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CHURCH OF ST MARY, STOCKPORT, GREATER MANCHESTER
TREE-RING ANALYSIS OF TIMBERS OF THE CHANCEL ROOF

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Analysis was undertaken on 12 samples taken from the timbers of the chancel roof. Site sequence STKCSQ01 contains three samples and spans the period AD 1019–1133. Site sequence STKCSQ02 contains eight samples and spans the period AD 1099–1293. Additionally, a single sample (STK-C04) was dated individually to span the period AD 1017–1133. Only one of the dated samples has the heartwood/sapwood, which gives an estimated felling date for the timber represented of AD 1308–33. It is thought quite likely that the other samples were also taken from timbers felled at this time with those with last-measured heartwood ring dates in the twelfth century possibly representing the inner portion of longer lived trees, thus indicating an early fourteenth-century date for the construction of the extant chancel roof.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Laboratory would like to thank the project architect, Graham Cunningham of Lloyd Evans Prichard for arranging access for the initial assessment and providing the drawings. We are also grateful to Mike Goulding, site agent for Lambert Walker Conservation, and Crispin Edwards, the local conservation officer, for on-site assistance provided. Reverend Scoones is also thanked for his assistance and enthusiasm for the project.

ARCHIVE LOCATION

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INTRODUCTION

The parish church of St Mary occupies an elevated position, dominating the old town centre of Stockport (Figs 1–3; SJ 898 905) adjacent to the Market Place. It comprises a three-bay chancel, five-bay nave which is galleried on the north and south sides, adjacent two-cell north-east block currently used as a heritage centre, and west tower with north-west and south-west porches. Much of the church was rebuilt in AD 1813–17 to the designs of Robert Goldsmith (revised by Lewis Wyatt after advice from John Soane) in Perpendicular Gothic style. It underwent further repair and alterations in AD 1882 (designs of J S Crowther). This description is based on the listed building description (www.lbonline.english-heritage.org.uk).

Chancel roof

This is of common rafter type with arch braces and scissor-bracing and comprises 23 frames, numbered from west to east (Figs 4–7). It is thought to be fourteenth century in date.

SAMPLING

Tree-ring dating was requested by Peter Barlow, of English Heritage's North-West region to inform grant-aided repairs being undertaken to the chancel arch. It was also hoped that successful dendrochronological dating would provide a better understanding of the chronological development of the building.

A total of 12 timbers was sampled with each sample being given the code STK-C and numbered 01–12. The location of samples was noted at the time of sampling and has been marked on Figures 8–14. Further details of the samples can be found in Table 1. The roof is believed to be of one constructional phase, with the exception of some 'modern' replacement timbers which were avoided during sampling. Given that it was necessary to allow public access to other parts of the church from the chancel at all times, there was a concern that the use of a tower scaffold would have proved unduly disruptive. This meant sampling was restricted to those timbers accessible from a ladder or the *in-situ* scaffolding around the chancel arch.

ANALYSIS AND RESULTS

All 12 samples were prepared by sanding and polishing and their growth ring widths measured; the data of these measurements are given at the end of the report. These samples were compared with each other by the Litton/Zainodin procedure (see Appendix). At a value of t=4.5, 11 samples matched to form two groups.

Firstly, three samples matched each other at a least value of t=7.9 and were combined at the relevant offset positions to form STKCSQ01, a site sequence of 115 rings (Fig 15).

This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1019 and a last-measured ring date of AD 1133. The evidence for this dating is given in Table 2. None of these samples have the heartwood/sapwood boundary ring which means that an estimated felling date cannot be calculated for the timbers represented, except to say that, with last measured heartwood ring dates of AD 1088 (STK-C08), AD 1109 (STK-C09), and AD 1133 (STK-C10), these would be estimated to be, at the earliest, AD 1104, AD 1125, AD 1149, respectively.

Secondly, eight samples matched each other at a value of t=4.5 and were combined at the relevant offset positions to form STKCSQ02, a site sequence of 195 rings (Fig 15). This site sequence was again compared with the reference chronologies where it was found to match consistently and securely at a first-ring date of AD 1099 and a last-measured ring date of AD 1293. The evidence for this dating is given in Table 3. Only one of these samples (STK-C05) has the heartwood/sapwood boundary ring, allowing an estimated felling date to be calculated for the timber represented of AD 1308–33. The last measured heartwood ring dates for the other samples in this site sequence range from AD 1241 (STK-C02) to AD 1291 (STK-C03) which makes it possible that these were also felled in AD 1308–33.

Finally, attempts were made to date the remaining ungrouped sample, STK-C04, by comparing it individually against the reference chronologies where it was found to span the period AD 1017–1133. The evidence for this dating is given by the t-values in Table 4. Again, this sample does not have the heartwood/sapwood boundary, but with a last-measured heartwood ring date of AD 1133, this would be estimated to be AD 1149 at the earliest.

The felling date range and the earliest possible felling dates have been calculated using the estimate that 95% of mature oak trees in this area have between 15 and 40 sapwood rings.

DISCUSSION

Prior to tree-ring analysis being undertaken the chancel roof was thought to be fourteenth century in date. Dendrochronological analysis has successfully dated 12 of the timbers of the roof, one to a felling of AD 1308–33. Unfortunately, without the heartwood/sapwood boundary ring it is not possible to demonstrate that the other dated timbers were also felled at this time. However, all of the last measured heartwood ring dates are in the twelfth or thirteenth century making it possible that all of the timbers represented were also felled in the early-fourteenth century. There were no indications that any of the sampled timbers had been used previously or represented a later modification to the roof, which appeared to be of a single phase. If those timbers with last-measured ring dates in the twelfth century represent the inner portions of trees felled in the fourteenth century they would be long lived trees; the centre of the tree does not appear on any of them and some of them have first measured ring dates in the first quarter of the eleventh century which would imply the use of trees in excess of 300 years old at felling. This longevity of timber used has been seen in structures of the fourteenth century elsewhere in the north-west area, such as at The Guildhall, Carlisle which has a sample of over 400 rings without the centre (Howard *et al* 1994).

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Table 1: Details of tree-ring samples from the Church of St Mary, Stockport

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
STK-C01	South scissor brace, frame 2	130	--	1128	----	1257
STK-C02	North rafter, frame 2	143	--	1099	----	1241
STK-C03	North scissor brace, frame 3	91	--	1201	----	1291
STK-C04	North rafter, frame 3	117	--	1017	----	1133
STK-C05	South rafter, frame 3	114	h/s	1180	1293	1293
STK-C06	South stub tie, frame 12	157	--	1105	----	1261
STK-C07	North archbrace, frame 14	106	--	1160	----	1265
STK-C08	South stub tie, frame 8	70	--	1019	----	1088
STK-C09	South stub tie, frame 9	71	--	1039	----	1109
STK-C10	North stub tie, frame 9	85	--	1049	----	1133
STK-C11	South rafter, frame 11	146	--	1104	----	1249
STK-C12	South ashlar, frame 11	104	--	1172	----	1275

Table 2: Results of the cross-matching of site sequence STKCSQ01 and relevant reference chronologies when the first-ring date is AD 1019 and the last-ring date is AD 1133

Reference chronology	*t*-value	Span of chronology	Reference
Gloucester Blackfriars, Gloucestershire	8.5	AD 1024–1237	Howard *et al* 2002
Peterborough Cathedral (nave), Cambridgeshire	8.0	AD 887–1225	Tyers 1999
Dundas Wharf, Avon-Bristol, Bristol	7.7	AD 770–1202	Nicholson and Hillam 1987
Staircase House, Stockport, Greater Manchester	6.8	AD 1069–1248	Howard *et al* 2003
Eastgate, Beverley, East Yorkshire	6.5	AD 858–1310	Groves 1992
St Hughs' Choir, Lincoln Cathedral, Lincolnshire	6.4	AD 882–1184	Howard *et al* 1984
Chapter House/Deanery, Brecon Cathedral, Brecon, Wales	6.4	AD 996–1227	Howard *et al* 1994

Table 3: Results of cross-matching of site sequence STKCSQ02 and relevant reference chronologies when the first-ring date is AD 1099 and the last-ring date is AD 1293

Reference chronology	*t*-value	Span of chronology	Reference
Wood Street, Nantwich, Cheshire	11.2	AD 932–1509	Tyers 2005
Ordsall Hall, Salford, Greater Manchester	9.8	AD 1076–1345	Arnold *et al* 2004
All Hallow's Church, Kirkburton, West Yorkshire	9.4	AD 999–1218	Arnold and Howard 2007
Gloucester Blackfriars, Gloucestershire	9.3	AD 1024–1237	Howard *et al* 2002
Angel Choir, Lincoln Cathedral, Lincolnshire	9.3	AD 904–1257	Laxton and Litton 1988
Bowers Row, Nantwich, Cheshire	8.7	AD 920–1240	Hillam 1994
Hansacre Hall, Staffordshire	8.5	AD 965–1279	Esling *et al* 1990

Table 4: Results of the cross-matching of sample STK-C04 and relevant reference chronologies when the first-ring date is AD 1017 and the last-ring date is AD 1133

Reference chronology	*t*-value	Span of chronology	Reference
Willaston, nr Nantwich, Cheshire	8.0	AD 917–1205	Groves 1990
Wood Street, Nantwich, Cheshire	6.4	AD 932–1509	Tyers 2005
Welsh Row, Nantwich, Cheshire	6.3	AD 971–1192	Lageard pers comm
Hansacre Hall, Staffordshire	6.0	AD 965–1279	Esling *et al* 1990
Dundas Wharf, Avon-Bristol, Bristol	5.9	AD 770–1202	Nicholson and Hillam 1987
Peterborough Cathedral (nave), Cambridgeshire	5.8	AD 887–1225	Tyers 1999
Barton coffins, North Lincolnshire	5.4	AD 785–1134	Tyers 2001

Figure 1: Map to show the location of Stockport (based on the Ordnance Survey Map, with the permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

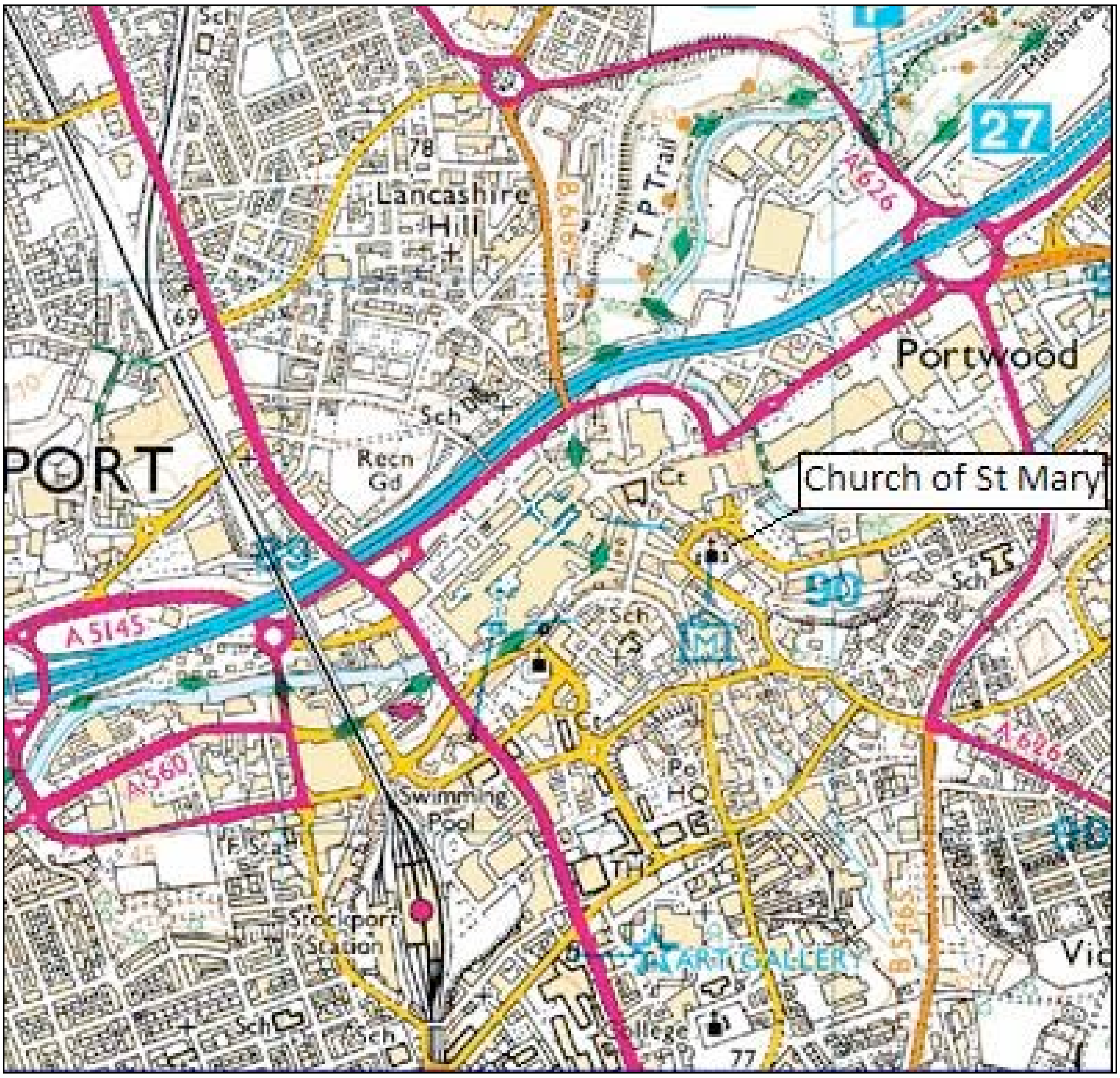

Figure 2: Map to show the approximate location of the Church of St Mary, (based on the Ordnance Survey Map, with the permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright

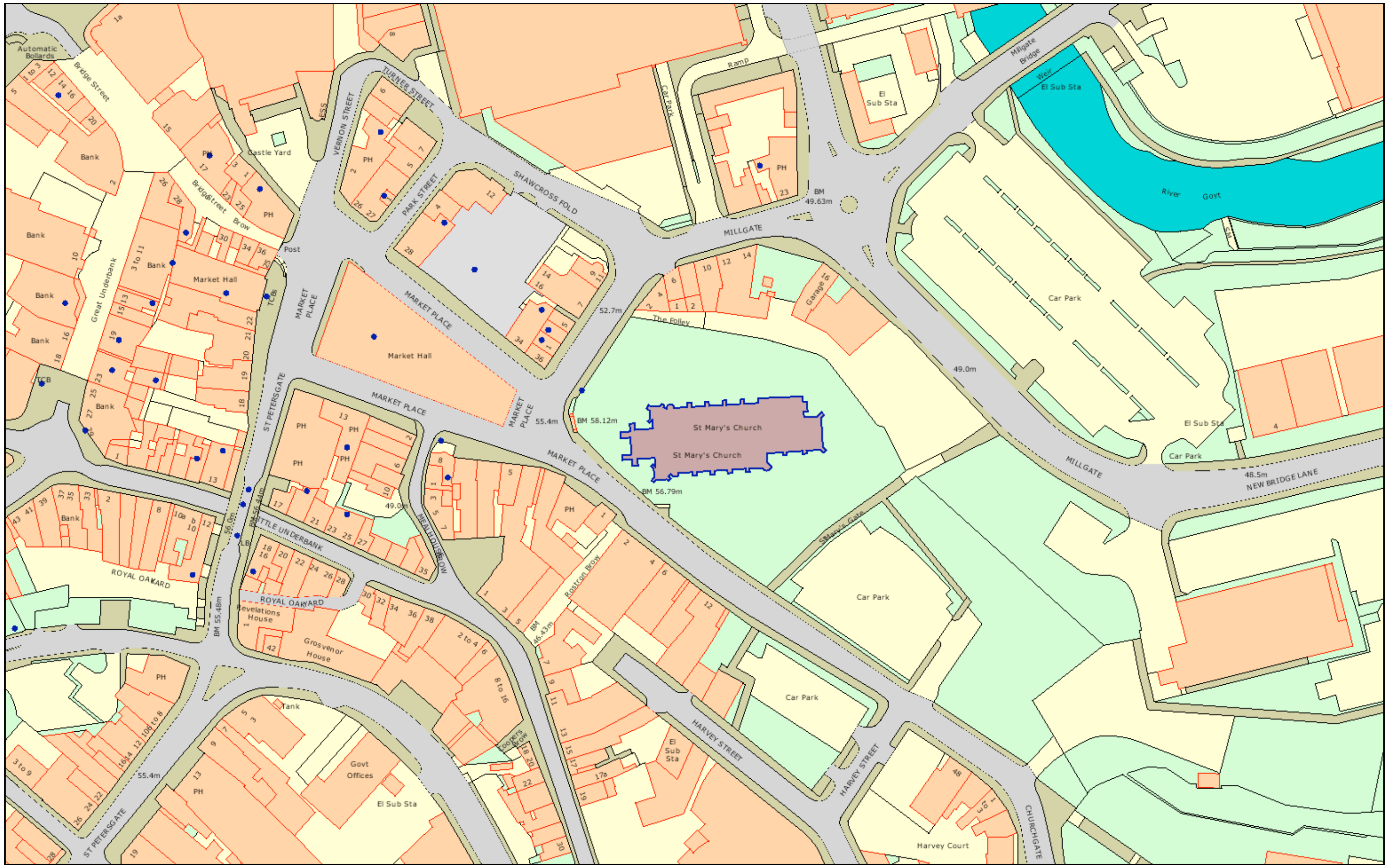

Figure 3: Map to show the location of the Church of St Mary (based on the Ordnance Survey Map, with the permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 4: Photograph taken of roof, collar down

Figure 5: Photograph taken of roof, collar upwards

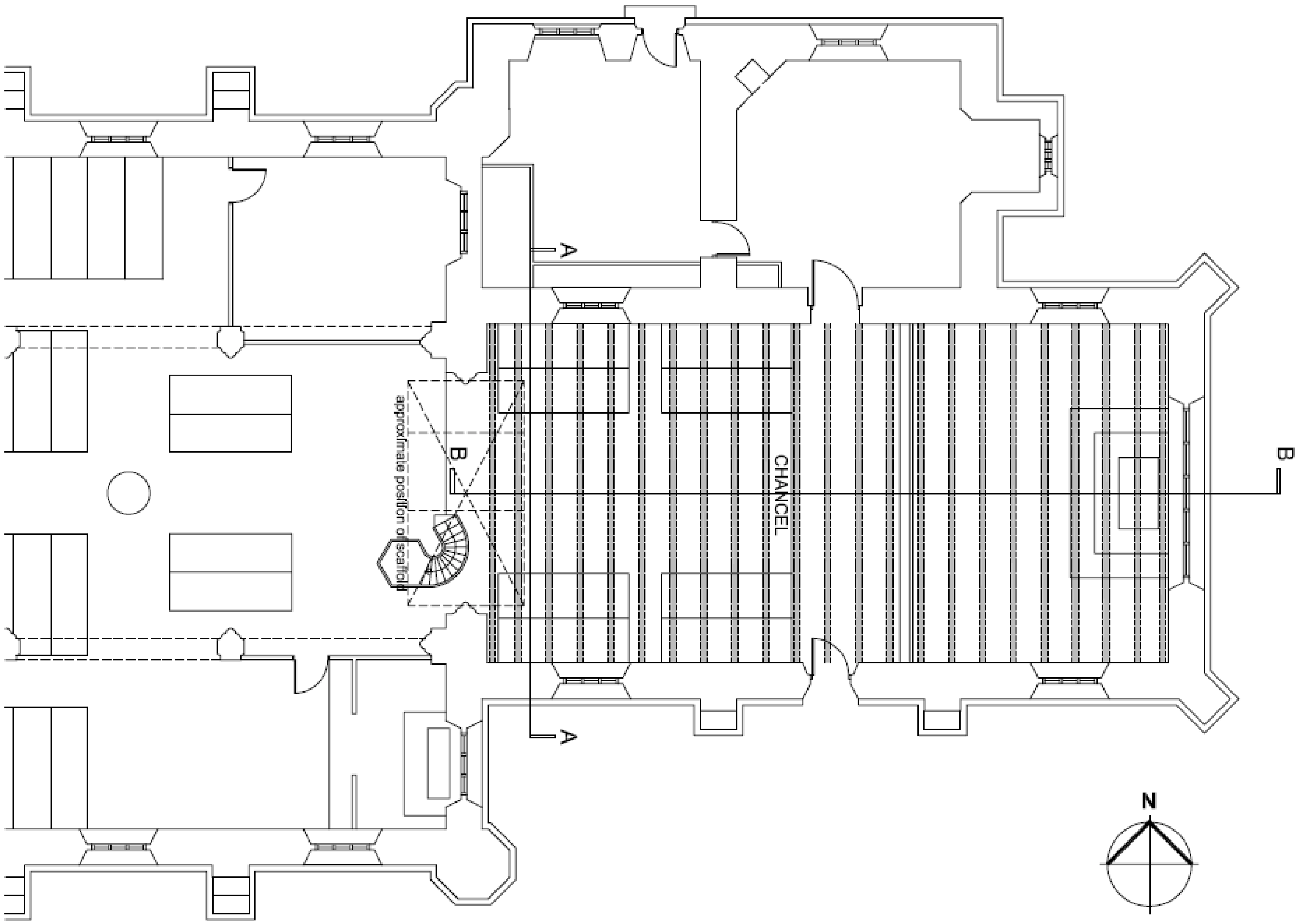

Figure 6: Ground-floor plan, showing the position of sections A–A and B–B (Lloyd Evans Pritchard)

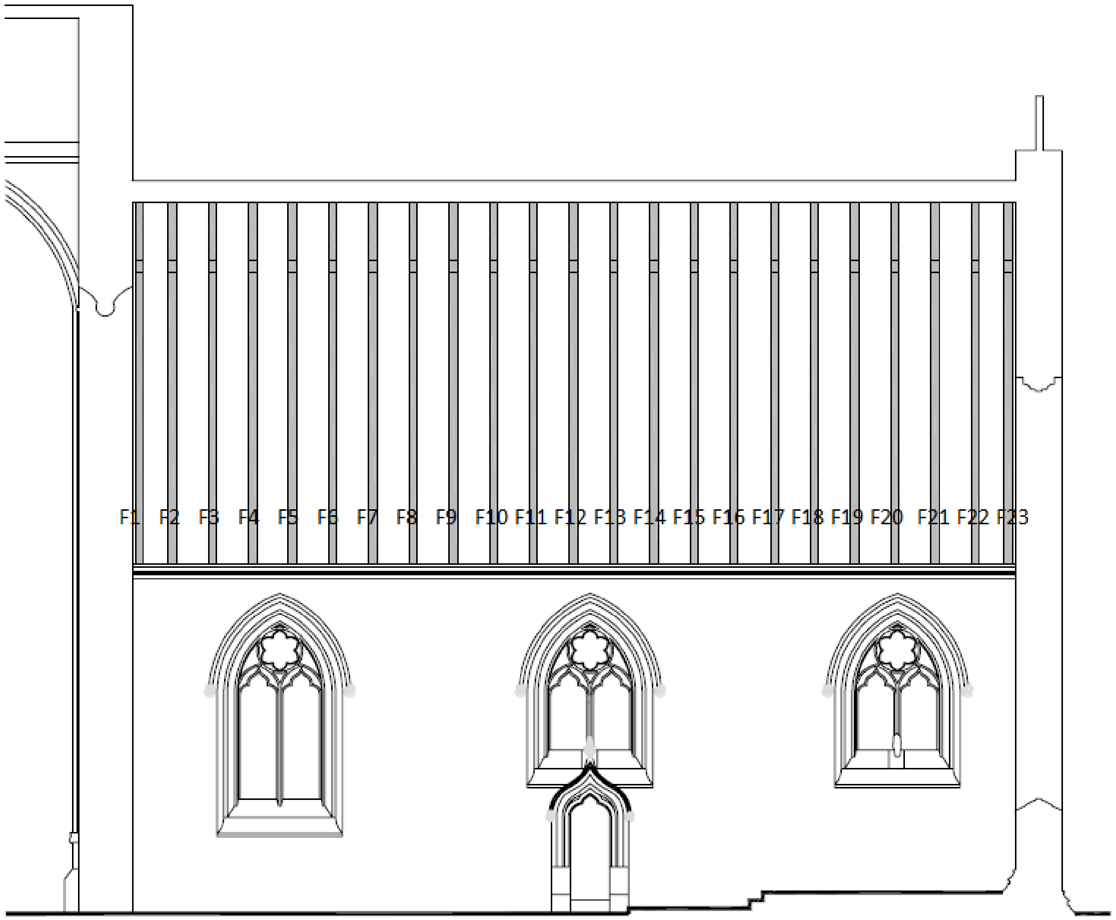

Figure 7: Section B–B, showing frame numbering (Lloyd Evans Pritchard)

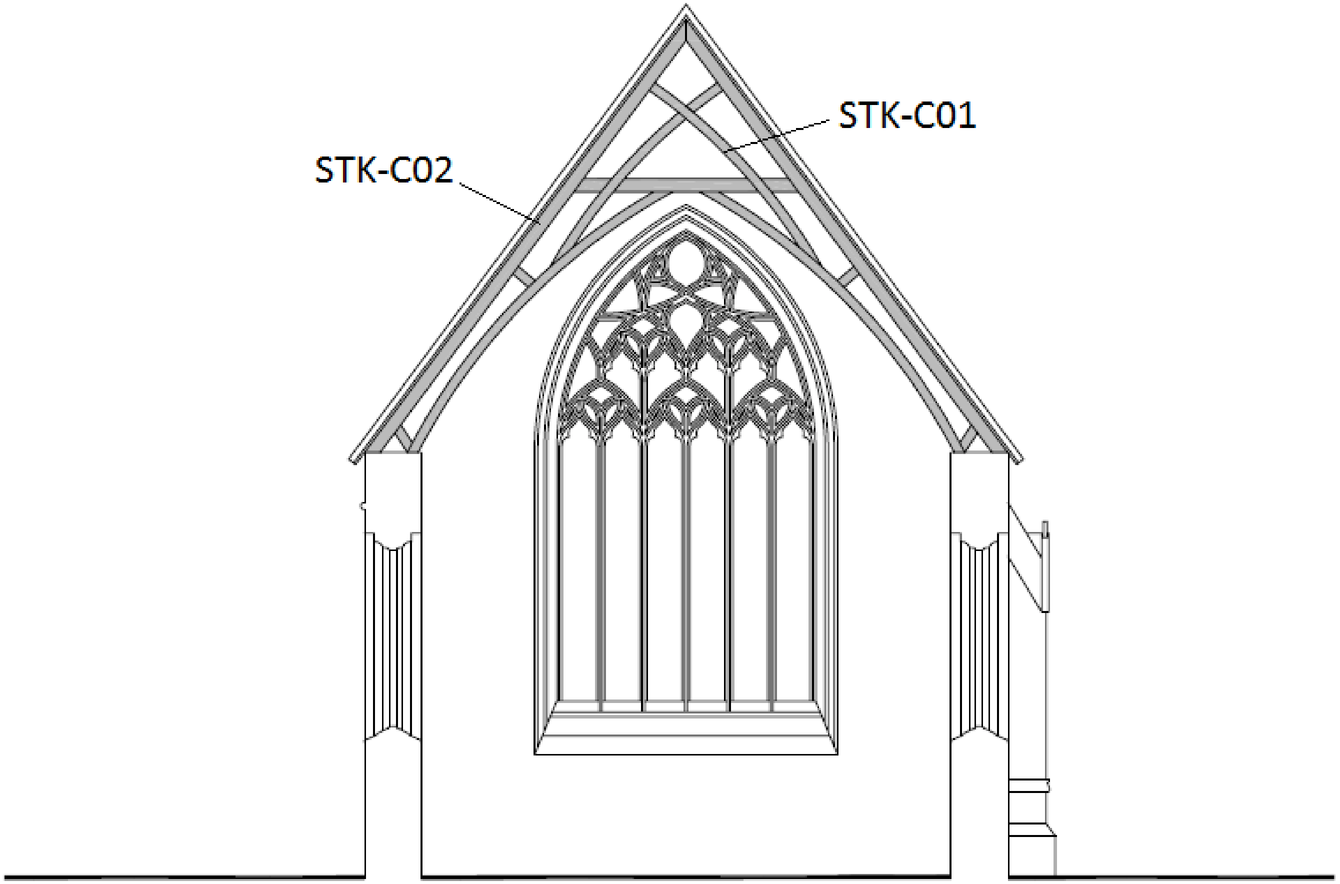

Figure 8: Frame 2, showing the location of samples STK-C01 and STK-C02 (Lloyd Evans Pritchard)

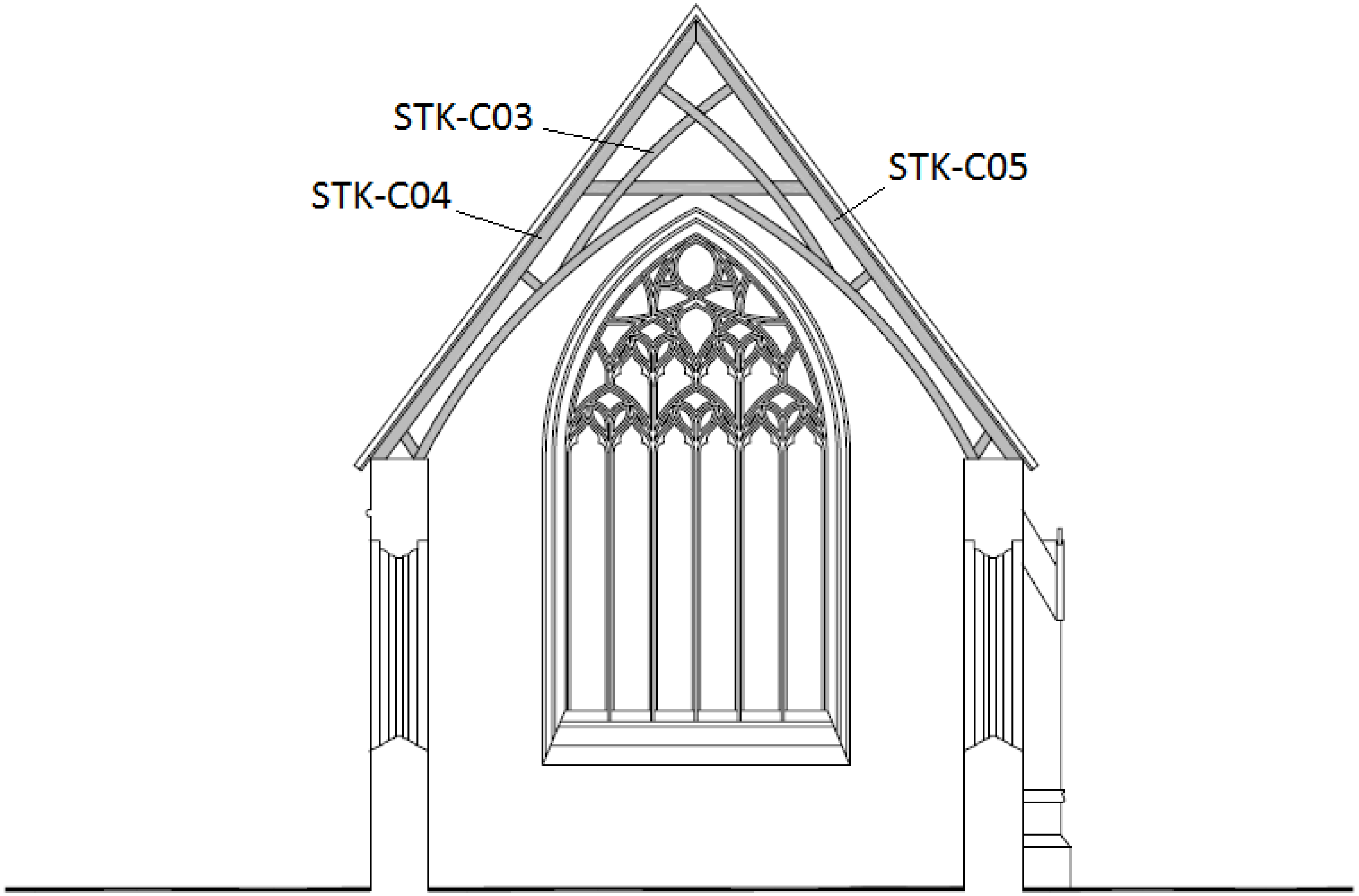

Figure 9: Frame 3, showing the location of samples STK-C03-05 (Lloyd Evans Pritchard)

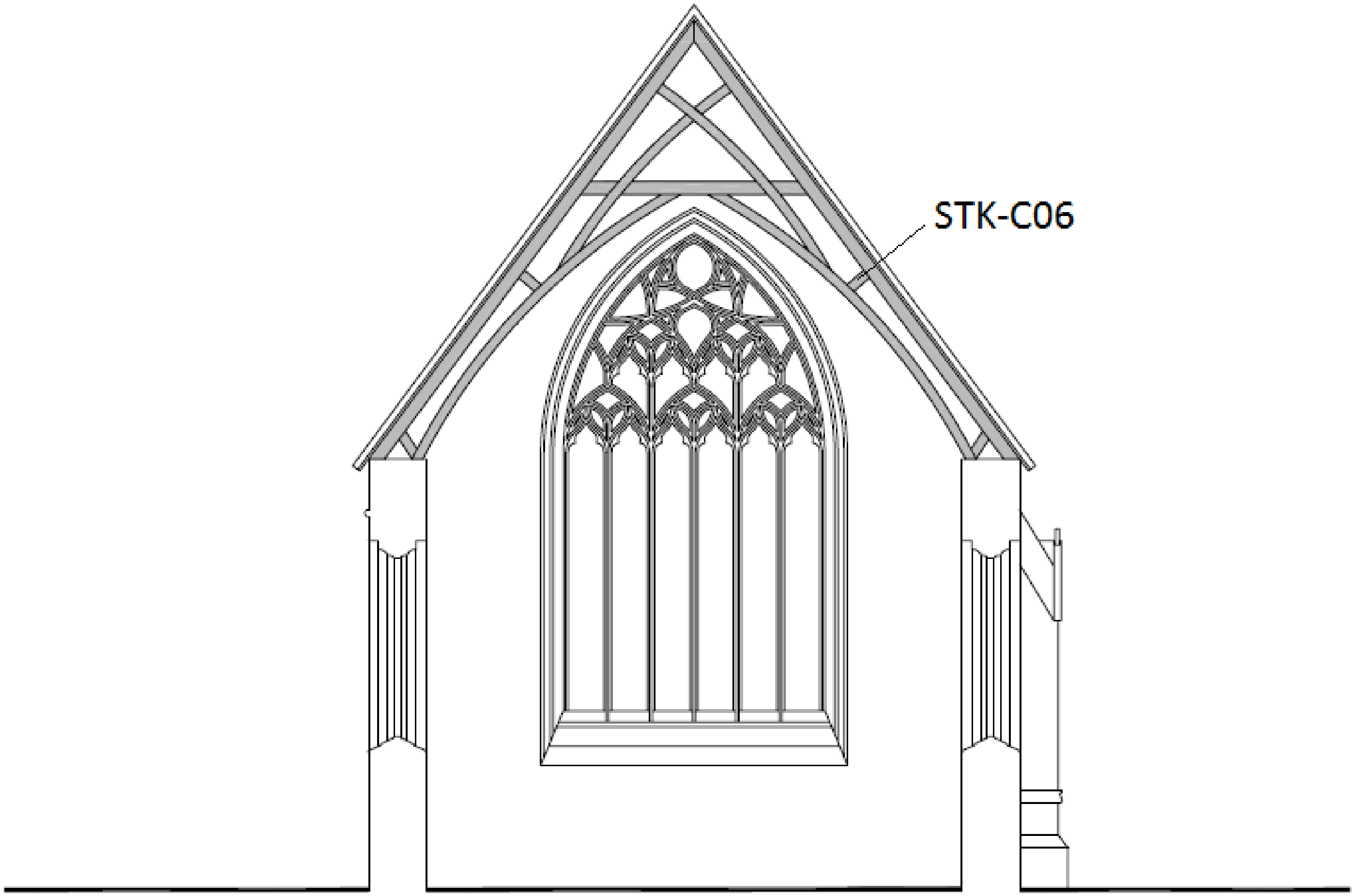

Figure 10: Frame 12, showing the location of sample STK-C06 (Lloyd Evans Pritchard)

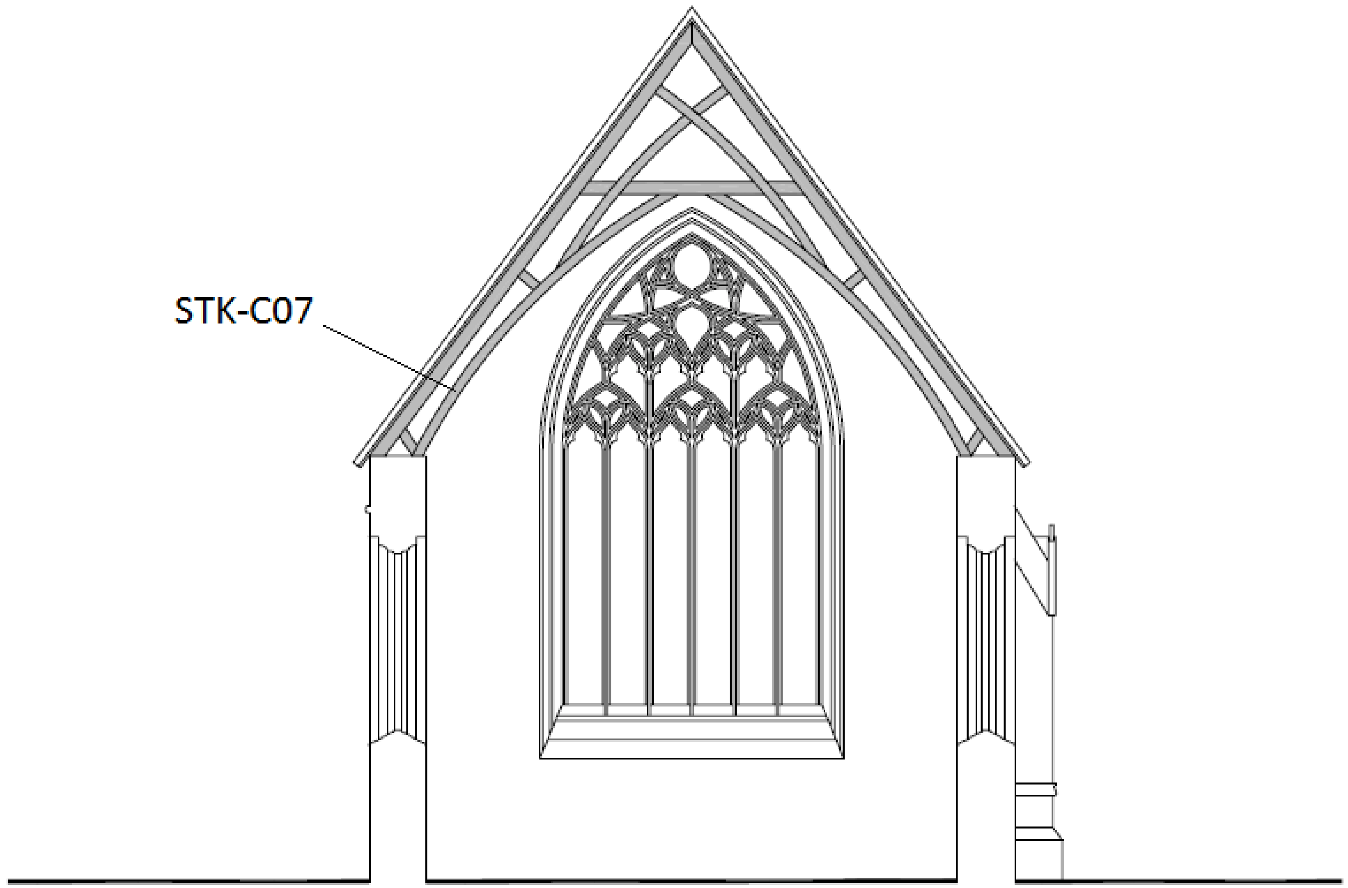

Figure 11: Frame 14, showing the location of sample STK-C07 (Lloyd Evans Pritchard)

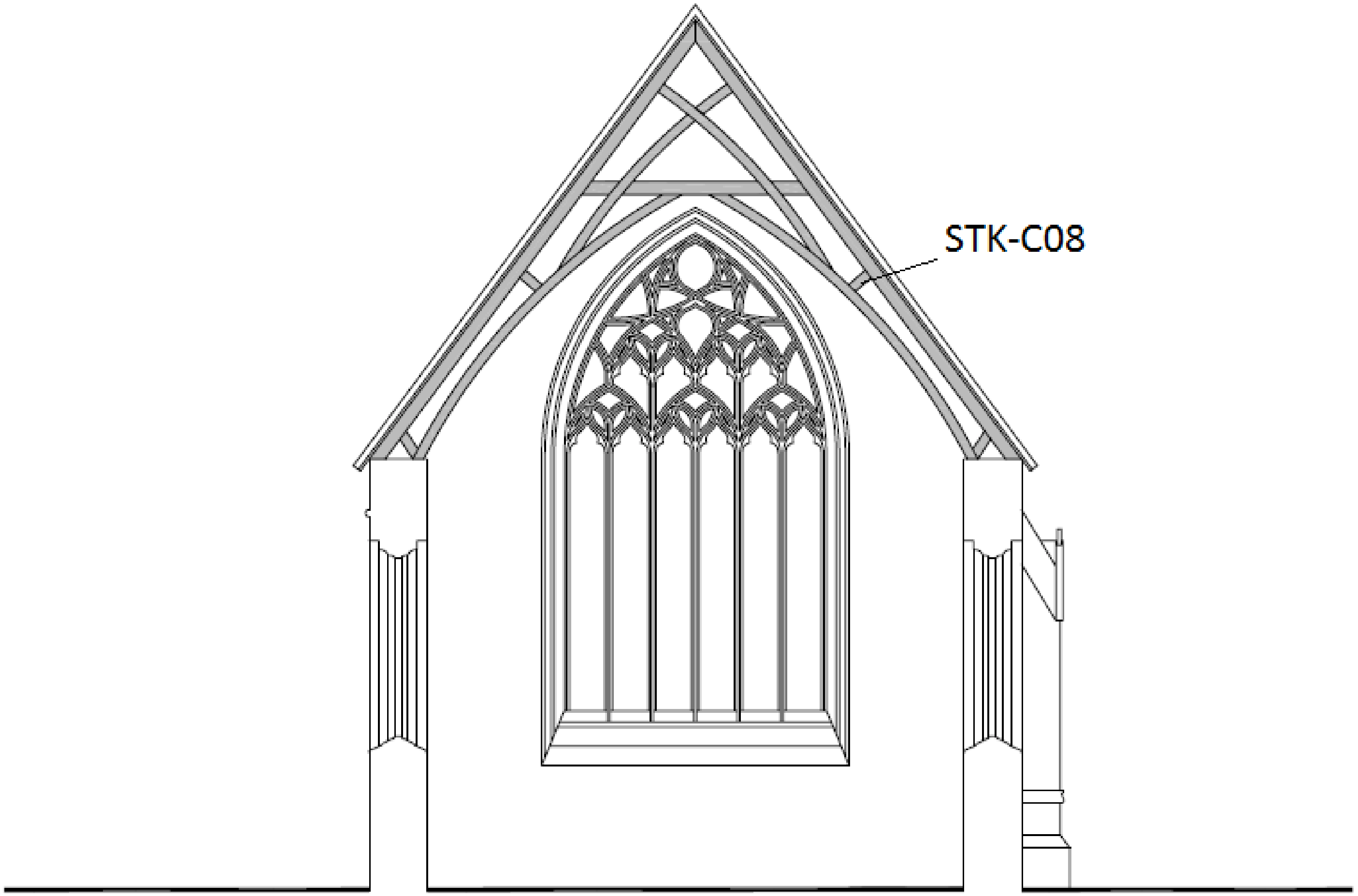

Figure 12: Frame 8, showing the location of sample STK-C08 (Lloyd Evans Pritchard)

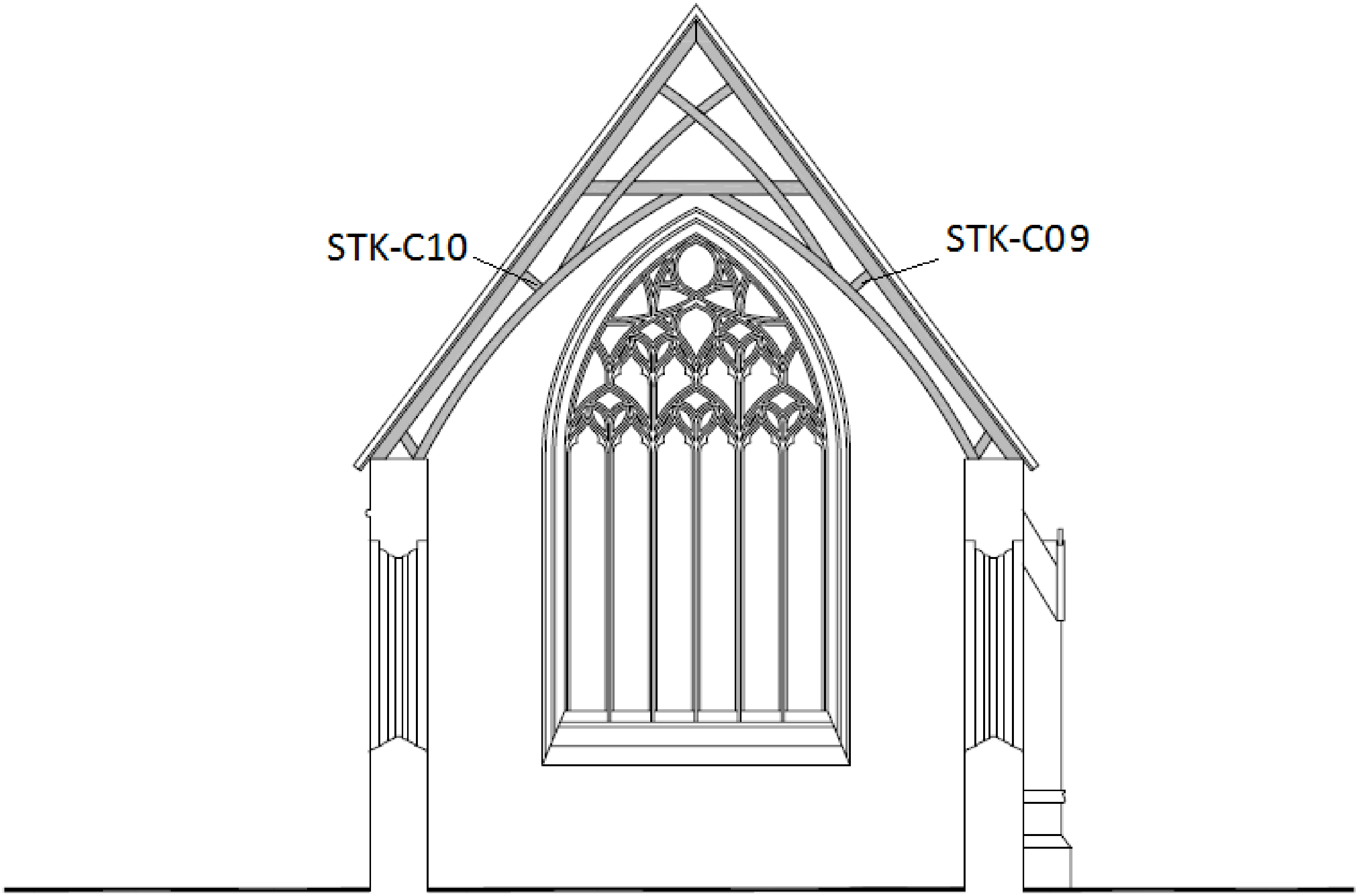

Figure 13: Frame 9, showing the location of samples STK-C09 and STK-C10 (Lloyd Evans Pritchard)

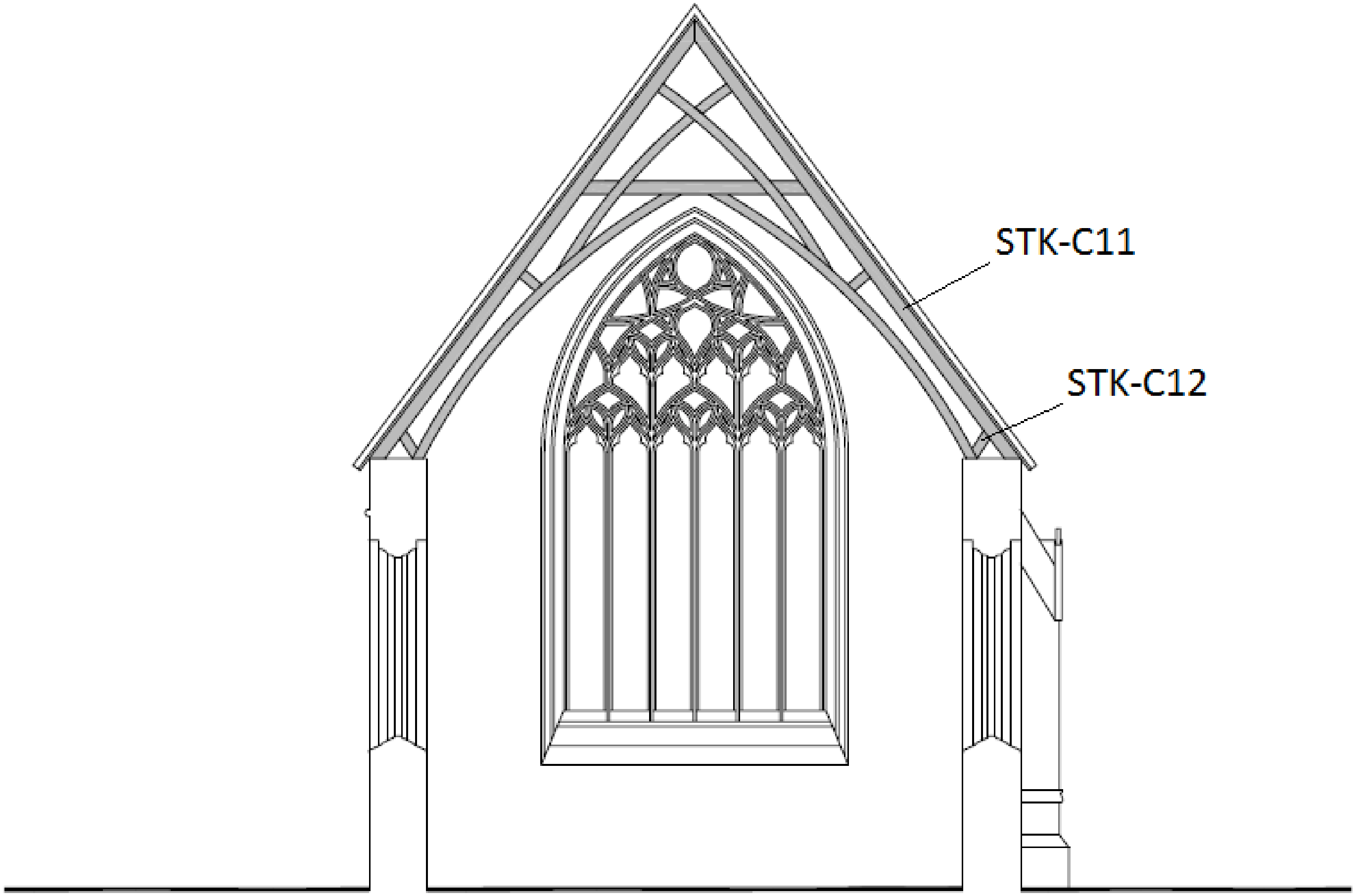

Figure 14: Frame 11, showing the location of samples STK-C11 and STK-C12 (Lloyd Evans Pritchard)

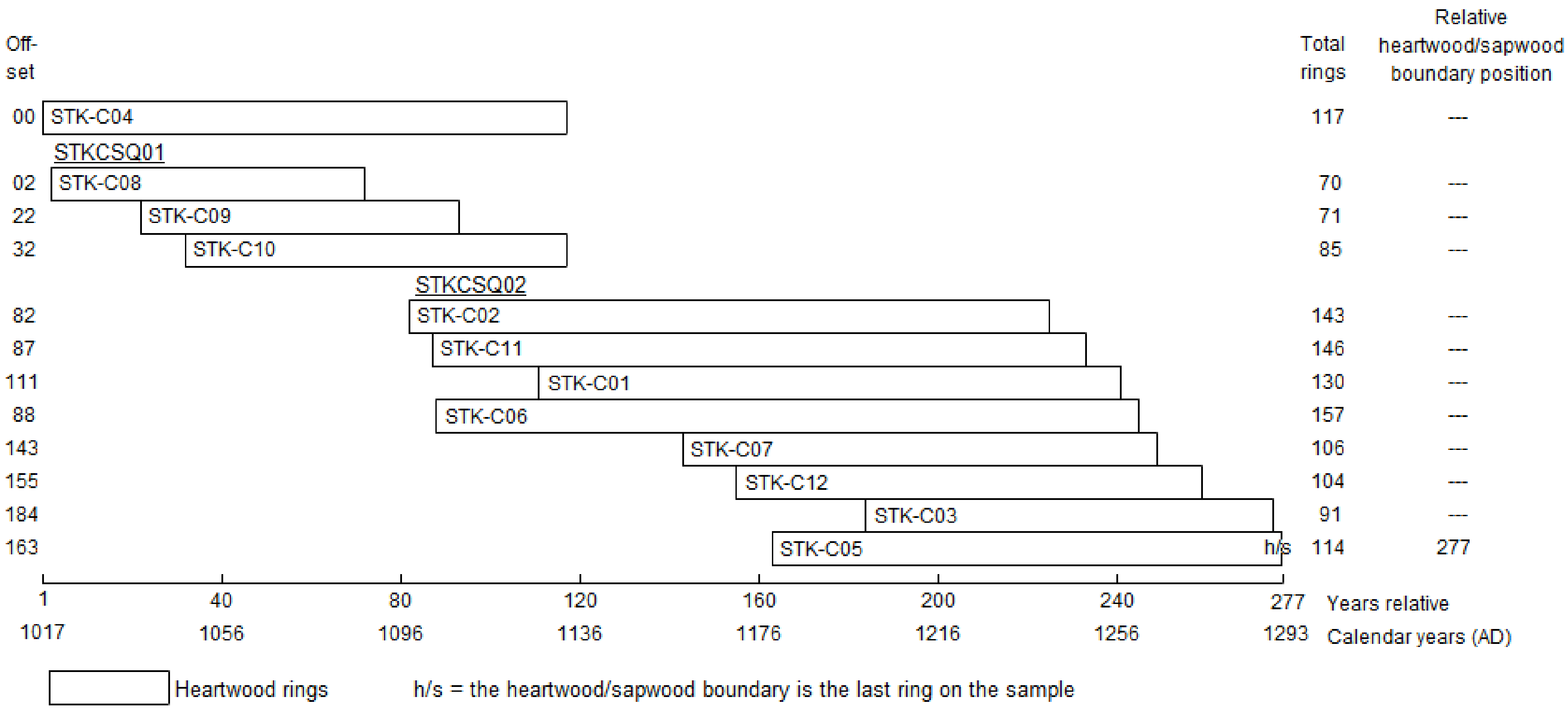

Figure 15: Bar diagram of all dated samples

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

STK-C01A 130
72 54 43 31 40 49 50 48 63 69 68 87 85 95 91 82 81 53 67 90
89 92 107 83 85 108 85 97 105 101 80 114 105 77 95 98 96 88 60 75
83 99 77 64 82 74 55 68 83 44 56 79 77 86 81 64 48 66 71 62
55 57 67 50 57 72 97 75 95 90 64 59 60 66 69 84 60 69 69 53
66 61 81 86 69 79 82 68 78 70 56 66 46 81 94 78 84 68 94 94
116 122 122 72 87 58 82 90 63 91 75 93 98 78 65 95 71 69 84 103
60 63 63 62 54 43 84 56 81 95
STK-C01B 130
79 47 41 37 42 41 47 56 66 66 73 77 93 89 96 79 80 50 74 84
88 94 104 83 88 104 90 86 115 99 83 113 103 79 94 107 85 91 62 76
78 100 77 62 85 75 53 71 74 53 60 80 77 82 82 59 58 63 72 69
54 56 68 53 50 78 88 75 92 91 67 67 61 67 71 82 54 79 63 60
67 66 85 82 74 74 73 68 73 71 60 65 51 68 85 75 90 70 95 91
118 125 122 73 86 56 84 86 61 88 79 95 95 75 73 91 73 68 82 99
63 65 58 69 60 39 82 62 73 100
STK-C02A 143
150 137 71 83 108 93 93 99 82 96 95 71 47 73 90 103 101 134 100 90
58 64 58 95 78 77 79 94 74 77 62 73 60 31 67 69 97 72 70 69
70 99 117 102 65 67 86 61 61 76 88 89 57 90 99 102 79 102 87 80
82 114 101 111 102 82 88 75 94 92 110 94 85 109 130 107 131 119 92 116
126 100 99 113 115 107 112 98 75 72 86 125 99 93 138 126 143 177 143 112
110 120 115 102 145 96 114 105 88 107 122 155 180 140 114 139 133 129 132 124
123 121 127 135 97 126 130 105 101 156 153 138 135 113 68 81 96 84 141 130
147 134 135
STK-C02B 143
144 128 83 71 120 84 100 95 81 105 91 67 50 71 91 100 109 132 95 94
65 43 75 82 88 75 95 103 83 78 72 69 57 51 63 71 93 75 77 60
72 100 113 85 74 65 85 64 57 87 96 90 58 88 100 104 77 101 87 82
79 121 111 117 99 77 91 73 96 93 115 96 87 102 126 109 132 123 90 100
116 107 98 113 109 108 117 92 84 68 76 122 101 102 136 155 130 174 141 104
111 125 112 114 150 97 114 103 86 102 117 160 174 147 113 140 135 128 137 121
118 128 123 134 98 121 130 117 96 153 160 142 134 109 72 73 104 82 143 120
138 137 126
STK-C03A 91
77 57 96 72 96 89 88 90 108 102 124 103 100 107 137 125 120 105 108 97
109 130 114 138 115 116 141 167 167 159 134 135 104 111 113 87 99 95 142 139
134 102 133 105 111 113 109 93 140 134 135 111 133 148 135 165 203 210 219 206
177 198 181 170 181 151 158 205 181 126 171 153 178 157 139 148 180 158 196 179
163 163 159 145 167 206 181 182 159 138 157
STK-C03B 91
70 68 87 75 87 97 83 92 93 113 125 96 108 105 135 127 125 98 115 92
111 130 109 139 120 116 135 161 164 162 144 130 105 113 109 89 94 99 142 136
137 101 134 107 114 112 103 96 131 147 131 113 130 147 139 160 204 195 231 197
170 198 177 169 180 145 163 214 179 133 155 161 175 155 133 151 167 152 194 201
176 161 159 152 160 207 180 174 158 138 165
STK-C04A 117
286 249 295 228 213 269 347 272 204 237 261 254 248 277 275 183 181 134 179 171

187 257 204 194 157 194 107 137 131 145 173 163 106 78 66 112 102 76 104 151
154 215 197 156 127 134 234 140 121 181 174 120 140 127 110 118 105 113 162 118
159 154 80 130 104 106 122 148 125 115 97 100 52 53 80 105 145 119 164 155
151 193 160 123 85 115 132 76 100 84 99 111 94 100 100 106 108 104 127 79
92 89 57 62 75 92 91 132 137 126 99 99 89 74 101 115 134
STK-C04B 117
277 256 293 234 222 253 352 275 206 228 262 252 246 275 281 181 191 126 164 174
201 250 203 188 163 192 117 130 133 140 173 158 102 79 69 103 106 70 113 147
152 212 205 149 131 132 221 137 115 179 166 137 140 118 121 116 106 120 155 126
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78 85 60 55 74 85 104 133 132 132 98 98 94 74 93 108 163
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142 191 229 195 134 140 102 132 92 100 99 109 71 86 104 109 128 120 157 158
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121 130 131 104 91 94 73 68 91 74 41 65 52 56 56 81 103 98 87 83
80 101 95 93 88 104 125 101 98 118 116 133 159 174
STK-C06A 157
114 135 118 130 174 106 81 88 105 107 107 157 92 124 86 100 113 107 134 114
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140 135 124 131 171 111 82 89 103 110 117 153 91 125 90 106 110 104 141 103
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137 113 240 180 179 212
STK-C07B 106
319 224 247 253 214 139 94 102 109 130 154 156 145 177 165 169 229 221 208 218

181 233 288 183 185 162 168 154 142 170 232 144 128 141 145 190 185 156 147 165
144 209 235 268 167 155 174 108 131 153 210 190 196 180 203 170 174 190 127 111
76 75 77 57 40 61 42 66 61 87 99 85 85 73 83 101 79 148 168 210
202 174 218 254 242 218 197 219 124 126 132 110 73 98 66 88 78 96 83 133
138 118 203 168 174 217
STK-C08A 70
154 190 185 245 272 205 184 198 188 221 203 245 203 200 205 215 225 150 205 197
131 161 152 181 167 164 209 178 199 183 224 188 213 191 188 160 176 178 182 204
209 157 147 149 149 144 96 135 147 171 149 139 157 159 130 172 200 325 240 224
195 171 100 172 133 112 136 130 106 147
STK-C08B 70
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STK-C09A 71
162 177 166 216 201 171 236 145 176 201 177 172 185 218 196 154 182 168 168 141
141 146 148 171 221 153 100 135 143 122 112 105 101 105 80 103 133 155 128 128
133 126 85 185 135 114 162 162 141 215 184 148 172 163 229 158 196 146 151 148
176 158 116 122 186 141 143 123 146 157 176
STK-C09B 71
162 176 166 216 200 174 234 147 173 199 183 175 189 212 199 155 183 166 163 147
144 150 143 174 231 146 106 132 139 130 111 108 95 116 73 108 135 159 123 135
139 121 86 177 133 119 165 173 147 211 192 147 164 158 218 164 195 138 154 149
169 166 115 121 182 145 135 138 137 148 176
STK-C10A 85
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131 87 95 88 133 122 162 126 151 132 150 131 108 128 177 141 130 124 144 167
158 105 106 130 137 119 120 170 108 142 97 124 127 148 187 145 110 128 118 143
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STK-C10B 85
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STK-C11A 146
208 231 248 245 269 172 126 112 121 137 178 218 227 148 138 115 117 143 174 188
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114 108 106 150 117 108 94 73 102 110 104 94 144 74 99 106 80 85 102 90
81 98 95 122 76 88 133 92 90 113 89 109 100 126 82 119 96 104 71 132
70 84 97 76 99 147 133 148 104 110 105 120 140 134 115 80 90 102 89 91

109 116 88 100 134 109 158 121 124 80 92 104 75 106 121 186 184 195 152 161
151 119 151 188 159 272
STK-C12A 104
114 114 97 80 90 92 91 118 101 94 111 105 94 76 95 103 72 75 133 145
116 153 154 175 179 213 147 129 138 118 110 148 102 137 115 102 131 137 154 157
149 184 138 153 140 116 103 119 105 102 100 91 109 100 99 81 99 105 94 86
86 68 57 63 80 95 106 107 115 115 102 139 119 106 107 104 93 114 96 96
75 95 82 86 94 101 92 91 90 86 102 75 71 76 66 55 82 98 63 68
53 36 41 46
STK-C12B 104
99 126 96 83 88 96 86 123 95 99 110 101 97 75 95 100 77 77 130 143
114 154 159 173 179 221 152 128 139 118 110 150 101 130 121 107 125 138 163 154
148 181 136 147 153 118 98 121 101 107 103 87 109 102 97 93 106 106 95 85
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48 37 44 48

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

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

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

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

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. **Measuring Ring Widths.** Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. **Cross-Matching and Dating the Samples.** Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

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

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

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

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

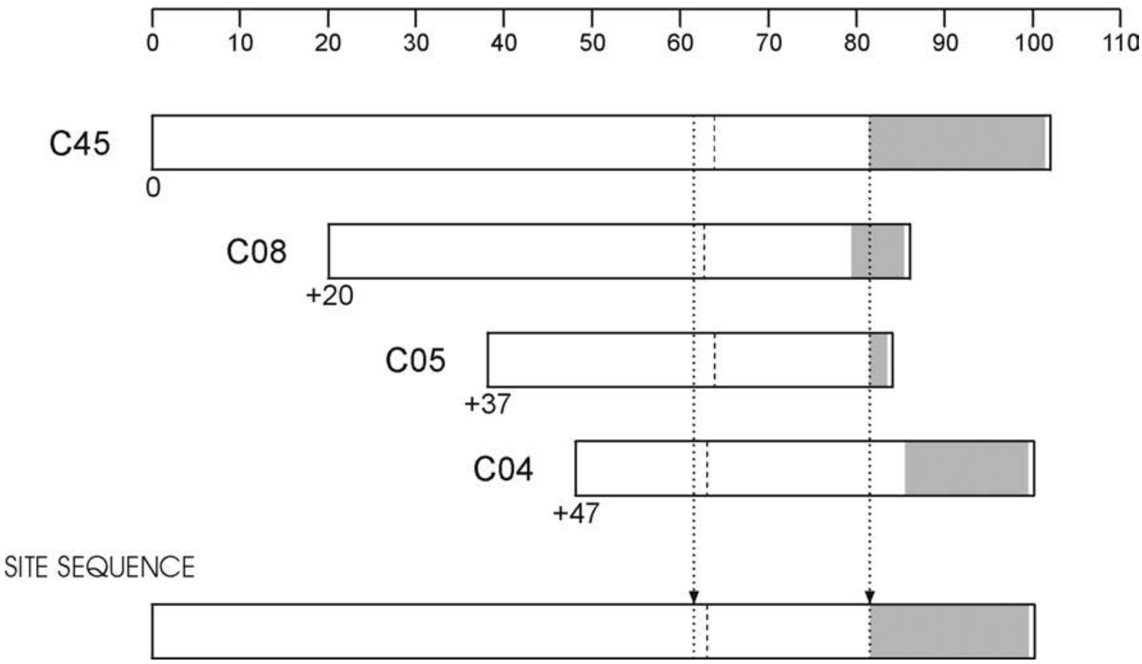


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

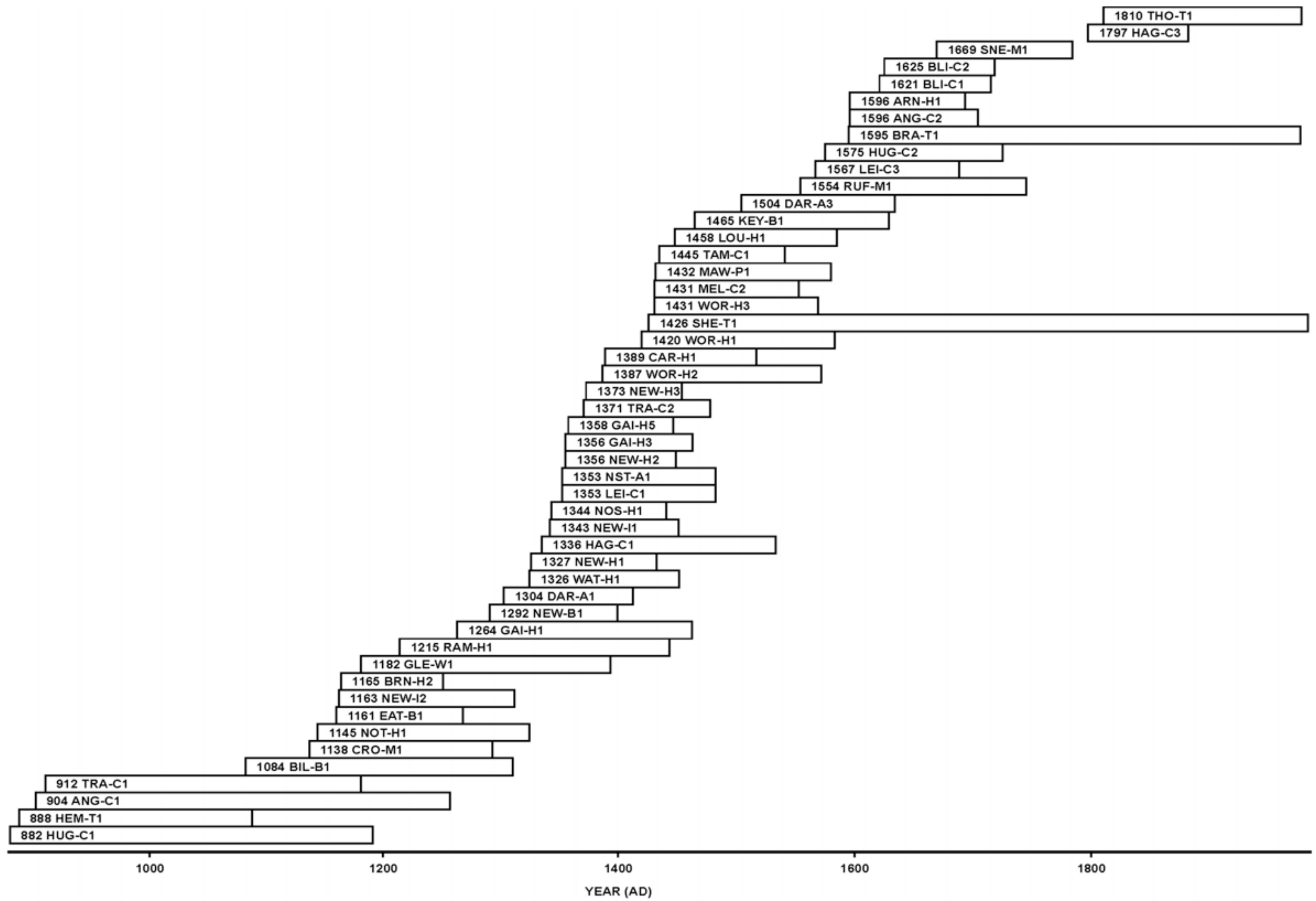
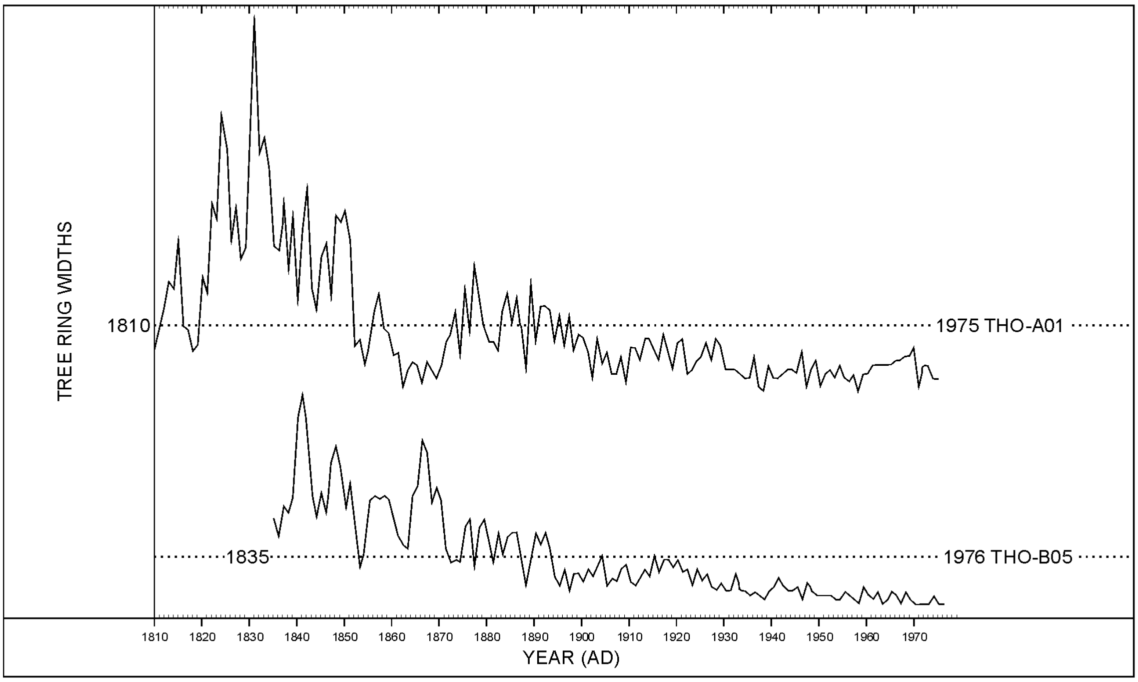


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

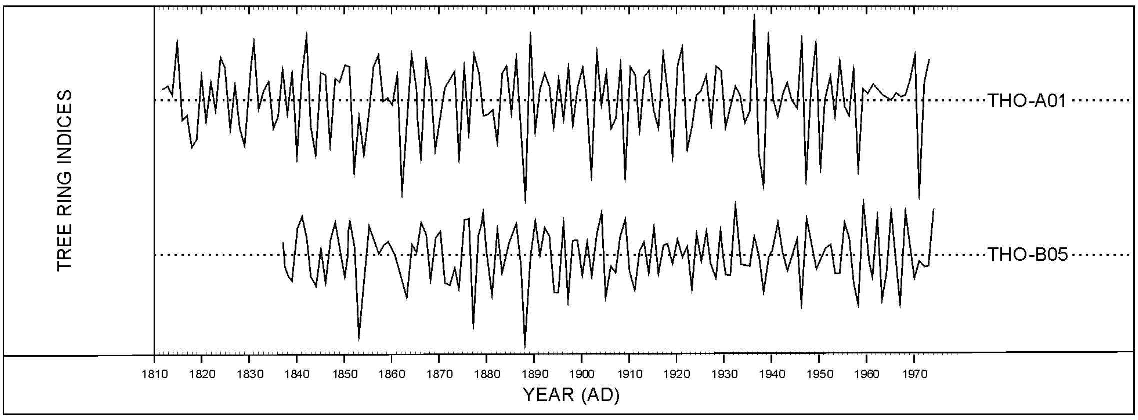


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

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

The growth trends have been removed completely

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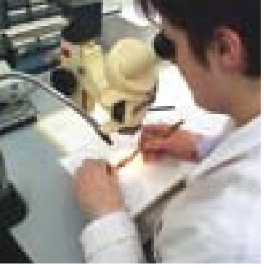
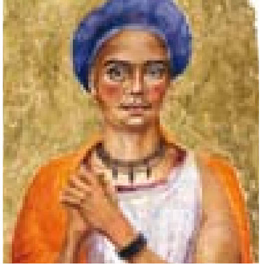



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