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ST ANDREW'S CHURCH, ALWINGTON, DEVON
TREE-RING ANALYSIS OF TIMBERS FROM THE SOUTH AISLE AND NAVE ROOFS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Samples were taken from the roof timbers of the south aisle and nave of this church, resulting in the construction and dating of two site sequences.

Site sequence ALWCSQ01 contains ten samples, all from the nave roof, and was found to span the period AD 1253–1391. Interpretation of the heartwood/sapwood boundary ring positions of these samples suggests felling in AD 1401–26.

Site sequence ALWCSQ02 contains nine samples, all from the south aisle roof, and spans the period AD 1342–1490. Interpretation of the heartwood/sapwood boundary ring position of these samples suggests felling in AD 1499–1524.

The tree-ring dating has demonstrated that the roof of the nave was probably constructed in the first quarter of the fifteenth century, whereas that of the south aisle in the first quarter of the sixteenth century.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Laboratory would like to thank Nigel Jaggard, of Magenta Building Conservation Ltd, for organising access and for his on-site assistance. Figures 7–33 were provided by Oliver West & John Scott Architects. We would also like to thank Isabelle Parsons, of the English Heritage Scientific Dating Section, for her assistance, and Cathy Tyers of the Sheffield Dendrochronology Laboratory for her comments and advice throughout the production of this report.

ARCHIVE LOCATION

Devon Historic Environment Record
Historic Environment Service
Matford Offices
County Hall
Exeter EX2 4QW

DATE OF INVESTIGATION

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT

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INTRODUCTION

The parish church of St Andrew, located in Alwington (SS405 232; Figs 1–3), is believed to date from the fifteenth century. In plan it consists of chancel (with north vestry), nave with north transept, south aisle, south porch, and three-stage west tower. The nave and chancel both have wagon roofs with moulded ribs and foliate-carved bosses (Fig 4), which have been stylistically dated to the fifteenth century. Also dated to the fifteenth century is the doorway to the south porch which has a hood mould. The south aisle also has a wagon roof; this part of the church is known to have undergone rebuilding in the sixteenth or seventeenth century. Further restoration at the church was undertaken in AD 1883.

SAMPLING

Tree-ring dating of the south aisle, nave, and south porch roofs at this church was requested by Francis Kelly, Historic Buildings Inspector in the English Heritage's Bristol Office. The south aisle is currently undergoing repair, necessitating the removal of roof slates from this structure and from the valley between it and the nave roof, exposing timbers (Figs 5 and 6). It was hoped that dendrochronology might provide construction dates for the roofs, thus establishing the relationship between them, and in such a way lead to an increased understanding of development of the church. Unfortunately, when the timbers of the south porch roof were examined they could be seen to be relatively modern, possibly dating to the nineteenth century restoration and so were not sampled.

Roof trusses of the nave and south aisle have been numbered from east to west, as indicated in Figure 7. In accordance with the brief provided by English Heritage, a total of 29 timbers was sampled. Each sample was given the code ALW-C (for Alwington Church) and numbered 01–29. Sixteen of these were taken from the south aisle (ALW-C01–16) and 13 from the nave (ALW-C17–29). With the removal of the slates covering the south aisle, the whole roof structure of this part of the church was accessible for sampling. However, only a small portion of the nave (and chancel) roof structure(s) were revealed (Fig 6), severely restricting the number of available timbers. In the case of the chancel the portion of the roof accessible was limited to that part of the rafters which contained the large mortice joint for the archbraces making it impossible to get any suitable samples. The location of samples was noted at the time of sampling and has been marked on Figures 8–33. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

At this stage it was noticed that two of the samples (one from the nave and one from the south aisle) had too few rings to make secure dating a possibility. These samples were rejected prior to measurement. The remaining 27 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 19 cross-matching to form two groups.

Firstly, ten samples, all from the nave roof, grouped and were combined at the relevant offset positions to form ALWCSQ01, a site sequence of 139 rings (Fig 34). This site sequence was compared against a series of relevant reference chronologies for oak, where it was found to match consistently at a first-ring date of AD 1253 and a last-measured ring date of AD 1391. The evidence for this dating is given by the *t*-values in Table 2.

Five of these samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1386, allowing an estimated felling date to be calculated for the five timbers represented to within the range AD 1401–26. The remaining five samples do not have the heartwood/sapwood boundary ring, but with last-measured ring dates ranging from AD 1321 (ALW-C23) to AD 1363 (ALW-C22) it is quite likely that these were also felled in AD 1401–26.

Secondly, nine samples from the south aisle matched and were combined at the relevant offset positions to form ALWCSQ02, a site sequence of 149 rings (Fig 35). This site sequence was found to match the reference chronologies at a first-ring date of AD 1342 and a last-measured ring date of AD 1490. The evidence for this dating is given by the *t*-values in Table 3. Eight of the samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1484, which allows an estimated felling date to be calculated for the eight timbers represented to within the range AD 1499–1524. The ninth sample, ALW-C05, does not have the heartwood/sapwood boundary, although the timber from which it was taken did. This beam was sampled from centre to heartwood/sapwood boundary and it could be seen that the boundary was only just missed and would probably have been within a few rings of the last ring on the sample. With a last-measured ring date of AD 1468, and with the heartwood/sapwood boundary thought to be only a few years later, it is quite likely that this sample was also felled in AD 1499–1524.

Attempts were then made to date the remaining ungrouped samples by individually comparing them against the reference chronologies. However, no conclusive matching was noted and all remain undated.

DISCUSSION

Prior to tree-ring analysis being undertaken, the nave roof had been stylistically dated to the fifteenth century, whereas the south aisle was known to have undergone rebuilding in the sixteenth or seventeenth century.

The nave roof is now known to contain timbers felled in AD 1401–26, making it likely that this roof was constructed some time in the first quarter of the fifteenth century. Although of similar construction, the south aisle roof contains timber felled in AD 1499–1524, putting it about a century later than the nave roof in the first quarter of the sixteenth century, and suggesting the rebuilding of the south aisle took place in the sixteenth rather than seventeenth century.

The good intra-site matching seen within the samples of the nave roof suggests construction was undertaken utilising a coherent series of trees probably taken from a single discrete source. The majority of the nave samples group at a value of t=6, with only two measured samples (ALW-C19 and ALW-C27) not matching at all. Sample ALW-C19 has a band of highly compacted rings which might have interfered, both with this sample matching the other nave samples and also with the chances of successful individual dating; no obvious problems were seen with sample ALW-C27.

The timbers utilised within the construction of the south aisle roof appear to be of a more diverse character. Although the majority of those samples dated within site sequence ALWCSQ02 grouped at a value of t=7, suggesting that these timbers were from a single source, a further six of the analysed south aisle samples did not match this group or each other, pointing to these samples representing a disparate series of trees from a potentially more diverse source or sources. Additionally, as these are undated it is possible, though not proven, that they might represent different felling phases, although nothing was noted at the time of sampling to suggest they were anything other than primary to the structure.

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TABLES AND FIGURES

Table 1: Details of tree-ring samples from the nave and south aisle roofs, Alwington Church, Devon

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
South aisle						
ALW-C01	North rafter, truss 1	79	h/s	1406	1484	1484
ALW-C02	South lower arch brace, truss 1.2	77	h/s	----	----	----
ALW-C03	North rafter, truss 2.2	71	h/s	1420	1490	1490
ALW-C04	South rafter, truss 2.2	60	h/s	----	----	----
ALW-C05	North rafter, truss 5	104	--	1365	----	1468
ALW-C06	North rafter, truss 5.3	57	h/s	----	----	----
ALW-C07	South lower arch brace, truss 5.3	71	11	----	----	----
ALW-C08	South rafter, truss 6	93	01	1393	1484	1485
ALW-C09	North rafter, truss 8	90	h/s	1398	1487	1487
ALW-C10	South rafter, truss 9.2	109	01	1371	1478	1479
ALW-C11	North rafer, truss 9.3	146	02	1342	1485	1487
ALW-C12	South rafter, truss 11.2	NM	--	----	----	----
ALW-C13	South rafter, truss 12	106	h/s	----	----	----
ALW-C14	South rafter, truss 14	44	03+16NM	----	----	----
ALW-C15	North rafter, truss 16	99	h/s	1389	1487	1487
ALW-C16	North rafter, truss 18	113	h/s	1365	1477	1477
Nave						
ALW-C17	South rafter, truss 9	60	--	1289	----	1348
ALW-C18	South rafter, truss 10	NM	--	----	----	----
ALW-C19	South lower arch brace, truss 11	129	h/s	----	----	----
ALW-C20	South rafter, truss 17	96	h/s	1286	1381	1381
ALW-C21	South lower arch brace, truss 17	87	h/s	1288	1374	1374
ALW-C22	South rafter, truss 19	99	--	1265	----	1363
ALW-C23	South rafter, truss 21	69	--	1253	----	1321
ALW-C24	South rafter, truss 22	51	--	1311	----	1361

ALW-C25	South rafter, truss 23	99	h/s	1293	1391	1391
ALW-C26	South rafter, truss 25	114	h/s	1278	1391	1391
ALW-C27	South rafter, truss 26	80	--	----	----	----
ALW-C28	South rafter, truss 27	81	--	1260	----	1340
ALW-C29	South rafter, truss 29	81	h/s	1311	1391	1391

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

**The core broke during the sampling process and it is not possible to be positive that no rings are missing between the two parts of the core, but it is possible to count how many rings are to be found in this outer portion.

Table 2: Results of the cross-matching of site sequence ALWCSQ01 and relevant reference chronologies when the first-ring date is AD 1253 and the last-ring date is AD 1391

Reference chronology	*t*-value	Span of chronology	Reference
St Brannock Church, Braunton, Devon	10.2	AD 1215–1378	Tyers 2004
St John's Chapel, Exeter, Devon	8.3	AD 1132–1337	Arnold *et al* 2006a
The Deanery, Exeter Cathedral	7.2	AD 1233–1403	Howard *et al* 2000
West Challacombe, Coombe Martin, Devon	6.7	AD 1319–1452	Tyers and Groves 1999
The Post Office, Oxhill Warwick	6.4	AD 1322–1447	Alcock *et al* 1989
Manor House, Abbey Green, Burton-upon-Trent, Staffs	6.3	AD 1162–1339	Howard *et al* 1998 unpubl
Kingswood Abbey, Gatehouse, Glos	5.8	AD 1307–1428	Arnold *et al* 2003

Table 3: Results of the cross-matching of site sequence AWLCSQ02 and relevant reference chronologies when the first-ring date is AD 1342 and the last-ring date is AD 1490

Reference chronology	*t*-value	Span of chronology	Reference
Warleigh House, Tamerton Foliot, Devon	9.7	AD 1367–1539	Howard *et al* 2006b
The Commandery, Worcester	9.4	AD 1284–1473	Arnold and Howard 2006
Mercer's Hall, Glos	9.6	AD 1289–1541	Howard *et al* 1996
The Post Office, Oxhill Warwick	8.4	AD 1322–1447	Alcock *et al* 1989
Prowse barn, Sandford, Devon	8.3	AD 1380–1473	Groves 2005
St Martin's Church, Looe, Devon	7.9	AD 1363–1518	Arnold *et al* 2006b
St Tetha's Church, St Teath, Cornwall	7.9	AD 1396–1477	Arnold and Howard 2007

FIGURES

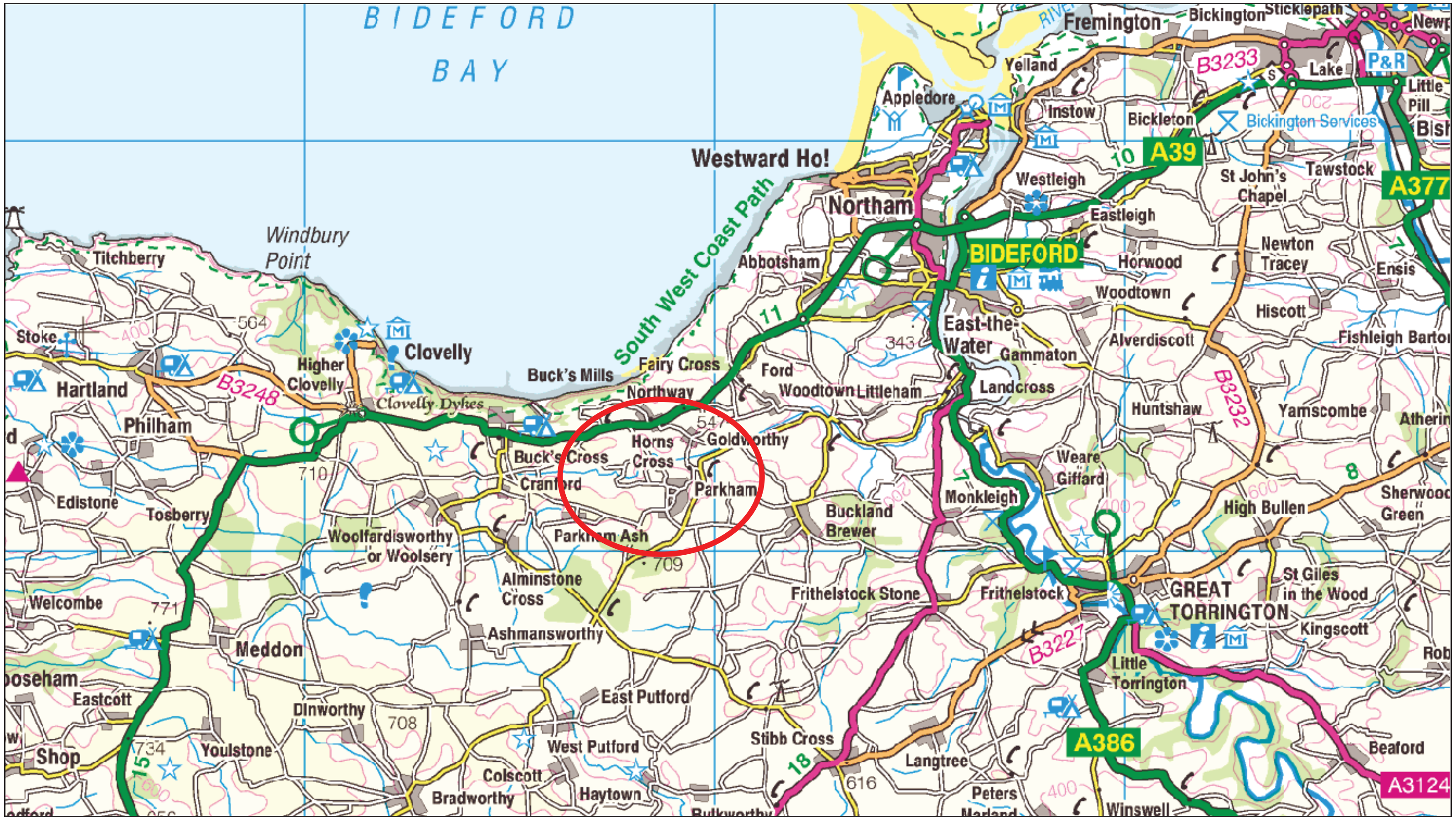


Figure 1: Map to show the general location of Alwington (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

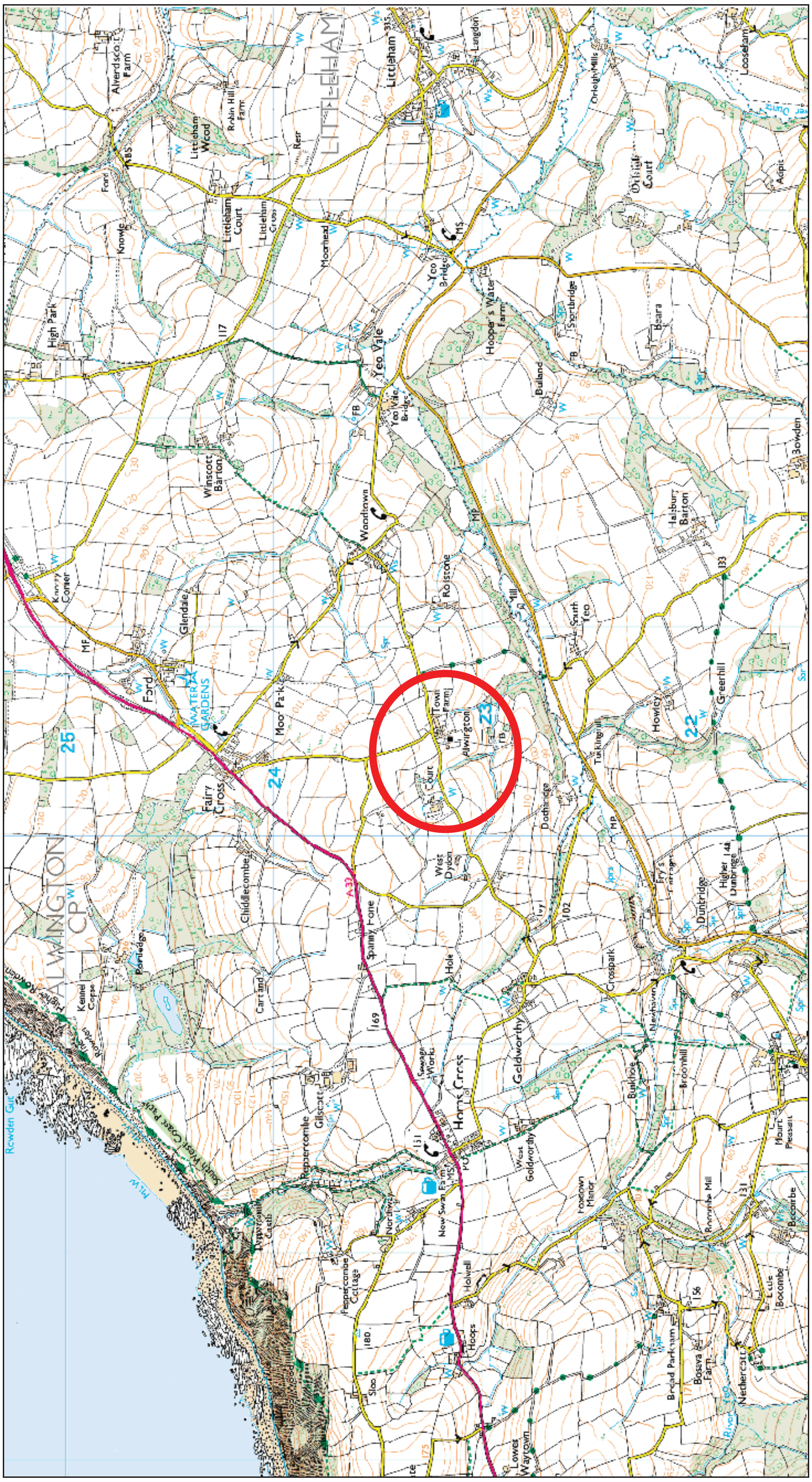


Figure 2: Map to show the location of Alwington (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

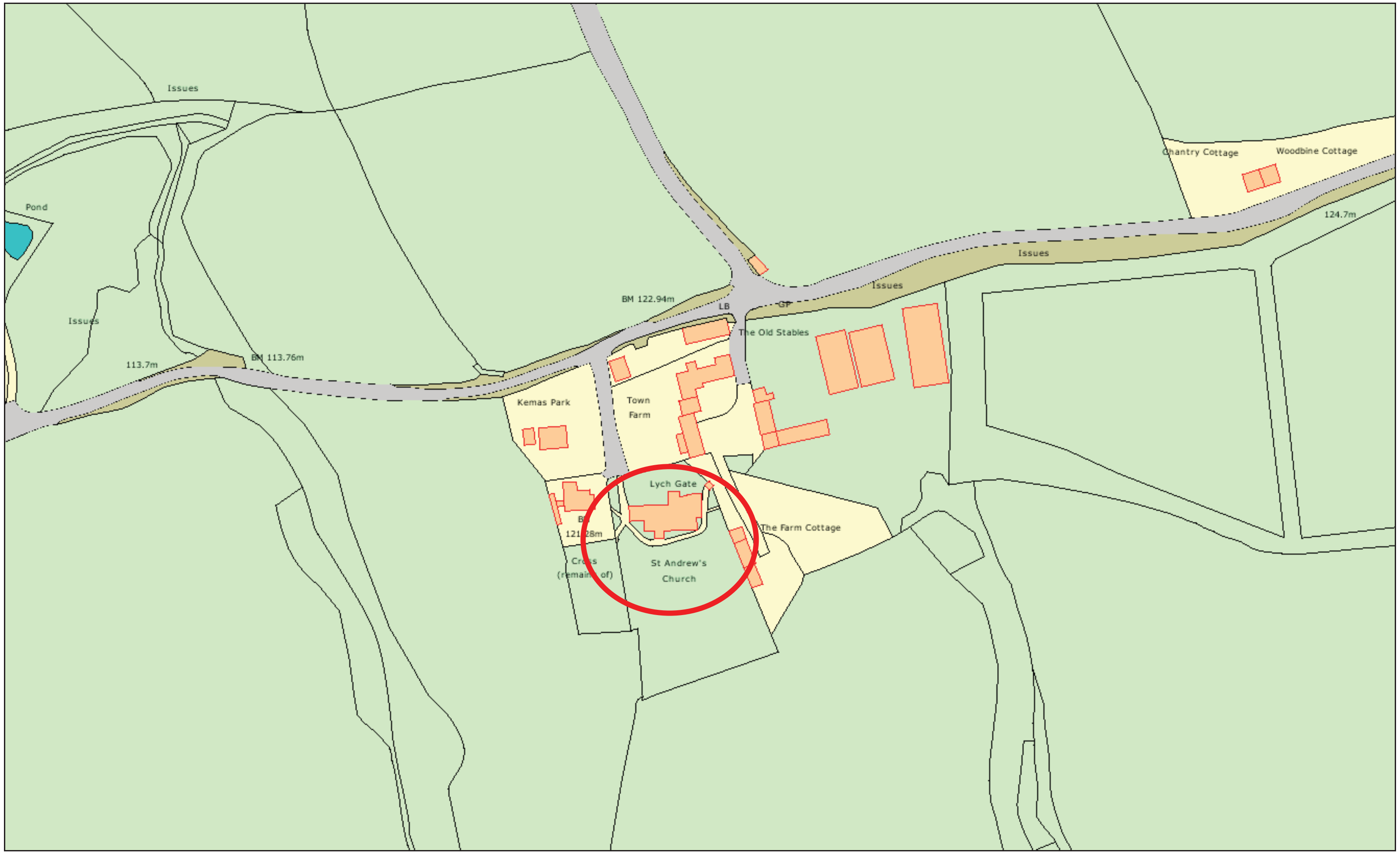


Figure 3: Map to show the location of St Andrew's Church (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 4: Nave and chancel ceiling (photograph taken facing east)

Figure 5: South aisle roof structure

Figure 6: Slates removed from the south aisle (to the right) and the valley between it and the nave, exposing roof timbers

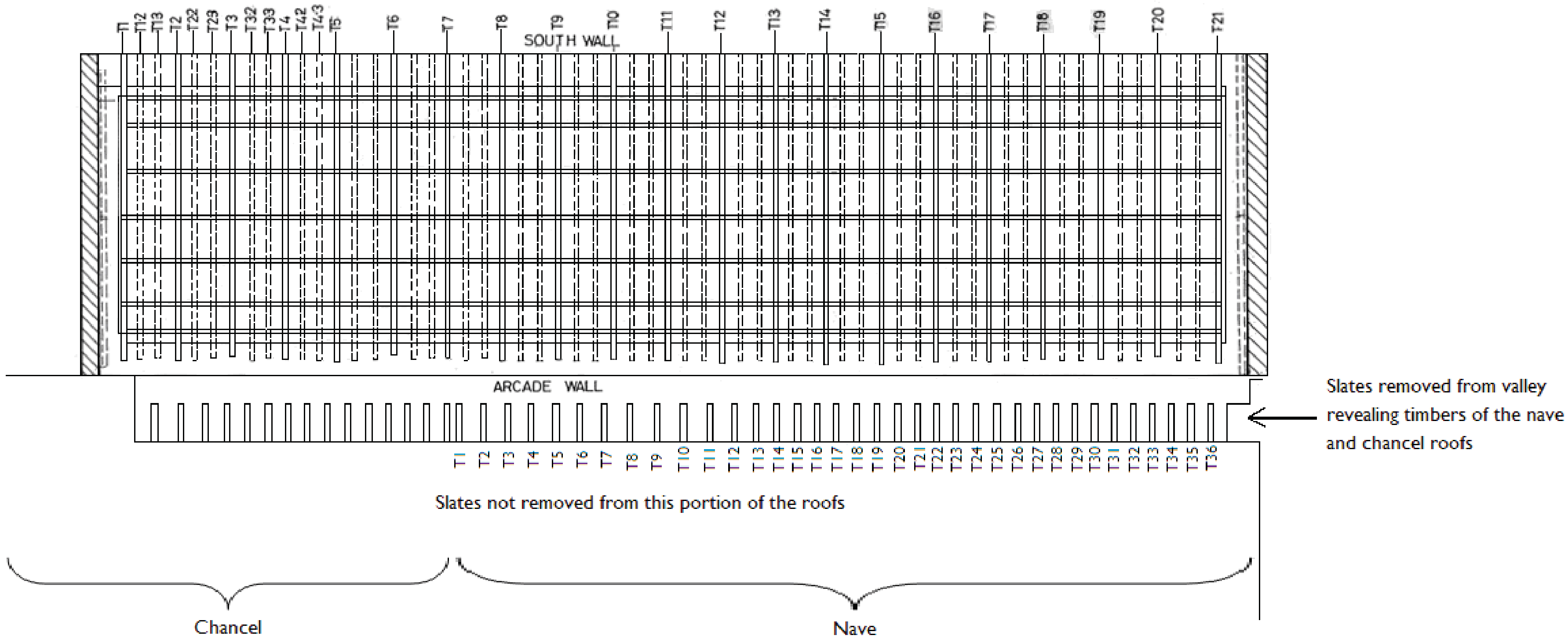


Figure 7: Plan of South Aisle and exposed Nave roof timbers (based on Oliver West & John Scott Architects), showing truss numbers

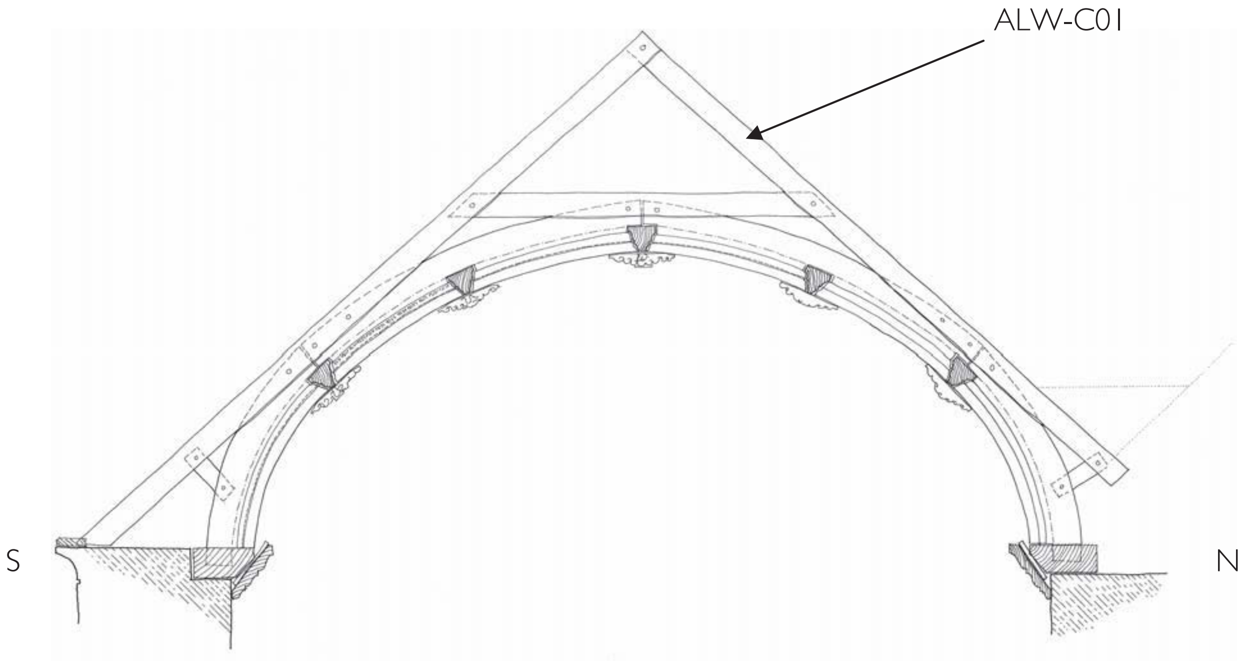


Figure 8: South aisle; truss 1, showing the location of sample ALW-C01 (based on example truss provided by Oliver West & John Scott Architects)

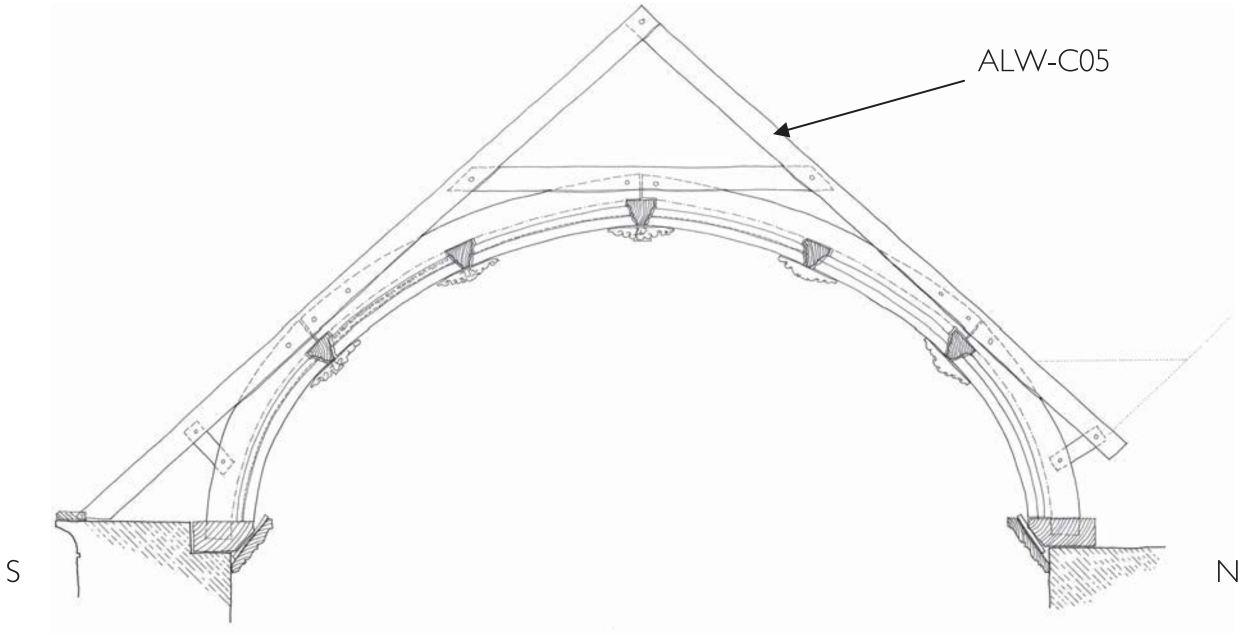


Figure 9: South aisle; truss 5, showing the location of sample ALW-C05 (based on example truss provided by Oliver West & John Scott Architects)

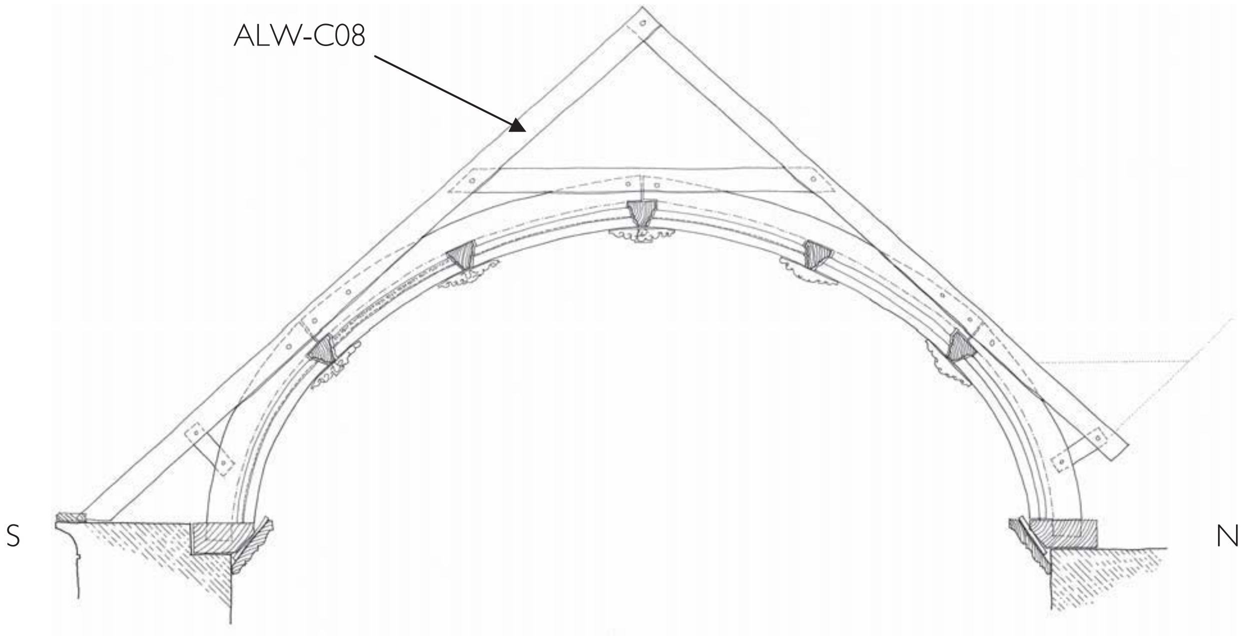


Figure 10: South aisle; truss 6, showing the location of sample ALW-C08 (based on example truss provided by Oliver West & John Scott Architects)

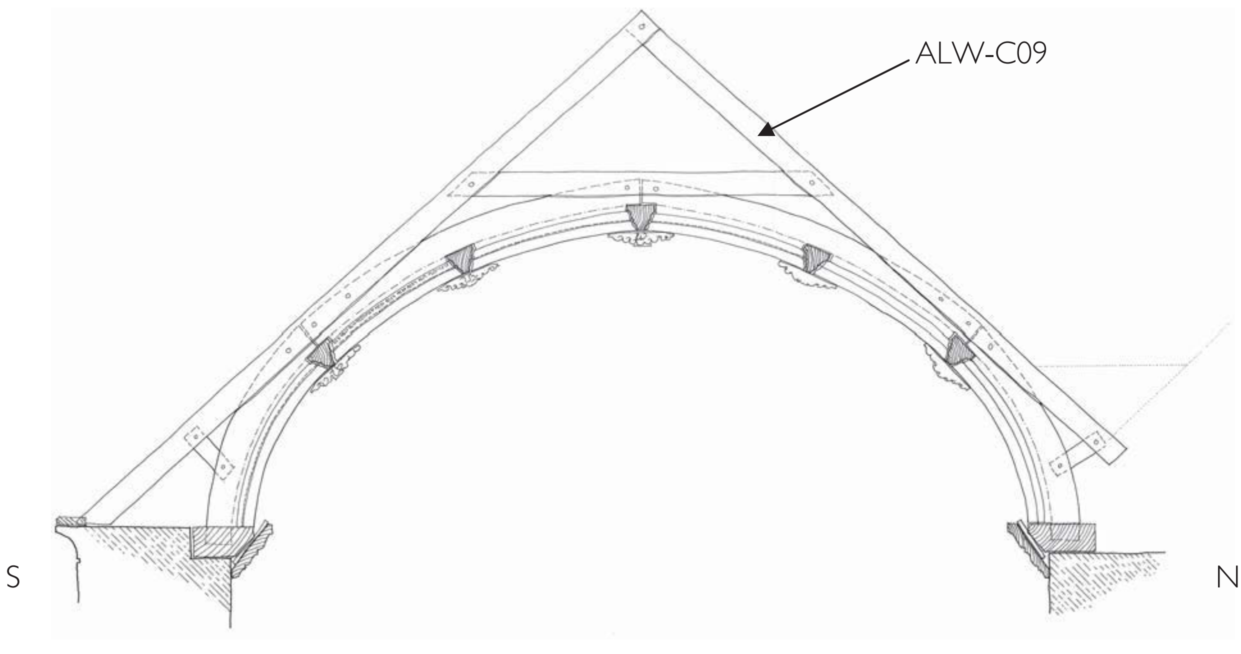


Figure 11: South aisle; truss 8, showing the location of sample ALW-C09 (based on example truss provided by Oliver West & John Scott Architects)

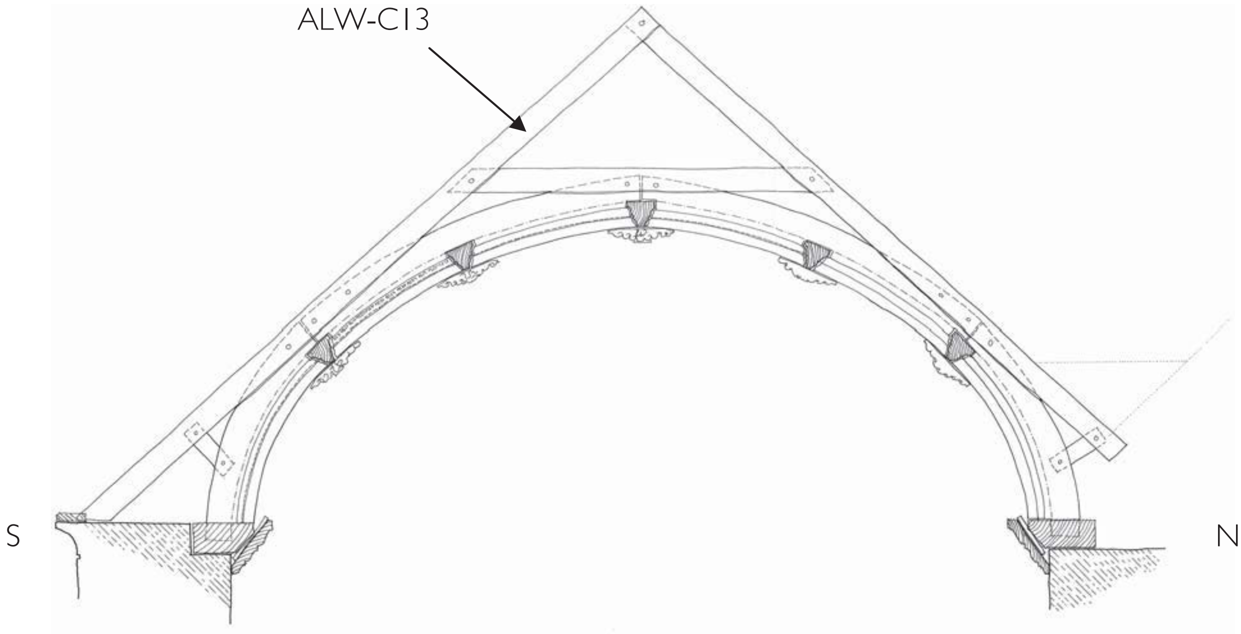


Figure 12: South aisle; truss 12, showing the location of sample ALW-C13 (based on example truss provided by Oliver West & John Scott Architects)

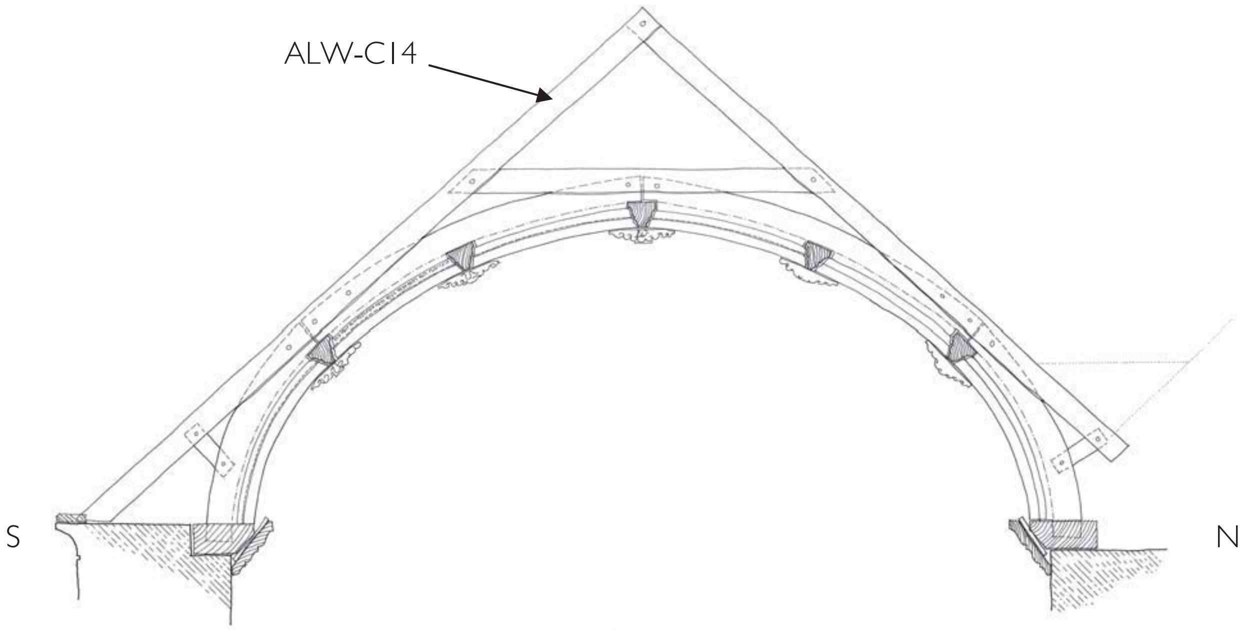


Figure 13: South aisle; truss 14, showing the location of sample ALW-C14 (based on example truss provided by Oliver West & John Scott Architects)

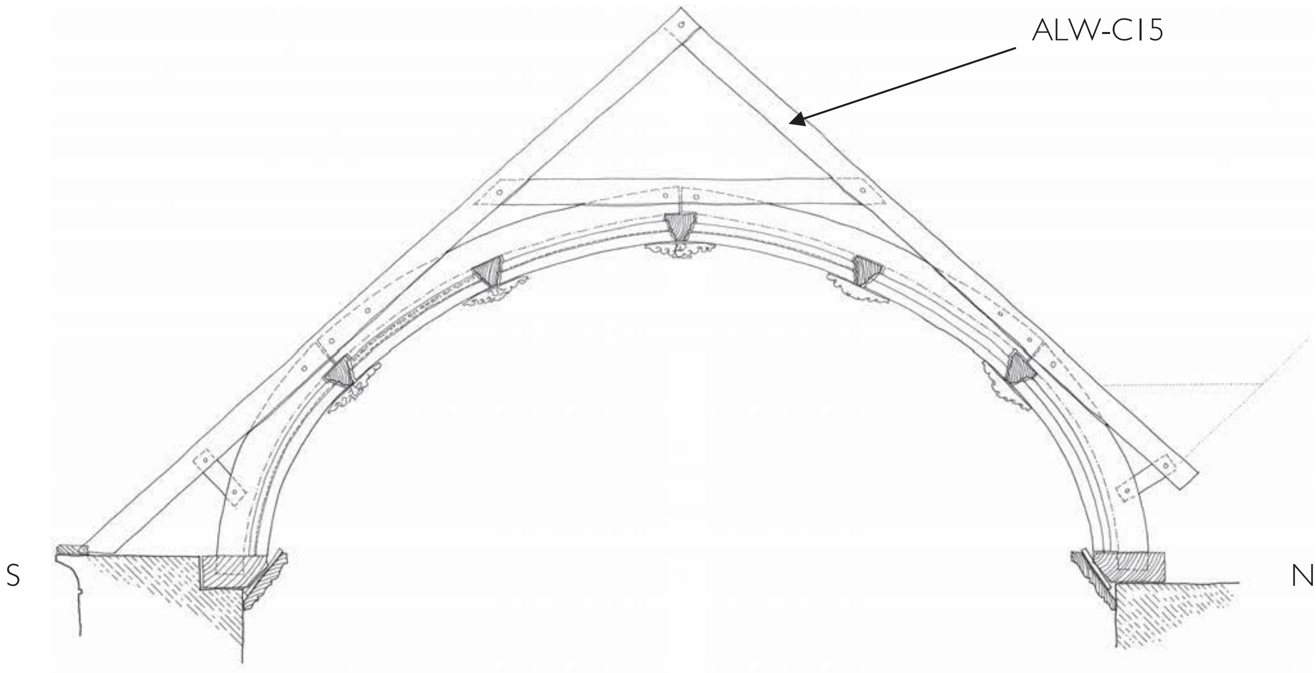


Figure 14: South aisle; truss 16, showing the location of sample ALW-C15 (based on example truss provided by Oliver West & John Scott Architects)

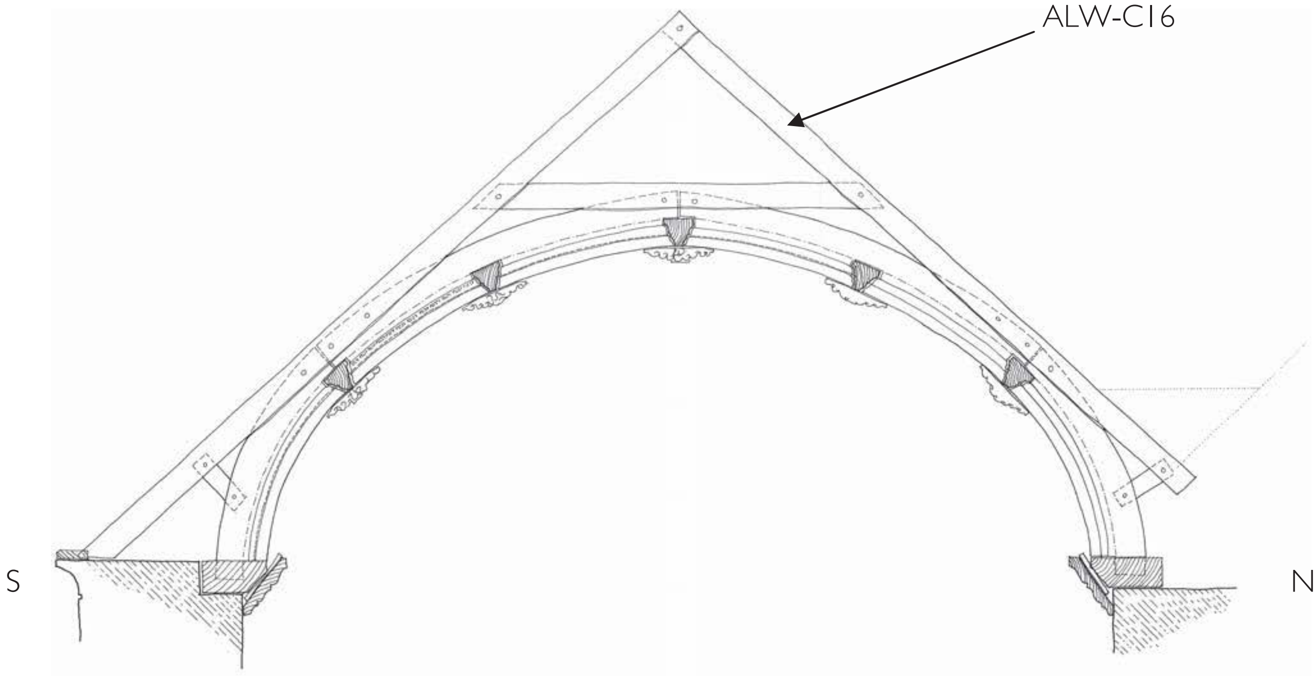


Figure 15: South aisle; truss 18, showing the location of sample ALW-C16 (based on example truss provided by Oliver West & John Scott Architects)

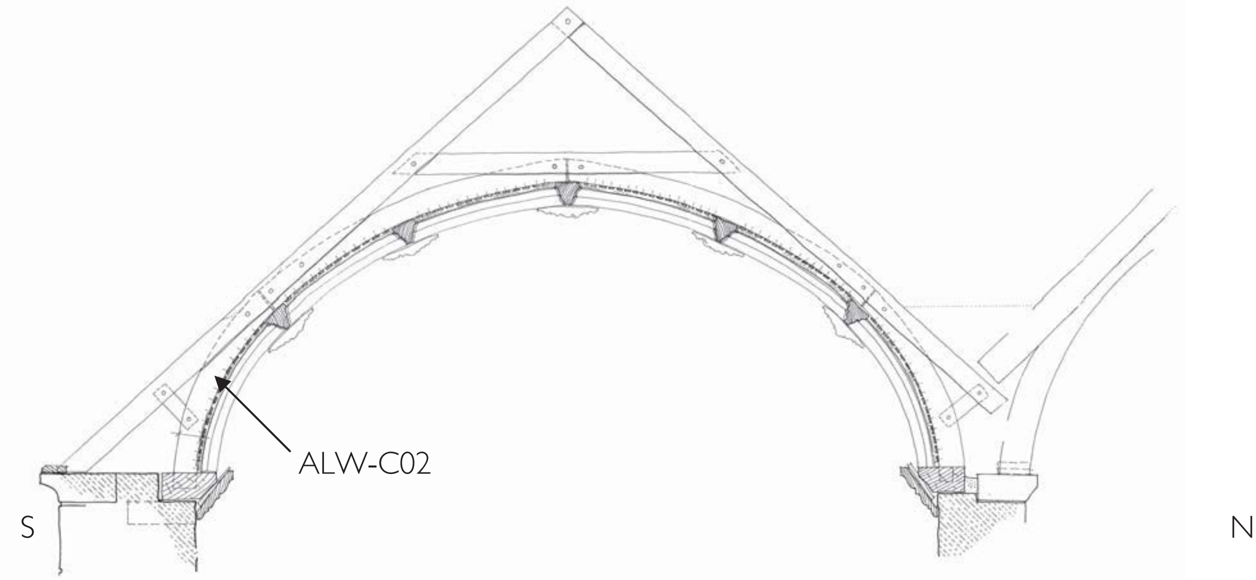


Figure 16: South aisle; truss 1.2, showing the location of sample ALW-C02 (based on example truss provided by Oliver West & John Scott Architects)

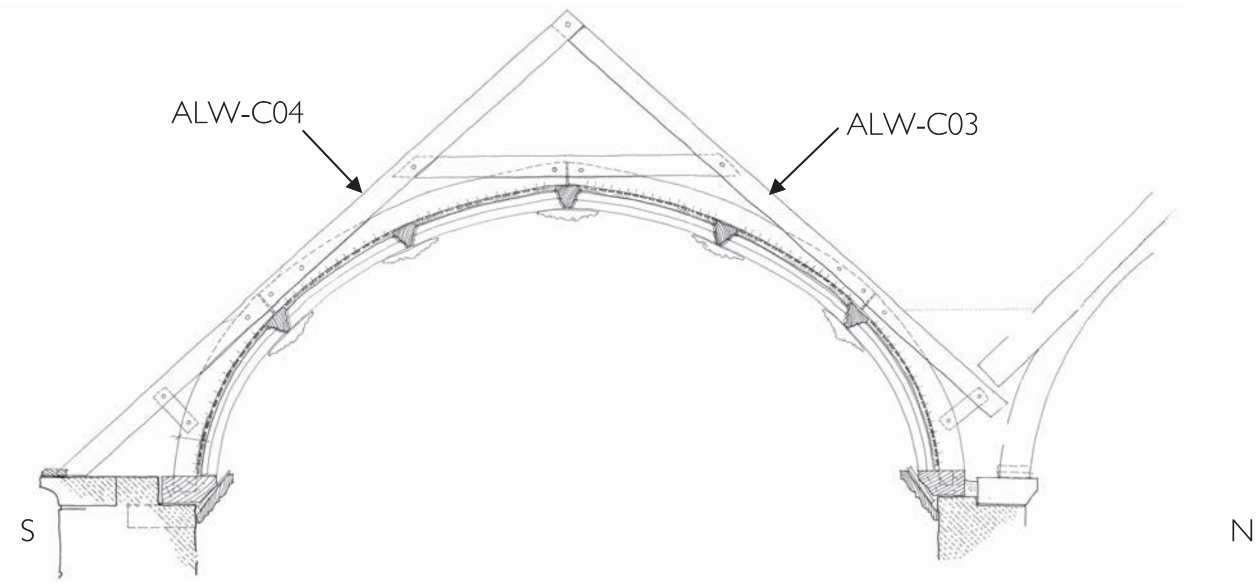


Figure 17: South aisle; truss 2.2, showing the location of samples ALW-C03 and ALW-C04 (based on example truss provided by Oliver West & John Scott Architects)

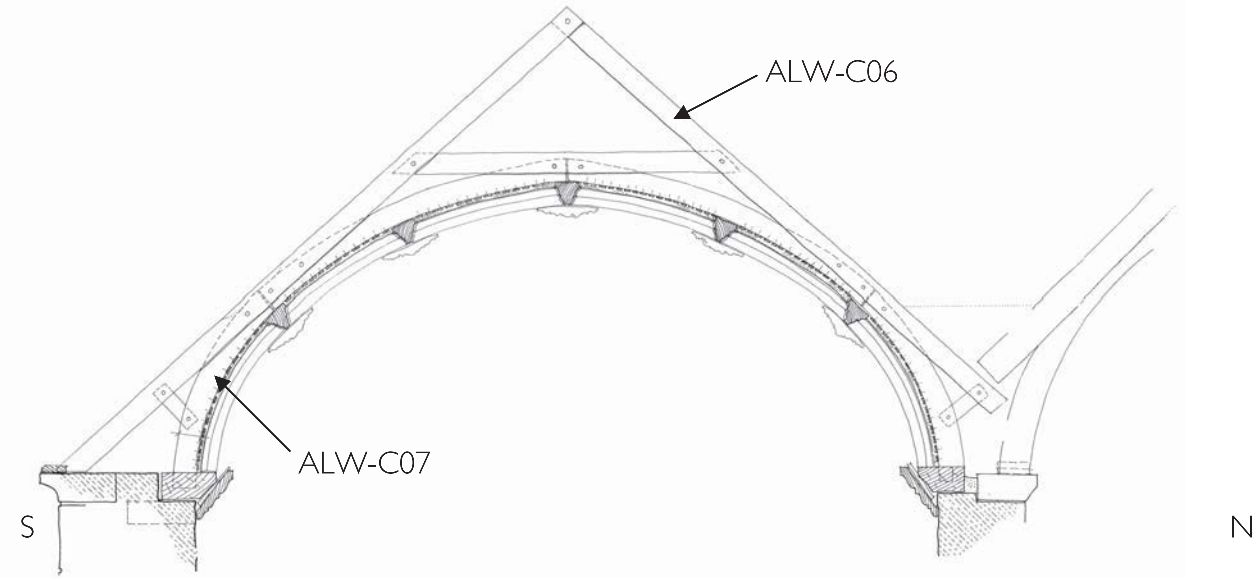


Figure 18: South aisle; truss 5.3, showing the location of samples ALW-C06 and ALW-C07 (based on example truss provided by Oliver West & John Scott Architects)

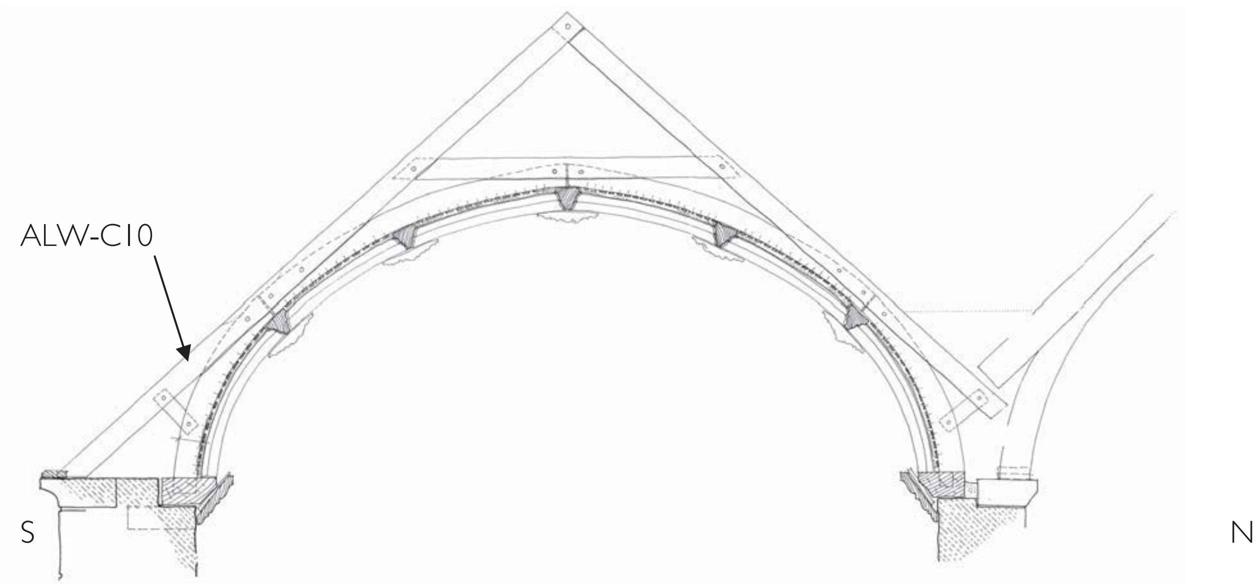


Figure 19: South aisle; truss 9.2, showing the location of sample ALW-C10 (based on example truss provided by Oliver West & John Scott Architects)

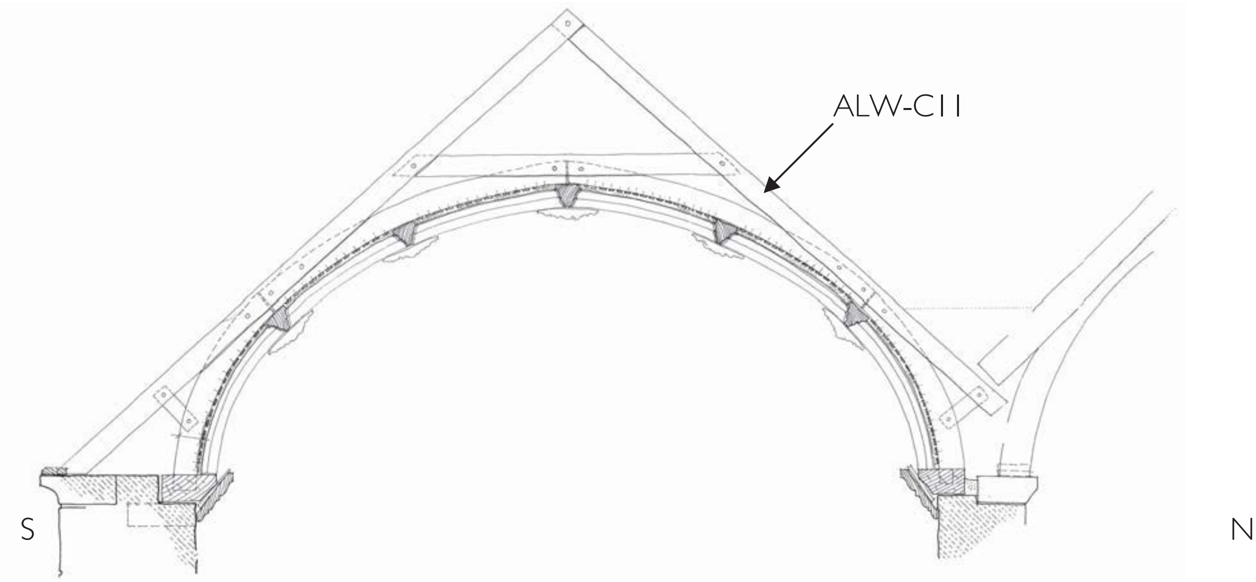


Figure 20: South aisle; truss 9.3, showing the location of sample ALW-C11 (based on example truss provided by Oliver West & John Scott Architects)

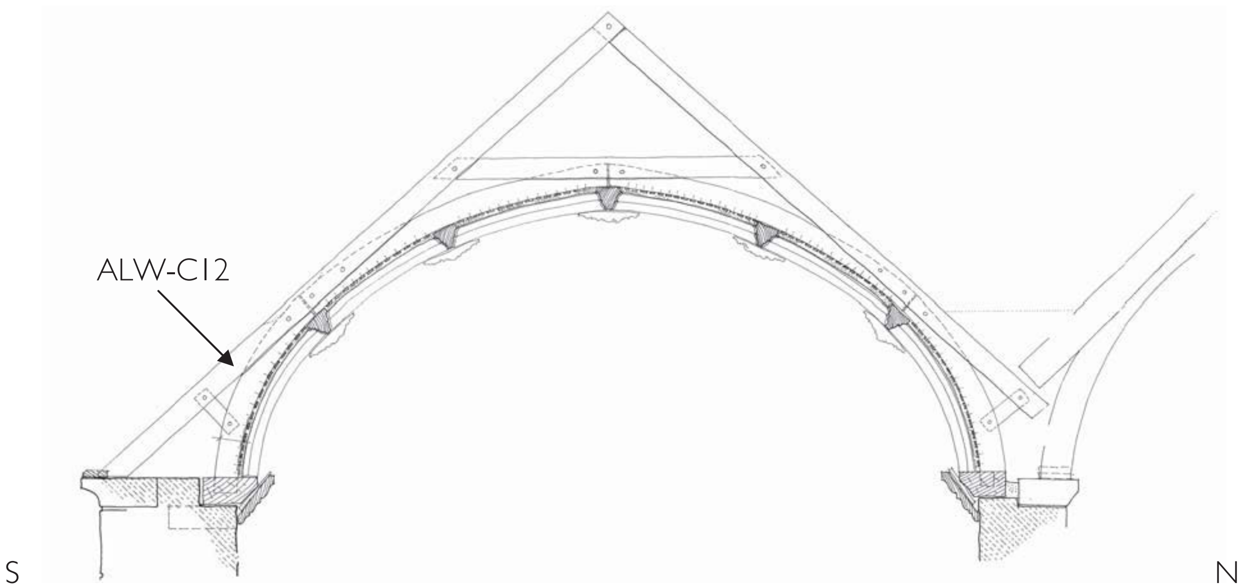


Figure 21: South aisle; truss 11.2, showing the location of sample ALW-C12 (based on example truss provided by Oliver West & John Scott Architects)

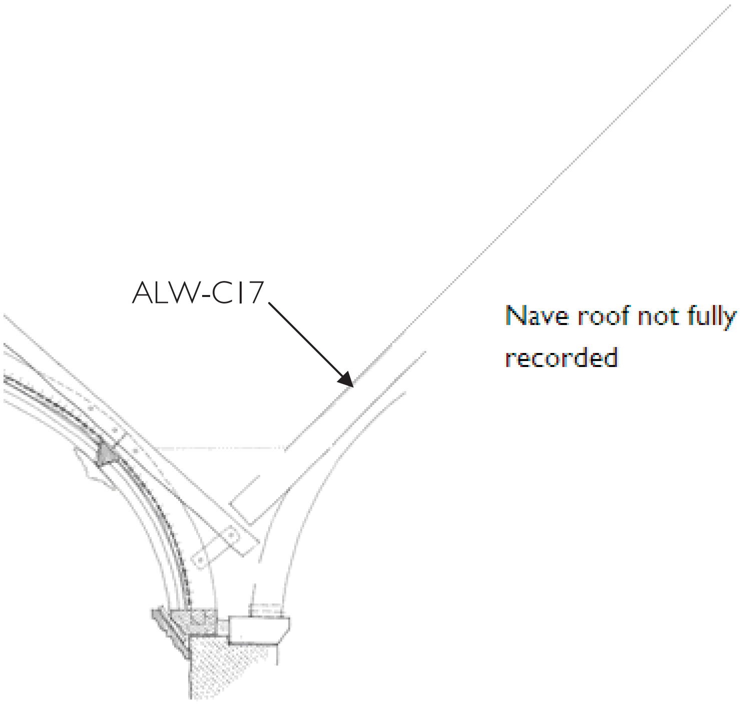


Figure 22: Nave; truss 9, showing the location of sample ALW-C17 (based on example truss provided by Oliver West & John Scott Architects)

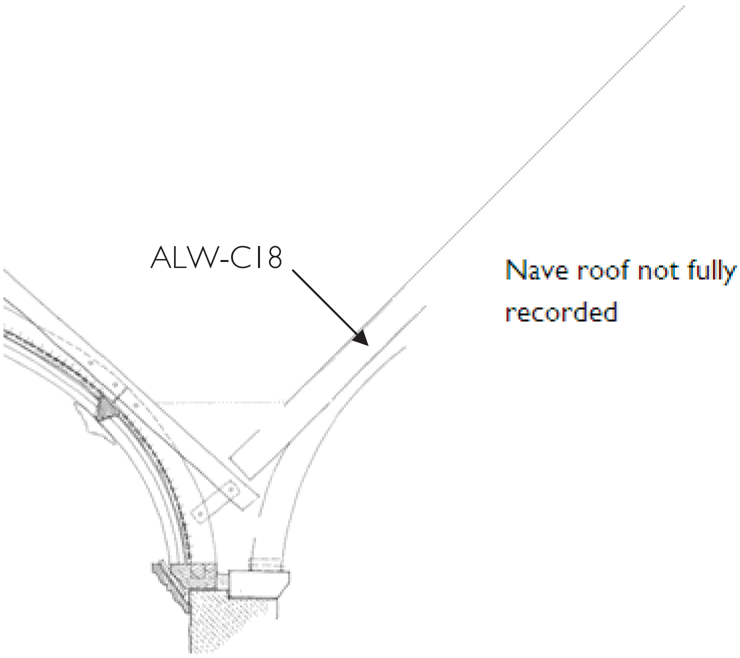


Figure 23: Nave; truss 10, showing the location of sample ALW-C18 (based on example truss provided by Oliver West & John Scott Architects)

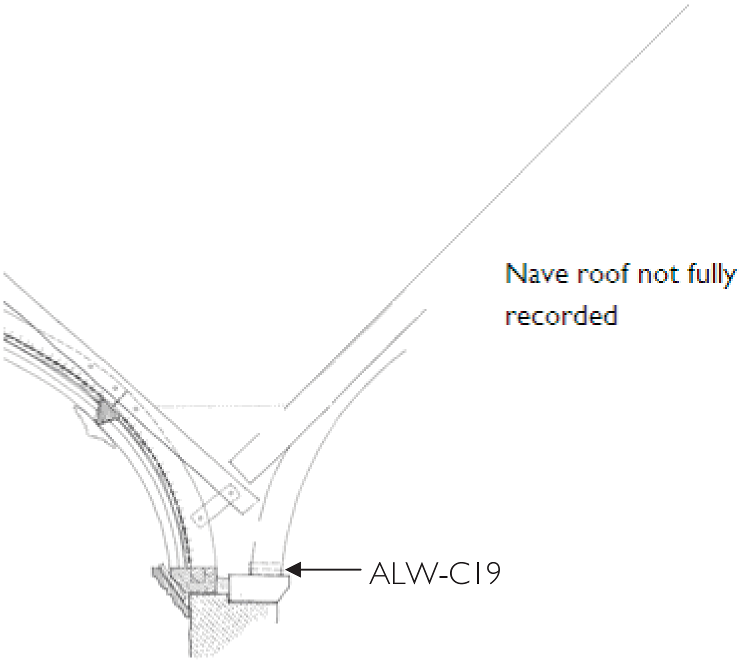


Figure 24: Nave; truss 11, showing the location of sample ALW-C19 (based on example truss provided by Oliver West & John Scott Architects)

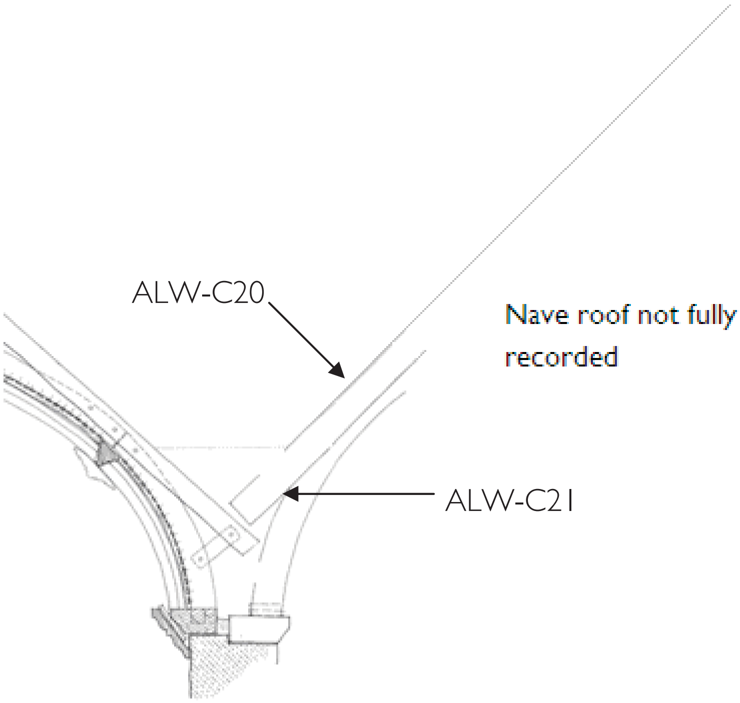


Figure 25: Nave; truss 17, showing the location of samples ALW-C20 and ALW-C21 (based on example truss provided by Oliver West & John Scott Architects)

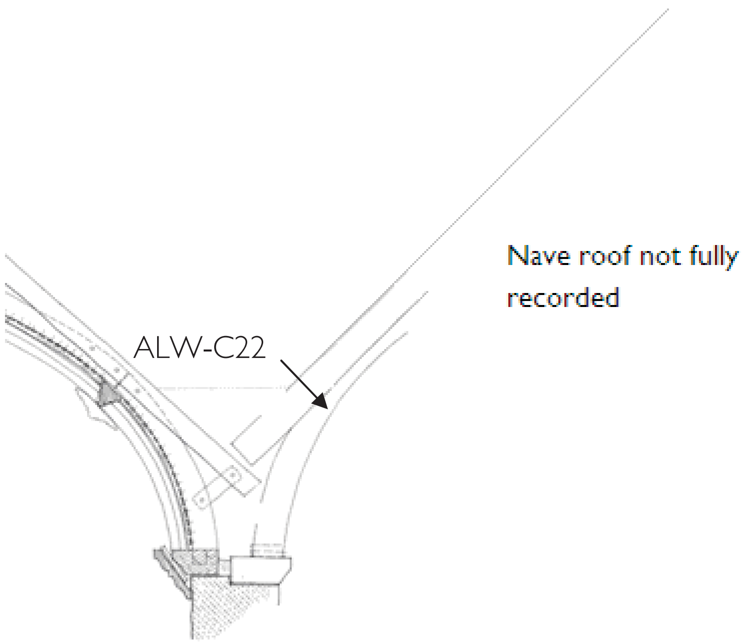


Figure 26: Nave; truss 19, showing the location of sample ALW-C22 (based on example truss provided by Oliver West & John Scott Architects)

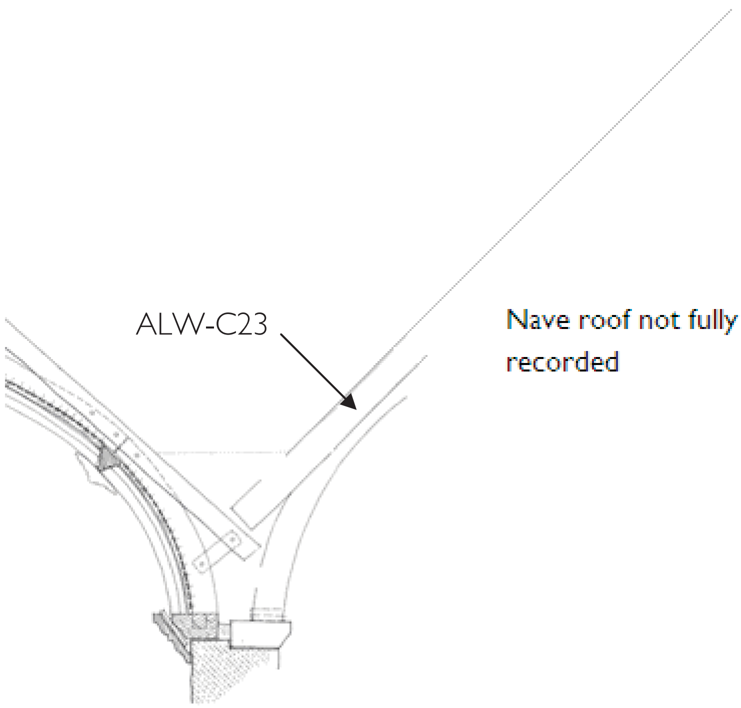


Figure 27: Nave; truss 21, showing the location of sample ALW-C23 (based on example truss provided by Oliver West & John Scott Architects)

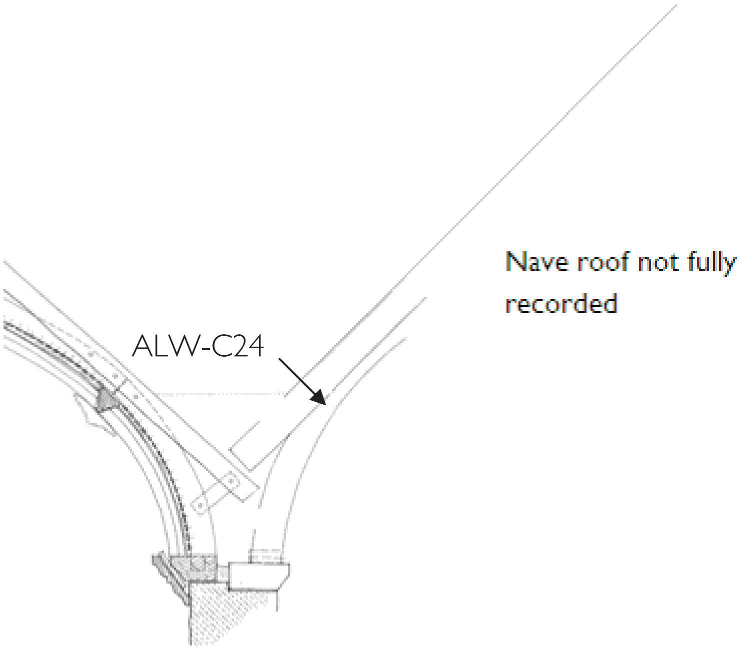


Figure 28: Nave; truss 22, showing the location of sample ALW-C24 (based on example truss provided by Oliver West & John Scott Architects)

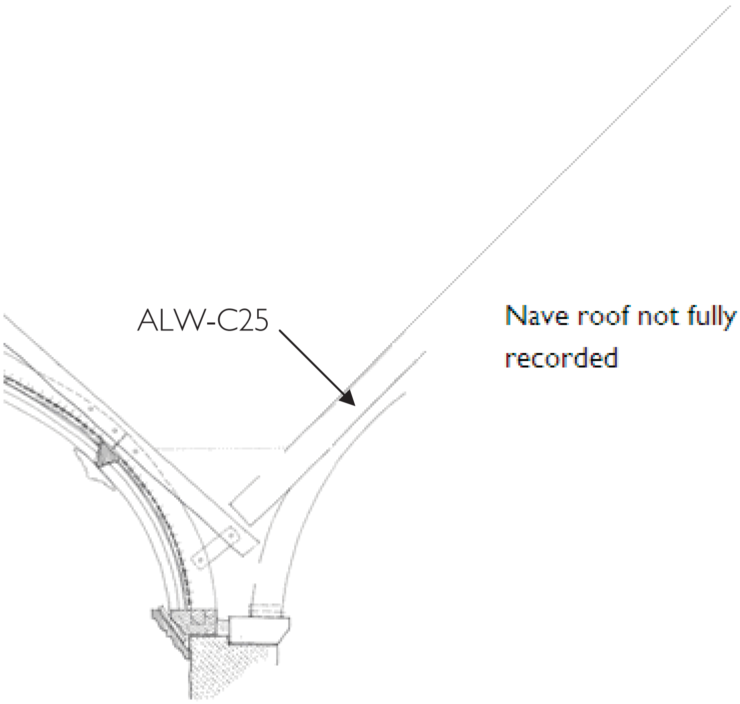


Figure 29: Nave; truss 23, showing the location of sample ALW-C25 (based on example truss provided by Oliver West & John Scott Architects)

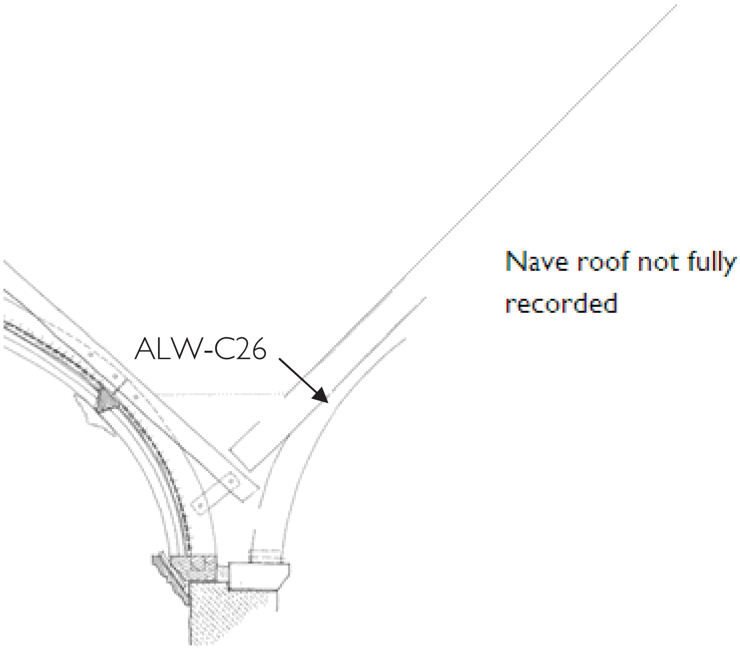


Figure 30: Nave; truss 25, showing the location of sample ALW-C26 (based on example truss provided by Oliver West & John Scott Architects)

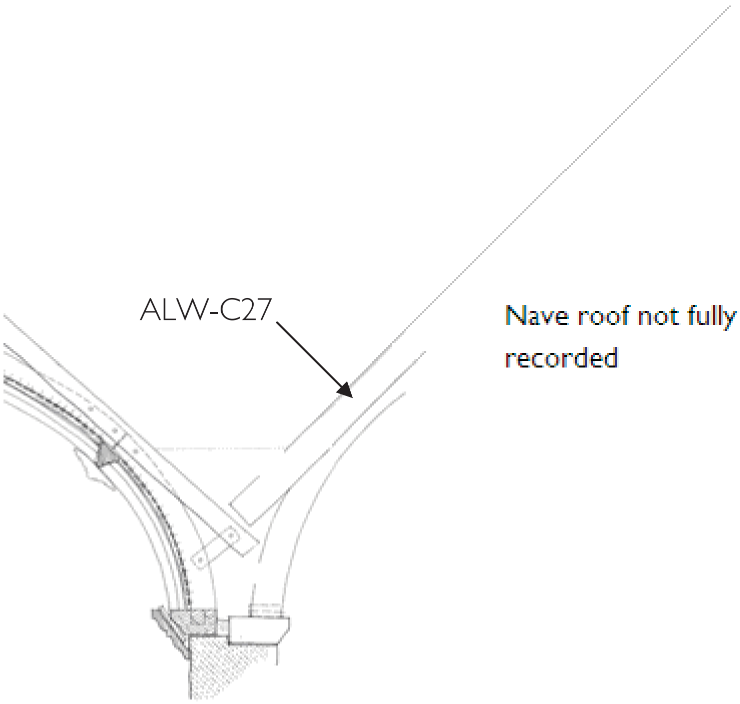


Figure 31: Nave; truss 26, showing the location of sample ALW-C27 (based on example truss provided by Oliver West & John Scott Architects)

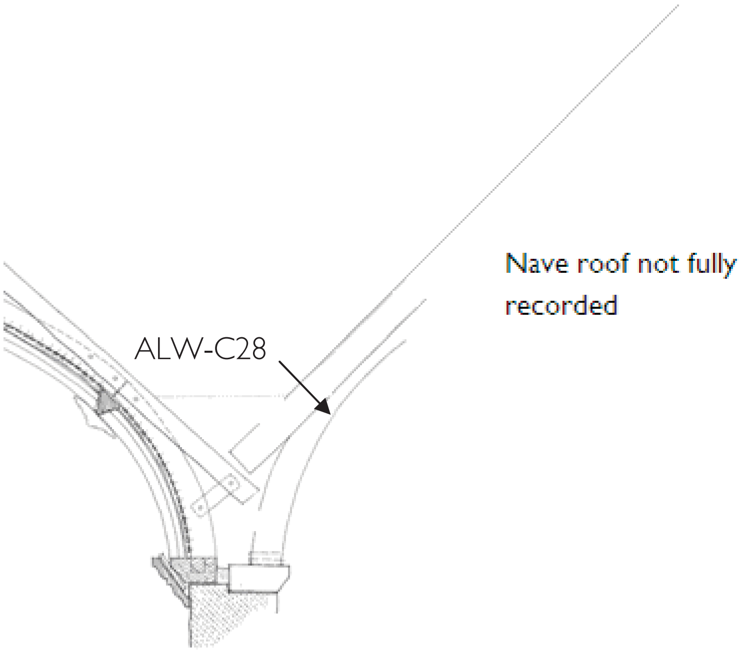


Figure 32: Nave; truss 27, showing the location of sample ALW-C28 (based on example truss provided by Oliver West & John Scott Architects)

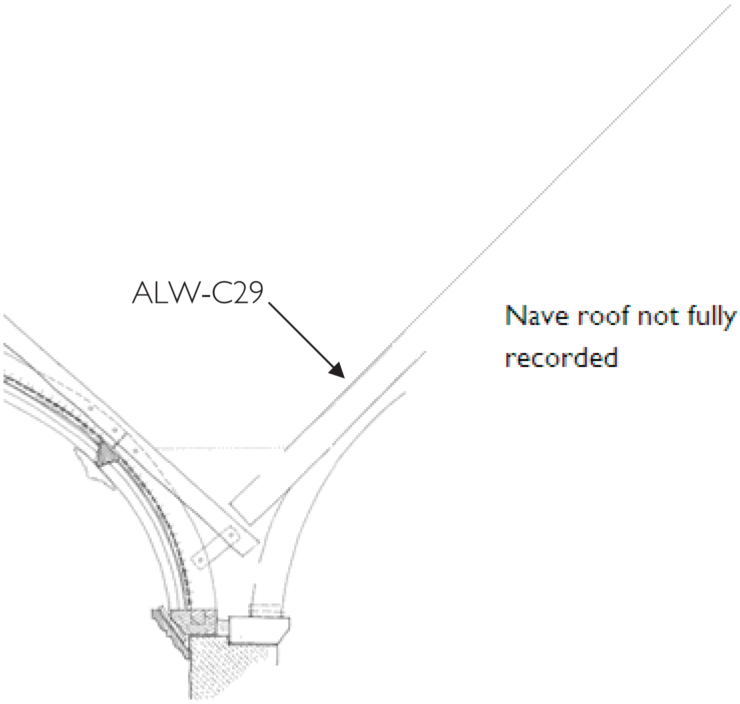


Figure 33: Nave; truss 29, showing the location of sample ALW-C29 (based on example truss provided by Oliver West & John Scott Architects)

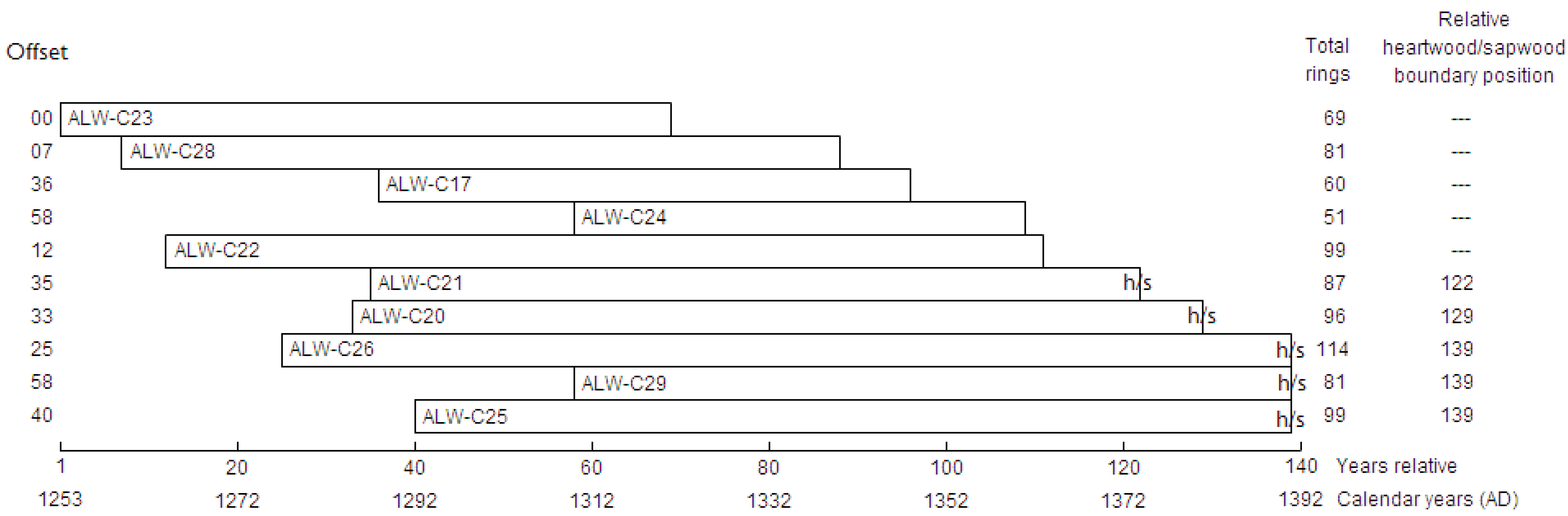


Figure 34: Bar diagram of samples in site sequence ALWCSQ01

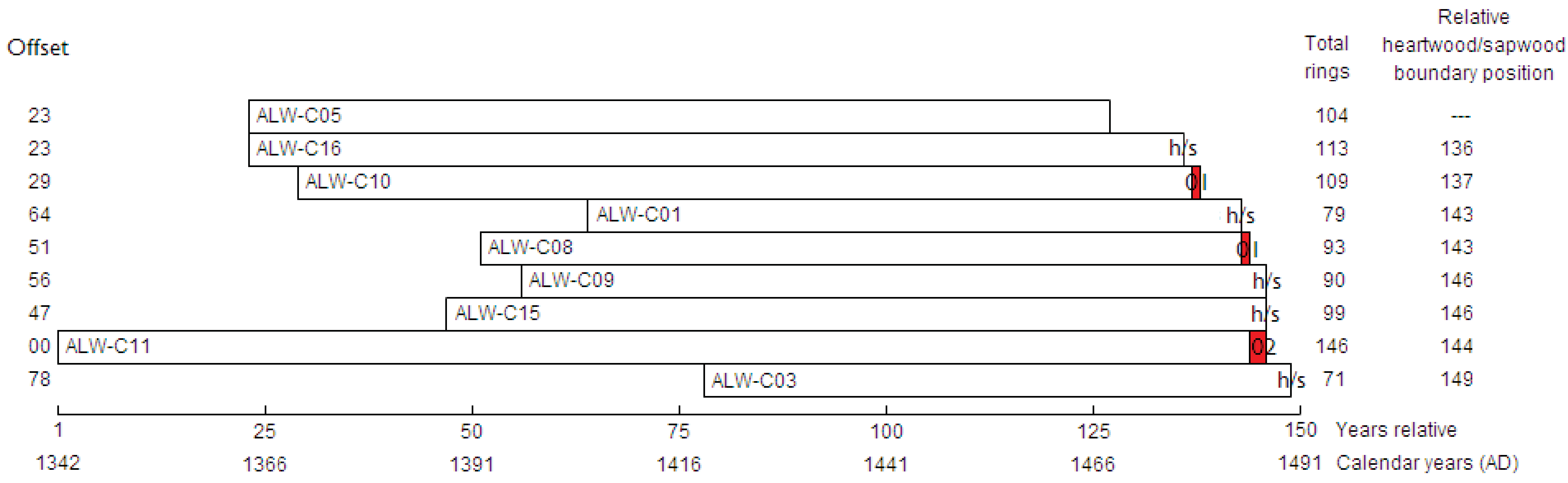


Figure 35: Bar diagram of samples in site sequence ALWCSQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

ALW-C01A 79
351 361 406 335 326 251 316 250 287 236 155 212 242 148 198 300 204 257 187 194
209 219 325 218 181 170 303 237 200 289 234 234 178 152 199 141 127 184 221 167
145 145 147 123 115 130 94 127 118 111 156 123 183 116 157 114 170 115 83 134
132 146 122 92 106 89 71 74 90 75 102 89 76 91 75 111 81 84 73
ALW-C01B 79
361 364 413 322 334 261 316 245 298 226 153 214 243 146 193 304 200 258 188 192
201 222 328 215 186 172 297 232 202 286 241 227 173 155 197 147 134 190 228 170
145 140 145 120 122 130 93 130 125 102 159 124 189 117 157 128 159 120 80 127
133 148 117 91 103 90 74 75 84 81 108 96 75 87 78 113 75 83 79
ALW-C02A 50
241 179 83 131 75 120 160 155 127 134 189 138 184 165 173 159 118 151 173 126
137 181 143 135 130 122 110 122 119 132 128 170 205 40 48 46 30 34 33 27
39 44 54 48 47 51 81 124 109 120
ALW-C02B 58
85 105 114 99 139 125 163 222 202 184 184 123 168 156 136 224 222 167 184 136
176 136 153 235 214 200 247 263 205 132 120 94 141 200 182 148 141 191 119 161
151 177 165 123 125 169 130 139 170 140 131 135 134 113 154 145 145 142
ALW-C03A 71
401 316 211 351 246 239 272 235 334 293 241 247 398 236 256 311 258 250 157 127
169 166 178 221 253 227 189 209 271 194 160 167 133 175 150 151 187 167 173 126
172 125 169 120 77 89 140 152 146 143 124 105 77 118 146 124 163 122 168 168
159 158 179 151 109 171 120 150 142 82 138
ALW-C03B 71
373 322 211 340 244 242 269 236 350 295 249 243 397 235 250 309 258 250 157 125
170 168 176 216 254 224 193 207 271 194 154 163 142 163 165 145 181 171 170 133
164 134 168 121 76 89 138 154 149 142 120 107 79 117 146 121 161 128 161 172
153 159 179 145 111 169 119 153 137 74 165
ALW-C04A 60
363 464 363 408 475 398 421 375 333 450 406 289 93 232 363 211 121 182 183 139
134 158 140 202 174 220 162 84 126 124 108 83 116 109 119 123 64 57 115 110
85 114 139 166 289 219 185 223 164 237 213 253 243 115 236 186 129 199 147 223
ALW-C04B 60
348 456 367 404 482 401 419 373 332 442 410 289 61 231 351 234 116 172 190 119
163 172 144 205 177 223 157 88 124 126 102 88 114 113 117 120 50 65 111 114
84 123 134 177 287 218 186 224 157 240 212 258 242 115 233 123 138 212 157 213
ALW-C05A 104
179 305 184 157 227 230 175 152 191 231 120 103 220 142 165 180 163 252 138 165
115 197 232 188 162 116 112 88 127 114 154 153 97 114 140 164 223 177 246 192
197 260 142 183 225 144 175 215 206 180 166 119 173 133 72 117 149 128 218 211
128 211 176 188 130 150 115 195 137 165 191 184 180 144 109 109 113 88 78 93
143 164 158 188 171 155 184 126 150 142 106 157 131 160 109 163 137 148 115 89
128 141 100 129
ALW-C05B 104
185 308 175 151 239 229 171 185 204 242 112 118 205 144 166 176 141 254 144 174
105 218 218 185 169 115 107 97 125 109 158 150 96 120 149 164 263 180 249 189
207 259 140 187 222 147 167 215 197 181 165 125 181 134 72 114 151 134 215 210
130 209 175 185 131 151 115 194 138 165 191 186 178 150 108 108 113 84 78 94

144 160 152 187 174 154 182 127 152 142 106 158 129 161 104 158 139 145 116 91
125 140 120 114
ALW-C06A 57
529 349 343 504 348 422 286 268 268 128 269 268 310 272 183 213 272 287 195 234
201 181 249 206 249 269 203 200 270 229 159 207 202 235 281 200 105 154 195 225
108 178 226 145 145 114 202 171 245 167 83 127 189 214 213 230 188
ALW-C06B 57
529 349 341 500 347 421 283 267 285 117 265 264 302 272 182 212 270 286 200 233
199 184 241 203 252 266 196 207 266 235 162 205 209 227 279 197 110 155 193 230
101 177 230 142 144 121 173 171 244 169 85 131 195 218 223 172 181
ALW-C07A 71
229 448 458 293 318 111 149 127 135 257 156 234 316 317 187 182 143 119 71 109
200 102 91 108 139 180 164 116 127 192 270 160 202 165 173 142 163 107 122 146
161 204 163 144 79 112 121 67 71 106 99 112 126 111 132 76 57 64 50 72
67 87 98 102 94 87 63 76 55 49 97
ALW-C07B 71
254 417 426 292 326 108 142 131 137 260 155 231 322 301 192 173 161 121 71 105
228 103 98 103 142 179 164 124 124 200 261 163 198 163 168 142 162 103 125 127
168 213 148 139 72 114 110 70 72 90 98 115 123 107 137 63 57 45 62 72
66 92 118 94 101 77 60 77 64 53 74
ALW-C08A 93
248 166 247 219 191 207 235 254 194 144 247 212 171 215 129 193 239 171 168 183
173 209 166 157 125 71 58 83 144 113 196 177 119 139 142 172 132 131 129 184
135 148 188 155 166 150 109 135 157 153 176 179 160 170 149 199 166 145 164 146
142 240 163 202 151 194 127 175 153 170 120 119 160 110 78 116 108 126 115 90
119 123 158 155 127 133 158 135 168 185 176 193 212
ALW-C08B 93
258 156 238 234 185 209 236 246 207 146 252 204 174 208 135 181 245 171 166 181
171 215 171 159 133 66 59 83 152 119 188 183 127 131 151 181 132 137 121 187
122 144 195 153 164 146 112 142 153 160 165 182 169 151 140 195 171 138 168 145
147 230 169 192 147 198 124 176 147 180 97 122 167 114 67 115 99 133 112 92
118 124 165 155 131 130 154 122 165 172 180 187 206
ALW-C09A 90
83 128 132 283 178 221 251 171 265 176 186 207 174 217 259 236 198 225 127 253
317 82 101 106 66 164 163 106 189 137 192 113 98 100 304 128 178 167 132 106
95 85 99 137 94 102 139 102 104 79 153 135 69 174 112 107 167 107 138 131
158 136 128 158 144 175 116 160 209 232 192 142 215 222 94 141 115 255 152 108
106 162 127 166 193 215 171 342 182 251
ALW-C09B 90
106 128 138 275 176 226 262 167 253 177 189 212 183 222 256 241 179 232 128 217
316 119 107 122 99 220 206 128 216 158 199 123 85 108 295 119 173 174 134 103
97 86 98 134 104 96 126 97 99 86 157 122 71 177 110 101 174 107 150 137
159 142 130 151 150 171 112 165 227 222 189 137 220 230 89 139 118 257 143 110
109 156 123 168 195 223 163 319 208 257
ALW-C10A 88
99 100 88 107 97 81 56 68 101 170 137 150 126 122 99 115 130 144 98 113
132 149 134 131 109 112 138 94 83 99 79 117 125 115 116 88 134 115 77 118
124 123 114 107 99 98 76 99 103 108 128 89 76 77 79 89 97 91 77 108
106 117 135 95 99 119 132 142 129 106 140 139 101 112 92 112 106 89 129 117
81 102 97 126 113 119 89 119
ALW-C10B 107
163 162 243 190 154 190 222 197 246 174 154 251 182 182 151 180 136 133 142 109
147 81 88 88 100 109 63 52 78 98 146 131 168 133 121 103 106 127 132 76

109 126 162 110 131 105 108 131 97 74 96 75 99 126 111 110 88 138 112 77
101 110 107 108 99 86 90 66 100 96 103 118 99 69 74 74 86 92 84 71
101 92 100 124 91 100 94 126 132 109 109 134 126 97 98 89 110 92 88 128
111 84 86 96 121 117 107
ALW-C11A 146
90 247 238 221 104 97 99 170 116 126 108 152 116 99 132 242 274 209 140 154
192 240 305 195 165 117 93 77 79 53 72 69 64 71 72 88 83 71 74 73
74 59 68 57 84 107 110 65 44 73 67 35 40 43 72 48 65 50 49 70
58 98 120 110 96 90 100 86 79 57 68 79 104 118 74 63 42 36 50 61
42 100 74 57 58 40 36 34 37 48 45 36 53 56 48 44 50 29 39 48
29 38 27 56 41 37 45 47 35 47 58 49 56 49 60 55 72 37 55 49
93 87 45 67 36 44 48 42 32 44 39 37 52 57 90 63 54 55 59 82
81 107 119 103 92 117
ALW-C11B 146
73 249 242 221 102 95 103 172 114 129 109 159 116 98 142 221 275 205 147 135
204 231 313 191 167 117 90 79 75 54 76 68 65 73 65 91 80 74 70 71
89 60 83 77 74 128 120 62 51 69 69 33 41 40 68 55 63 45 62 62
61 93 126 99 107 78 107 90 83 56 69 80 110 119 73 66 47 33 46 74
51 96 75 54 62 40 30 39 34 47 51 36 45 62 48 45 37 37 42 69
41 39 43 48 35 46 55 35 40 59 56 47 50 51 66 53 75 35 51 49
96 88 58 70 41 50 45 33 32 46 41 46 57 68 81 74 45 55 76 92
80 114 120 94 95 128
ALW-C13A 106
202 238 200 244 261 266 196 295 170 186 176 312 241 199 206 139 167 158 178 146
135 121 107 115 146 126 113 95 172 152 134 190 122 154 131 123 113 96 120 152
114 126 133 127 77 83 145 96 128 102 87 100 103 117 98 89 74 136 109 107
171 139 112 108 76 97 102 113 160 178 132 130 129 164 137 80 36 47 79 72
98 85 89 82 134 111 96 47 65 97 79 82 95 81 98 77 64 104 124 56
74 96 81 96 156 128
ALW-C13B 106
194 239 208 235 262 264 205 289 173 194 164 324 236 196 213 126 169 153 185 144
141 133 95 120 142 129 100 107 171 147 142 193 122 159 129 118 110 96 117 145
125 120 138 131 78 86 147 88 131 120 89 99 101 114 92 90 86 133 102 107
172 132 119 108 71 101 102 113 158 183 126 131 133 163 139 76 49 47 73 84
84 89 83 83 134 116 87 57 54 99 77 81 93 81 94 80 70 105 110 66
77 72 102 87 153 126
ALW-C14A 42
454 525 509 491 298 292 312 320 329 402 321 351 352 419 417 270 235 270 329 239
182 239 267 192 214 263 273 261 192 250 232 258 290 331 424 347 391 307 301 323
151 252
ALW-C14B 38
325 337 355 427 366 396 345 397 434 305 237 273 362 257 198 232 283 200 236 280
300 275 223 238 237 287 312 339 444 385 417 337 297 326 175 263 194 152
ALW-C15A 99
99 121 217 93 137 101 138 184 74 93 169 146 229 165 234 210 167 223 148 263
320 181 149 176 151 161 173 106 166 198 102 113 153 114 136 160 118 242 181 182
216 205 151 222 137 212 224 202 138 148 105 112 225 100 91 146 155 103 81 108
143 95 150 96 106 126 88 157 130 166 105 151 140 155 123 90 110 109 144 186
153 176 201 91 100 81 164 131 116 85 131 104 132 110 172 150 216 163 222
ALW-C15B 99
132 132 208 98 139 91 149 188 66 102 170 144 230 165 221 208 177 221 153 255
323 181 148 173 164 158 170 113 166 208 93 114 163 106 159 159 120 222 177 184
198 234 169 235 138 227 228 204 152 144 95 201 194 107 87 144 159 99 87 108

151 89 155 92 107 116 96 149 139 163 103 152 137 156 123 90 110 111 147 184
152 180 200 88 103 85 158 129 117 98 123 93 125 115 169 160 191 170 225
ALW-C16A 113
156 207 212 160 276 276 256 282 328 342 218 242 227 244 274 300 245 283 192 199
186 141 216 189 164 156 158 204 267 132 174 199 139 146 205 158 150 131 201 166
139 171 154 199 192 162 143 148 166 179 139 141 151 143 93 86 131 104 134 121
86 96 86 96 98 76 83 137 99 99 182 133 104 100 52 83 92 82 59 85
116 105 117 120 106 68 87 84 89 84 85 80 71 45 37 81 85 116 58 71
78 99 80 92 66 90 74 72 56 57 60 78 72
ALW-C16B 113
153 226 213 156 257 293 252 292 351 353 220 241 239 244 275 300 252 278 195 210
189 151 210 194 161 155 148 205 254 141 163 213 139 149 203 149 145 132 199 166
152 165 152 208 202 160 137 143 162 175 133 134 162 143 93 86 129 108 142 125
89 100 88 100 96 74 86 135 101 101 181 129 104 96 58 78 91 90 47 96
108 109 114 121 112 73 96 81 91 82 83 77 78 42 35 84 82 116 69 71
82 97 76 98 55 77 76 72 68 58 65 63 76
ALW-C17A 60
179 226 240 181 140 136 157 90 103 80 79 81 85 111 83 76 109 89 86 95
87 85 76 58 74 81 108 140 120 85 94 178 164 186 186 138 139 116 147 254
170 141 58 67 104 144 137 108 104 116 95 102 79 127 90 93 65 79 54 68
ALW-C17B 60
139 213 193 205 130 145 156 104 112 80 82 81 78 117 88 72 112 85 91 89
105 81 79 50 73 77 107 135 151 114 91 169 169 188 184 127 144 114 141 272
174 143 58 67 104 138 133 106 103 115 91 101 77 124 91 94 63 80 51 89
ALW-C19A 129
255 271 263 114 212 267 324 222 275 339 181 237 218 195 109 124 126 151 156 137
101 55 108 72 100 114 92 91 97 139 150 132 103 94 70 68 84 125 58 46
53 74 56 86 37 76 98 52 36 42 24 21 28 30 30 21 33 36 37 38
15 39 38 30 26 25 44 45 34 26 39 53 78 82 53 29 45 30 34 76
158 128 176 216 152 94 114 162 190 186 100 68 85 119 109 103 69 67 52 74
88 167 125 145 73 54 73 65 30 56 40 53 58 90 97 58 81 105 75 93
116 100 141 231 144 108 78 113 87
ALW-C19B 129
255 263 263 117 211 262 307 229 264 334 176 233 209 195 111 123 134 150 149 132
106 52 108 71 92 118 101 83 96 133 153 140 120 113 65 69 96 121 66 42
56 65 54 87 25 66 95 53 48 32 20 23 21 29 31 25 35 30 34 33
25 43 38 27 31 27 39 46 33 25 42 47 77 72 50 32 47 30 41 84
156 127 175 218 159 99 108 160 190 183 101 71 80 126 108 125 68 71 44 73
90 168 114 126 75 51 73 63 33 55 43 68 51 92 91 64 75 92 81 97
108 93 134 241 147 110 82 107 98
ALW-C20A 96
34 202 234 210 276 185 215 192 238 223 137 146 141 75 106 89 226 159 184 148
154 180 197 162 174 123 123 85 53 65 90 130 90 91 83 123 140 152 115 79
86 136 132 121 99 52 79 96 91 82 116 112 187 256 139 111 121 113 123 104
44 48 68 66 89 158 96 105 88 69 81 93 64 100 85 110 149 238 310 185
258 191 123 144 130 98 151 155 80 106 134 209 243 375 304 151
ALW-C20B 96
343 199 231 214 268 185 224 193 236 219 141 148 140 75 111 82 227 160 188 144
157 176 198 163 178 123 131 82 58 62 90 131 95 87 86 118 127 150 119 69
100 125 135 121 93 59 78 98 87 87 112 113 193 242 149 111 109 119 124 100
59 42 61 61 82 145 89 103 100 61 87 86 61 93 74 119 153 238 291 177
256 198 123 147 126 97 156 157 76 110 130 205 245 371 296 169
ALW-C21A 87

173 224 277 262 382 234 272 297 243 198 177 147 123 150 211 143 128 188 211 190
152 128 155 112 93 80 59 92 111 164 111 127 112 188 163 171 92 92 73 97
131 91 79 58 59 82 115 108 89 69 98 96 93 69 97 85 68 48 44 64
79 74 76 96 73 76 69 49 77 67 51 94 80 90 83 144 149 114 113 51
74 158 127 88 97 103 81
ALW-C21B 87
177 215 277 278 384 229 279 291 248 199 173 135 130 152 199 145 117 187 218 189
149 125 164 129 91 87 56 105 107 169 127 127 115 181 168 170 94 89 81 94
130 94 79 57 60 79 124 107 89 68 103 93 92 69 103 82 65 50 45 63
79 82 71 93 74 73 63 53 81 67 56 88 83 100 76 145 151 119 102 65
74 138 112 82 103 101 82
ALW-C22A 99
179 229 192 267 213 247 350 199 233 204 163 128 140 132 174 174 207 188 155 164
203 229 230 195 152 146 169 193 151 220 173 154 125 122 118 97 103 150 139 107
111 149 135 191 134 116 110 78 85 69 92 124 141 85 99 97 136 160 117 92
71 95 111 101 76 57 36 52 72 66 85 77 88 91 80 81 63 71 80 81
63 54 52 54 60 61 74 69 83 81 62 55 82 57 78 52 72 93 86
ALW-C22B 99
202 228 195 269 203 248 350 185 240 208 161 130 133 139 168 183 210 188 155 174
201 237 228 192 144 157 169 185 161 218 162 153 122 118 123 96 102 153 139 107
120 150 147 186 137 116 109 77 87 69 94 109 138 89 90 110 137 160 114 98
70 93 110 93 77 56 34 42 79 67 75 82 89 91 87 76 59 83 74 85
63 57 47 60 60 61 73 72 81 83 62 60 75 61 71 49 76 89 96
ALW-C23A 69
356 440 509 375 476 518 327 452 345 419 286 258 319 260 214 315 162 104 200 165
206 187 102 110 99 94 95 123 159 147 121 138 136 145 110 51 98 108 132 185
116 138 135 118 95 92 83 84 90 133 96 67 98 138 127 136 142 123 118 76
71 57 68 112 150 92 59 64 91
ALW-C23B 69
352 429 460 368 450 521 328 448 336 427 277 260 317 248 238 315 166 122 199 163
206 204 98 113 98 93 95 127 154 146 120 135 141 146 102 61 95 104 133 189
112 136 135 116 97 93 84 81 91 134 92 70 89 142 130 137 141 126 124 72
74 54 70 116 149 90 67 64 84
ALW-C24A 51
174 246 231 136 234 241 218 170 209 225 256 277 293 201 205 197 326 354 398 308
224 234 243 255 261 333 278 423 372 330 261 301 325 204 170 151 167 243 275 218
359 269 241 188 175 220 222 150 257 189 163
ALW-C24B 51
220 247 232 153 228 239 220 170 212 221 245 284 301 186 204 195 342 342 380 302
220 226 262 234 244 325 289 396 372 331 262 320 315 203 162 150 162 251 272 219
359 265 246 197 172 212 223 182 258 185 162
ALW-C25A 99
336 350 323 209 208 159 169 189 228 233 125 133 162 171 176 209 204 169 165 136
90 86 100 105 175 118 141 144 166 128 135 110 83 114 152 142 150 111 88 104
106 146 149 165 158 136 151 150 122 151 169 130 115 107 86 121 161 129 247 211
163 154 127 164 119 106 127 104 128 105 125 132 146 91 111 54 65 49 47 57
39 66 62 60 82 78 111 90 91 120 128 159 100 140 103 140 125 109 185
ALW-C25B 99
343 338 326 197 197 158 169 188 232 224 120 135 159 171 179 207 204 165 161 140
92 83 97 107 175 112 129 136 182 135 138 92 101 107 135 142 169 123 95 99
109 144 150 162 158 149 137 158 119 150 167 127 118 114 72 131 153 128 241 214
157 153 140 147 116 112 113 113 137 89 125 111 147 109 102 60 68 53 51 61
46 60 69 69 82 75 109 93 99 111 129 163 102 137 104 126 129 109 152

ALW-C26A 114
221 229 264 256 262 241 205 223 286 179 191 123 195 190 236 170 195 204 129 122
143 95 93 109 152 131 142 105 182 180 153 115 117 140 89 70 79 130 213 141
110 120 180 202 200 176 123 91 93 224 148 166 101 84 74 89 133 142 152 153
145 153 116 99 196 117 108 78 45 38 87 124 81 106 89 81 77 67 63 73
41 79 71 98 77 128 103 95 119 74 67 104 69 68 111 88 86 82 100 118
124 149 123 138 152 146 181 150 192 161 126 120 103 93
ALW-C26B 114
221 228 261 255 260 247 202 219 291 178 191 121 199 184 240 171 192 198 140 126
146 96 105 110 149 129 141 113 188 171 150 120 128 134 91 75 69 141 205 146
113 128 184 194 214 177 120 96 96 226 147 174 90 95 82 97 116 144 158 156
146 147 120 100 198 113 122 70 45 56 65 122 89 97 93 76 77 67 64 71
46 87 69 102 81 121 104 95 123 66 66 108 73 68 100 101 94 85 119 121
119 151 113 139 162 134 181 135 201 180 131 120 106 81
ALW-C27A 75
224 278 181 173 202 241 154 229 233 167 181 130 130 89 97 133 116 124 182 214
163 191 169 170 111 120 102 117 139 169 163 156 122 141 128 80 79 83 53 94
63 45 40 59 57 50 89 134 137 113 114 91 67 64 105 138 119 109 71 95
99 77 124 107 103 98 150 125 147 106 96 110 102 99 86
ALW-C27B 80
170 207 183 154 216 118 177 107 104 139 179 111 176 155 100 114 75 68 65 80
102 81 111 166 201 141 136 145 137 107 91 85 99 115 153 158 145 103 117 118
75 85 71 65 107 57 52 38 65 61 41 80 128 140 118 122 108 74 94 111
148 128 118 85 96 108 79 120 108 104 111 152 135 155 116 114 123 99 121 78
ALW-C28A 81
323 290 326 194 165 196 226 236 304 183 173 299 233 286 275 173 152 188 163 183
259 281 213 175 174 240 242 119 124 101 126 162 181 126 178 153 139 92 101 72
65 54 102 80 82 95 123 127 145 120 117 74 73 74 50 61 79 95 64 76
85 101 113 85 75 70 71 90 82 67 50 33 40 55 81 89 54 75 73 55
57
ALW-C28B 81
310 267 301 199 163 195 228 219 305 185 171 292 229 302 270 159 159 182 166 186
271 275 225 164 174 239 237 122 122 97 127 162 180 128 177 150 140 88 98 77
60 57 104 79 81 95 117 134 144 123 112 79 71 70 53 60 82 90 65 79
79 109 105 84 84 63 79 90 83 64 41 31 44 61 68 85 54 70 76 55
57
ALW-C29A 73
156 157 103 89 196 283 260 140 239 192 214 247 338 140 107 107 204 256 290 135
112 158 169 229 162 94 161 204 195 158 216 456 593 333 147 147 152 232 392 204
473 179 173 248 210 227 296 410 396 318 196 258 315 340 201 295 180 136 204 211
134 193 220 258 164 168 217 200 266 124 123 137 102
ALW-C29B 34
126 205 154 139 177 281 283 226 278 117 78 146 140 79 110 137 138 107 129 234
196 316 160 138 189 153 427 254 355 305 227 287 170 109

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

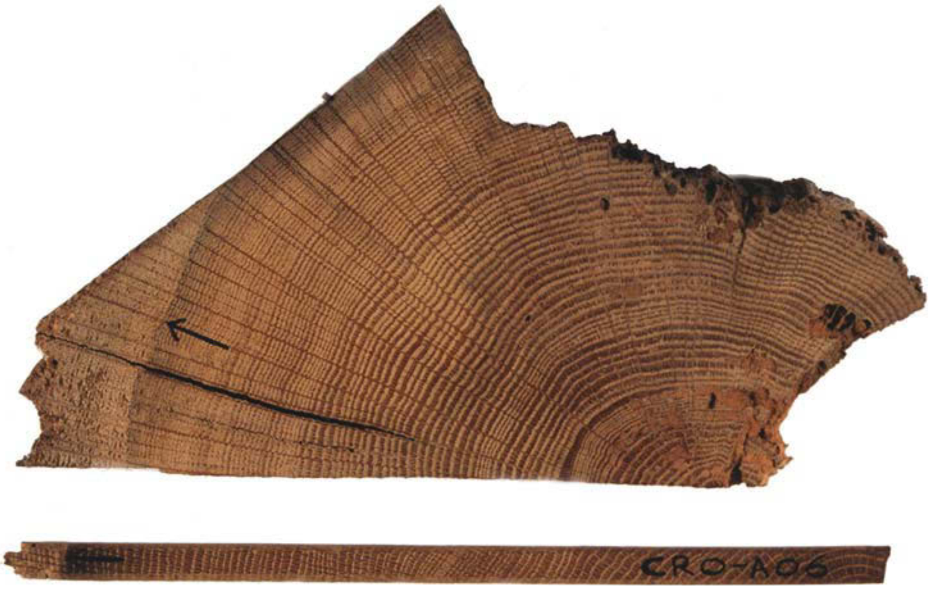


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

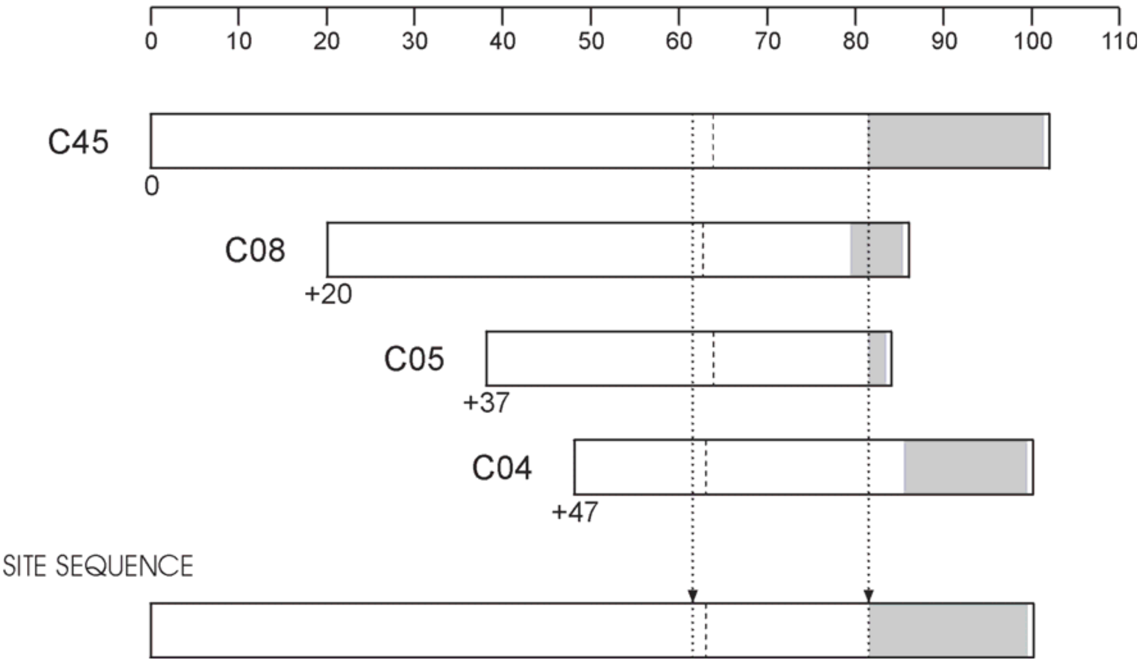


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

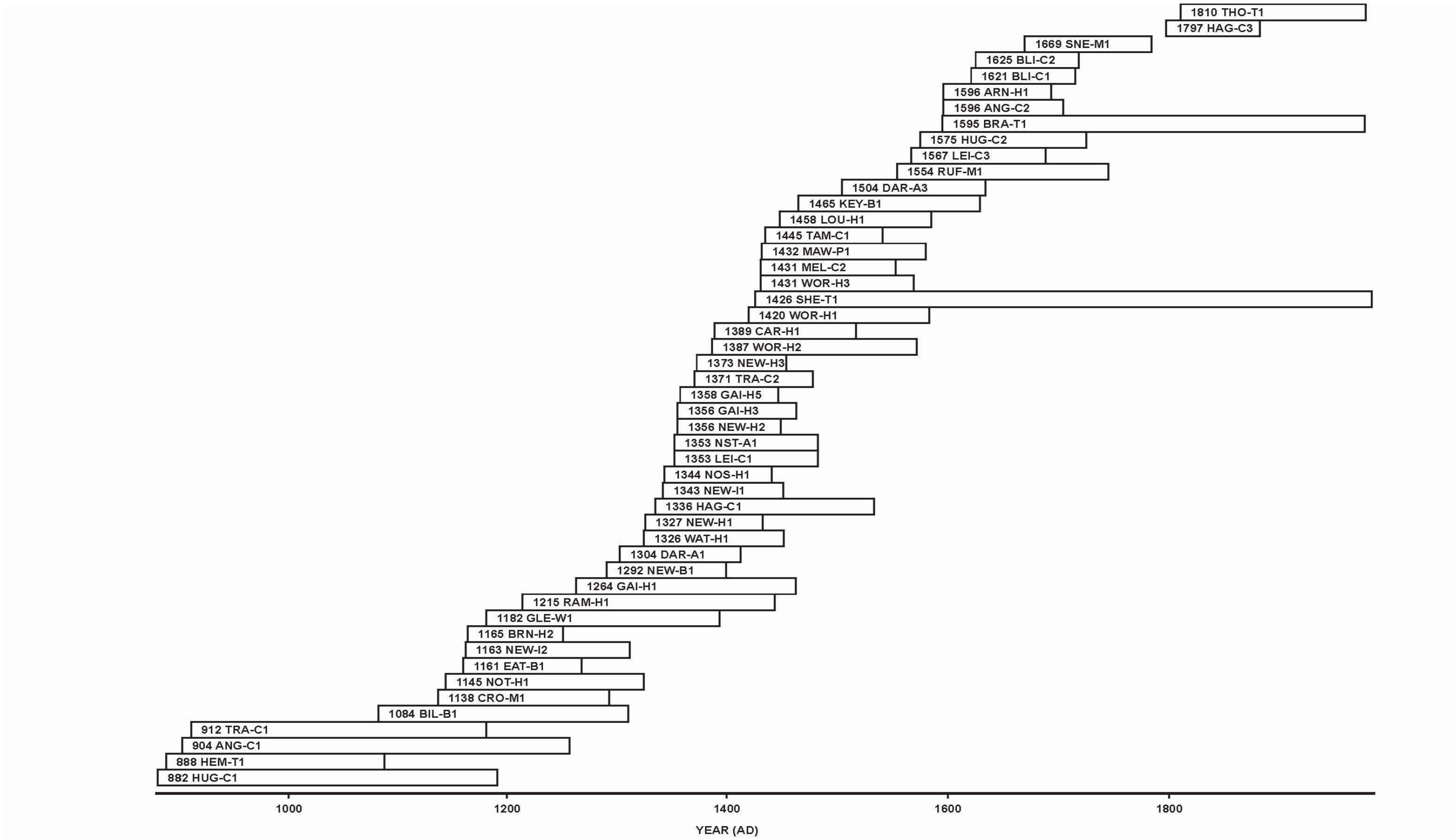
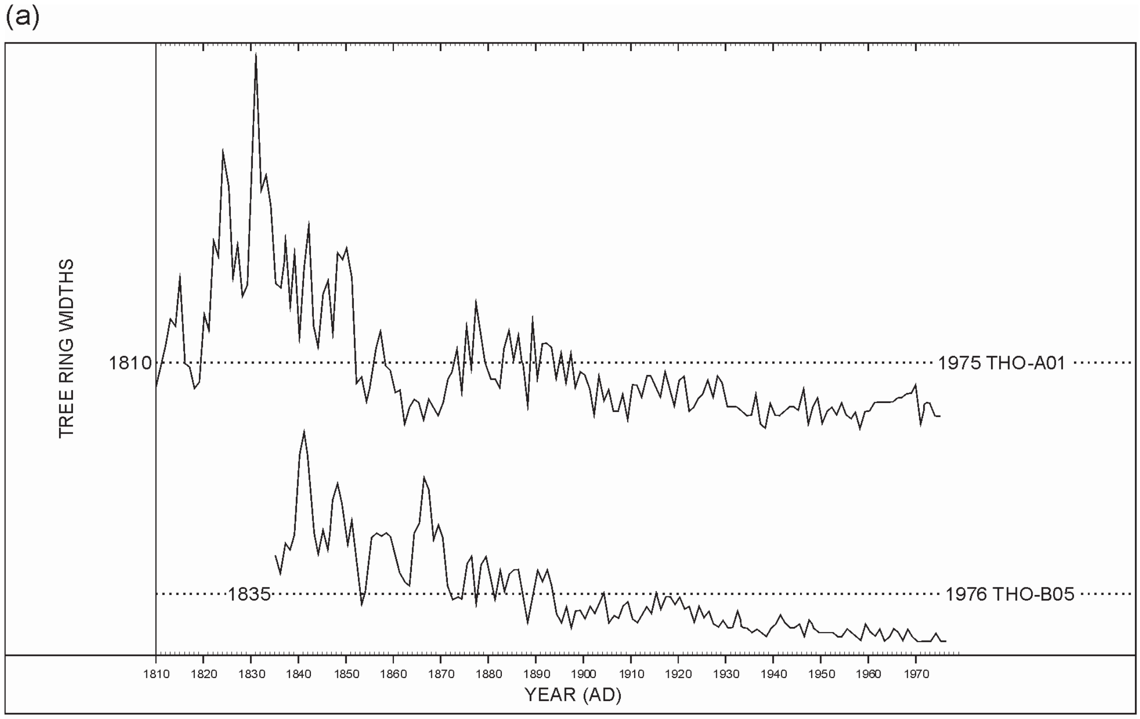


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence. EM08/87



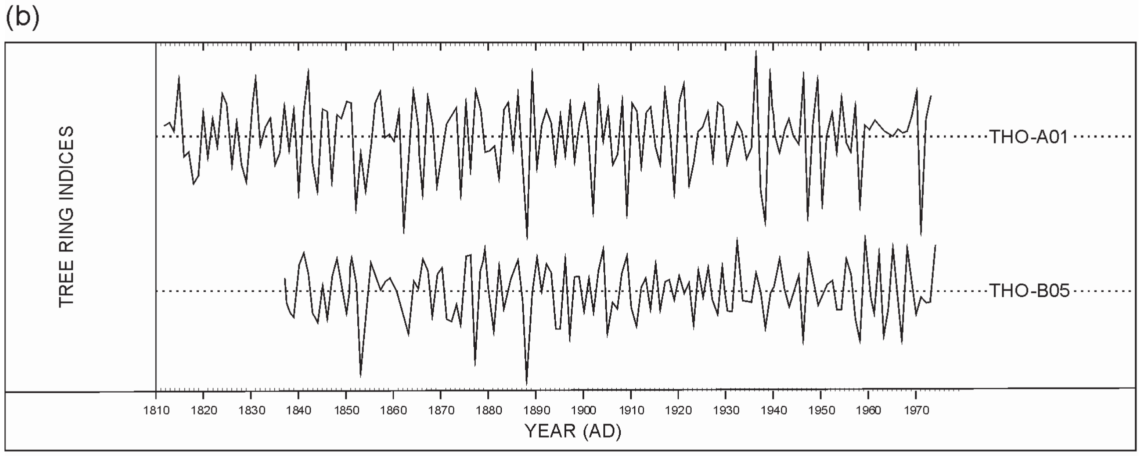


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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