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Brook Hall, 27 Broad Street, Leominster, Herefordshire

Tree-ring Dating of Oak Timbers

Alison Arnold, Robert Howard and Cathy Tyers

Scientific Dating

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Summary

Dendrochronological analysis was undertaken on samples taken from this building resulting in the successful dating of 15 timbers from the main and north range roofs. The results demonstrate that the two ranges are broadly contemporary, utilising timber felled in AD 1570–95 (main range) and AD 1575–97 (north range).

A small number of timbers from a potentially secondary phase is undated.

Contributors

Alison Arnold, Robert Howard, and Cathy Tyers

Acknowledgements

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Front cover image

Brook Hall, Leominster. [© Mr John Burrows. Source: Historic England IOE01/10551/19]

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Contact details

Alison Arnold and Robert Howard, Nottingham Tree-ring Dating Laboratory, 20 Hillcrest Grove, Sherwood, Nottingham NG5 1FT
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Cathy Tyers, Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA cathy.tyers@historicengland.org.uk

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Introduction

Leominster High Street Heritage Action Zone

The Herefordshire town of Leominster, located 19km north of Hereford and 11km south of Ludlow (Fig 1) has a high number of listed buildings. Historic maps indicate that the majority of the buildings fronting the High Street, Corn Square, and those streets immediately off it have changed little since at least the mid-nineteenth century with many of them thought to have far earlier origins hidden behind later frontages.

The town is one of over 60 successful High Street Heritage Action Zones (HSHAZ) bids selected in 2019, which is being delivered by Historic England to unlock the potential of high streets across England, fuelling economic, social, and cultural recovery. Dendrochronology is one of the supporting elements to the HSHAZ programme to improve the understanding of the town centre area to inform and support future planning and improvement decisions.

Brook Hall

This Grade II-listed building (List Entry Number: 1255393) is located on the western side of Broad Street at the junction with Vicarage Street (Fig 1) and is situated within the Leominster Conservation Area. It consists of a two storey plus attic front range, orientated roughly north-south, and, at its north end, a coeval cross-wing, jettied at first-floor level (Figs 2 and 3). It is thought to be a mid- to late-sixteenth century timber-framed building refronted in the late-nineteenth century.

Front range roof

The roof over the front range consists of five principal rafter and tiebeam trusses with high collars and queen posts, between which are a double tier of quasi-trenched purlins (Fig 4). Above two of the principal rafters on the east side are later principal rafters and purlins which have altered the pitch on the roof (Fig 5). These are a modification related to the refacing of the timber framing with a brick façade. This additional wall thickness, along with the over-hang at the eaves made it necessary to fit longer rafters, hence the slight reduction in pitch on the east side (Duncan James pers. comm.).

North range roof

The north range roof is of the same form as that over the front range, consisting of four principal rafter and tiebeam trusses, with high collars and queen posts (Fig 6). This range once extended further west but was part demolished in the 1930s and replaced by a large meeting hall (James 2016).

Sampling

Dendrochronological investigation was requested by Rebecca Lane, Historic England Senior Architectural Investigator, as one of the supporting elements to the High Street Heritage Action Zone programme to inform the conservation and repair towards the future care of this space.

Samples were taken from 22 oak timbers (*Quercus* spp), from the main and north range roofs, with each being given the code LEO-A and numbered 01–22. Four of these were taken from timbers which might represent a later alteration (LEO-A13–16). Details relating to these samples can be found in Table 1 with location of sampled timbers marked on Figure 3. Trusses have been numbered from north to south (main range) and east to west (north range). Initial assessment had also identified some ceiling beams on the first floor, however, access to these were deemed too disruptive for the tenant and it was decided that sampling was unnecessary due to these being considered contemporary with the main roof.

Analysis and Results

During analysis it was noted that four of the samples, three from the ‘later’ alterations and one from the north-range roof, had too few rings (<30) to make successful dating a possibility, and so were rejected. Some samples broke during sampling and those where the break was clean were glued using a poly vinyl acetate (PVA) wood adhesive. Eighteen 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 measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 15 samples grouping at a minimum value of t = 5.7.

These 15 samples were combined at the relevant offset positions to form LEOASQ01, a site sequence of 199 rings (Fig 7). This site sequence was then compared against a series of relevant oak reference chronologies at which point it was found to match consistently and securely at a first-ring date of AD 1376 and a last-measured ring date of AD 1574. The evidence for this dating is given by the t – values in Table 2.

Attempts were then made to date the remaining three measured but ungrouped samples by comparing them individually against the reference chronologies, but these were unsuccessful and all remain undated.

Interpretation

Tree-ring dating has resulted in the successful dating of 15 samples from the main and north range roofs (Fig 8). To aid interpretation these have been dealt with by area, below. Felling date ranges have been calculated using the estimate that 95% of mature oak trees in the area have between 15 and 40 sapwood rings.

Front range roof

Ten of the samples taken from this roof have been dated, four of which have the heartwood/sapwood boundary. The dates are broadly contemporary, varying from AD 1549 (LEO-A07) to AD 1560 (LEO-A12), and suggestive of a single felling episode. The combined average heartwood/sapwood boundary ring date is AD 1555, allowing an estimated felling date to be calculated for the four timbers represented to within the range AD 1570–95. The other six samples from this roof do not have the heartwood/sapwood boundary ring but with last-measured heartwood ring dates ranging from AD 1448 (LEO-A06) to AD 1541 (LEO-A02), several being clustered in the first half of the sixteenth century, these would have estimated *termini post quem* for felling dates of (at the earliest) AD 1463 to (at the latest) AD 1556. All of these *terminus post quem* dates for felling make it possible that they were also felled in AD 1570–95. The cross-matching between individual samples within this group produces a number of *t*-values in excess of 7.0 which lends support to the likelihood that all ten dated timbers were part of the same felling episode.

North range roof

Five of the samples from the north range roof have been successfully dated, two of which have the heartwood/sapwood boundary: LEO-A20 at AD 1549 and LEO-A19 at AD 1564. The average heartwood/sapwood boundary ring date is AD 1557, allowing an estimated felling date to be calculated for the two timbers represented to within the range of AD 1575–97. This felling date range takes into account sample LEO-A19 having a last-measured ring date of AD 1574 with incomplete sapwood. The other dated samples from this roof do not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated for them. However, with the last-measured ring dates of AD 1464 (LEO-A21), AD1496 (LEO-A22), and AD 1529 (LEO-A18) these would be estimated to be, at the earliest AD 1479, AD 1511, and AD 1544, respectively. Again, these *terminus post quem* dates for felling make it possible that these were also felled in AD 1575–97, an interpretation that is supported by the level of cross-matching between individual samples within this group, with several *t*-values in excess of 6.0.

Discussion

The timbers of the front range roof and the north range roof can be seen to be broadly contemporary, dating to AD 1570–95 and AD 1575–97, respectively. This suggests construction of the two ranges occurred in the later-sixteenth century as had been suggested on stylistic grounds. Indeed, the intra-site matching seen between the components of LEOASQ01 is generally of a level one would expect to see within a coherent series of trees felled at the same, or close together in-time and from the same woodland source. The location of this woodland source, however, cannot be stated with certainty but, given the location of those reference chronologies against which LEOASQ01 matches most highly (Table 2), it is likely to be relatively local, as was usual during this period.

It is unfortunate that, of the four samples taken from the possibly secondary roof timbers from the front range, three were unsuitable for analysis having too few rings for secure dating, and the fourth is undated. This might suggest a different date and/or source for the timber utilised as the trees used in the primary-main, and in the north range roofs, are reasonably long lived, whereas those from the secondary timbers are notably faster grown (wider growth rings).

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Tables

Table 1: Details of tree-ring samples from Brook Hall, 27 Broad Street, Leominster, Herefordshire.

Sample number	**Sample location**		**Total rings**	**Sapwood rings**	**First measured ring date (AD)**	**Last heartwood ring date (AD)**	**Last measured ring date (AD)**
	Front range						
LEO-A01	East principal rafter, truss 1		91	--	1430	----	1520
LEO-A02	West principal rafter, truss 1		161	--	1381	----	1541
LEO-A03	East queen post, truss 2		98	h/s	1454	1551	1551
LEO-A04	West queen post, truss 2		109	02	----	----	----
LEO-A05	West purlin, truss 2-3		92	--	----	----	----
LEO-A06	East principal rafter, truss 3		63	--	1386	----	1448
LEO-A07	West principal rafter, truss 3		143	h/s	1407	1549	1549
LEO-A08	East queen post, truss 3		93	--	1406	----	1498
LEO-A09	West queen post, truss 3		126	h/s	1433	1558	1558
LEO-A10	East purlin, truss 3-4		78	--	1456	----	1533
LEO-A11	East principal rafter, truss 4		86	--	1438	----	1523
LEO-A12	West principal rafter, truss 4		145	04	1420	1560	1564
	Potentially later phase						
LEO-A13	East principal rafter, truss 1A		NM (16)	--	----	----	----

LEO-A14	East principal rafter, truss 3A		NM (15)	--	----	----	----
LEO-A15	East lower purlin		NM (26)	--	----	----	----
LEO-A16	East upper purlin		48	h/s	----	----	----
	North range						
LEO-A17	South upper purlin, truss 7-8		NM (29)	--	----	----	----
LEO-A18	North principal rafter, truss 8		154	--	1376	----	1529
LEO-A19	South principal rafter, truss 8		127	10	1448	1564	1574
LEO-A20	Collar, truss 8		80	h/s	1470	1549	1549
LEO-A21	South queen post, truss 8		63	--	1402	----	1464
LEO-A22	South upper purlin, truss 8-9		97	--	1400	----	1496

NM = not measured, ring count is given in brackets; h/s = the heartwood/sapwood boundary is the last ring on the sample.

Table 2: Results of the cross-matching of site sequence LEOASQ01 and example reference chronologies when the first-ring date is AD 1376 and the last-measured ring date is AD 1574.

Site reference	***t* – value**	**Span of chronology AD**	**Reference**
Wigmore Abbey, near Adforton, Herefordshire	13.4	1055–1729	Tyers 2002
Lower Brockhampton Manor, near Bromyard, Herefordshire	11.6	1304–1505	Arnold and Howard 2014 unpubl
St Swithun's Church, Clunbury, Shropshire	11.6	1239–1494	Tyers 2000
White House, Vowchurch, Herefordshire	11.6	1364–1602	Nayling 1999
Porch House, Bishops Castle, Shropshire	11.4	1416–1564	Miles and Worthington 2000
Black Ladies, near Brewood, Staffordshire	10.7	1372–1671	Tyers 1999
Stokesay Castle, Shropshire	9.9	1449–1640	Miles and Worthington 1997
St Michael's Church, Knighton on Teme, Worcestershire	9.9	1326–1516	Arnold and Howard 2016
Gatley Park, near Leominster, Herefordshire	9.9	1365–1516	Tyers 1991
St Barnabas Church, Brampton Bryan, Shropshire	9.8	1233–1622	Arnold *et al* 2021a
Kingsbury Hall, Kingsbury, Warwickshire	9.5	1391–1564	Arnold and Howard 2006
Ribbesford House, Worcestershire	9.4	1366–1535	Arnold *et al* 2021b

Figures

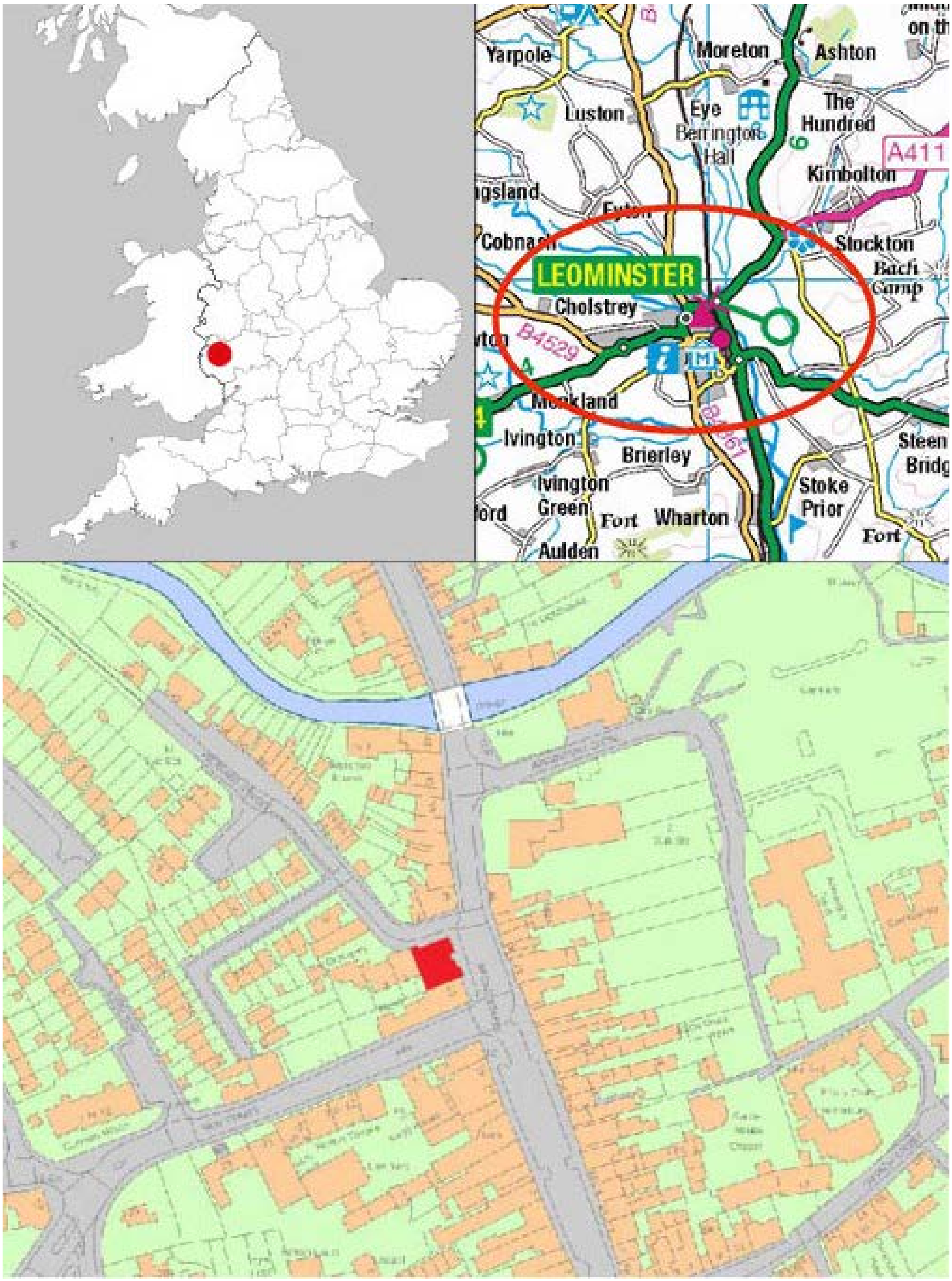

Figure 1: Maps to show the location of Brook Hall at 27 Broad Street in Leominster, Herefordshire, marked in red. Scale: top right 1:105,000; bottom: 1:1,600. © Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900.

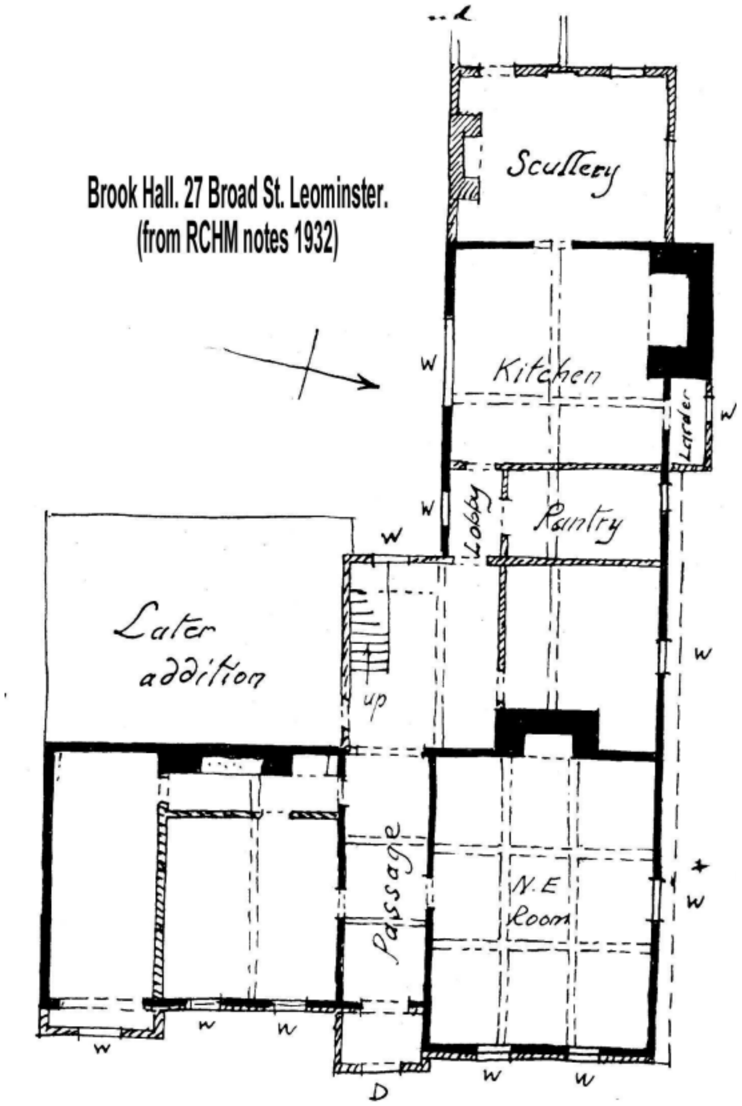

Figure 2: Ground-floor plan of Brook Hall (RCHM 1932) [H.M.S.O 1934]

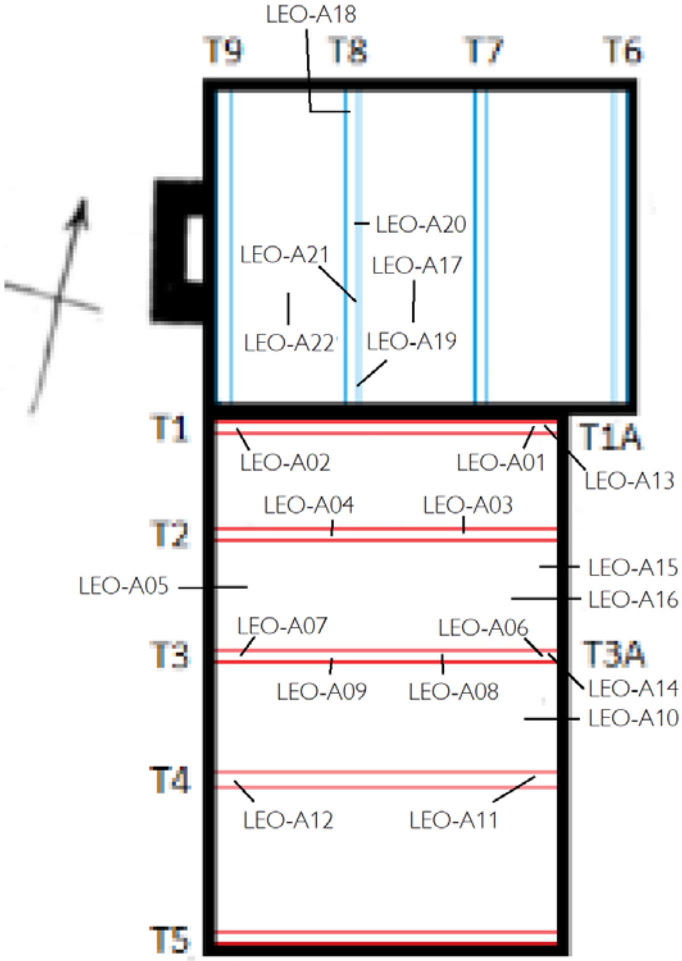

Figure 3: Sketch plan of Brook Hall at attic level, showing the approximate position of trusses and sampled timbers.

Figure 4: Main range roof, photograph taken from the south. [Alison Arnold]

Figure 5: Potentially 'secondary' rafters behind timbers of the primary range roof, truss 1 / 1A, photograph taken from the south. [Alison Arnold]

Figure 6: North range roof, photograph taken from the east. [Alison Arnold]

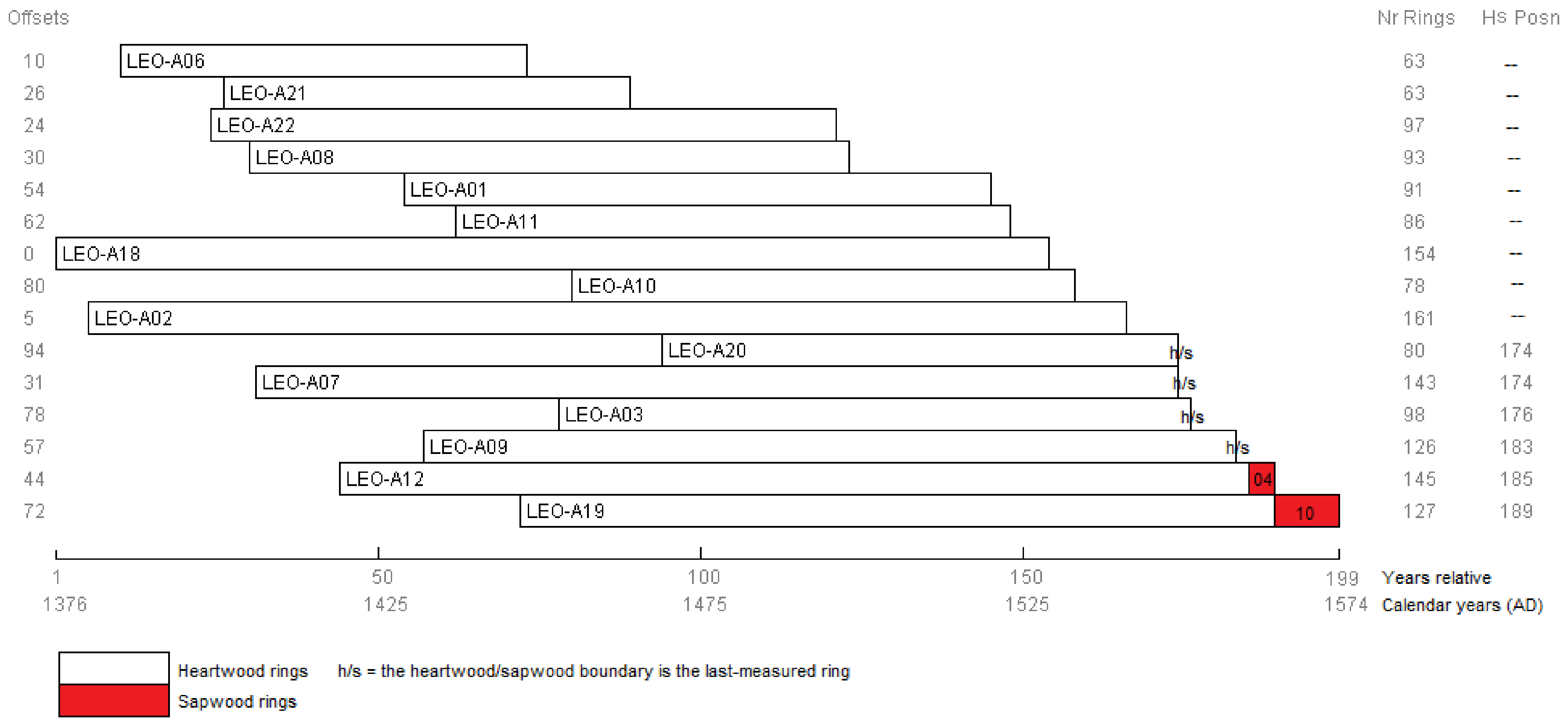

Figure 7: Bar diagram of samples in site sequence LEOASQ01.

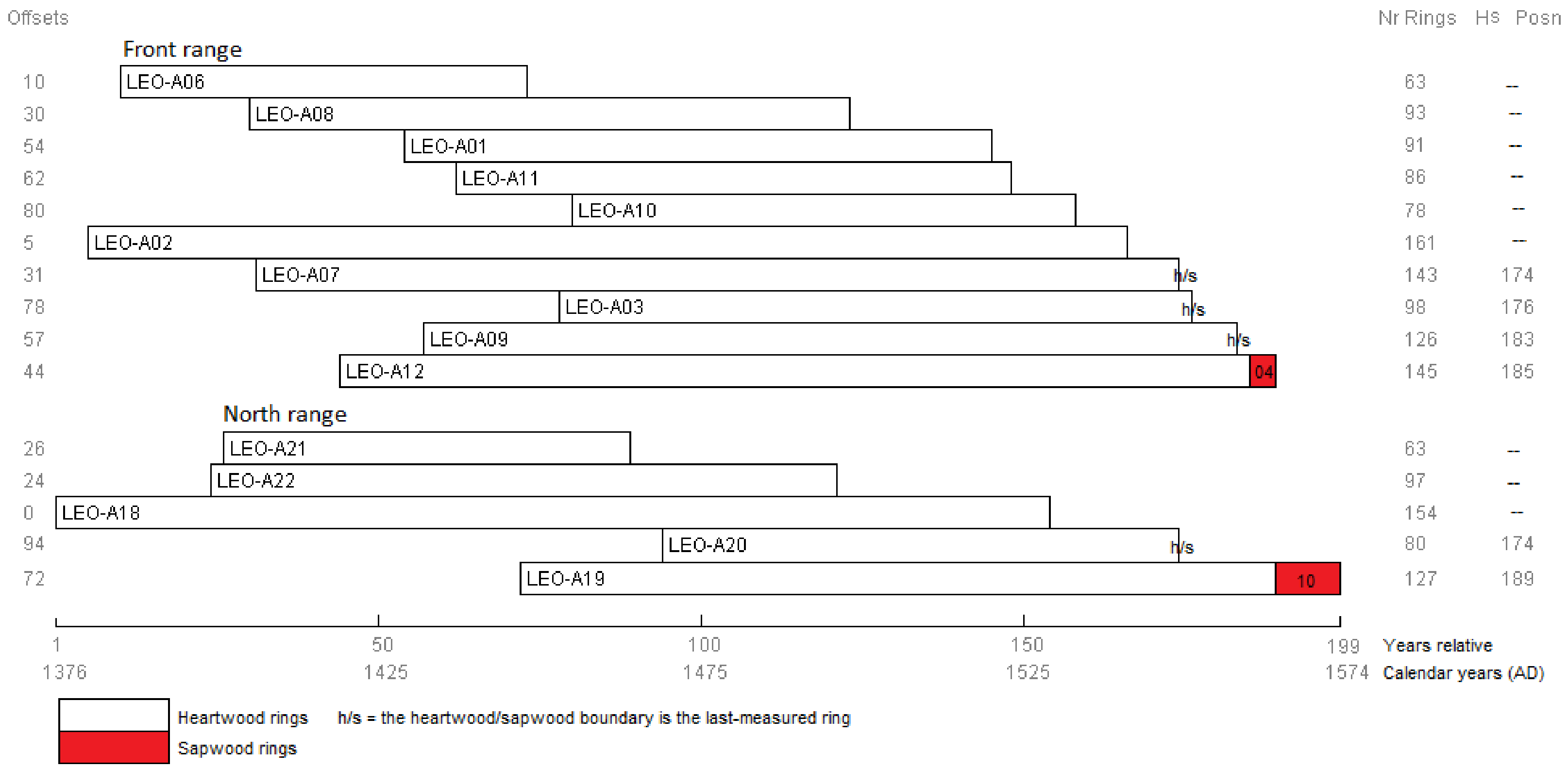

Figure 8: Bar diagram of all dated samples, sorted by area.

Data of Measured Samples

Measurements in 0.01mm units

LEO-A01A 91
221 204 226 171 184 189 217 256 300 217 272 191 167 190 219 217 202 189 180 164
179 196 167 162 199 170 180 186 132 92 146 148 131 164 138 126 159 184 181 153
152 167 128 117 152 187 146 140 130 115 102 146 135 123 84 58 71 80 69 65
61 52 67 95 88 128 153 110 99 99 94 97 115 137 130 108 131 109 105 113
124 158 130 109 134 94 102 114 159 136 119
LEO-A01B 91
222 193 228 182 191 163 220 253 310 227 274 191 168 205 213 220 199 194 189 164
182 197 167 149 198 171 189 187 132 105 131 136 124 159 148 128 159 187 180 143
149 166 127 128 141 165 165 141 135 113 102 148 131 125 82 59 70 79 71 66
61 53 66 95 90 129 157 104 98 103 94 105 133 119 130 113 130 107 102 115
126 136 133 114 138 96 108 116 159 133 140
LEO-A02A 161
136 118 144 198 187 174 146 160 125 125 168 126 131 93 77 71 98 128 121 132
107 112 123 121 109 104 96 106 131 126 78 100 85 94 111 99 121 91 83 99
105 101 129 112 95 88 79 108 129 123 108 122 88 95 100 95 106 103 81 87
111 94 127 143 123 99 136 126 109 119 108 109 119 116 118 145 165 76 54 91
96 93 111 74 83 110 109 121 106 93 117 88 85 86 117 136 97 135 111 85
109 98 116 77 72 97 105 75 73 61 69 65 86 70 83 112 85 88 100 82
94 80 100 94 96 94 93 111 106 102 99 94 84 94 88 100 82 96 106 79
93 97 84 91 108 112 73 93 117 107 188 133 161 154 153 118 133 180 198 294
159
LEO-A02B 161
128 120 150 189 200 175 149 152 113 135 142 136 133 88 79 68 100 125 122 129
120 111 130 112 99 112 92 110 135 133 76 97 86 91 106 97 119 103 80 113
104 102 129 114 97 98 77 111 125 123 111 119 80 98 106 96 99 111 74 99
120 91 126 134 123 103 142 130 110 123 117 105 114 120 120 136 139 97 54 86
97 89 116 74 85 104 116 117 100 102 118 89 84 88 119 135 91 129 122 80
113 101 108 84 71 94 106 81 64 72 66 58 87 74 80 112 88 92 99 82
95 82 96 102 94 89 94 98 112 104 98 93 86 95 90 101 80 101 102 79
92 96 79 100 110 103 79 93 113 115 187 129 155 151 152 121 133 170 189 232
161
LEO-A03A 98
248 226 256 203 168 133 169 173 128 145 104 128 125 148 129 116 139 127 113 81
89 124 134 120 127 180 154 158 143 168 174 164 166 176 160 153 176 168 136 169
166 206 177 172 113 174 145 120 113 134 143 136 162 168 183 167 122 141 192 136
115 107 103 96 95 119 102 115 122 103 90 97 101 106 117 102 89 125 81 91
79 86 99 76 106 93 107 106 91 96 78 86 89 83 74 89 69 96
LEO-A03B 98
257 223 264 203 166 130 165 165 131 152 101 119 129 152 128 119 137 130 107 87
85 130 138 134 119 175 150 157 141 174 169 176 156 180 161 151 181 159 130 167
169 201 175 167 118 176 158 122 105 133 157 126 157 159 180 149 123 149 178 131
118 113 100 100 86 127 104 110 125 101 89 100 95 108 123 99 93 110 86 104
89 79 102 80 98 99 105 111 94 94 81 78 87 76 83 95 83 91
LEO-A04A 109
252 212 290 251 235 239 198 210 195 217 213 89 91 116 74 78 103 113 121 114
100 96 101 110 95 96 111 111 115 145 177 183 163 151 151 128 136 156 165 253
225 195 186 137 130 124 99 100 130 140 136 186 165 161 154 132 137 137 169 195
162 182 141 149 189 153 190 160 181 203 125 128 134 188 175 148 168 183 132 135

103 116 103 106 111 105 110 112 120 128 125 120 113 108 118 91 98 111 125 165
171 214 172 183 195 153 160 168 160
LEO-A04B 109
242 214 295 262 224 242 199 216 187 216 215 89 85 118 73 78 107 107 126 112
103 107 97 116 88 101 119 103 118 140 175 185 169 144 152 125 130 160 168 249
229 192 183 139 132 128 107 93 139 138 143 189 166 162 147 139 135 142 176 198
167 174 149 156 197 146 175 158 165 200 120 134 135 188 174 145 163 171 144 134
109 128 92 110 106 106 112 105 121 131 112 135 103 103 118 92 102 105 135 165
156 221 178 177 178 149 154 170 181
LEO-A05A 92
53 59 76 54 52 63 45 57 75 43 53 44 51 34 52 53 51 46 46 46
29 31 45 49 41 42 52 51 52 48 63 63 81 74 72 67 163 184 174 151
146 189 101 87 87 125 126 111 148 73 89 83 90 105 115 99 88 103 94 86
103 67 95 85 158 147 125 128 129 134 130 92 114 118 119 117 124 91 131 112
121 122 137 114 137 106 133 102 112 132 94 156
LEO-A05B 92
39 68 69 57 52 56 42 57 84 39 49 41 49 38 53 56 45 47 50 42
36 23 48 47 39 44 57 50 52 43 68 58 86 78 67 71 153 187 174 154
151 187 103 85 89 123 132 103 141 91 107 92 99 107 109 106 87 106 87 95
102 81 95 105 153 158 126 121 124 137 116 100 114 123 135 110 131 94 131 123
123 110 127 107 127 92 143 90 107 121 91 134
LEO-A06A 63
375 339 290 213 211 288 268 255 230 185 314 308 378 387 429 329 241 256 222 234
181 245 194 279 221 231 328 330 219 241 246 199 214 130 221 247 238 309 228 224
158 162 199 221 207 195 225 174 136 152 164 168 208 127 188 138 120 207 238 207
215 267 149
LEO-A06B 63
326 316 270 219 210 287 268 254 237 184 303 296 372 397 420 322 230 263 222 228
195 252 188 279 219 234 323 334 211 244 240 200 207 146 195 246 242 313 223 223
156 159 205 223 203 196 221 177 134 148 169 161 210 128 185 146 115 209 244 210
209 275 156
LEO-A07A 143
167 105 129 137 94 110 108 52 90 89 77 96 69 91 89 49 100 96 108 73
108 73 94 84 77 79 51 52 90 95 76 72 53 81 76 41 79 72 70 73
68 68 61 64 60 74 54 88 84 123 124 72 69 102 167 165 200 125 107 168
147 191 247 202 245 141 190 182 247 213 125 161 198 114 150 129 145 118 141 138
154 140 137 118 98 120 188 122 119 143 132 95 144 134 99 114 125 123 170 104
170 193 184 186 122 139 117 101 113 131 133 128 167 97 122 108 75 76 98 139
99 110 111 105 138 111 86 95 178 148 127 142 139 162 161 142 137 143 179 128
75 66 87
LEO-A07B 143
156 97 127 163 81 115 98 60 75 91 77 121 70 101 88 52 93 98 112 65
103 77 96 80 72 81 47 55 88 99 76 66 53 82 67 44 72 79 67 75
66 64 63 62 64 65 64 87 80 125 128 66 73 112 158 168 193 128 106 164
144 180 253 197 239 144 193 185 252 205 117 155 205 113 152 137 146 106 142 143
153 142 140 132 110 110 185 139 122 137 133 81 148 137 100 114 126 124 154 104
178 177 181 195 117 131 113 102 99 122 140 121 158 102 127 109 78 75 100 143
101 109 119 98 133 106 80 89 176 153 124 147 145 166 159 138 145 138 193 123
73 63 85
LEO-A08A 93
174 164 127 112 185 138 148 150 128 134 96 154 139 76 161 140 92 244 155 145
133 90 166 168 245 395 273 208 269 315 240 165 210 116 152 235 146 195 224 175
234 296 316 278 205 171 292 230 300 271 318 273 174 117 189 257 261 286 237 195
202 307 287 350 338 349 264 179 219 327 418 295 252 237 180 268 244 269 302 175
202 230 198 158 237 129 97 160 140 196 265 176 107

LEO-A08B 93
172 166 121 114 176 141 149 149 134 134 97 151 137 75 164 143 90 241 156 146
137 79 167 169 247 392 277 205 271 319 245 165 207 120 149 239 151 194 230 174
230 299 312 286 202 173 298 217 315 267 325 276 177 108 198 252 270 278 237 200
199 305 296 349 328 356 259 180 216 325 424 285 259 246 176 267 213 271 288 176
222 225 194 166 234 122 106 158 144 185 276 169 115
LEO-A09A 126
137 99 89 102 106 82 90 160 257 156 151 136 132 145 123 150 136 128 174 160
122 139 161 143 126 117 104 132 150 120 118 105 92 95 118 109 118 203 161 109
91 100 231 192 145 126 180 162 153 95 156 178 178 169 209 167 122 119 102 92
129 138 172 218 177 101 144 162 138 108 134 133 145 114 91 144 139 105 123 139
99 115 85 111 85 96 124 88 140 129 109 124 98 149 124 153 114 117 140 107
108 108 108 125 100 100 151 165 151 101 124 112 122 118 103 141 140 124 157 131
134 114 163 132 107 88
LEO-A09B 126
134 100 83 103 106 86 92 161 256 154 141 139 128 152 117 151 138 123 164 161
121 130 159 155 122 114 108 125 141 124 107 104 100 93 108 114 114 201 155 116
86 98 249 187 125 116 178 159 154 92 159 176 178 175 220 160 120 121 97 90
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98 105 93 107 85 94 134 88 124 128 110 115 105 149 133 156 110 132 140 101
106 114 101 122 111 95 140 184 131 100 120 112 107 131 116 131 141 129 156 126
139 116 165 129 109 94
LEO-A10A 78
447 350 299 293 345 299 346 331 156 334 473 359 258 329 378 291 172 163 304 372
216 215 157 223 153 207 140 156 153 155 147 170 137 154 171 142 83 141 169 127
201 117 89 147 117 98 102 100 109 126 146 109 118 82 86 95 115 114 114 94
94 98 110 119 60 94 114 76 69 73 88 78 110 98 109 143 109 117
LEO-A10B 78
442 369 293 322 351 312 342 342 160 339 476 358 262 346 392 290 176 160 311 384
224 216 167 213 151 213 135 155 158 154 146 174 133 164 165 141 82 138 171 130
198 123 88 141 119 95 104 103 114 128 140 111 111 79 90 99 110 118 110 102
93 98 127 119 62 85 105 90 70 77 82 81 120 104 103 136 109 135
LEO-A11A 86
64 71 89 72 81 94 85 72 55 70 83 83 47 55 59 53 139 220 281 289
339 216 262 360 369 437 299 196 201 258 372 431 349 363 220 165 245 344 251 124
166 215 108 113 130 164 234 294 172 229 171 135 141 112 137 226 214 151 190 157
89 111 109 112 138 148 117 135 147 171 173 149 163 132 130 130 121 84 103 133
172 173 156 171 131 105
LEO-A11B 86
72 62 81 73 77 87 77 67 58 68 79 68 47 63 40 53 122 226 273 266
324 240 292 357 366 440 300 196 201 243 378 432 369 351 223 159 242 352 249 127
165 211 110 109 130 167 245 283 178 242 166 142 133 117 136 232 212 158 191 146
89 121 117 111 132 146 121 134 143 171 167 157 162 140 121 134 113 86 101 140
170 170 155 172 149 114
LEO-A12A 145
52 44 40 112 81 70 36 55 33 38 71 65 55 45 44 56 71 93 68 53
86 83 63 71 83 71 92 82 92 82 101 75 103 79 97 144 135 162 113 141
195 224 190 241 143 93 136 144 200 257 211 227 194 142 171 208 183 122 137 209
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142 143 129 125 134 176 131 168 159 166 133 159 151 174 151 110 99 119 129 195
210 188 189 216 160
LEO-A12B 145
46 46 39 110 93 63 43 60 37 42 64 66 55 36 54 44 74 96 55 47

91 77 57 72 92 74 86 73 116 91 98 72 107 83 94 144 132 167 116 133
200 221 184 238 139 89 139 141 194 251 211 234 176 132 171 212 182 117 142 206
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74 74 95 121 105 118 117 136 156 122 122 105 115 113 97 88 76 92 102 100
91 126 141 73 93 102 138 129 110 104 111 170 112 95 150 174 151 134 149 125
147 137 132 123 140 171 131 165 160 160 133 169 148 173 145 114 100 113 129 197
208 203 204 219 166
LEO-A16A 48
535 481 381 207 439 312 456 252 330 312 272 345 250 356 265 369 69 39 50 56
55 63 100 169 114 137 136 155 274 331 490 332 380 389 225 318 355 315 214 196
224 348 330 370 421 354 332 384
LEO-A16B 48
525 482 370 175 402 258 404 197 280 283 281 333 222 320 267 373 76 50 45 50
56 59 97 168 119 146 140 163 280 305 516 335 393 392 265 312 347 312 222 190
228 345 334 379 417 355 343 415
LEO-A18A 154
308 248 289 335 291 224 185 205 228 201 190 156 179 233 179 230 158 170 114 92
186 182 179 176 205 232 212 225 118 134 148 165 180 205 178 119 127 116 135 128
99 117 108 98 202 137 132 153 125 137 107 124 125 140 156 139 160 105 124 153
141 144 104 58 76 96 73 111 93 82 68 98 107 100 98 113 95 100 94 78
101 103 72 67 64 84 85 97 70 81 90 118 143 122 144 128 100 126 111 109
103 72 66 81 62 63 71 76 113 79 92 102 90 68 78 58 60 66 60 75
84 71 57 73 90 68 65 68 88 101 98 112 106 131 115 125 133 116 133 125
102 93 105 101 89 94 100 80 93 77 90 96 119 120
LEO-A18B 154
275 239 283 334 294 220 190 205 224 200 189 164 177 238 176 231 159 169 113 99
185 192 173 174 208 213 226 230 135 144 148 170 181 206 173 114 133 125 136 110
112 128 115 96 204 140 128 165 114 129 97 124 122 145 151 131 154 115 119 158
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90 85 65 82 61 67 69 81 110 85 93 99 84 71 77 56 55 61 59 73
101 74 64 81 82 76 78 58 86 97 102 116 107 131 110 133 129 115 130 119
104 86 116 97 91 100 100 78 87 82 86 100 107 111
LEO-A19A 127
137 115 130 107 115 116 105 86 113 94 84 73 75 81 82 119 83 84 92 83
124 98 151 126 74 78 112 120 137 88 112 103 83 92 101 94 128 112 146 140
138 82 116 81 85 122 143 128 140 108 86 148 140 136 163 120 182 157 186 152
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160 130 164 128 99 105 104 120 121 141 122 151 138 84 56 48 66 59 67 100
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108 81 90 122 146 153 160 126 75 135 114 135 146 111 171 153 167 182 200 201
207 250 160 205 187 245 165 160 158 253 208 212 224 143 160 148 162 165 177 176
164 233 148 171 177 194 180 164 178 176 251 184 150 141 144 124 165 138 149 147
LEO-A20B 80

185 202 161 174 160 149 175 169 129 155 94 91 111 112 113 108 133 121 109 97
101 77 88 126 171 148 150 123 73 127 117 139 135 109 160 141 166 179 186 202
219 238 195 197 197 232 140 160 168 267 195 207 217 144 159 147 164 165 166 166
164 246 144 171 172 198 185 167 178 180 247 180 138 153 145 126 163 139 169 142
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146 223 222 195 161 170 182 208 194 183 243 170 196 222 165 170 189 111 170 235
139 167 196 190 167 235 241 232 213 253 289 281 228 187 252 191 142 99 126 164
139 178 150
LEO-A21B 63
301 344 326 275 286 318 265 307 213 161 167 219 173 178 164 139 142 89 170 147
156 223 225 184 150 164 177 197 201 199 222 156 201 218 169 171 186 115 173 224
139 153 198 184 167 239 247 238 219 240 314 235 225 215 253 174 128 103 110 161
132 169 164
LEO-A22A 97
434 338 266 263 203 184 139 169 180 305 164 106 218 354 433 411 390 346 203 114
229 209 196 308 340 372 219 230 287 329 339 329 296 170 217 212 164 166 102 63
107 325 211 211 315 223 227 318 295 197 180 268 303 183 204 168 202 167 91 67
 99 143 117 249 214 215 379 358 196 252 274 158 91 74 95 119 116 122 406 569
259 242 172 168 319 292 200 296 263 220 248 167 145 211 235 263 175
LEO-A22B 97
428 326 240 230 195 180 127 148 163 319 169 113 190 352 419 388 382 342 185 110
252 219 213 346 348 365 215 203 291 317 312 317 301 164 218 197 169 152 84 101
105 328 210 214 287 201 214 311 279 213 201 276 291 177 202 180 206 161 88 69
101 136 129 247 218 216 374 366 192 246 284 156 97 69 95 128 116 117 417 566
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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 Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). 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

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 AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 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	

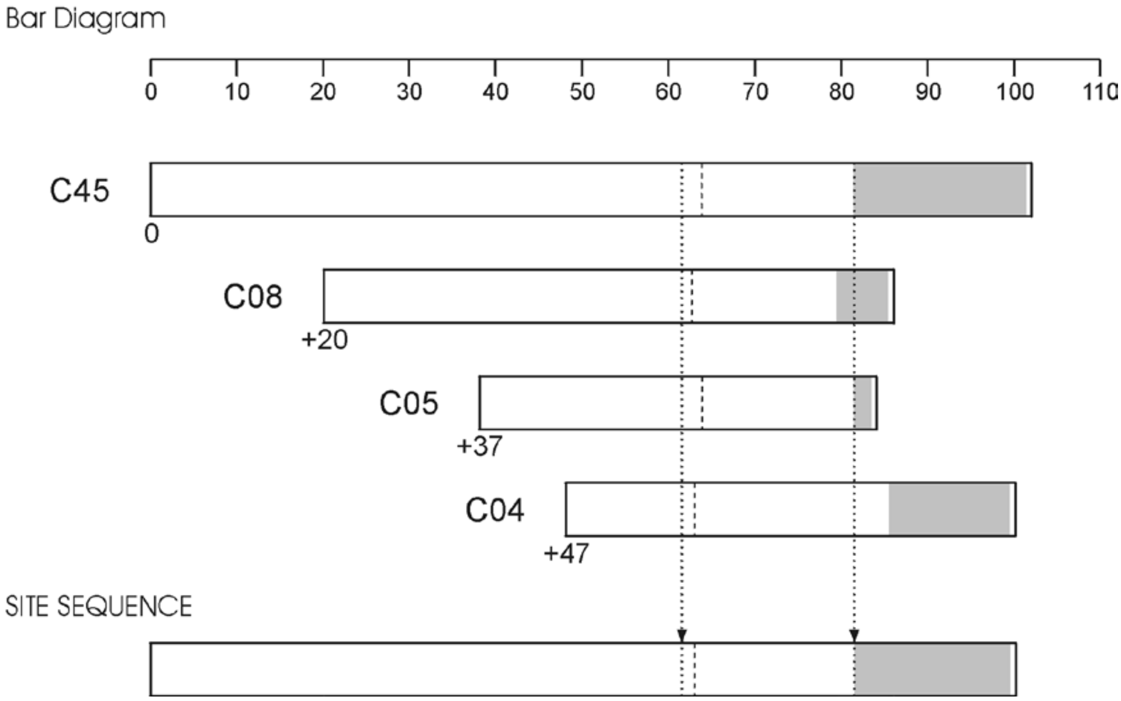


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

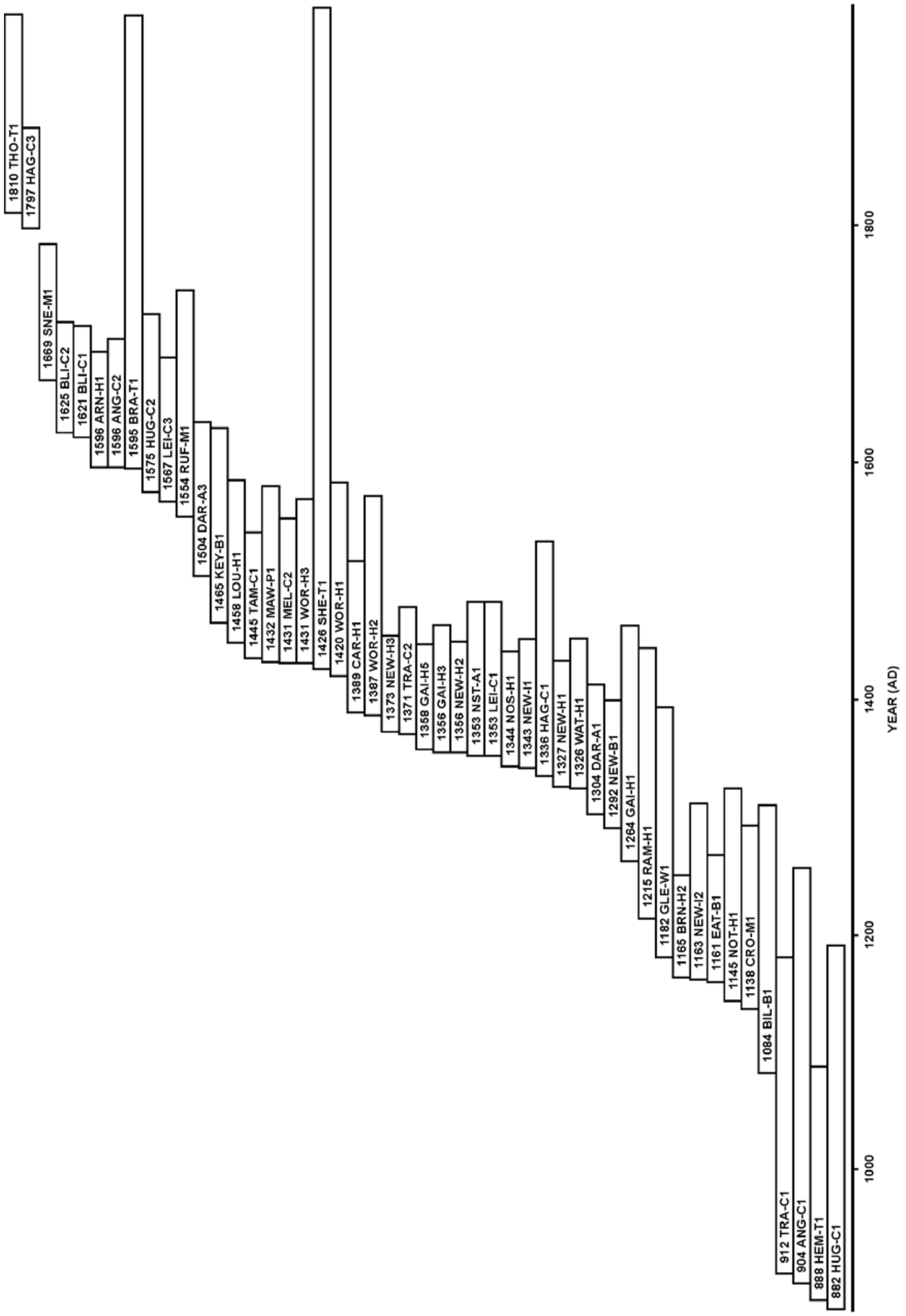
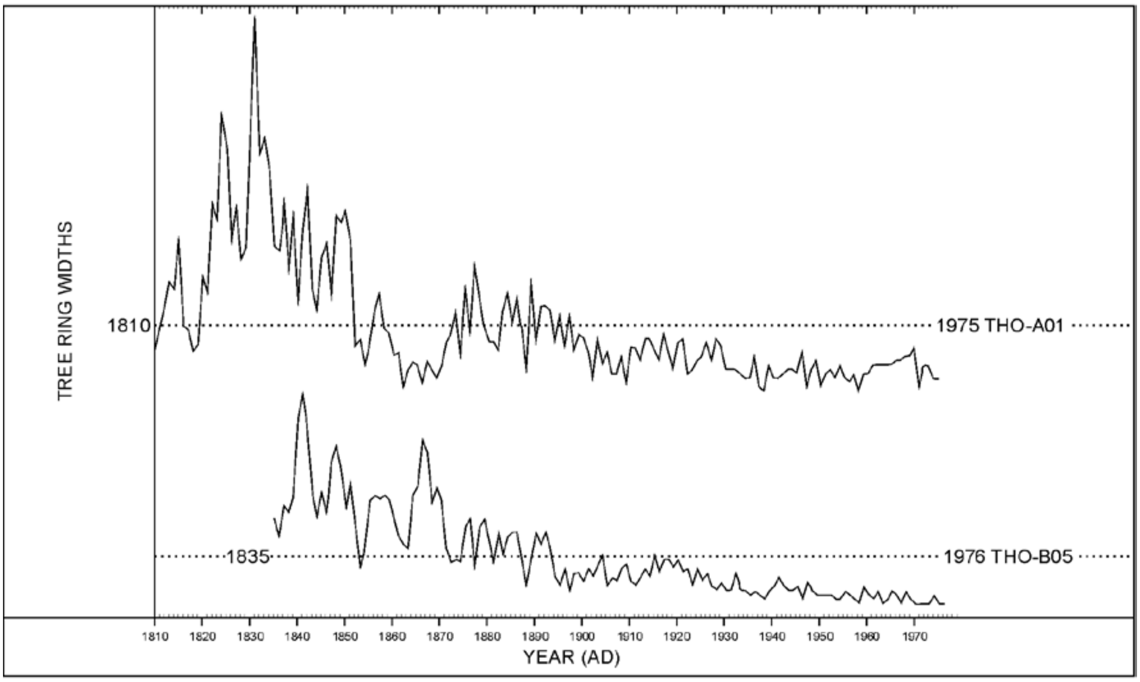


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

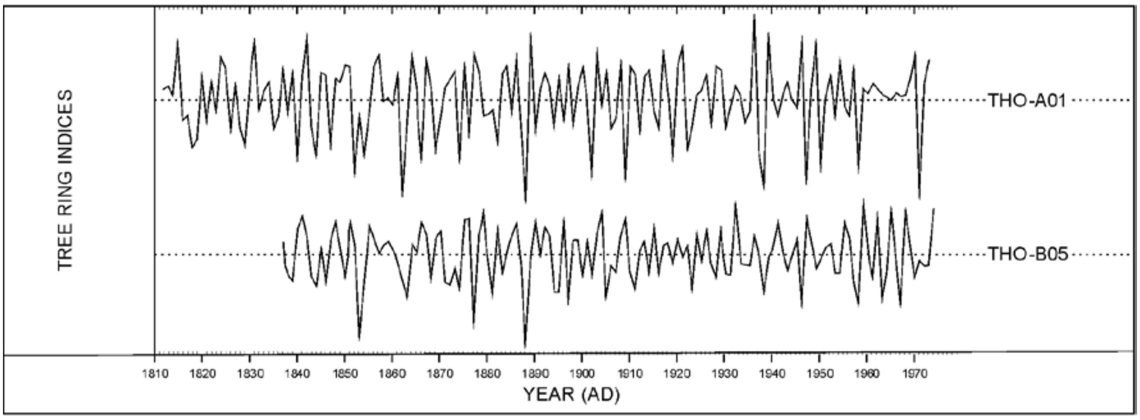


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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