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Scientific Dating

The Guildhouse, 19–21 Ladygate, Beverley East Riding of Yorkshire Tree-ring and radiocarbon wiggle-matching of oak timbers

Alison Arnold, Robert Howard, Cathy Tyers, Elaine Dunbar, Paula Reimer and Peter Marshall

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THE GUILDHOUSE
19–21 LADYGATE
BEVERLEY
EAST RIDING OF YORKSHIRE
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SUMMARY
Tree-ring analysis was undertaken on samples taken from the roof and a first-floor frame of 19–21 Ladygate, Beverley, resulting in the construction of two site sequences. Site sequence BEVASQ01 contains 20 samples, from both the roof and the floor frame of 19–21 Ladygate, and spans the period AD 1194–1330. Interpretation of surviving sapwood suggests that the floor frame and roof are contemporary, dating to, or soon after, felling of the timbers utilised in AD 1330. The second site sequence, BEVASQ02, produced from samples from 19 Ladygate remains undated.

Radiocarbon wiggle matching undertaken part way through the tree-ring dating programme, when access to 21 Ladygate was not expected, estimated the final ring of BEVASQ01 formed in *cal AD 1310–1335* (*95% probability*) and was thus subsequently found to include the dendrochronological date of AD 1330.

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INTRODUCTION

The *Early Fabric in Historic Towns: Voluntary Group Projects*, funded by Historic England, have been developed in the recognition and acknowledgement of the excellent work being undertaken by local vernacular groups in the study of local architectural trends and fabrics. The project's intention is to encourage this type of study through the provision of support and facilitate training of more people in building analysis and recording. The local projects were coordinated by Rebecca Lane (Historic England South West Region: Senior Architectural Investigation).

Early Fabric in Beverley Project

Whilst there is a corpus of research on form and age of the town of Beverley, it does not cover detailed examination of early fabric or aspects of typology, with analysis and interpretation of existing buildings until now not having benefited from dendrochronology, with the exception of some limited work on the Minster.

Initially, 13 properties were identified that were thought to be key to understanding the town's architectural development for a programme of comprehensive investigation. These properties were assessed for their suitability for tree-ring dating and those found to contain timbers potentially suitable for analysis were sampled. As the project progressed and some of the original buildings identified were rejected as unsuitable for tree-ring dating, further candidates for tree-ring analysis were assessed and sampled if appropriate.

It was hoped that successful dating of these buildings would extend the knowledge of early fabric and selected buildings in the historic town of Beverley in support of Historic England's responsibility to identify and understand the urban vernacular and historic environment of a market town. The reports produced on the buildings recorded as part of this project by the Yorkshire Vernacular Buildings Study Group, led by David Cook, will be held in the YVBSG archive and will be available through their website (www.yvbsg.org.uk), whilst a summary of the project is presented in Vernacular Architecture (Cook and Neave 2018).

19–21 LADYGATE

Numbers 19–21 Ladygate (List Entry Number 1161506), located on the east side of Ladygate (Figs 1–3), are orientated north-west/south-east (for simplicity in this report north/south). The primary range (that fronting onto Ladygate) consists of five bays, separated by six trusses, and was originally jettied to the front. At ground-floor level, the second bay from the south is a passageway which allows access to the rear of the building. The first floor of number 21 is open to the roof. To the rear of this range is a small extension and other small ranges (Fig 4).

Roof

The roof consists of six crown post with collar and tiebeam trusses, each with down braces from the crown post to the tiebeam and further braces from the crown post to the collar purlin. With the exception of truss 2 which has had its removed, there are also raking struts from the tiebeams to the principal rafters. Between the trusses are collared common rafters (Fig 5). The roof has been dated stylistically to the fifteenth century (Pevsner 1995; YVBSG 2016).

Floor frame

In the northernmost room of number 19 there is an exposed spine beam with eight joists running from it to the west wall (Fig 6).

SAMPLING

Initially, it was only possible to gain access to number 19 Ladygate, sampling here resulted in 18 core samples being taken from oak (*Quercus* sp) timbers to the roof and first-floor frame. At a later date it became possible to sample at 21 Ladygate and a further eight samples were taken from the roof over this part of the building. Each core sample was given the code BEV-A and numbered 01–26 (BEV-A01–13 and BEV-A19–26 from the roof and BEV-A14–18 from the floor frame). The location of all samples was noted at the time of sampling and has been marked on Figures 7–14. One of the crown posts in 19 Ladygate (BEV-A04) was sampled twice in an effort to get as long a ring width sequence as possible. The two ring-series crossed matched (t = 17.7) and were combined to form the 63-year timber series reported in Table 1. Further details relating to the samples can be found in Table 1. Trusses and joists were initially numbered from north to south but have been altered to follow the numbering in the YVBSG survey (south to north; YVBSG (2016)).

ANALYSIS AND RESULTS

Dendrochronological dating: phase 1

From the initial sampling at 19 Ladygate, 17 suitable samples were produced, with one sample (BEV-A01 taken from a brace) having too few rings for secure dating to be a possibility. These 17 samples were prepared by sanding and polishing and their growth-ring widths measured. They were then compared with each other by the Litton/Zainodin grouping programme (see Appendix 1), resulting in 13 samples matching to form two groups.

Firstly, 11 samples matched each other at a minimum t-value of 5.1 and were combined at their relevant offset positions to form BEVASQ01, a site sequence of 110 rings (Fig 15). A further two samples also matched each other (minimum t-value of 6.9) and were combined to form a second site sequence (BEVASQ02) of 63 rings (Fig 16). Attempts to date these two site sequences and the remaining ungrouped samples by comparing them against a series of reference chronologies for oak were unsuccessful, although a tentative match was noted for site sequence BEVASQ01.

Dendrochronological dating: phase 2

The sampling at 21 Ladygate produced a further eight samples, seven of which were found to be suitable for analysis (sample BEV-A24 from a principal rafter was found to have too few rings for secure dating and rejected). These seven were prepared, measured, and compared against each other and the previously taken samples at which point they matched to form two groups.

Site sequence BEVASQ02 produced from the analysis on the samples from 19 Ladygate is unchanged and remains undated.

However, the components of site sequence BEVASQ01 matched against a further nine samples (minimum *t*-value of 4.2), seven of the new samples and two from the original set which could now be grouped in. These 20 samples were combined at the relevant offset positions to form an updated BEVASQ01, a new site sequence of 137 rings (Fig 17). This site sequence was compared against a series of relevant reference chronologies for oak where the tentative end date noted previously of AD 1330 was supported and strengthened. The evidence for this dating is given in Table 2. This dating is also supported by radiocarbon dating carried out on two of the components of the original BEVASQ01 (see Appendix 2).

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 20 samples, 16 from the roof and four from the floor frame. Felling date ranges have been calculated using the estimate that 95% of mature trees in this region have 15–40 sapwood rings.

Roof

Two of the samples dated from the roof have complete sapwood and the last-measured ring date of AD 1330, the felling date of the two timbers represented. A further 11 roof samples have the heartwood/sapwood boundary which is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1309, allowing an estimated felling date to be calculated for the 11 timbers represented to within the range AD 1324–49, consistent with these timbers also having been felled in AD 1330.

The final three dated samples do not have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be calculated for these. However, with last-measured ring dates of AD 1278 (BEV-A20), AD 1299 (BEV-A13), and AD 1306 (BEV-A22), the earliest estimated felling dates for the timbers represented would be AD 1294, AD 1315, and AD 1322, respectively. Therefore, making it possible that these were also felled in AD 1330. Furthermore, sample BEV-A22 matches BEV-A10 (with an estimated felling date within the range AD 1324–49) at the value of t = 10.8, making it likely that both timbers were cut from the same tree and hence would have the same felling.

Floor frame

One of the samples taken from the floor frame has complete sapwood and the last-measured ring date of AD 1330, the felling date of the timber represented. The other three dated samples all have the heartwood/sapwood boundary ring date which in all cases is similar and suggestive of a single felling. The average heartwood/sapwood boundary ring date for the three samples is AD 1307 which, allowing for sample BEV-A14 having a last-measured ring date of AD 1329 with incomplete sapwood, gives an estimated felling date for the three timbers to within the range AD 1330–47, consistent with these samples also having been felled in AD 1330.

DISCUSSION

Tree-ring analysis has successfully dated timbers utilised within both the roof and a floor frame of this building to a felling of AD 1330, with construction of both elements thought to have occurred shortly after. This dating confirms the contemporaneous nature of the two structures and that the floor frame is part of the primary construction. With dated samples coming from the whole length of the roof this analysis also shows that the roof was built as the result of a single phase of construction.

The roof was previously thought to be fifteenth century, however, the tree-ring dating has shown it to be considerably earlier, belonging to the first half of the fourteenth century. This makes 19–21 Ladygate one of the earliest secular buildings still surviving in Beverley today and one of the earliest buildings of its type in North and East Yorkshire (YVBSG 2016).

Similar roofs to that of 19–21 Ladygate have been identified by the Yorkshire Vernacular Buildings Study Group at 49–51 Northbar Within and 15 Flemingate; buildings which have been shown to utilise timbers dated to AD 1336 and AD 1431, respectively (Arnold *et al* 2019; 2020) demonstrating a tradition of crown post roofs in Beverley spanning a hundred years.

In addition to the potential same tree match noted between samples BEV-A10 and BEV-A22 (see above), samples BEV-A05 and BEV-A06 also match each other at a level high enough to suggest that both beams (braces of truss 5) are cut from the same tree (t = 13.9). The overall level of similarity suggests that the dated timbers are likely to represent a single woodland source. The highest levels of similarity between the dated site sequence, BEVASQ01, and reference chronologies (Table 2) are generally with those in the surrounding regions in northern England including several from elsewhere in Yorkshire. This suggests that the dated timbers are likely to be source from woodland with the surrounding region.

The successful dating of site sequence BEVASQ01 demonstrates clearly the importance of producing a well replicated and long site sequence when attempting tree-ring dating generally, but perhaps even more importantly in areas where dendrochronological dating is more problematic as has previously been recognised for this area in Yorkshire.

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YVBSG, 2016 19–21 Ladygate, Beverley

TABLES

Table 1: Details of tree-ring samples from The Guildhouse, 19–21 Ladygate, Beverley, East Riding of Yorkshire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
BEV-A01	South brace, truss 6	NM	--	----	----	----
BEV-A02	Collar purlin, bay 5	58	h/s	1247	1304	1304
BEV-A03	East rafter 5, bay 5	54	h/s	----	----	----
BEV-A04	Crown post, truss 5	63	02	1256	1316	1318
BEV-A05	East brace, truss 5	72	13	1251	1309	1322
BEV-A06	West brace, truss 5	86	18C	1245	1312	1330
BEV-A07	Crown post, truss 4	51	06	----	----	----
BEV-A08	North brace, truss 4	66	18	1256	1303	1321
BEV-A09	East brace, truss 4	57	08	1259	1307	1315
BEV-A10	West rafter 3, bay 3	64	h/s	1251	1314	1314
BEV-A11	West rafter 1, bay 3	56	h/s	----	----	----
BEV-A12	Collar purlin, bay 3	58	02	1254	1309	1311
BEV-A13	North brace, truss 3	70	--	1230	----	1299
BEV-A19	Crown post, truss 3	82	h/s	1235	1316	1316
BEV-A20	Tiebeam, truss 3	78	--	1201	----	1278
BEV-A21	East brace, truss 3	77	03	1239	1312	1315
BEV-A22	Crown post, truss 2	65	--	1242	----	1306
BEV-A23	Tiebeam, truss 2	129	27	1194	1295	1322
BEV-A24	West principal rafter, truss 2	NM	--	----	----	----
BEV-A25	East brace, truss 2	74	14	1250	1309	1323
BEV-	Tiebeam, truss	88	25C	1243	1305	1330

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
A26	1					
First-floor frame						
BEV-A14	Main beam	59	20	1271	1309	1329
BEV-A15	Joist 6	69	15C	----	----	----
BEV-A16	Joist 3	82	21C	1249	1309	1330
BEV-A17	Joist 2	83	h/s	1221	1303	1303
BEV-A18	Joist 1	72	h/s	1239	1310	1310

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

Table 2: Results of the cross-matching of site sequence BEVASQ01 and the reference chronologies when the first-ring date is AD 1194 and the last-measured ring date is AD 1330

Reference chronology	*t*-value	Span of chronology	Reference
Manor Farm, Scotton, Nr Knaresborough, North Yorkshire	6.9	AD 1096-1342	Tyers 2001a
Tabley Old Hall, Knutsford, Cheshire	6.3	AD 1179–1336	Arnold *et al* 2018
The Merchant Taylor's Hall, York, North Yorkshire	6.1	AD 1216–1424	Arnold and Howard 2013
Lamb Hotel, Nantwich, Cheshire	6.1	AD 941–1276	Tyers 2004
30-31 Market Place, Stockport, Greater Manchester	6.0	AD 1079–1253	Tyers 1999
Church Street, Whitby, North Yorkshire	5.9	AD 1038–1261	Tyers 2001b
Lancaster Castle, Lancashire	5.8	AD 950–1404	Arnold *et al* 2016
Baguley Hall, Manchester	5.8	AD 1015–1398	Nayling 2005
Newcastle Cathedral (north transept roof), Newcastle, Northumberland	5.5	AD 1187–1367	Howard *et al* 2002
Hall Garth, Beverley, East Riding of Yorkshire	5.5	AD 1002–1324	Hillam 1980

FIGURES

Figure 1: Map to show the location of Beverley (red ellipse).

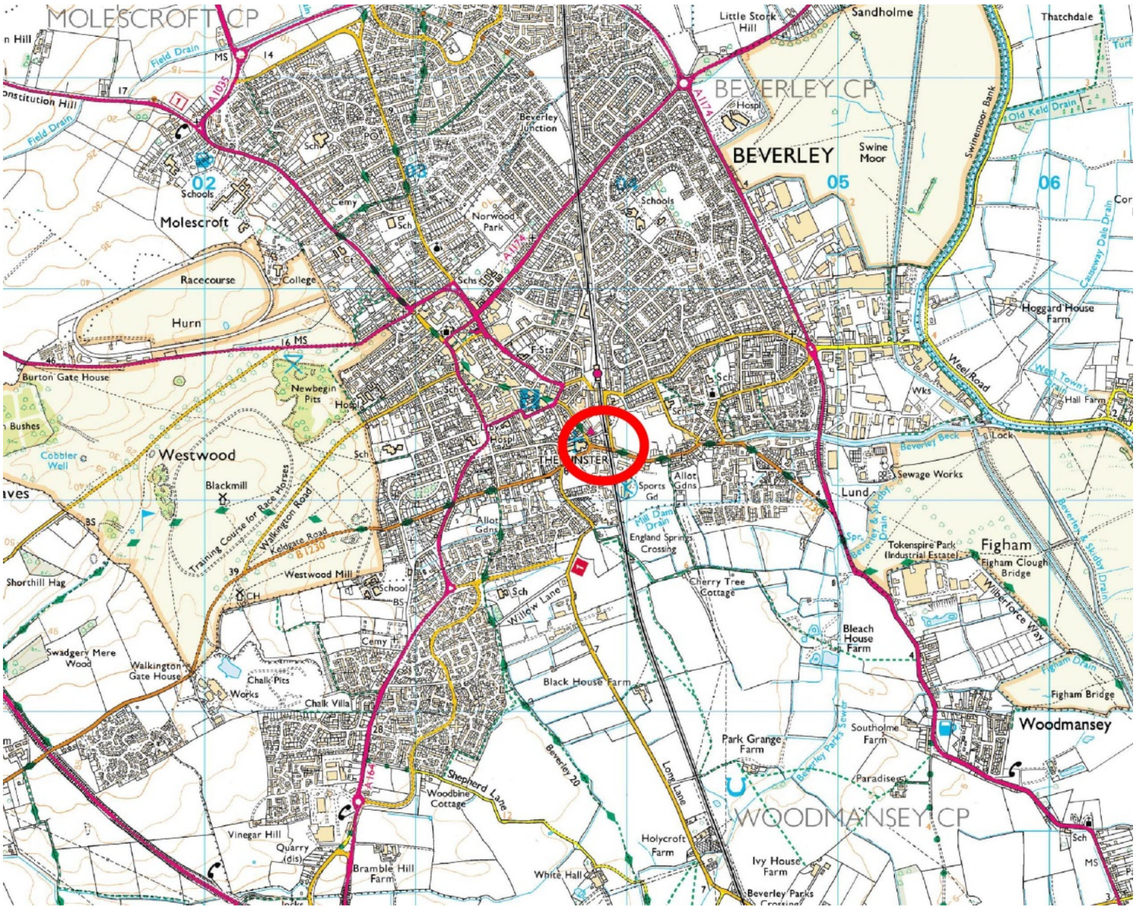

Figure 2: Map to show the general location of 19–21 Ladygate in Beverley (red ellipse). © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the location of the Guildhouse, 19–21 Ladygate, hashed. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

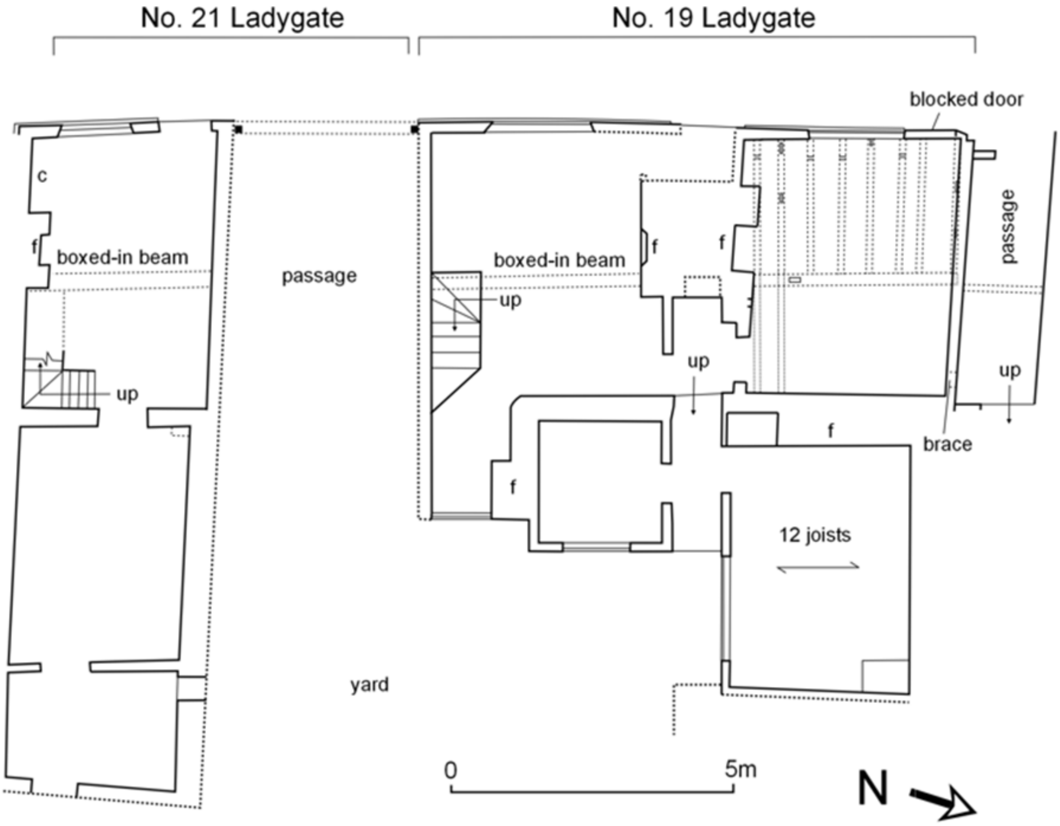

Figure 4: Ground-floor plan of 19–21 Ladygate (YVBSG 2016)

Figure 5: 19 Ladygate, photograph of the roof with truss 5 in the foreground, photograph taken from the south (Alison Arnold)

Figure 6: 19 Ladygate, exposed ceiling beams, photograph taken from the east (Alison Arnold)

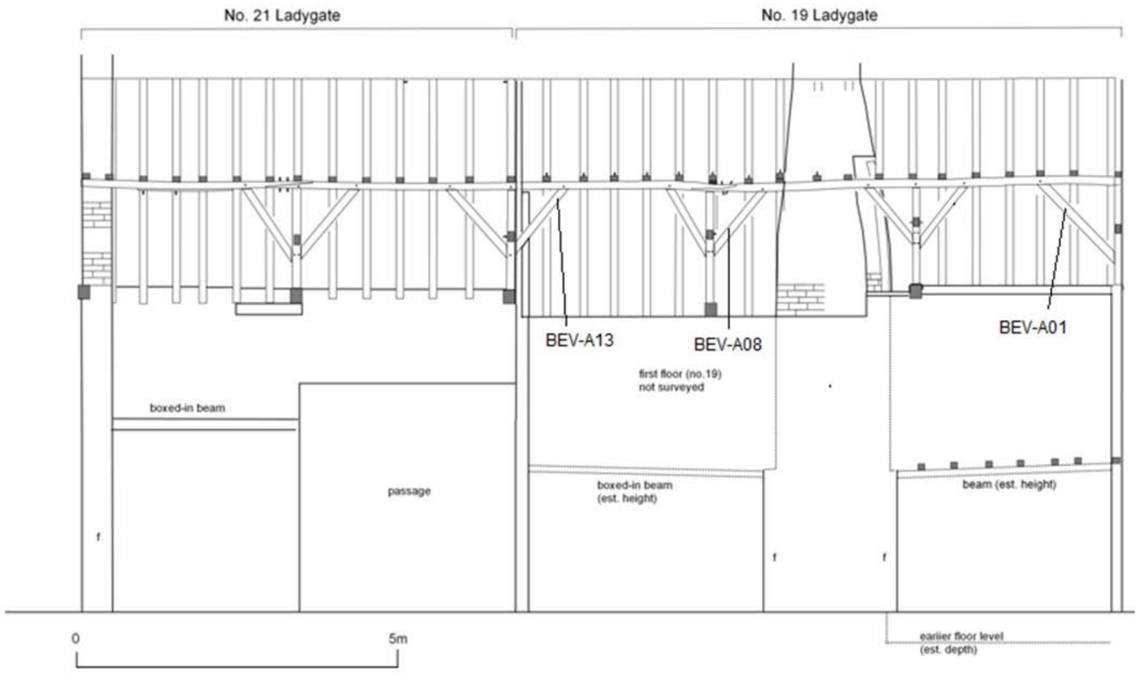

Figure 7: Long section (west side) from the east, showing the location of samples BEV-A01, BEV-A08, and BEV-A13 (YVBSG 2016)

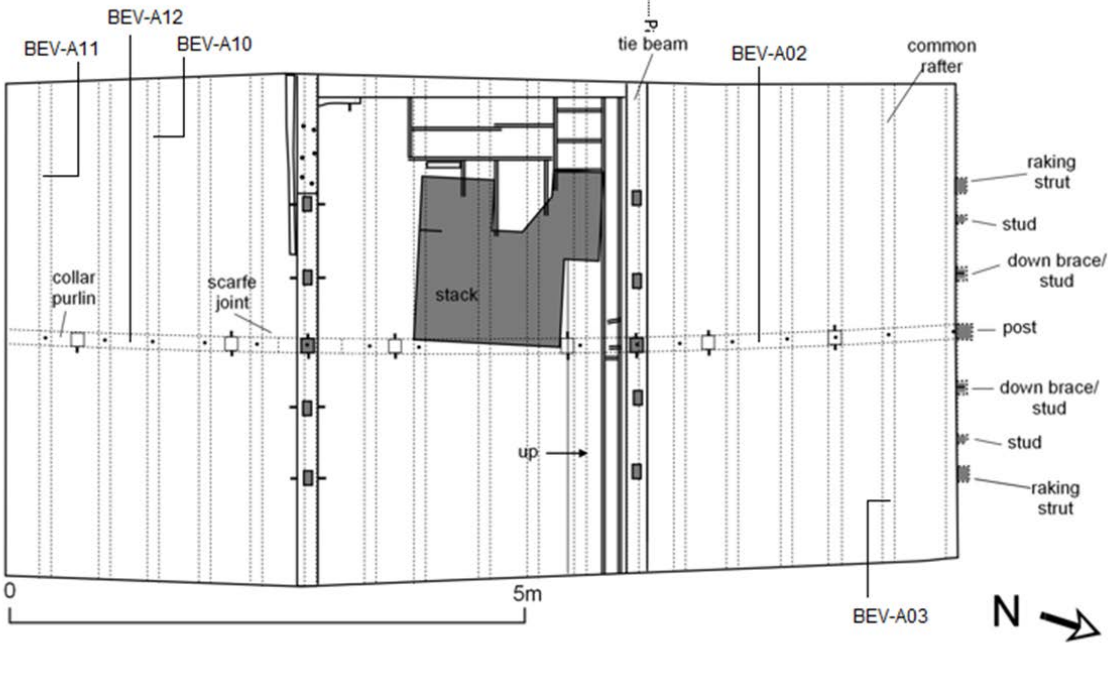

Figure 8: Roof plan, showing the location of samples BEV-A02, BEV-A03, and BEV-A10–12 (YVBSG 2016)

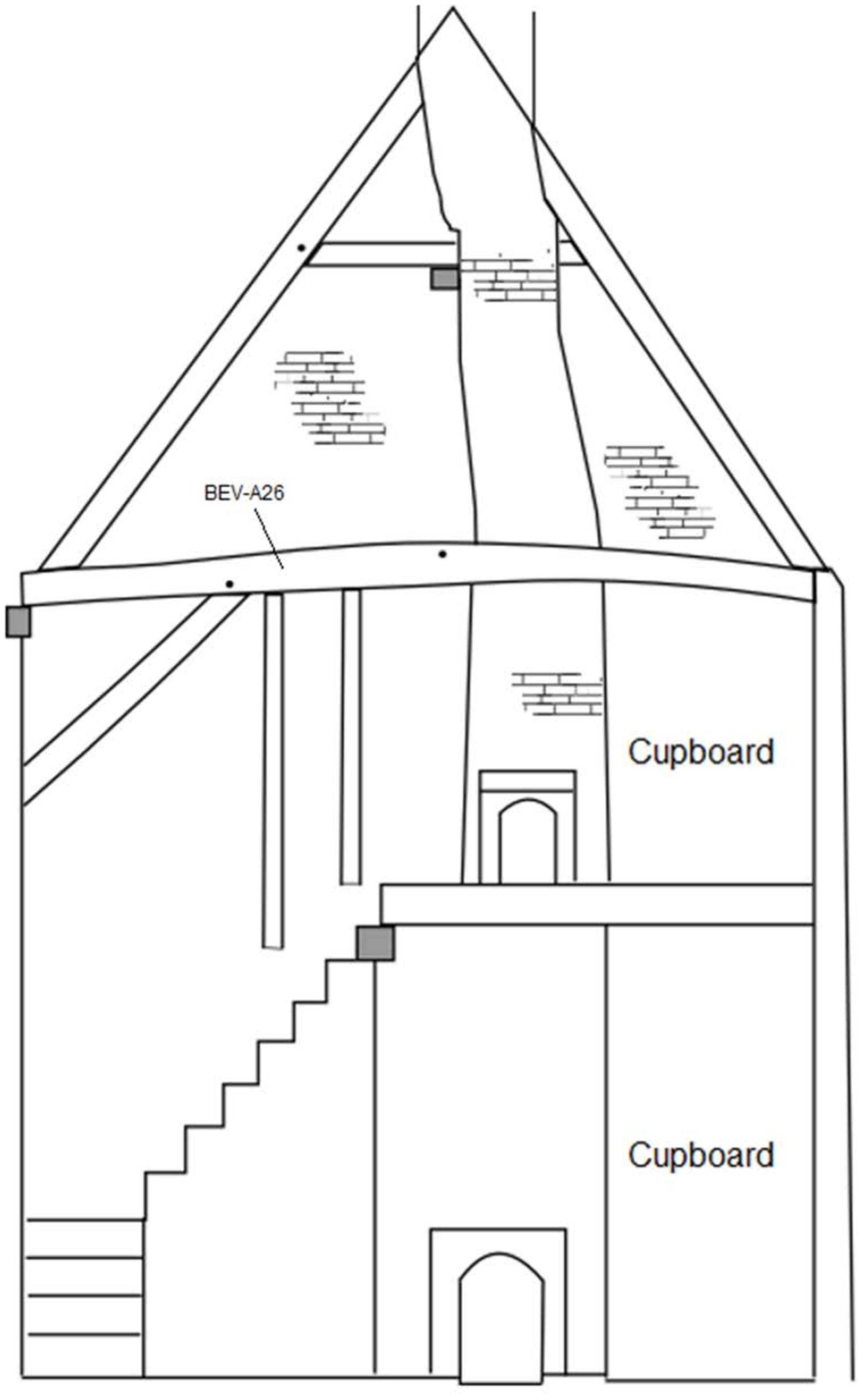

Figure 9: Truss 1 (from south), showing the location of sample BEV-A26 (YVBSG 2016)

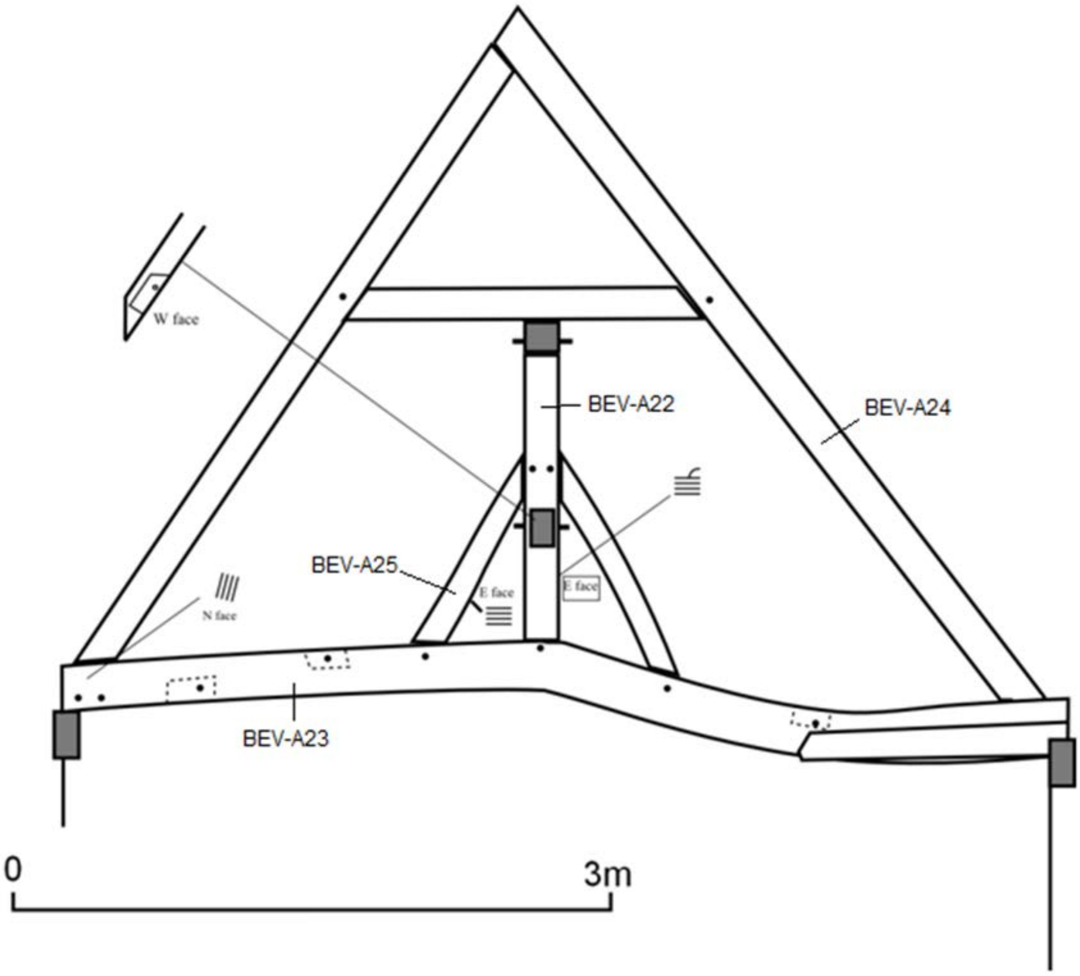

Figure 10: Truss 2 (from south), showing the location of samples BEV-A22–25 (YVBSG 2016)

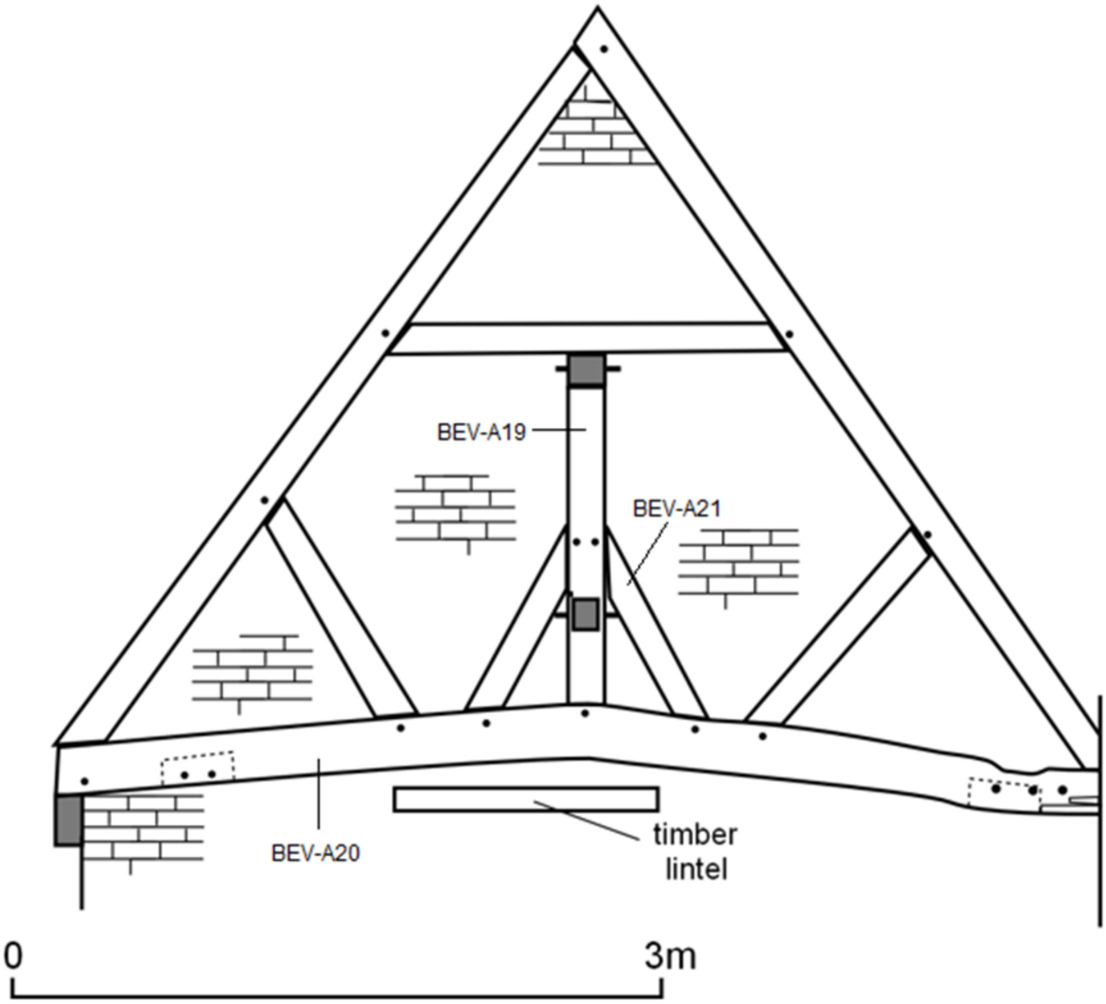

Figure 11: Truss 3 (from south), showing the location of samples BEV-A19–21 (YVBSG 2016)

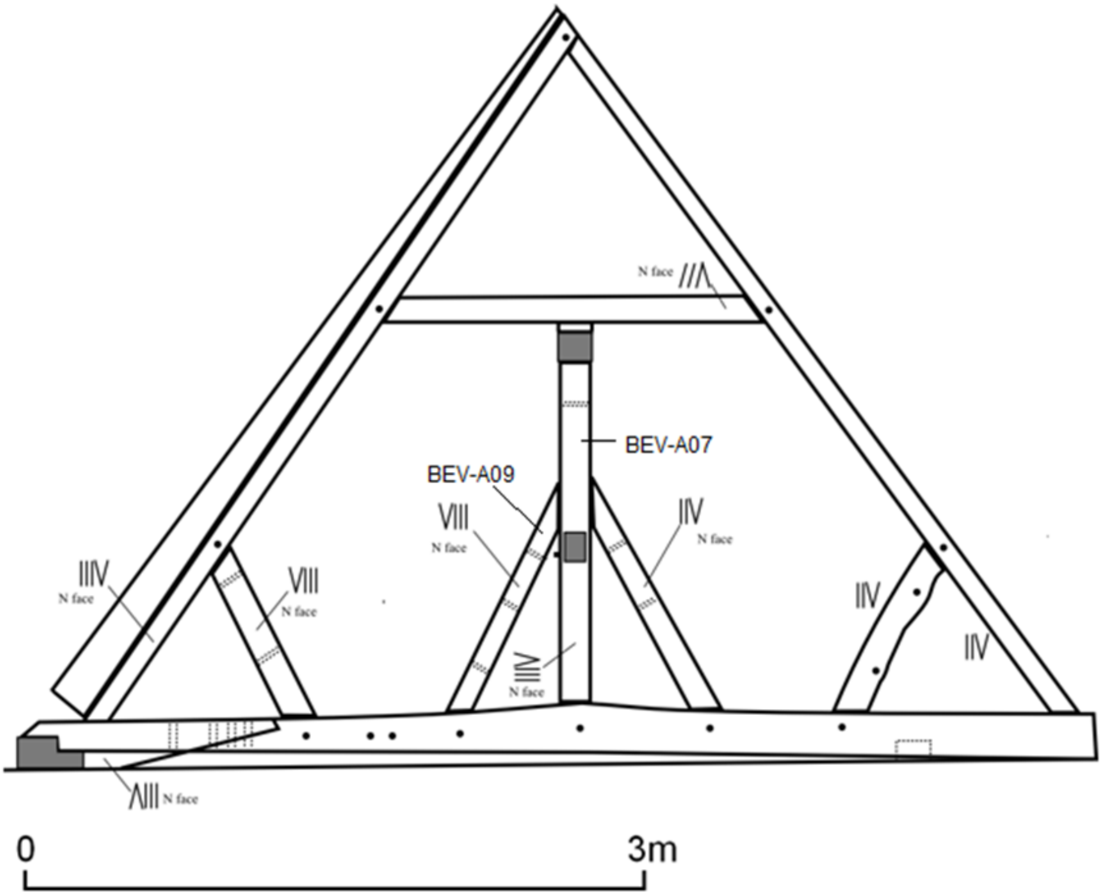

Figure 12: Truss 4 (from north), showing the location of samples BEV-A07 and BEV-A09 (YVGSG 2016)

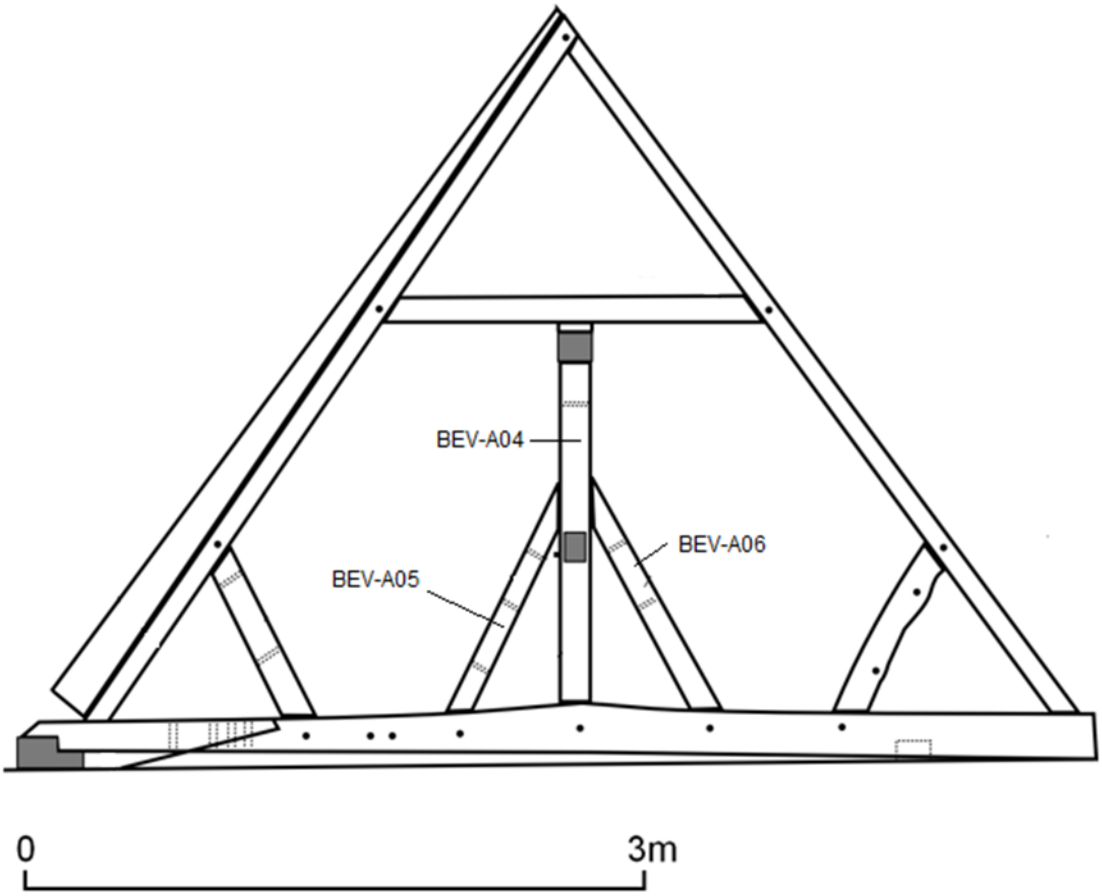

Figure 13: Truss 5 (from north, based on truss 4), showing the location of samples BEV-A04–6 (YVGSG 2016)

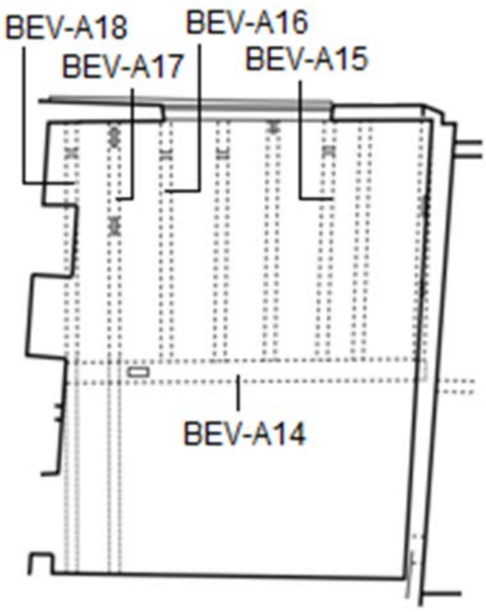

Figure 14: Plan of exposed ceiling beams in 19 Ladygate, showing the location of samples BEV-A14–18 (after YVBSG 2016)

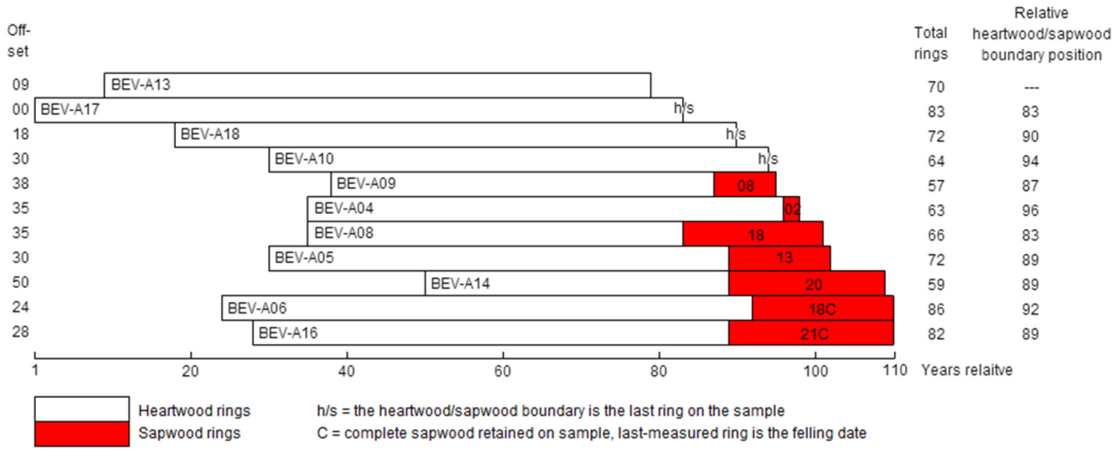

Figure 15: Bar diagram to show the position of samples in original undated site sequence BEVASQ01

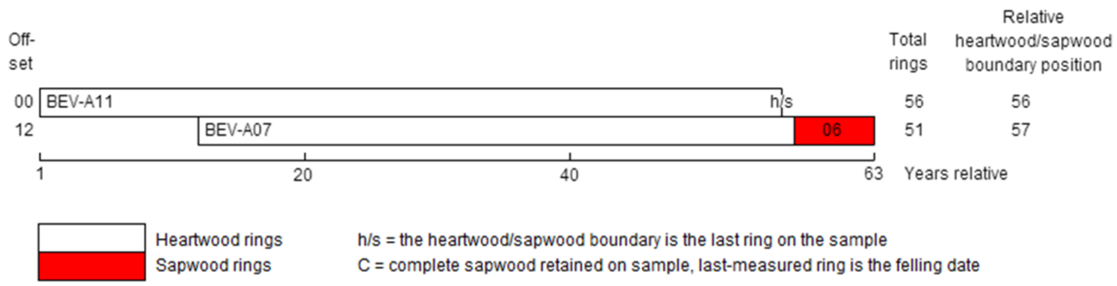

Figure 16: Bar diagram to show the position of samples in undated site sequence BEVASQ02

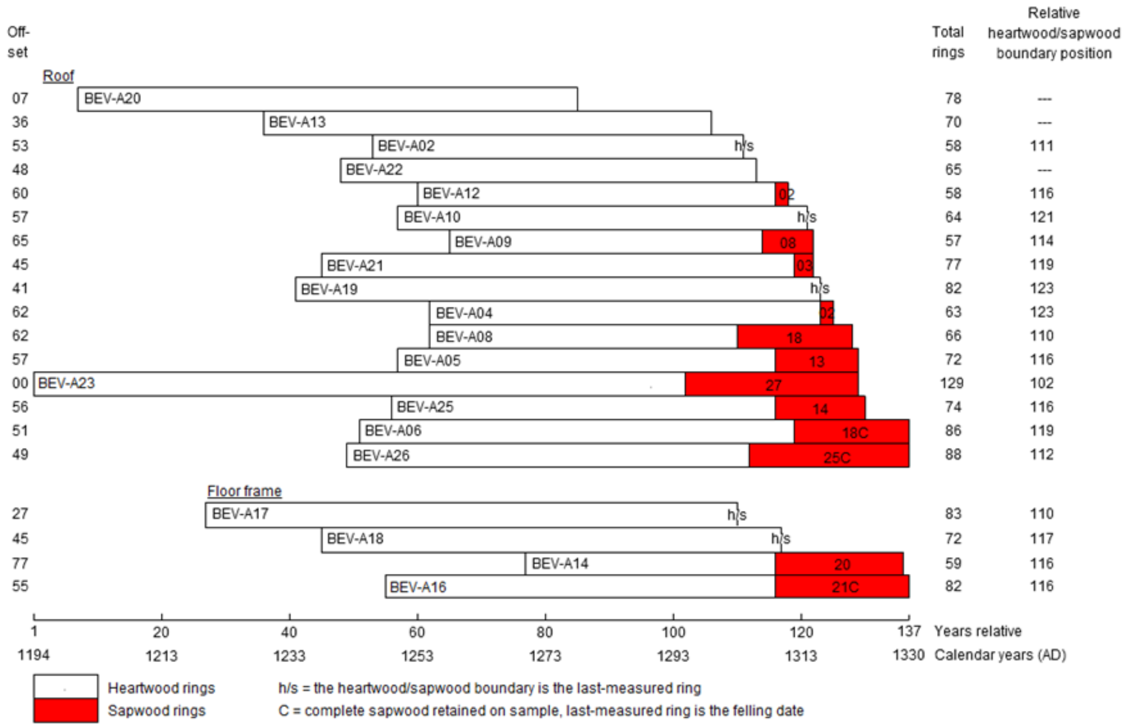

Figure 17: Bar diagram of samples in updated site sequence BEVASQ01, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BEV-A02A 58
197 252 277 184 443 397 455 225 141 95 178 134 232 295 149 177 249 224 253 245
195 248 207 156 243 252 214 107 72 116 190 151 114 101 178 175 222 283 258 265
150 160 206 257 363 259 187 156 206 161 156 128 85 85 125 138 103 90
BEV-A02B 58
215 254 281 183 431 391 446 224 140 105 174 131 231 294 153 177 244 226 253 243
190 262 198 156 238 253 213 97 82 113 192 155 107 97 183 180 201 273 283 271
155 170 226 247 351 290 183 152 207 161 157 126 94 75 124 138 102 88
BEV-A03A 54
448 498 472 324 225 398 365 365 347 219 228 248 138 150 209 117 81 137 133 140
121 96 225 237 166 231 160 143 302 272 245 224 168 124 110 145 266 227 148 267
246 212 234 193 148 131 80 172 237 301 339 182 150 137
BEV-A03B 54
441 507 475 300 234 390 359 378 337 197 215 244 140 149 203 119 86 135 136 132
109 97 208 238 168 226 173 140 306 270 242 213 162 114 121 131 256 224 149 264
243 210 238 189 145 128 84 172 235 307 335 207 148 138
BEV-A04A 61
251 278 211 211 289 198 165 267 184 162 141 101 137 111 128 183 204 188 115 93
166 195 140 183 163 168 193 198 162 157 107 108 160 271 237 286 286 211 250 141
142 158 140 131 169 177 159 165 144 119 81 162 134 204 185 239 235 157 203 269
180
BEV-A04B 52
80 115 102 112 185 185 182 115 77 135 195 113 164 119 143 138 187 186 181 113
93 154 280 231 274 262 218 271 149 148 149 146 143 160 190 179 172 148 132 79
157 138 198 197 256 245 166 197 265 168 178 126
BEV-A05A 72
254 229 222 180 245 158 200 267 281 339 198 214 291 200 200 163 156 190 200 214
262 334 238 158 163 217 327 208 162 151 200 264 240 203 206 177 162 179 263 266
213 276 215 142 190 159 144 188 129 159 253 229 140 202 220 212 245 136 188 236
198 253 174 181 234 294 287 269 135 166 206 148
BEV-A05B 72
235 227 224 182 234 162 201 274 281 337 203 215 292 203 201 162 159 204 197 209
256 340 246 161 164 216 331 211 160 155 192 251 249 218 201 172 153 184 250 270
219 269 195 160 194 157 151 185 124 143 258 220 146 199 216 200 236 149 183 231
194 254 162 187 234 294 267 276 117 151 200 165
BEV-A06A 86
317 242 241 194 236 198 222 195 192 136 204 118 186 195 209 299 164 150 221 177
161 140 133 186 164 198 275 286 222 126 126 143 273 172 150 114 145 208 196 163
160 135 100 154 173 164 147 196 152 87 120 155 148 173 144 153 198 225 130 137
186 200 198 137 164 190 161 229 113 141 192 200 227 219 132 142 203 142 83 75
112 90 181 191 254 216
BEV-A06B 86
310 254 232 198 237 202 249 192 192 141 202 122 188 198 211 298 167 153 212 179
155 146 136 186 160 197 275 291 218 132 126 140 278 172 150 109 149 209 190 163
154 130 100 154 183 181 152 206 145 89 124 160 138 174 155 151 208 224 137 129
199 200 223 119 173 190 153 229 133 137 196 195 239 219 128 150 196 153 80 70
114 91 177 198 251 224
BEV-A07A 51
118 115 116 149 211 210 203 281 326 326 220 191 214 189 128 215 272 364 384 253
313 223 191 159 194 280 158 146 203 141 139 140 110 112 135 179 128 162 103 143
176 119 215 200 166 124 214 202 152 196 170
BEV-A07B 51
115 118 118 156 204 230 192 279 309 315 237 190 219 201 116 221 269 370 387 265

318 237 182 171 190 275 145 153 202 148 134 142 110 108 140 173 137 150 116 159
180 118 203 203 175 128 206 209 152 197 178
BEV-A08A 66
174 256 236 221 300 162 165 195 151 118 101 111 172 119 196 221 245 170 112 77
125 155 118 121 111 149 169 183 164 99 92 74 122 180 175 132 158 116 92 110
94 101 75 55 139 85 96 65 65 79 99 69 61 74 101 108 92 106 94 60
109 96 108 102 109 133
BEV-A08B 66
174 256 231 218 291 158 158 187 151 127 103 106 153 135 186 226 252 169 105 85
118 147 124 117 104 139 170 186 167 105 78 81 145 157 175 124 160 108 98 114
90 101 86 57 130 90 95 65 55 89 82 75 66 68 102 98 91 106 92 59
109 101 101 104 110 132
BEV-A09A 57
157 213 63 60 72 97 81 69 61 77 106 93 134 131 127 82 74 76 133 107
115 101 143 175 174 183 141 97 105 163 156 153 123 125 107 67 61 104 125 82
95 96 78 70 57 55 54 68 75 70 102 121 99 153 90 164 102
BEV-A09B 57
177 212 64 55 77 93 83 70 57 70 105 80 152 136 123 79 76 86 129 103
120 104 137 174 174 178 137 109 105 160 159 162 128 115 113 66 74 100 121 83
89 102 71 65 52 55 59 80 74 71 102 122 106 150 96 162 109
BEV-A10A 64
477 327 286 229 319 196 210 206 217 216 138 140 163 171 141 100 73 100 98 133
183 181 143 84 100 119 195 142 152 110 165 156 177 154 149 107 96 136 177 195
168 177 118 136 97 109 137 95 94 126 132 131 129 112 132 117 172 170 244 177
305 251 189 165
BEV-A10B 64
480 335 275 235 323 198 203 215 209 218 135 142 164 174 139 102 70 101 95 136
190 185 137 76 109 118 196 136 149 114 169 158 173 159 146 108 98 138 183 191
172 182 115 137 94 107 147 86 100 127 135 129 126 113 128 119 178 168 253 172
310 247 190 156
BEV-A11A 56
173 142 241 218 183 211 213 180 284 242 264 151 108 67 75 82 200 193 150 169
157 182 222 143 156 109 76 165 265 293 248 154 199 174 169 203 265 316 198 274
317 269 217 231 191 195 204 280 287 318 160 285 288 176 268 269
BEV-A11B 56
166 141 237 223 188 201 212 171 289 238 274 160 86 70 74 84 197 199 155 160
151 181 225 153 151 104 67 174 265 292 246 149 199 176 167 206 269 331 194 273
318 295 227 237 195 185 197 262 284 309 159 283 280 184 281 264
BEV-A12A 58
267 355 239 290 263 288 175 227 253 296 224 228 147 191 255 214 280 261 287 240
229 136 194 261 192 154 173 173 199 181 188 175 238 114 222 213 260 203 301 203
156 149 107 170 111 102 175 178 140 157 199 179 205 205 164 208 149 124
BEV-A12B 58
257 361 252 308 254 305 178 226 240 303 229 233 159 205 265 213 279 267 286 242
232 139 192 267 194 149 176 172 205 180 193 178 236 126 210 229 265 227 276 207
156 147 112 172 108 105 176 178 139 157 194 182 201 207 158 212 150 124
BEV-A13A 70
400 419 370 275 392 356 332 473 431 402 317 272 308 325 262 237 279 169 185 325
210 223 152 139 146 166 118 149 144 129 146 92 91 123 98 119 95 72 123 137
118 176 222 159 97 72 119 185 114 118 96 119 146 136 105 81 74 59 76 71
90 56 82 52 55 55 49 60 63 45
BEV-A13B 70
389 411 366 286 392 355 353 448 414 397 293 267 311 310 252 245 270 187 188 323
208 223 154 136 151 164 122 146 148 120 163 87 93 116 100 117 95 79 119 117
134 178 225 157 101 73 120 184 115 118 94 123 143 140 108 75 75 61 74 71
92 63 71 55 59 51 48 58 59 44
BEV-A14A 39
166 187 305 401 289 270 239 278 255 279 301 333 211 242 249 323 302 257 219 190
169 142 132 151 148 177 190 205 170 148 108 106 111 176 114 150 115 96 151

BEV-A14B 59
290 298 228 173 175 272 419 270 260 263 266 227 275 295 345 220 260 248 324 287
269 222 187 167 136 151 160 168 171 192 165 163 129 117 109 112 155 108 153 123
114 141 121 122 165 140 132 113 75 77 70 80 72 57 55 64 85 86 57
BEV-A15A 69
74 109 125 105 72 89 116 98 114 252 197 235 124 117 95 172 159 167 124 177
211 180 196 274 196 122 167 185 215 230 162 146 128 125 113 79 100 82 88 113
91 91 94 84 62 75 105 84 61 84 141 121 217 160 206 154 140 122 153 210
104 79 56 54 50 66 75 81 83
BEV-A15B 69
68 113 103 108 74 88 115 82 118 247 211 253 127 114 106 172 169 164 117 165
217 167 192 263 188 132 162 177 214 235 161 153 125 139 116 72 103 75 90 108
99 87 97 80 67 69 106 84 69 80 142 127 216 155 209 153 140 119 146 207
110 82 58 46 49 75 70 78 84
BEV-A16A 82
366 357 466 310 209 222 224 203 269 297 422 348 325 261 245 268 266 212 214 266
277 284 309 244 218 195 180 228 293 209 215 162 259 327 292 295 342 169 211 171
275 249 211 221 247 191 196 250 188 209 210 179 224 219 149 110 124 127 124 119
176 159 165 144 150 106 160 162 196 139 85 100 159 75 103 75 111 92 88 134
125 102
BEV-A16B 82
374 355 468 321 208 223 225 201 256 305 435 337 317 276 234 273 264 224 212 266
296 285 312 249 217 200 181 229 292 213 220 174 264 337 292 318 341 169 209 173
284 244 211 233 233 187 187 253 183 215 209 190 225 223 144 114 114 129 132 122
170 160 174 140 147 106 155 176 194 145 82 103 156 86 99 88 103 93 86 137
121 101
BEV-A17A 83
163 165 140 184 106 60 95 117 145 101 79 108 61 95 138 144 156 116 79 61
75 83 65 61 59 54 35 35 80 68 94 68 65 93 112 77 110 75 102 68
57 64 104 73 57 44 42 46 71 80 117 110 103 49 69 93 115 99 84 76
105 100 96 99 94 63 65 68 92 109 142 144 132 90 107 121 111 107 106 141
150 139 150
BEV-A17B 83
134 173 146 177 107 55 87 123 120 80 81 93 72 79 143 155 150 102 84 52
78 83 80 69 59 58 37 42 76 70 85 71 57 99 104 73 104 86 103 69
55 74 97 70 62 40 42 46 73 74 119 112 101 57 66 94 113 105 75 77
102 104 83 100 92 65 67 77 83 114 142 143 130 90 108 114 118 105 107 147
144 133 163
BEV-A18A 72
360 256 237 296 285 338 332 286 245 201 265 226 312 215 263 246 360 263 285 213
261 353 210 204 339 324 290 260 211 231 314 310 345 380 304 156 113 199 293 190
127 132 155 205 197 185 137 90 79 159 184 232 106 209 174 153 98 70 88 104
75 106 104 93 73 81 108 116 87 64 53 74
BEV-A18B 72
369 249 237 288 291 322 322 275 259 223 289 243 322 177 252 216 354 251 285 207
260 356 221 202 345 321 301 258 212 234 312 310 340 381 307 150 118 194 286 195
136 130 150 212 195 184 135 98 80 163 185 230 112 210 174 149 99 64 88 109
64 108 100 93 63 62 105 117 92 64 49 73
BEV-A19A 82
62 58 88 61 121 53 107 128 151 223 245 407 276 321 446 424 381 258 380 209
409 282 349 258 255 240 190 197 256 190 161 163 106 131 127 130 192 145 143 99
97 121 180 108 162 134 233 190 143 127 124 76 79 137 199 208 211 170 119 153
85 102 109 106 98 120 119 150 122 112 106 126 202 135 196 176 284 159 123 139
177 142
BEV-A19B 82
113 53 92 55 128 47 111 127 147 240 237 391 271 331 434 429 357 257 376 212
406 285 346 261 256 241 187 196 255 202 161 156 109 132 134 121 191 146 138 104
85 128 182 109 162 128 239 190 140 126 120 80 82 137 196 210 207 167 127 150
79 108 108 106 103 110 126 147 124 113 106 123 210 130 201 176 287 157 126 137

179 140
BEV-A20A 78
365 332 374 267 284 388 326 446 615 590 795 571 642 601 570 610 774 527 558 539
556 659 577 671 630 603 441 618 551 643 704 633 340 388 389 301 445 276 302 275
248 286 345 217 231 279 262 195 291 250 223 100 100 95 170 112 129 120 161 80
70 107 105 99 68 74 86 125 202 113 135 158 127 83 72 94 102 117
BEV-A20B 78
355 339 368 284 275 401 306 436 629 580 799 569 640 599 564 618 762 506 558 531
550 656 576 666 632 599 440 615 557 645 694 647 333 387 389 299 475 261 307 263
229 273 360 218 256 266 262 205 282 254 221 101 98 98 172 92 133 121 160 82
69 101 112 95 76 67 87 122 202 115 136 168 113 86 61 93 104 128
BEV-A21A 77
144 148 137 171 208 248 156 153 207 141 232 232 271 199 169 148 193 165 238 327
232 198 105 64 128 83 125 87 121 166 163 243 218 280 194 146 114 190 253 102
80 75 80 70 91 84 62 53 52 83 71 85 43 127 100 100 70 75 159 181
139 135 98 148 208 310 346 360 311 201 167 124 181 197 152 121 123
BEV-A21B 77
128 123 113 167 236 212 152 151 194 174 240 249 282 219 165 148 215 159 237 297
221 206 93 62 108 77 106 61 120 168 166 232 246 277 202 143 104 179 240 113
80 70 67 82 89 76 65 50 57 85 78 92 44 124 94 95 71 87 159 181
128 134 116 186 303 316 354 357 319 188 175 129 173 203 157 118 125
BEV-A22A 65
282 286 308 346 447 362 525 414 368 418 335 454 367 692 479 626 518 454 390 231
196 238 171 127 101 62 76 70 84 149 110 89 47 65 91 159 69 85 67 121
86 98 121 97 64 70 116 150 180 164 146 113 142 72 102 109 87 102 169 200
167 111 91 132 105
BEV-A22B 65
281 290 304 362 452 359 512 416 385 424 342 459 349 701 469 627 533 489 381 237
203 242 173 130 103 61 76 77 83 141 113 89 50 62 97 178 73 83 67 106
94 104 125 104 67 61 116 159 180 167 147 111 139 76 99 110 87 114 164 199
165 109 91 136 82
BEV-A23A 129
121 178 234 218 268 212 201 242 283 290 197 139 225 180 190 207 276 396 338 413
428 389 433 567 416 447 485 466 576 538 610 607 485 450 519 419 455 351 459 273
441 405 197 327 180 252 236 196 207 171 134 224 278 314 313 349 248 230 115 100
108 105 78 74 112 153 109 108 177 232 121 114 95 77 108 148 104 165 188 150
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158 149 104 124 90 82 108 94 86 73 33 55 45 32 28 56 60 45 44 48
57 55 78 95 138 98 87 83 52
BEV-A23B 129
135 180 227 222 234 196 204 255 320 304 226 160 213 178 193 204 271 383 359 453
414 353 396 595 404 437 478 449 585 523 603 589 499 436 517 408 446 345 450 275
405 407 197 321 179 243 237 199 203 166 119 210 256 316 312 354 253 233 109 89
95 98 79 68 104 142 108 104 170 217 126 120 87 78 102 131 100 167 194 140
79 76 85 101 80 79 93 105 200 163 160 142 94 175 112 100 137 138 167 161
153 152 112 123 85 90 97 101 85 71 35 42 44 44 40 42 46 66 40 45
58 59 71 101 139 95 80 79 56
BEV-A25A 74
161 140 105 85 111 114 97 147 126 108 124 68 136 158 127 118 54 53 79 148
131 239 187 167 80 111 103 145 152 111 84 187 150 117 197 173 151 115 137 126
130 94 131 116 97 85 95 117 104 92 96 162 166 132 129 168 145 148 108 196
226 288 218 172 218 154 170 172 175 131 129 109 94 94
BEV-A25B 74
156 139 100 97 108 123 92 129 134 122 127 72 135 161 115 122 51 61 75 152
118 232 183 157 78 112 109 143 156 107 90 183 150 112 193 174 153 113 146 118
126 104 126 116 107 78 100 116 111 102 107 151 162 133 114 168 140 150 116 199
227 285 214 173 212 148 176 168 169 133 136 102 99 90
BEV-A26A 88
747 628 668 645 651 717 772 612 644 361 438 359 435 273 383 328 354 247 179 379

392 200 189 155 172 297 408 298 341 347 290 217 162 192 214 180 223 216 245 276
231 202 210 143 140 128 128 152 148 146 132 119 96 98 202 166 202 207 174 157
119 71 112 134 140 99 115 106 147 135 76 87 124 114 130 126 124 106 103 119
93 81 63 62 41 94 197 106
BEV-A26B 88
743 629 641 672 665 710 763 623 646 357 481 373 440 281 389 339 364 260 184 386
377 192 191 150 167 301 400 301 348 362 286 206 150 184 203 181 217 212 251 275
227 202 209 149 141 118 136 146 145 141 133 121 97 103 202 163 202 215 174 164
114 60 115 136 141 107 103 113 150 137 73 89 119 118 135 117 131 93 109 113
95 83 67 56 43 88 199 110

APPENDIX 1: 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 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1.1 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 A1.1, 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 A1.2 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 A1.2; 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 A1.1: 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

Figure A1.2: 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 A1.3: 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 A1.4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that,

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 A1.2. 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 A1.4). 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 A1.5 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 Figure A1.5 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 A1.2, 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 A1.6. 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 A1.7. 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

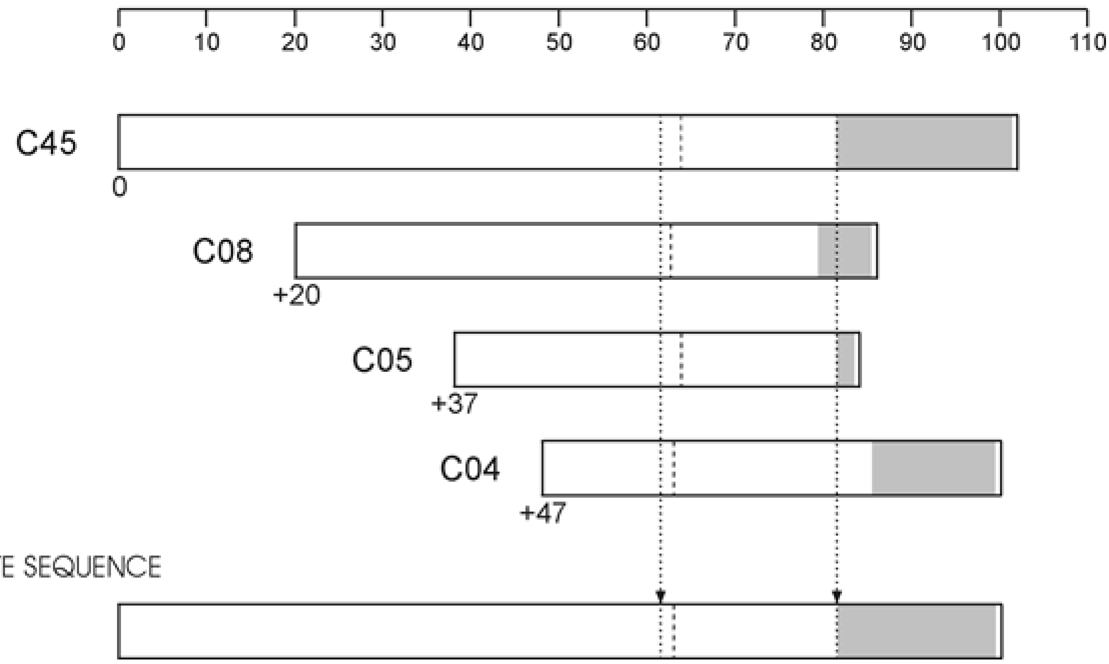

Figure A1.5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

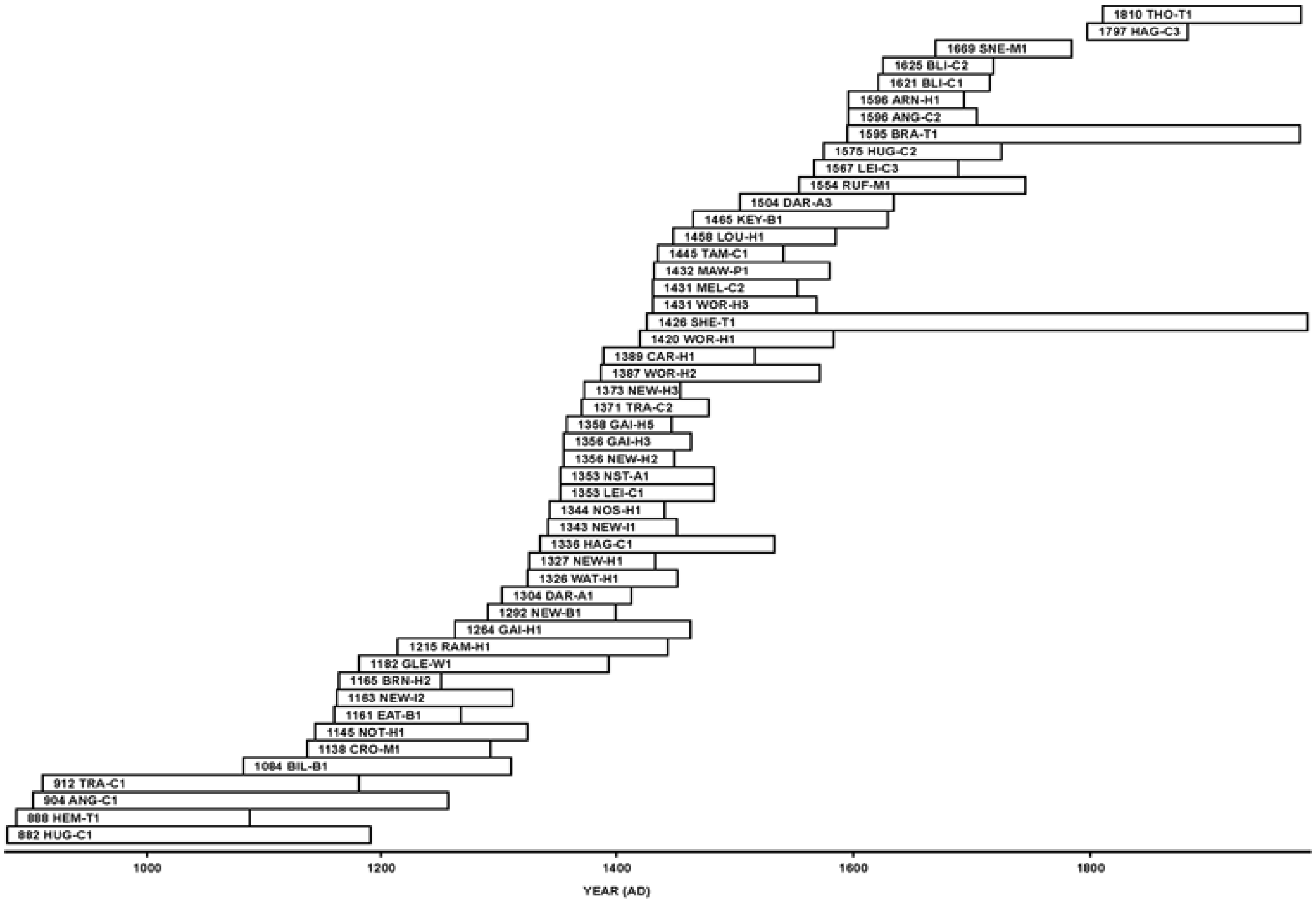

Figure A1.6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

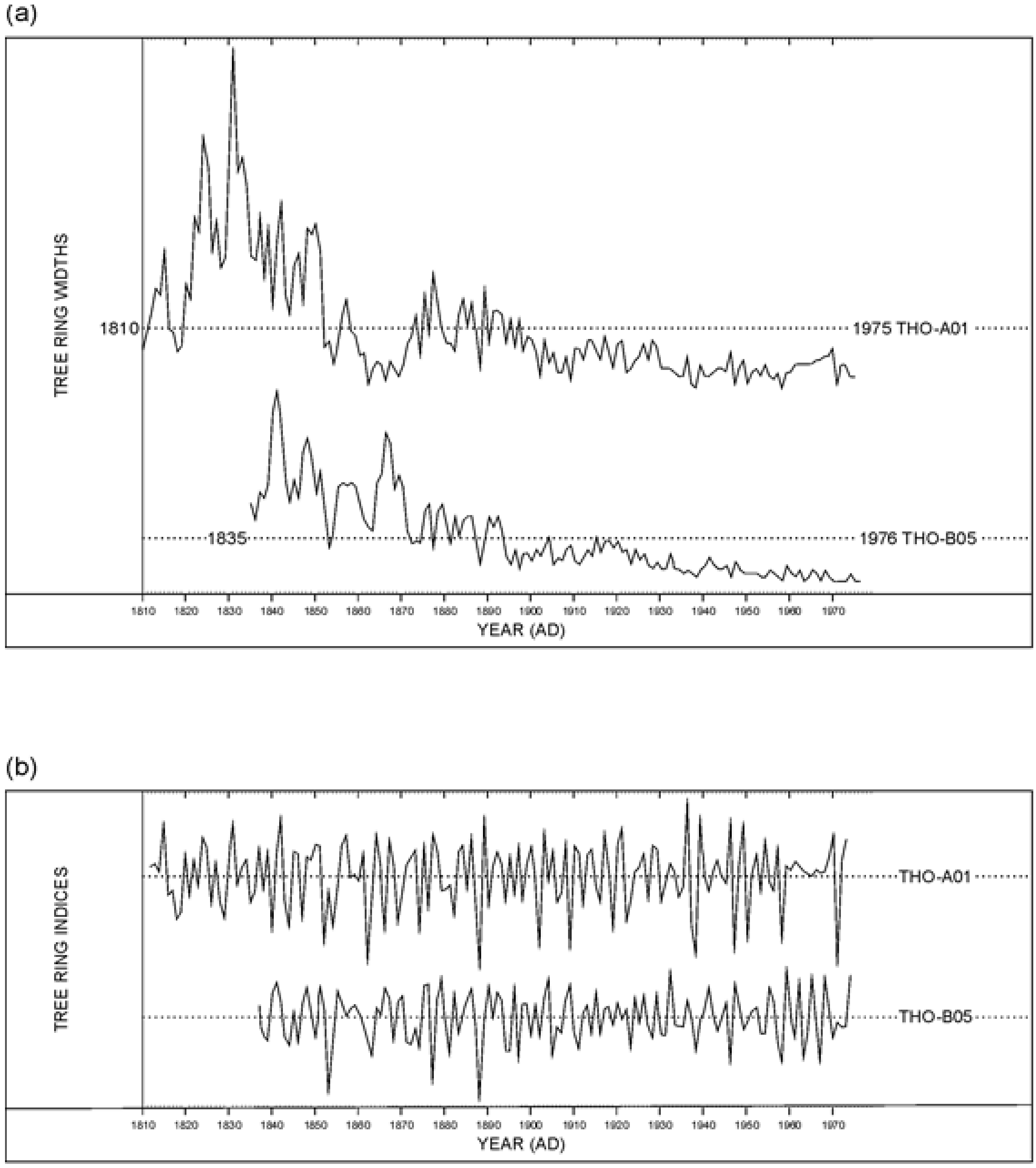

Figure A1.7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known
Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A1.7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely

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APPENDIX 2 RADIOCARBON DATING AND WIGGLE-MATCHING

Radiocarbon dating

Following the failure of the dendrochronology to provide calendar dating for the felling of the oak timbers in site sequence BEVASQ01, two tree-ring sequences (BEV-A17 and BEV-A06) that formed part of the 110 rings site sequence were selected for radiocarbon dating and wiggle-matching.

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table A2.1, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Five radiocarbon measurements have been obtained from single annual tree-rings from timbers BEV-A17 and BEV-A06 (Table A2.1; Fig A2.1). Dissection was undertaken by Alison Arnold at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the ^{14}CHRONO Centre, Queens University, Belfast and Scottish Universities Environmental Research Centre (SUERC) in 2015.

Samples measured at Belfast were processed and dated by Accelerator Mass Spectrometry (AMS) as described in Reimer *et al* (2015). The three rings submitted to the SUERC were converted to α-cellulose, combusted, graphitised, and dated by AMS as described by Dunbar *et al* (2016).

Both facilities maintain continual programmes of quality assurance procedures in addition to participation in international inter-comparison exercises (Scott 2003; Scott *et al* 2010). This demonstrates the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table A2.1). The $\delta^{13}C$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Wiggle Matching

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal13 calibration curve (Reimer *et al* 2013). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from BEVASQ01, derived from the probability method (Stuiver and Reimer 1993) are shown in outline in Figure A2.1.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al* (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.3 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figure A2.1 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure A2.1 illustrates the chronological model for BEVASQ01. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 21 of the measured tree-ring series (SUERC-60194) was laid down 59 years before the carbon in ring 80 of the series (SUERC-60195); Fig A2.1), with the radiocarbon measurements (Table A2.1) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal13 (Reimer *et al* 2013).

The model shown in Figure A2.1 has good overall agreement (Acomb: 34.0, An: 31.6, n:5). It suggests that the final ring of site sequence BEVASQ01 formed in *cal AD 1310–1335* (*95% probability*; *BEVASQ01 felling*; FigA2.1), probably in *cal AD 1315–1325* (*68% probability*).

Following the second tranche of dendrochronological sampling at 21 Ladygate a second site sequence, BEVASQ01 of 137 rings, was formed that has an end date of AD 1330. The estimated date for the last ring obtained by the radiocarbon wiggle match *cal AD 1310–1335* (*95% probability*; *BEVASQ01 felling*; FigA2.1) was thus consequently found to include the dendrochronological date of AD 1330

Table A2.1: 19 Ladygate, Beverley (BEVASQ01)– radiocarbon and stable isotope results

Laboratory number	Sample reference, material & context	$\delta^{13}C_{IRMS}$ (‰)	Radiocarbon Age (BP)	*Highest Posterior Density interval -cal AD (95% probability)*
UBA-28903	BEV-A17 ring 1 *Quercus* sp. heartwood, relative year 1 of the 110 year chronology BEVASQ01, from joist 6 of the first floor frame.	−24.3±0.22	876±25	*1200–1225*
SUERC-60194	BEV-A17 ring 21 *Quercus* sp. heartwood, relative year 21 of the 110 year chronology BEVASQ01, from joist 6 of the first floor frame.	−23.4±0.2	759±27	*1220–1245*
SUERC-60195	BEV-A17 ring 80 *Quercus* sp. heartwood, relative year 80 of the 110 year chronology BEVASQ01, from joist 6 of the first floor frame.	−23.7±0.2	705±29	*1280–1305*
UBA-28902	BEV-A06 ring 95 *Quercus* sp. sapwood, relative year 95 of the 110 year chronology BEVASQ01, from joist 6 of the first floor frame.	−26.10.22	566±38	*1295–1320*
SUERC-60196	BEV-A06 ring 105 *Quercus* sp. sapwood, relative year 105 of the 110 year chronology BEVASQ01, from joist 6 of the first floor frame.	−24.9±0.2	569±27	*1305–1330*

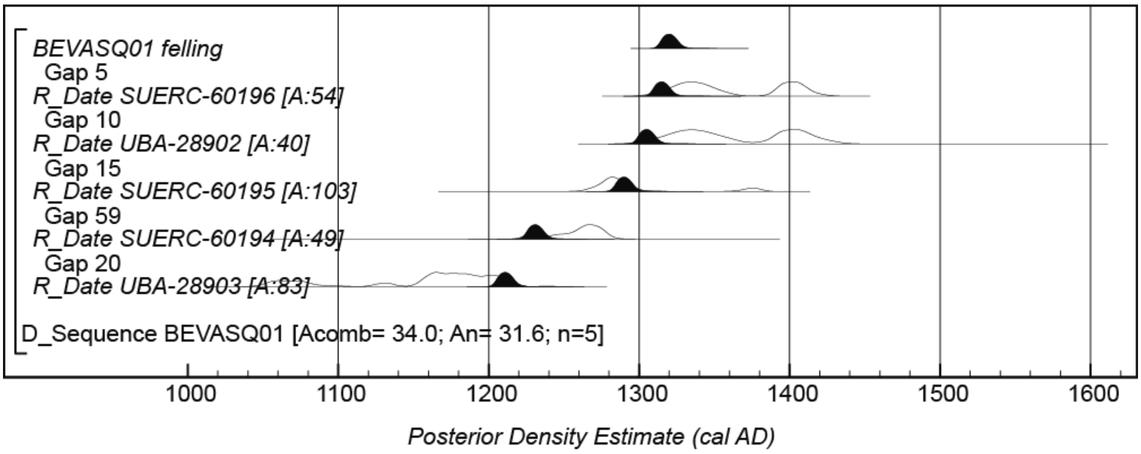

Figure A2.1: Probability distributions of dates from 19 Ladygate, Beverley site sequence BEVASQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

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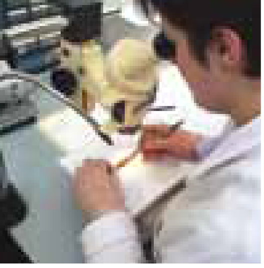
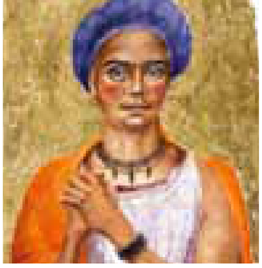


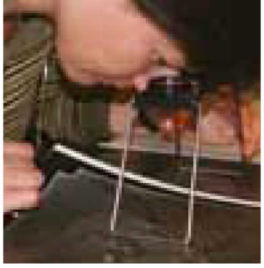


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