 164
 128  94 103 121 119 139 153 109  97  76  73  42  90  76  46  73  84  70  61  65
  60  85
DER-A23A 49
 259 301 389 262 206 191 264 334 265 227 266 195 237 128 176 218 232 267 244 247
 248 301 218 227 261 269 192 172 169 157 122 141 188 186 196 176 134 130 158 142
 146 191 108  94 127  70  70 150 114
DER-A23B 49
 240 326 397 271 210 193 269 331 261 225 273 188 232 130 179 212 236 259 252 249
 242 312 220 233 243 279 188 188 166 157 117 143 189 191 204 179 146 126 162 146
 157 166 122  91 120  77  67 150 115
DER-A24A 73
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 162 241 176 157 280 314 194 208 329 336 228 174 320 396 583 303 494 390 236 185
 281 310 384 238 226 264 250 196 166  76  64  68 124  78 113  72 106  89 151 117
 139  65 100 100 165 157 174 161 169 225 102  90 114
DER-A24B 73
 126 222 150 223 136  82 155 268 424 313 159 154 210 117 160 132 193 243 200 183
 145 244 179 159 275 318 193 208 327 334 232 191 304 402 589 308 483 402 246 189
 293 309 362 233 208 285 225 184 186  76  63  60 130  92  96  76  94 110 162 113
 146  68  87 103 170 151 180 147 159 225  86  90 113
DER-A25A 58
 185 314 338 484 438 531 443 395 325 407 463 481 323 260 312 226 154  92 111 166
 126 156 138 159 140 190  94 113 104  94  78  96  66  64  39  43  64  83  92  96
  61  67  72  91  65  77  85  48  45  51  61  72  79  52  74  57  55  52
DER-A25B 58
 174 316 345 458 438 538 444 392 326 404 472 470 326 269 300 225 160  66 129 168
 124 160 130 170 146 177  93 111 104  90  79  94  75  56  47  43  57  82  88  85
  75  61  80  78  74  74  87  45  46  48  67  72  85  46  76  58  51  54
DER-A26A 93
 202 282 207 110 200 205 128 216  91  94 102 157 227 137 174 163 124 196 158 118
 141 114 117 118 174 182 183 176 162 137 185 138 135 126  40  89 108 129 113 151
 171 133 117  98 131 162 104  92 118  81 116 139  85 106 171 110  50  85 107 132
  91  81  77  90  74  76  64  86  85  71 101  74  82  88 111  93 106 109  97  96
  85  60  70  79  85  66  64  61  56  84  57  58  28
DER-A26B 93
 214 272 208 107 185 209 133 226 104  81 103 165 220 133 177 174 151 190 163 100
 141 129 124 113 167 181 185 152 144 145 182 142 131 124  61  78 128 129 102 155
 170 146 103 111 126 162  96 104 111  88 107 139  94  99 169 116  49  87 101 132
  95  85  80  84  83  77  70  81  83  73  85  86  70 101 104  86 108 106 101  93
  71  43  98  86  75  80  53  58  67  76  61  51  27
DER-A27A 105
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  94  91 132 157 173 136 189 204 119 133 134 128 157 156 108 123 172 112 134 142
 121  97 112 125 106  92  61  83  72 102 109 106  95  80  84  92 105 124  83  76
  74  58  65 108  75  99 117  59  46  55  86 106  63  78  63  71  71  64  69  80
  75  51  64  43  56  55  87  71  80  70  66  43  41  43  57  48  55  58  71  61
  42  68  60  50  22
DER-A27B 105
 154 151 237 243 215 140 145 183 108 122 136 178 190 225 120  82 134 171 151 204
 103  80 129 141 176 127 207 180 137 126 123 131 151 142 107 140 156 112 127 142
 125  99 103 130 106  91  60  88  71 103 106 105  91  73  84  88  96 117  77  75
  77  65  58 114  73  93 116  74  50  57  71  97  56  78  62  73  70  69  62  71
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  46  63  60  65  19
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DER-A28A 77
 243 203  90 126 147 160 219 113  94 111 119 228 145 247 258 204 191 169 150 141
 177 140 158 227 223 206 279 255 189 233 240 167 180  89 133 143 170 142 126 157
 132 148 137 151 173  84  94  87  67  88 128 115 149 215 126  67  65  78 101  53
  61  50  63  55  64  65  84  82  71  73  66  54  78 111  82  96  74
DER-A28B 65
 210 161 184 175 193 169  91 125 154 151 140 143 165 144 157 149 163 209  96  97
  93  63  92 110 122 139 199 133  65  62  68  99  48  58  55  61  50  56  58  71
  84  63  52  58  65  75 113  94  96  80  87  73  56  37  67  60  51  97  88  76
  38  84  79  76  30
DER-A29A 84
 162 128 161 203 112 167 111  86  63  71  46  47  49  45  45  72 125 140 171 191
 153 141 130  83  91  83  83 103  93 104 102 110  99  87  63  98 118  83  67  65
  54  69  85  84 124 158 126  86  77  71  88  59  67  78  60  60  62  53  71  80
  76  90  88  84  82 100  89 108  96  86  96  82  58  69  84  83  84  81  81  65
  79  85  99  80
DER-A29B 84
 160 119 186 197 157 157 113  86  54  77  46  57  48  59  37  67 132 151 171 200
 142 138 134  84  94  76  82 106 100  98 128 120 103  86  64  97 115  79  71  61
  58  75  71 100 115 147 129  76  77  75  90  59  65  81  63  64  54  58  68  91
  82  92  88  88  66 108  90 109  91  99  89  85  52  73  85  79  86  73  83  59
  84  77 105  72
DER-A30A 100
 178 181 109 176 273 221 232 201 186 184 130 134 194 166 222 157 101 163 220 240
 222 207 139 115  85 100  67 106  81  81  75 102 148 162 156 110  97  85  73  85
  65  52  84 123 136 131 138 150  85  82  73  96 130  63  65  50  70  64  69  72
  92 101  60  47  49  39  46  41  43  29  24  37  47  33  35  43  37  39  25  31
  28  37  35  27  25  27  32  31  38  27  31  25  49  39  42  37  61  46  51  25
DER-A30B 100
 162 181 112 175 276 222 237 199 191 175 134 137 192 169 217 151 104 157 217 258
 233 216 156 134  80 111  73 119  82  80  85  97 149 157 142 102  99  90  74  85
  71  57  76 117 143 124 143 143  93  76  82  92 134  56  72  54  61  73  68  71
  92 112  51  42  44  47  46  31  42  34  34  32  38  39  39  29  38  32  28  35
  33  30  29  31  25  31  32  30  31  30  29  36  45  37  43  42  53  51  45  27
DER-A31A 50
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 167 261 203 205 147 126 101  88 146 245 357 250 126 235 249 297 168 320 203 240
 268 326 286 291 235 167 245 141 152 205
DER-A31B 50
 146 285 215 110  69  82  43  41  48  60 127 124  92 209 156 100  81 187 289 297
 147 275 202 214 140 124 104  85 151 243 361 250 138 236 248 291 183 347 214 216
 254 324 286 281 216 164 246 134 153 202
DER-A32A 51
 193 480 307 124 183 241 428 201 413 315 228 201 215 318 392 230 219 249 237 152
 169  88  84  59 130 188 172 280 259 144 243 208 183 105 127 116 224 219 192 125
 221 177  76  81  84 144 165 117 237  94 181
DER-A32B 51
 196 462 315 110 188 245 463 210 409 312 248 189 217 312 396 250 210 249 250 150
 172  82  90  50 139 187 163 284 245 148 251 193 194  96 125 106 212 210 184 133
 224 173  71  84  84 156 170 117 234  98 173
DER-A33A 52
 189 238 200 144 397 522 285 249 277 355 460 302 464 324 172 123 276 290 385 267
 251 320 221 229 197 125  42  84  94 124  79 126  79 125 100 127  74  96  75 150
 140  97  94 171 138  85  71  84  99 125  99 143
DER-A33B 52
 189 246 193 147 315 507 297 252 271 347 430 297 474 313 177 140 261 291 391 273
 263 289 220 227 204 123  43  88  86 116  87 130  80 113 105 130  69 100  71 148
 140  94  97 170 153  88  74  77 108 118 107 140
DER-A34A 51
 250 356 362 402 385 507 372 287 273 175 269 232 136 211 171 115  69  92  81 145
  98  97  50  65  35  98  79 125 163 114 130 104 104 125 194 187 133 164 111 133
  91  91 126  78  62  53  49  33  57  64  73
DER-A34B 51
 243 349 362 390 382 467 321 320 270 161 263 231 153 213 156 133  79  93  73 153
 102  95  53  63  38  96  78 129 159 103 129 102 106 127 186 183 134 159  99 136
  99  87 132  77  66  60  51  26  59  58  68
DER-A35A 52
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 192 240 239 211 173 199 149 132 192 134 133 108 112
DER-A35B 52
  78 138 228 225 264 186 218 255 368 323 286 159 144  42  54  58  64  98 174
 113 105  71 185 276 274 317 336 268 318 185 141 129 223 249 175 211 255 178 163
 181 229 245 215 182 213 153 133 193 131 106 104 107
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular 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,

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

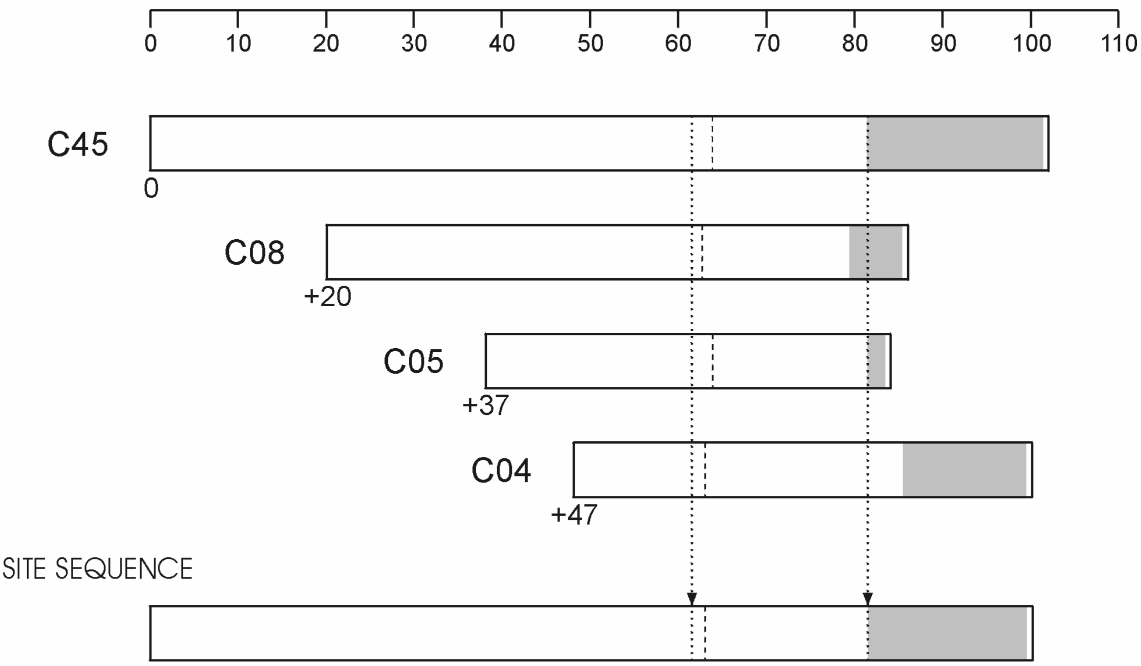


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

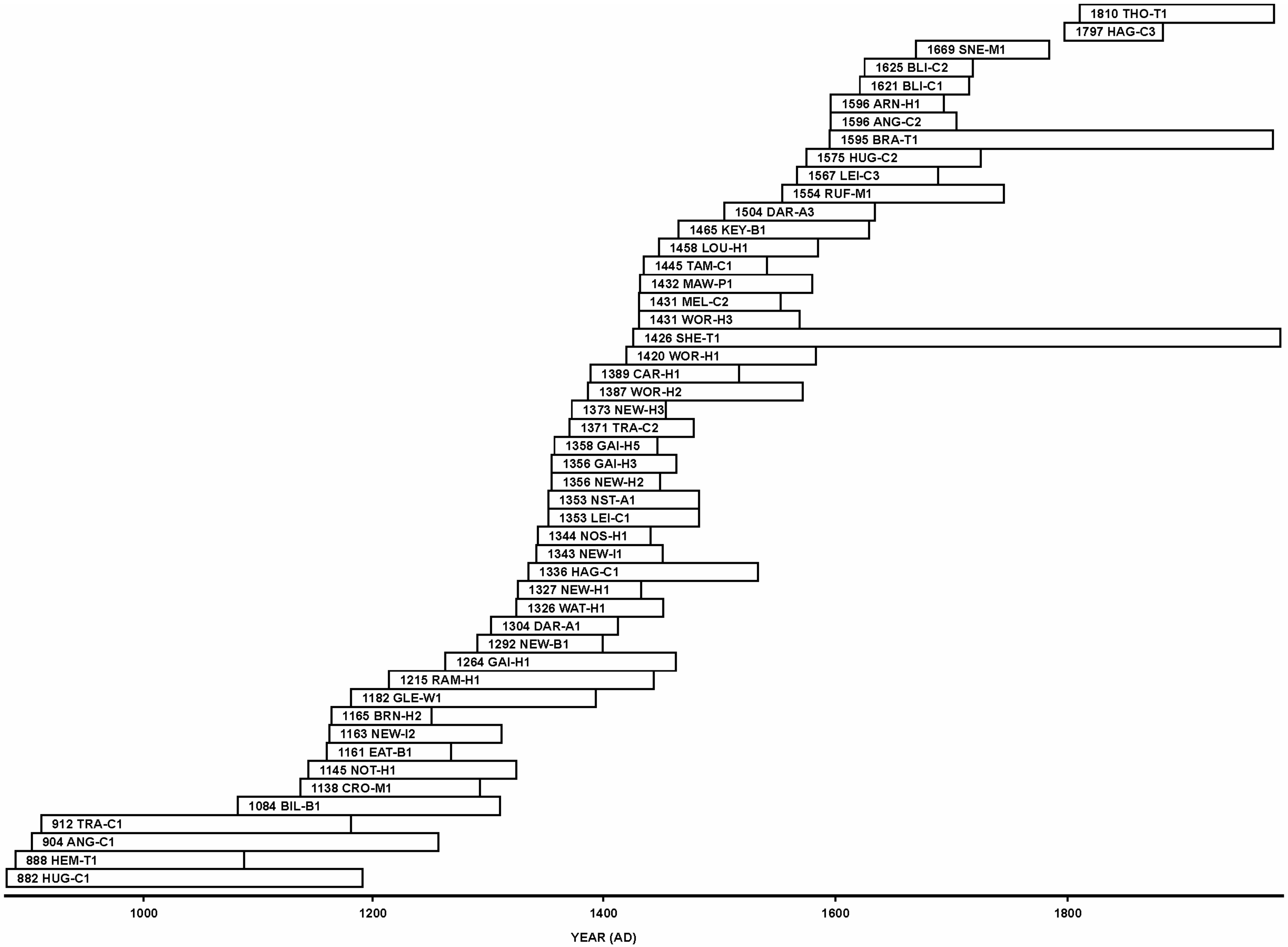
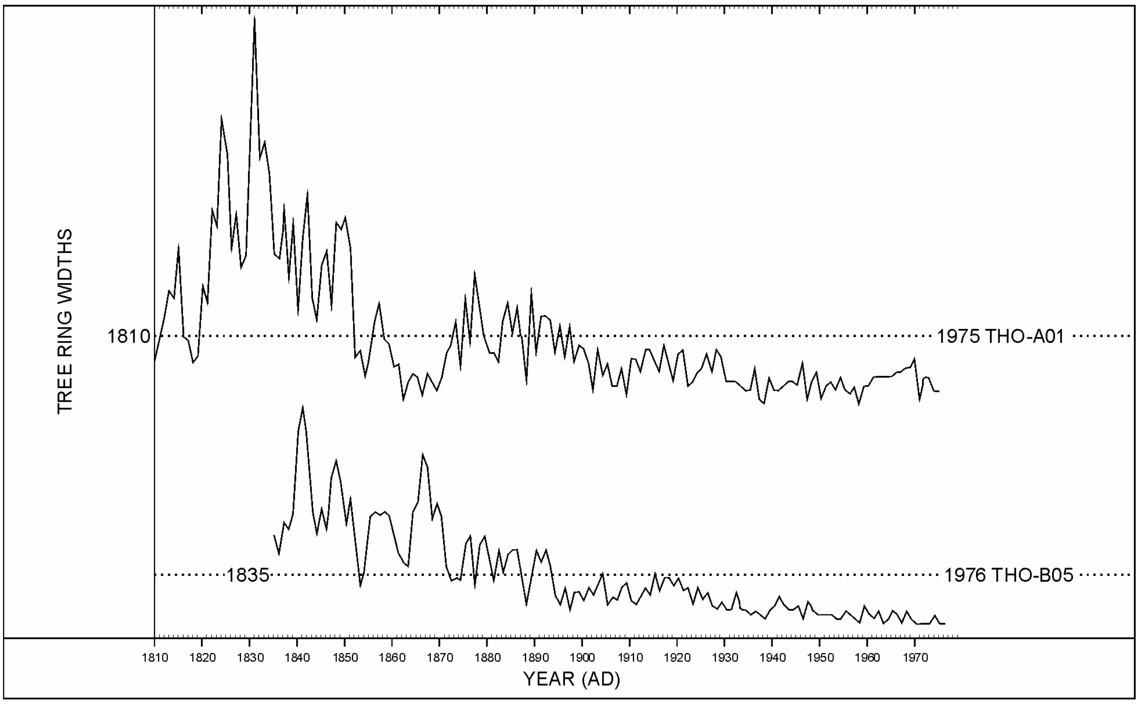


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

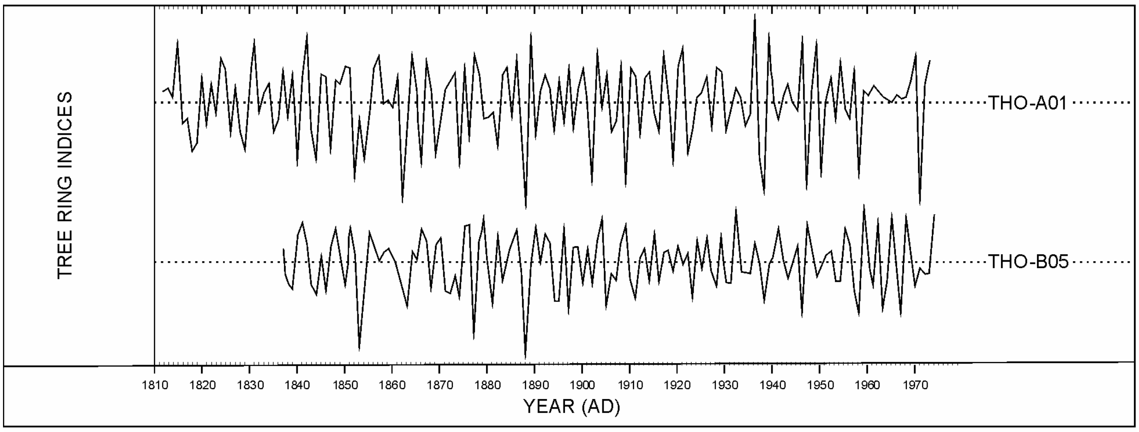


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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