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LOW BISHOPLEY, FROSTERLEY, WEARDALE, COUNTY DURHAM
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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LOW BISHOPLEY
FROSTERLEY
WEARDALE
COUNTY DURHAM

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SUMMARY
Samples were taken from the three surviving historic ranges of this building resulting in the construction of seven site sequences, only two of which could be dated.
Site sequence, LBSASQ04, contains two samples taken from common rafters of the central hall/parlour range roof, and spans the period AD 1501–81; both timbers are thought to have been felled in AD 1581.
A second site sequence contains eight samples (six from roof timbers and two from ground-floor ceiling beams), all taken from the east range, and spans the period AD 1401–1575. Interpretation of the sapwood suggests felling of all timbers represented occurred some time between AD 1576–1588.
Dendrochronological research has demonstrated that the roof of the central hall/parlour range contains some common rafters felled in AD 1581 and that the roof and floor of the east range are broadly contemporary and are constructed with timber felled in AD 1576–88.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Laboratory would like to thank Mr and Mrs Frank Holmes, the owner of the building, for their hospitality and allowing the sampling to be undertaken. Martin Roberts, English Heritage Regional Inspector for the North-East at the time of sampling, provided the information upon which the introduction below is based and Figures 4 and 11–24. His enthusiasm and knowledge of the building under investigation was, as always, of great assistance. Thanks are also given to the Scientific Dating Section at English Heritage and Cathy Tyers of the Sheffield University Dendrochronology Laboratory for their advice and assistance throughout the production of this report.

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INTRODUCTION

Low Bishopley, located about 3km to the south east of the town of Stanhope (NZ 0249 3596; Figs 1–3) is a long, linear Weardale farmstead, orientated roughly east-west and facing south. It is thought to have been established as a farm in the thirteenth century but may also have served as a hunting lodge for the Bishops of Durham. No obvious building evidence is seen of these early medieval origins, with the surviving, historic remains consisting of a central hall/parlour range, an extended east range, and a west range (Fig 4). The description below is based on information provided by Martin Roberts (pers comm) and Roberts (2008).

Central hall/parlour range

This is thought to be the oldest part of the building, being of possible late-sixteenth or early seventeenth-century date. Timbers from this phase survive in the first-floor structure (Fig 5) and roof space (Fig 6). The roof consists of three trusses and is of simple, collared principal rafter trusses without tiebeams (although these may have been lost rather than never existed).

East range

This range is slightly narrower than the central hall/parlour range and contains the hearth passage and low end kitchen; it continues eastwards into a barn. The roof over the whole of the east range is of upper-cruck type with double collars and principal rafters abutting the ridge purlin (Fig 7). Timbers of the ceiling also survive in this part of the building (Fig 8). This range post-dates the central hall/parlour range and is thought to date to the seventeenth century.

West range

Originally thought to be of the same date as the east range extension it is now felt likely to be a little later, perhaps dating to the last quarter of the seventeenth century. Surviving timbers consist of finely chamfered beams and joists on the ground floor (Fig 9) and the roof timbers. The roof has rather crude, collared principal rafters and tiebeam trusses, pegged at the apex (Fig 10).

SAMPLING

Tree-ring sampling and analysis was requested by Martin Roberts in order to establish with greater reliability and accuracy the probable construction date of the central hall/parlour range and elucidate the sequence of development relating to the addition of the east and west ranges. The results would also be added to the growing body of recorded and tree-ring dated evidence for both the hearth passage plan and upper cruck roof trusses in this region in particular.

A total of 33 timbers were sampled. Each sample was given the code LBS-A (for Low Bishopley) and numbered 01–33. Seven of the samples were taken from the timbers of the west range (LBS-A01–07), 11 from the east range (LBS-A08–18), and 15 from the central hall/parlour range (LBS-A19–33). The location of samples was noted at the time of sampling and has been marked on Figures 11–24. Further details relating to the samples can be found in Table 1. Trusses have, for all ranges, been numbered east to west (Fig 11).

ANALYSIS AND RESULTS

At this stage it was noted that one of the east range samples (LBS-A14) had too few rings to make secure dating a possibility and so it was discarded prior to analysis. The remaining 32 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. All samples were then compared with all other samples by the Litton/Zainodin grouping procedure (see Appendix).

East range

Eight of these samples (five taken from cruck blades, one from a yoke, and two from ground-floor ceiling beams) matched each other at a value of *t*=5.0. The measurements of these samples were combined at the relevant offset positions to form LBSASQ01, a site sequence of 175 rings (Fig 25). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1401 and a last-measured ring date of AD 1575. The evidence for this dating is given in Table 2. Seven of these samples have the heartwood/sapwood boundary ring, the date of which is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1548, which allows an estimated felling date to be calculated for the seven timbers represented to the range AD 1576–88 (this allows for sample LBS-A13 to have the last-measured ring date of AD 1575 with incomplete sapwood). The eighth sample (LBS-A12) does not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated. However, with a last-measured heartwood ring date of AD 1519, it is possible that this sample was also felled in AD 1576–88 with the rest of the timbers.

Attempts to date the remaining two east range samples by individually comparing them against the reference chronologies were unsuccessful and they remain undated.

West range

Five of these samples (four taken from principal rafters and one from a ground-floor ceiling beam) matched each other and were combined to form LBSASQ02, a site sequence of 84 rings (Fig 26). Attempts to date this site sequence by comparing it against the reference material were unsuccessful and it remains undated.

The other two west range samples (both from collars) matched each other and were combined to form LBSASQ03, a site sequence of 142 rings (Fig 27). Again, attempts to match this site sequence against the reference material were unsuccessful and it is also undated.

Central hall/parlour range

Analysis of the samples from this part of the building resulted in nine of them grouping to form four site sequences. Firstly, two samples, both taken from common rafters, matched each other and were combined to form LBSASQ04, a site sequence of 81 rings (Fig 28). This site sequence was found to span the period AD 1501–81. Evidence to support this dating is given in Table 3. One of these samples (LBS-A32) has complete sapwood and the last-measured ring date of AD 1581, the felling date of the timber represented. The heartwood/sapwood boundary ring date of the other sample is consistent with this sample also having been felled in AD 1581.

A further two samples (taken from ground-floor ceiling beams) were combined to form LBSASQ05, a site sequence of 123 rings (Fig 29). Three more samples (all taken from principal rafters) grouped to form LBSASQ06, a site sequence of 61 rings (Fig 30). Finally, two further principal rafter samples matched and were combined at the relative offset position to form LBSASQ07, a site sequence of 51 rings (Fig 31). Attempts to date these three site sequences and the remaining six ungrouped samples by comparing them against the reference material were unsuccessful and all are undated.

DISCUSSION

Prior to tree-ring analysis being undertaken the oldest part of the building was thought to be the central hall/parlour range which was believed to date to the late sixteenth or early-seventeenth century. The east range with its cruck roof was thought to date to the seventeenth century and the west range was believed to be slightly later, and date to the late-seventeenth century.

Only two of the timbers sampled within the central hall/parlour range have been successfully dated. Two common rafters are now known to have been cut from timber felled in AD 1581. Whilst this appears to agree with the late-sixteenth century date suggested on stylistic grounds it should be noted that the felling date relates to only two common rafters and no major elements associated with the trusses. Further investigation of the structural integrity of this roof may ascertain whether the felling date identified relates to the initial construction of the central range or whether the roof was perhaps modified at about the same time as the construction of the east range (see below).

Six of the roof timbers and two of the floor beams from the east range have now been dated to AD 1576–88. This shows that the roof and floor are contemporary and most likely date to the final quarter of the sixteenth century, slightly earlier than had been suggested on stylistic grounds.

It is unfortunate that, despite the construction of two site sequences, it was not possible to date any of the timbers of the west range. However, by looking at the relative heartwood/sapwood boundary ring positions on the five samples contained within site sequence LBSASQ02, it is possible to say that the five timbers represented were probably felled at the same time. These five samples were taken from four roof timbers and a ground-floor ceiling beam, suggesting the roof and floor frame are contemporary. The two collars represented within the undated site sequence LBSASQ03 are also likely to have been felled at the same time as each other although again it is not possible to say when this might have been with dendrochronology.

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TABLES

Table 1: Details of tree-ring samples from Low Bishopley, Frosterley, County Durham

Sample Number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
West range						
LBS-A01	North principal rafter, truss 1	74	21C	----	----	----
LBS-A02	South principal rafter, truss 1	46	20C	----	----	----
LBS-A03	Collar, truss 1	74	01	----	----	----
LBS-A04	North principal rafter, truss 2	53	h/s	----	----	----
LBS-A05	South principal rafter, truss 2	77	11	----	----	----
LBS-A06	Collar, truss 2	142	23	----	----	----
LBS-A07	Ground-floor ceiling beam (kitchen)	68	h/s	----	----	----
East range						
LBS-A08	North blade, truss 1	127	h/s	1423	1549	1549
LBS-A09	South blade, truss 1	100	h/s	1444	1543	1543
LBS-A10	North blade, truss 2	88	h/s	1458	1545	1545
LBS-A11	North blade, truss 3	105	h/s	1439	1543	1543
LBS-A12	South blade, truss 3	106	--	1414	----	1519
LBS-A13	Yoke, truss 3	96	17	1480	1558	1575
LBS-A14	South common rafter, truss 2–3	NM	--	----	----	----
LBS-A15	South purlin, truss 3–west gable	83	06	----	----	----
LBS-A16	Ground-floor ceiling beam 1	100	h/s	1451	1550	1550
LBS-A17	Ground-floor ceiling beam 3	79	07	----	----	----
LBS-A18	Ground-floor ceiling beam 4	150	h/s	1401	1550	1550
Central hall/parlour range						
LBS-A19	East ceiling beam (lounge)	92	12	----	----	----
LBS-A20	East central ceiling beam (lounge)	106	08	----	----	----
LBS-A21	West central ceiling beam (lounge)	104	17	----	----	----
LBS-A22	West ceiling beam (lounge)	63	--	----	----	----
LBS-A23	First-floor ceiling beam	74	h/s	----	----	----

LBS-A24	Ceiling beam (bedroom)	70	--	----	----	----
LBS-A25	North principal rafter, truss 1	45	18	----	----	----
LBS-A26	South principal rafter, truss 1	53	16	----	----	----
LBS-A27	North principal rafter, truss 2	61	18C	----	----	----
LBS-A28	North principal rafter, truss 3	48	17C	----	----	----
LBS-A29	South principal rafter, truss 3	49	13	----	----	----
LBS-A30	North common rafter 8	50	h/s	----	----	----
LBS-A31	North common rafter 13	51	--	----	----	----
LBS-A32	South common rafter 18	74	23C	1508	1558	1581
LBS-A33	South common rafter 11	57	h/s	1501	1557	1557

*NM = not measured

**h/s = the heartwood/sapwood boundary is the last ring on the sample; C = complete sapwood retained on sample

Table 2: Results of the cross-matching of site sequence LBSASQ01 and relevant reference chronologies when the first-ring date is AD 1401 and the last-measured ring date is AD 1575

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Low Harperley Farmhouse, Wolsingham, County Durham	11.4	AD 1356–1604	Arnold *et al* 2006a
Aydon Castle (kitchen), Corbridge, Northumberland	11.3	AD 1424–1543	Hillam and Groves 1991
1–2 The College, Cathedral Precinct, Durham	10.3	AD 1364–1531	Howard *et al* 1992
Aydon Castle (latrine block), Corbridge, Northumberland	9.5	AD 1406–1545	Arnold *et al* 2002
White Hart Yard, Newcastle upon Tyne, Tyne and Wear	9.4	AD 1391–1529	Arnold *et al* 2005
Blanchland Abbey Gatehouse, Northumberland	9.2	AD 1326–1532	Arnold and Howard 2009
Middridge Grange, Heighington, County Durham	9.0	AD 1427–1516	Arnold *et al* 2006b

Table 3: Results of the cross-matching of site sequence LBSASQ04 and relevant reference chronologies when the first-ring date is AD 1401 and the last-measured ring date is AD 1581

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Dilston Castle, Corbridge, Northumberland	7.7	AD 1402–1611	Arnold *et al* 2003
Middridge Grange, Heighington, County Durham	6.7	AD 1470–1578	Arnold *et al* 2006b
Hallgarth Manor Cottages, Pittington, County Durham	5.9	AD 1336–1624	Howard *et al* 2001
Fell Close, Healeyfield, Conset, County Durham	5.8	AD 1496–1651	Arnold *et al* 2004
Unthank Hall, Holmesfield, Derbyshire	5.3	AD 1359–1589	Howard *et al* 1993
Low Harperley Farmhouse, Wolsingham, County Durham	5.2	AD 1356–1604	Arnold *et al* 2006a
Crowtrees, Ripley, Derbyshire	5.2	AD 1504–1616	Howard *et al* 1997

FIGURES

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

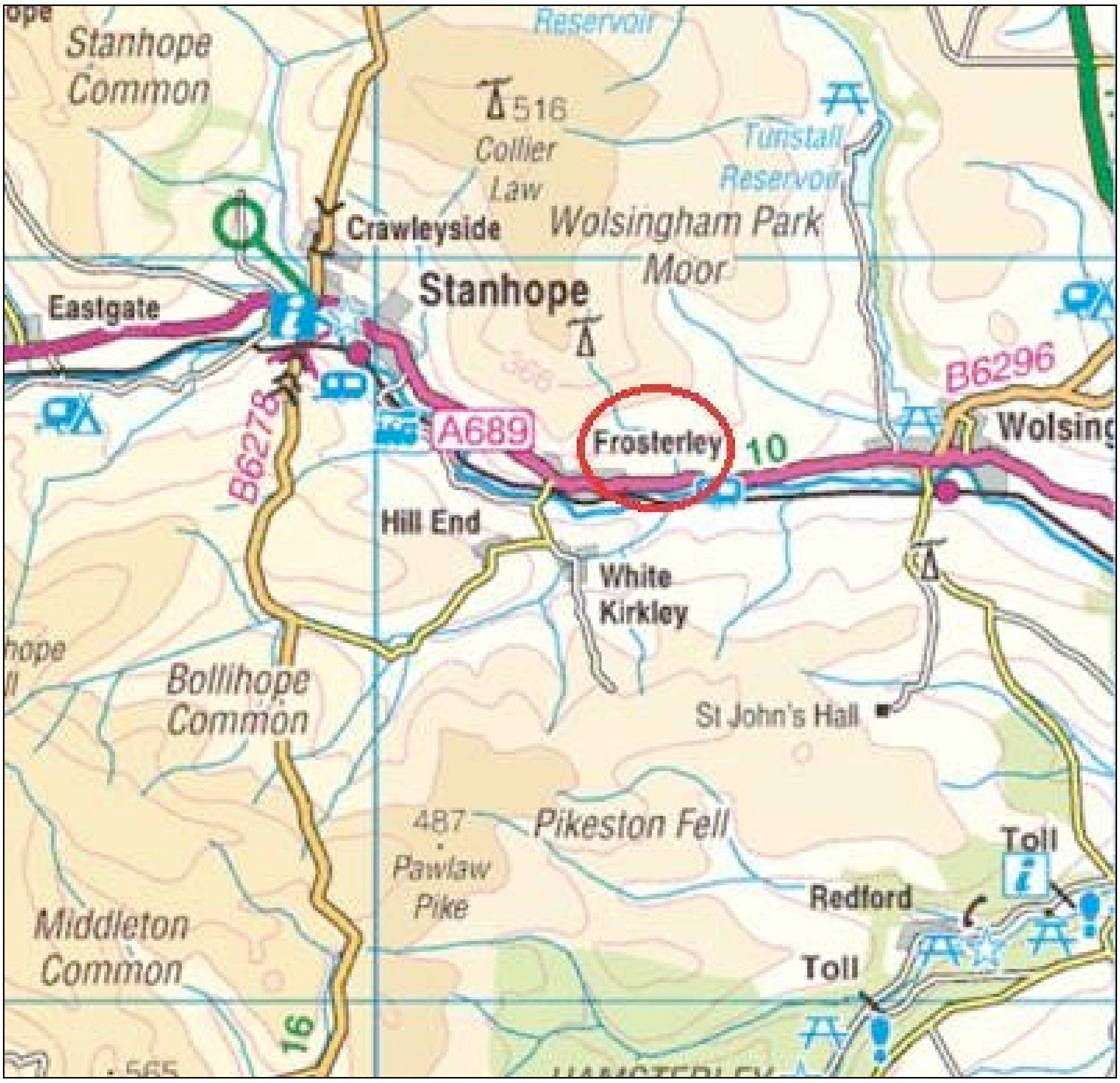


Figure 2: Map to show the location of Frosterley, circled, (based on the Ordnance Survey Map, with the permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 3: Map to show the location of Low Bishopley Farmhouse, arrowed (map reproduced with the permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)

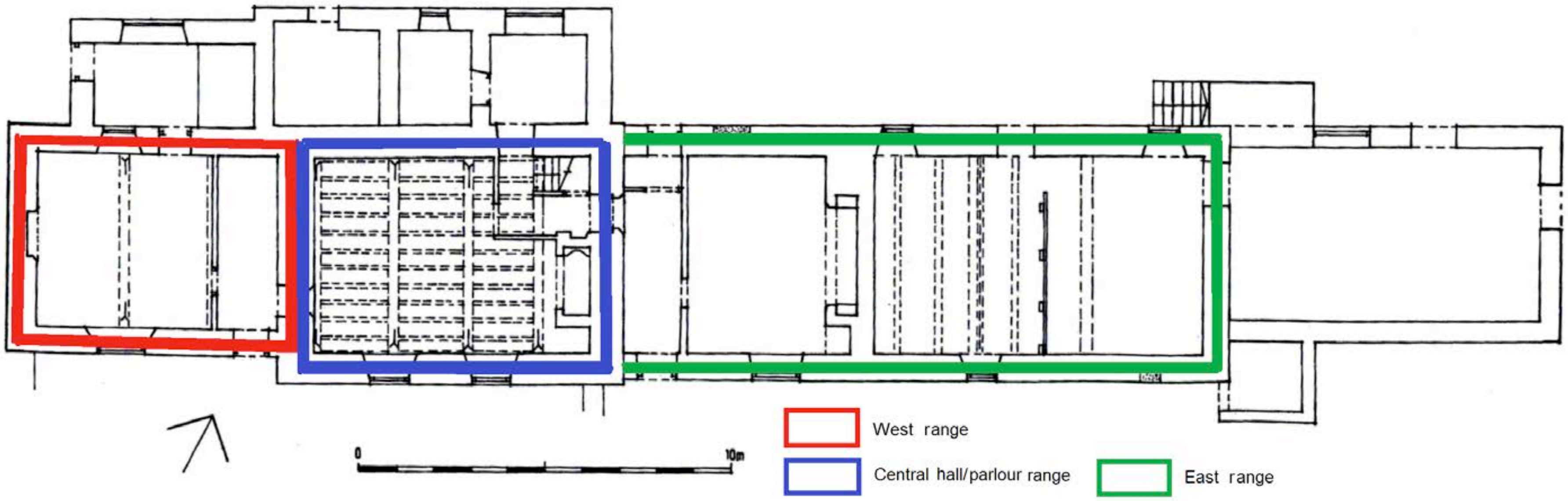


Figure 4: Ground-floor plan (Martin Roberts)

Figure 5: Central hall/parlour range; ceiling (photograph taken from the east)

Figure 6: Central hall/parlour range; roof (photograph taken at truss 1, looking south-west)

Figure 7: East range; roof (truss 2, photograph taken from the north-east)

Figure 8: East range; ceiling beams (photograph taken from the north)

Figure 9: West range; ceiling (photograph taken from the east)

Figure 10: West range; roof (truss 1, photograph taken from the south-west)

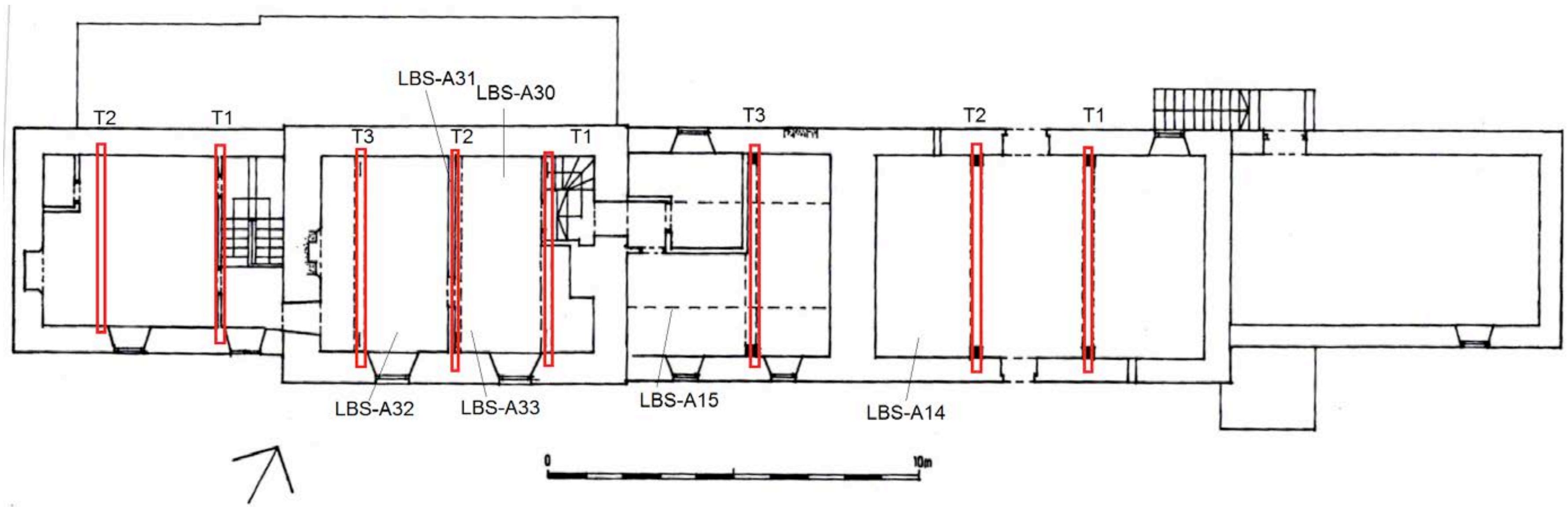


Figure 11: First-floor plan, showing the approximate position of sampled trusses and location of samples LBS-A14–15 and LBS-A30–33 (Martin Roberts)

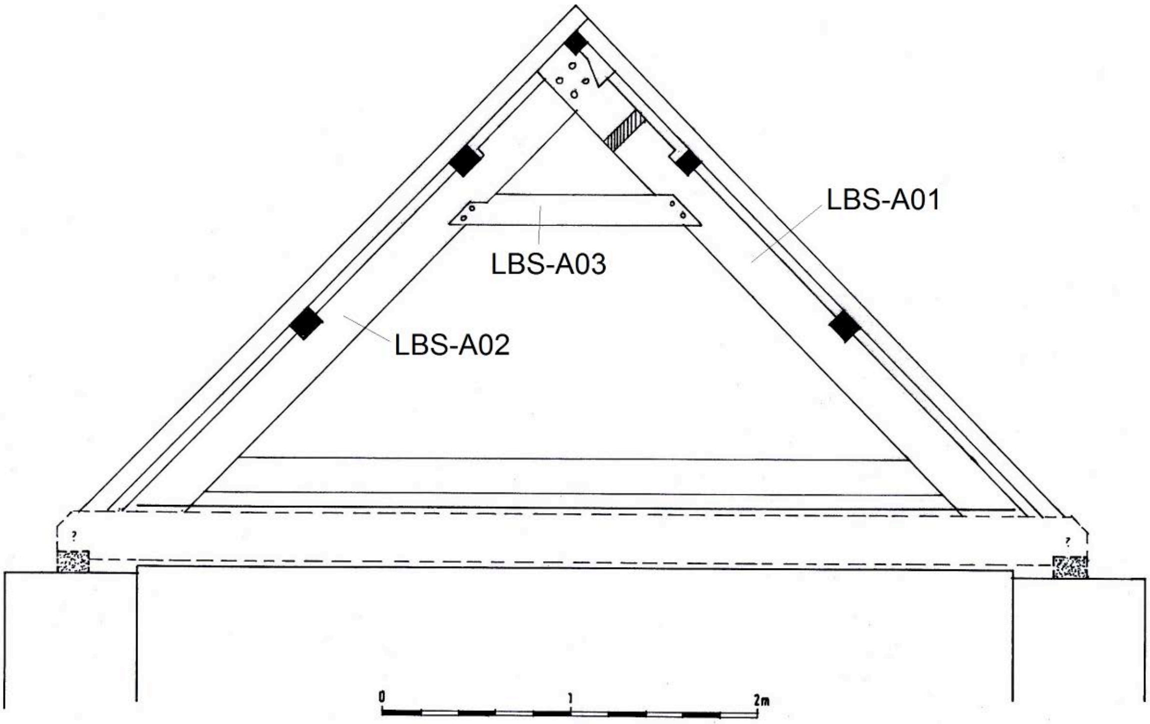


Figure 12: West range; truss 1 (east face), showing the location of samples LBS-A01–03 (Martin Roberts)

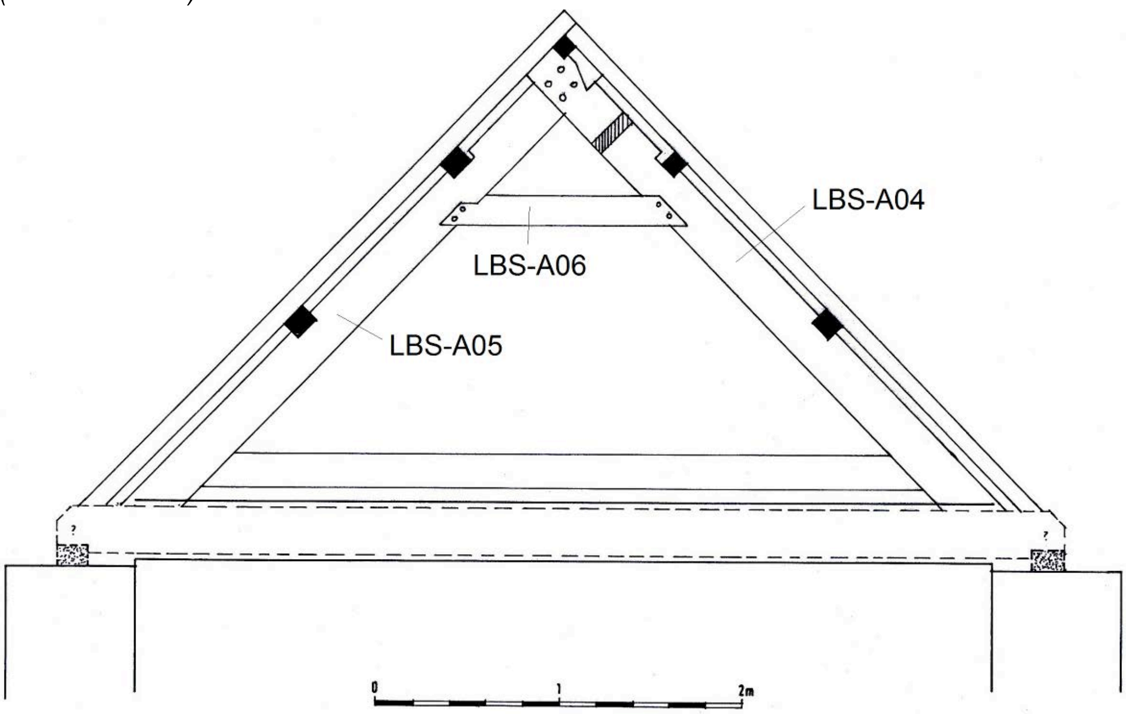


Figure 13: West range; truss 2 (east face), showing the location of samples LBS-A04-06 (Martin Roberts)

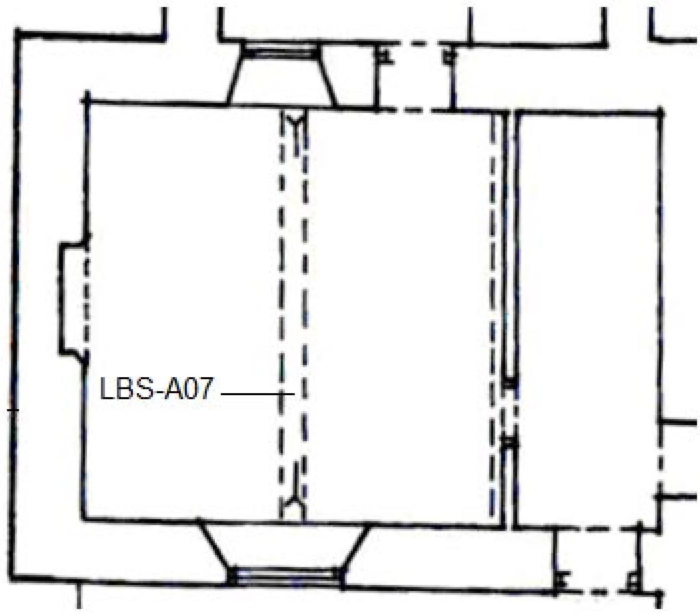


Figure 14: West range; showing the location of sample LBS-A07 (Martin Roberts)

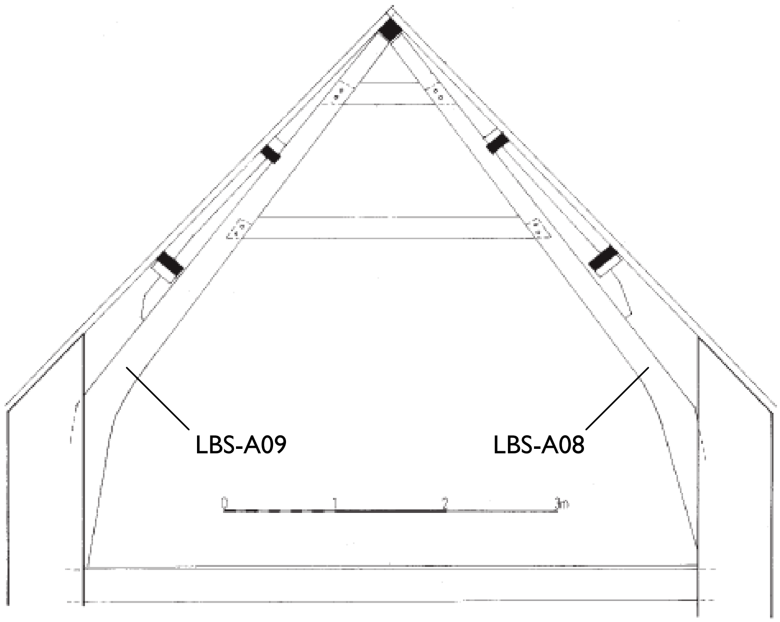


Figure 15: East range; truss 1 (east face), showing the location of samples LBS-A08–09 (Martin Roberts)

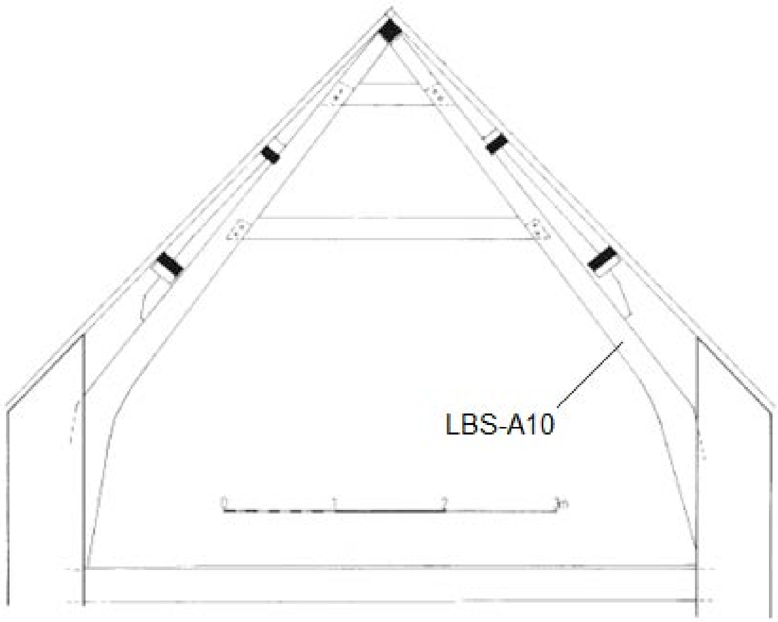


Figure 16: East range; truss 2 (east face), showing the location of sample LBS-A10 (Martin Roberts)

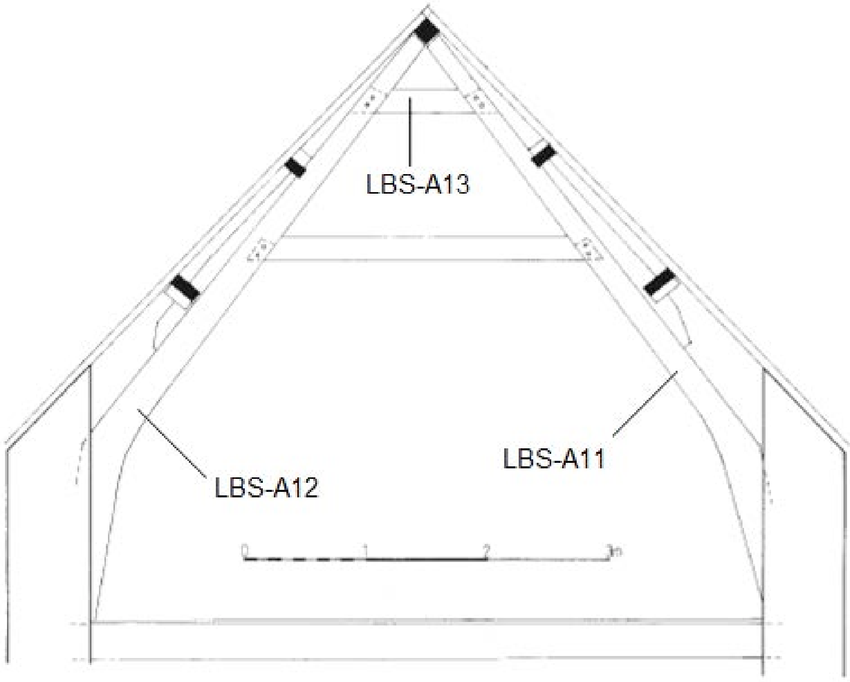


Figure 17: East range; truss 3 (east face), showing the location of samples LBS-A11–13 (Martin Roberts)

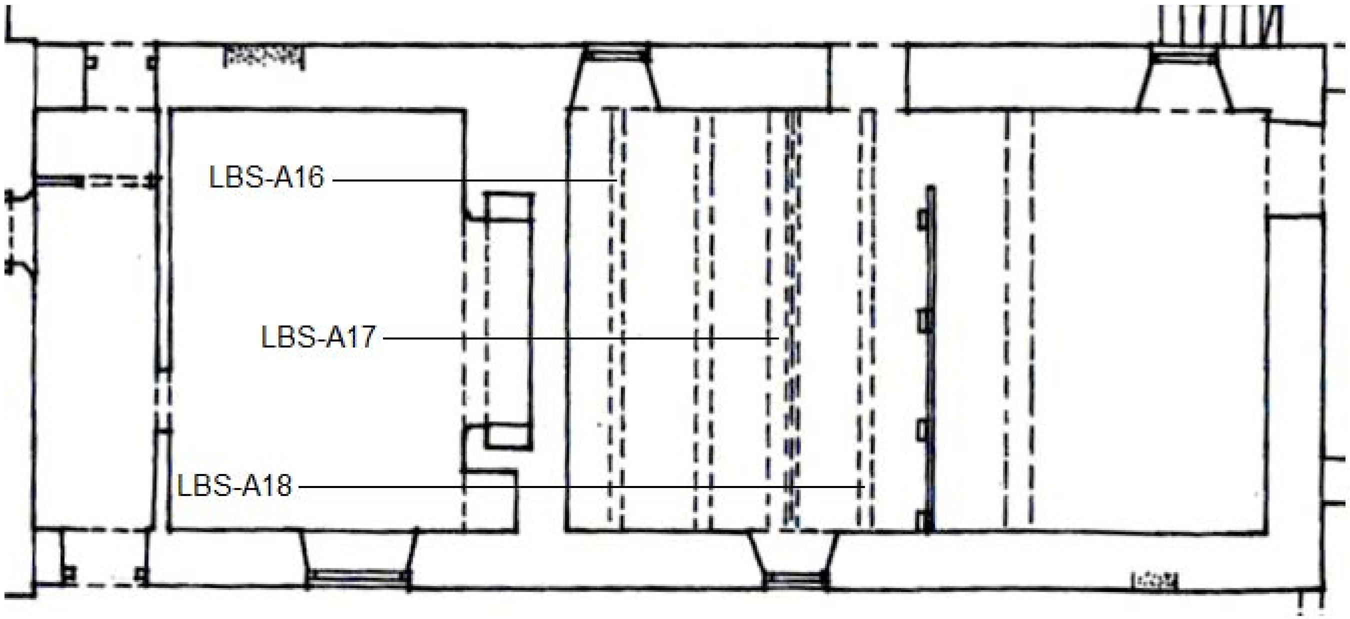


Figure 18: East range, showing the location of samples LBS-A16–8 (Martin Roberts)

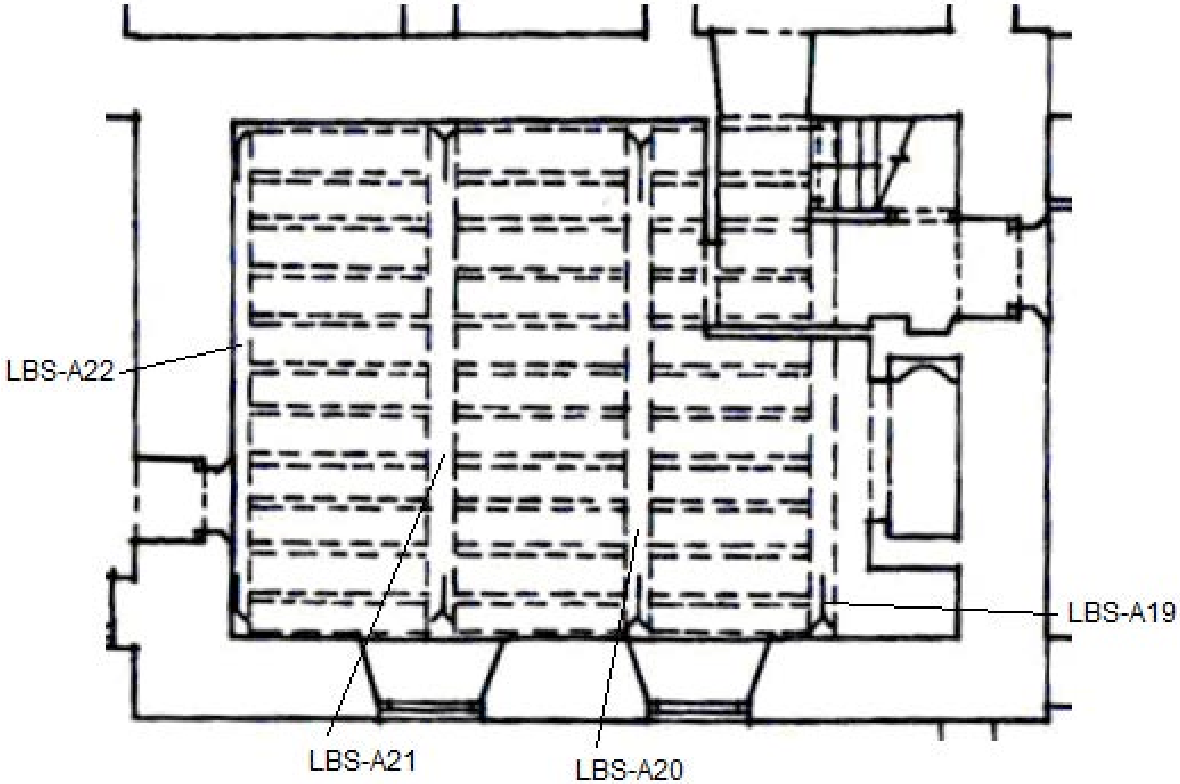


Figure 20: Central hall/parlour range; showing the location of samples LBS-A19-22 (Martin Roberts)

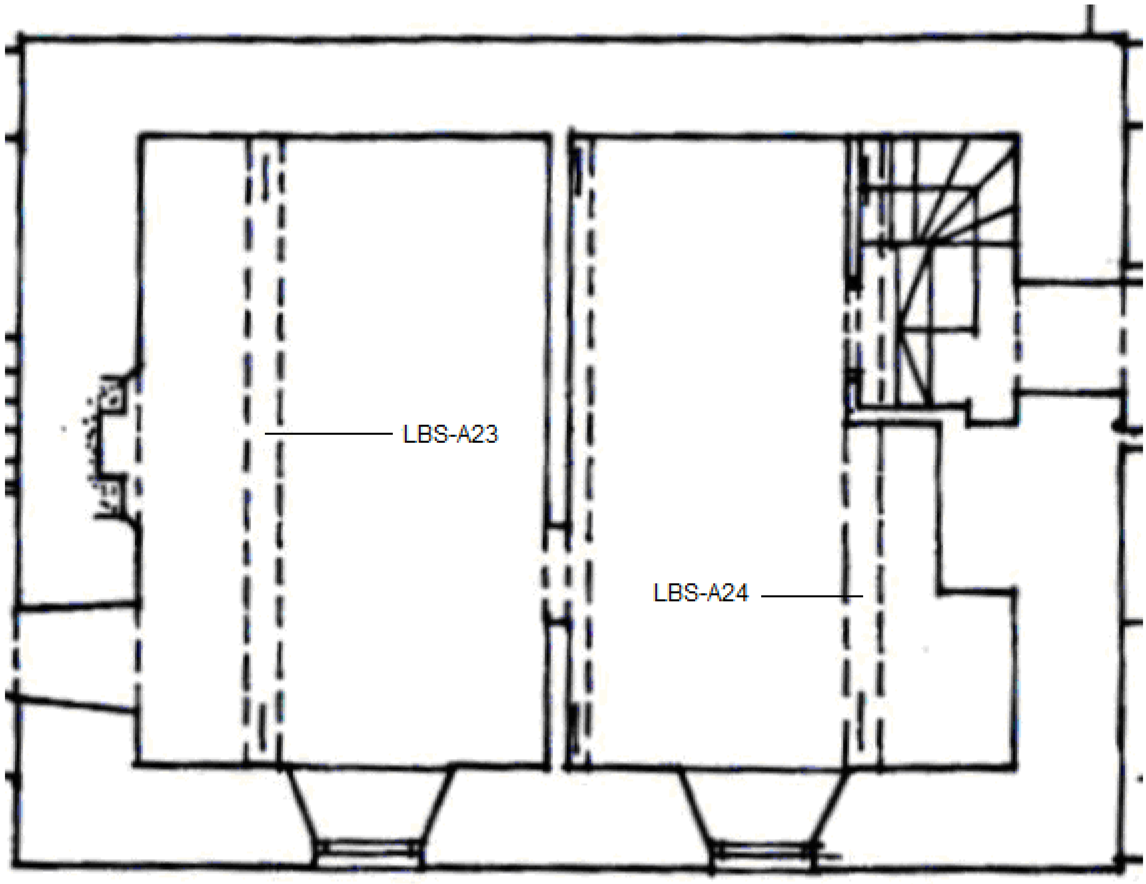


Figure 21: Central hall/parlour range; showing the location of samples LBS-A23 and LBS-A24 (Martin Roberts)

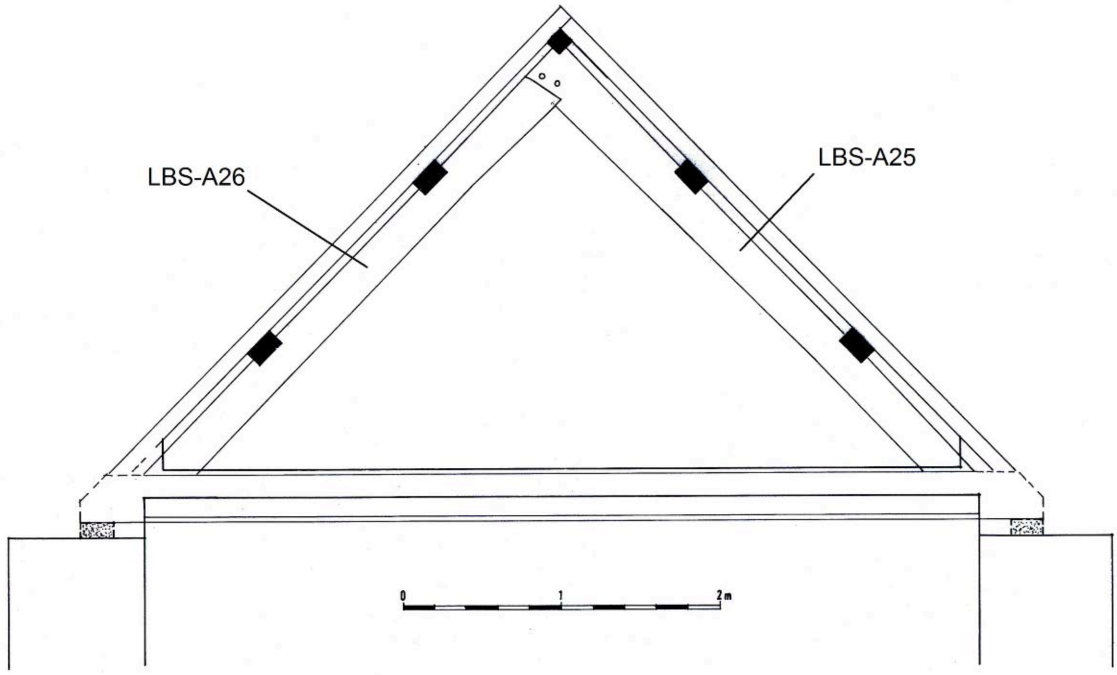


Figure 22: Central hall/parlour range; truss 1 (east face), showing the location of samples LBS-A25 and LBS-A26 (Martin Roberts)

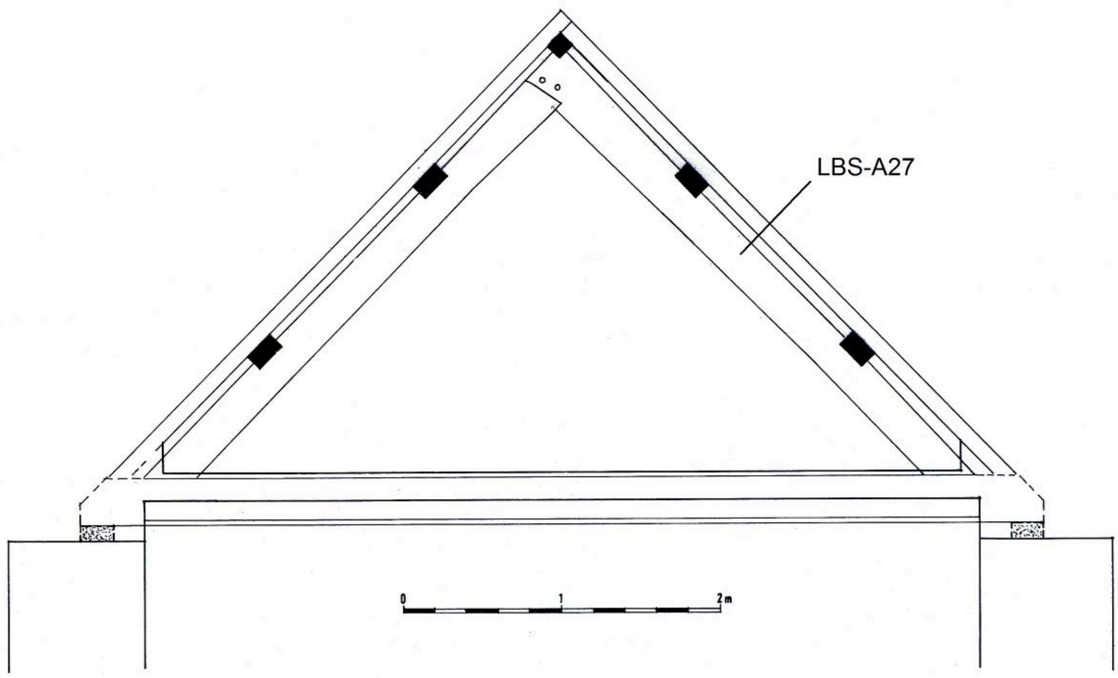


Figure 23: Central hall/parlour range; truss 2 (east face), showing the location of sample LBS-A27 (Martin Roberts)

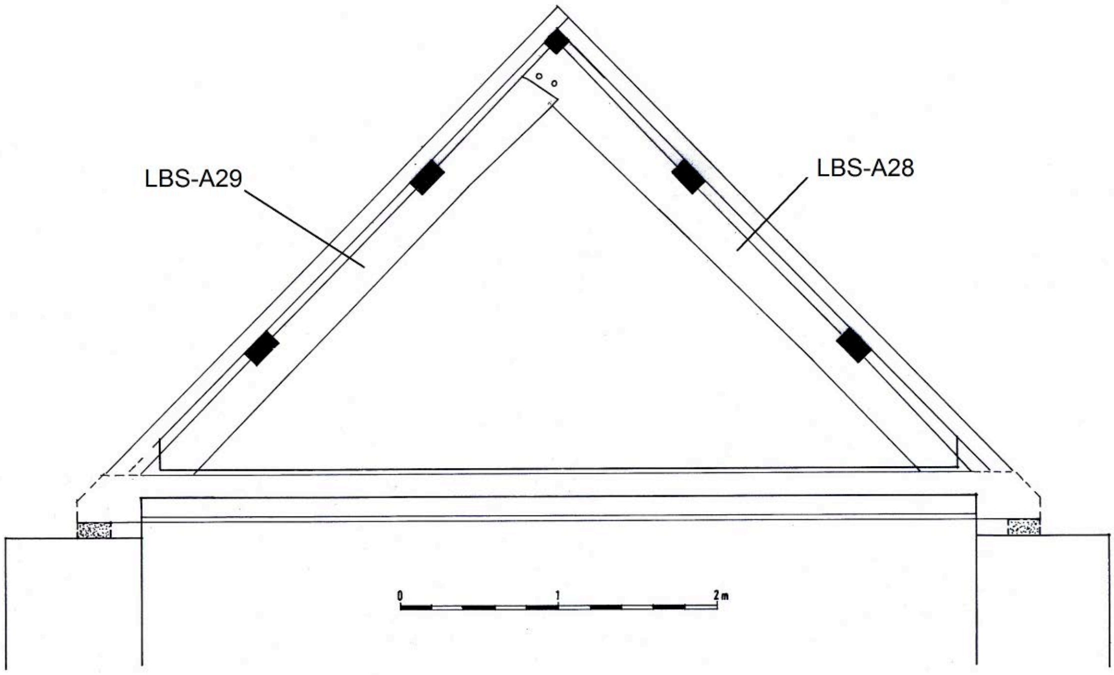


Figure 24: Central hall/parlour range; truss 3 (east face), showing the location of samples LBS-A28 and LBS-A29 (Martin Roberts)

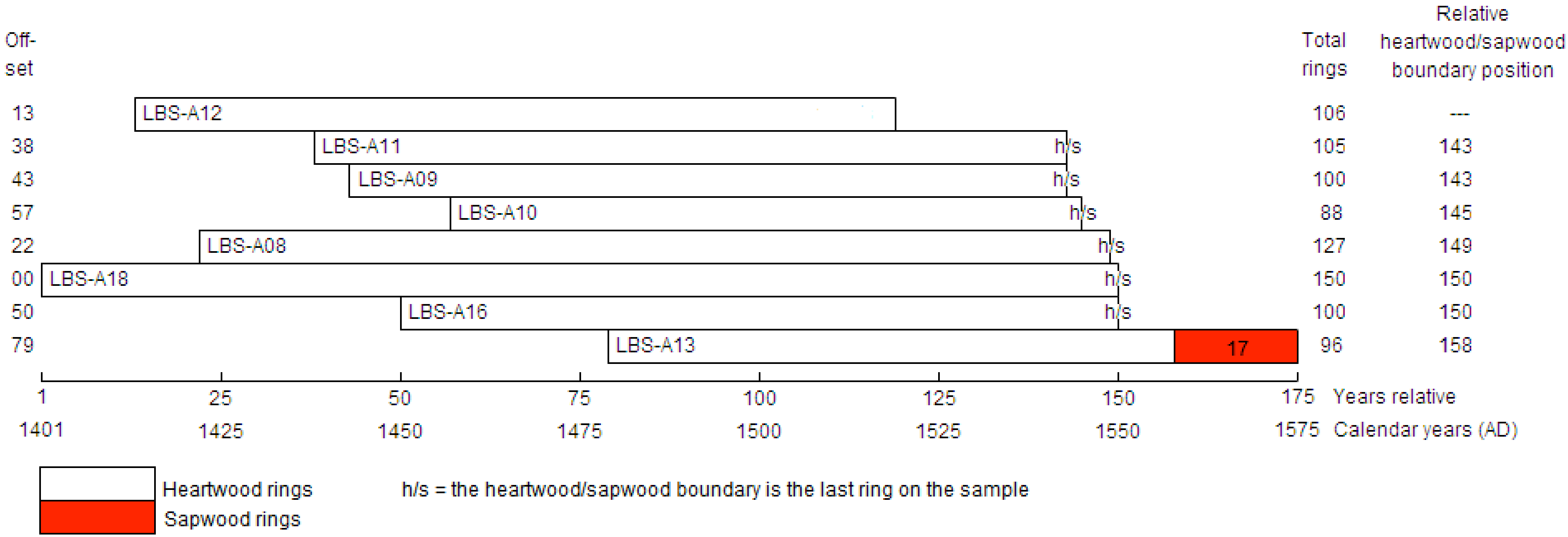


Figure 25: Bar diagram of samples in site sequence LBSASQ01

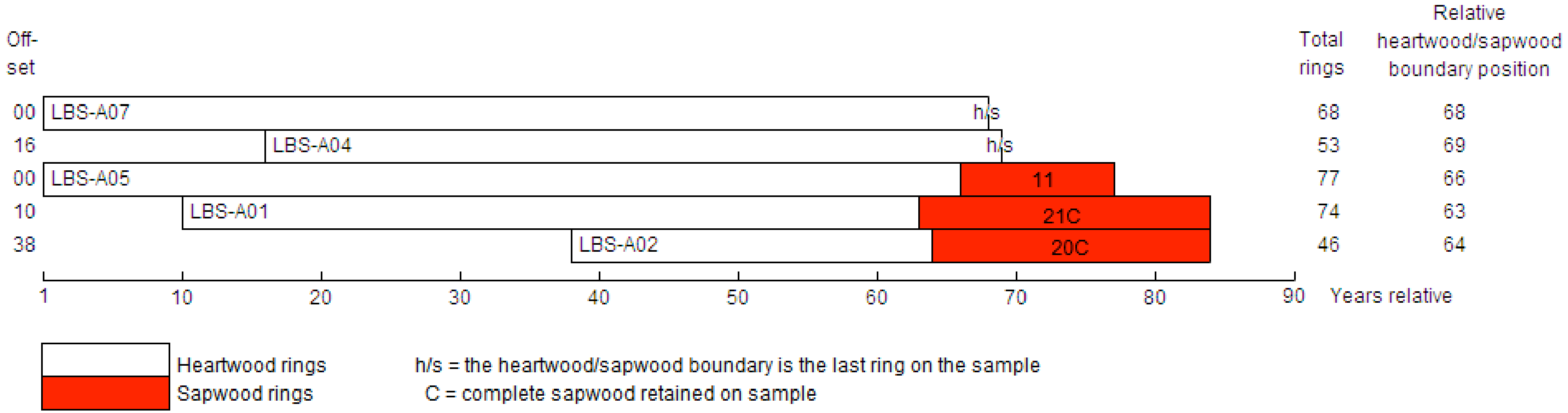


Figure 26: Bar diagram of samples in undated site sequence LBSASQ02

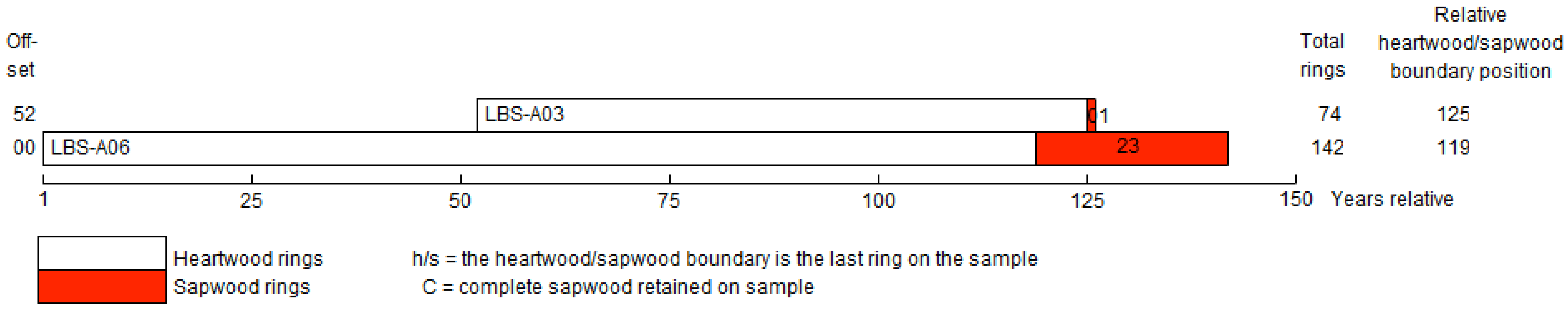


Figure 27: Bar diagram of samples in undated site sequence LBSASQ03

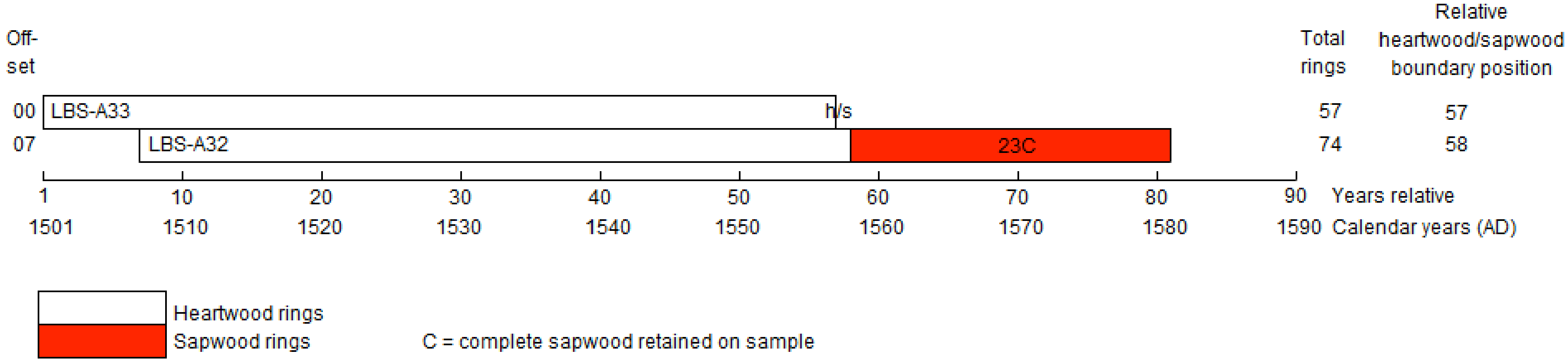


Figure 28: Bar diagram of samples in site sequence LBSASQ04

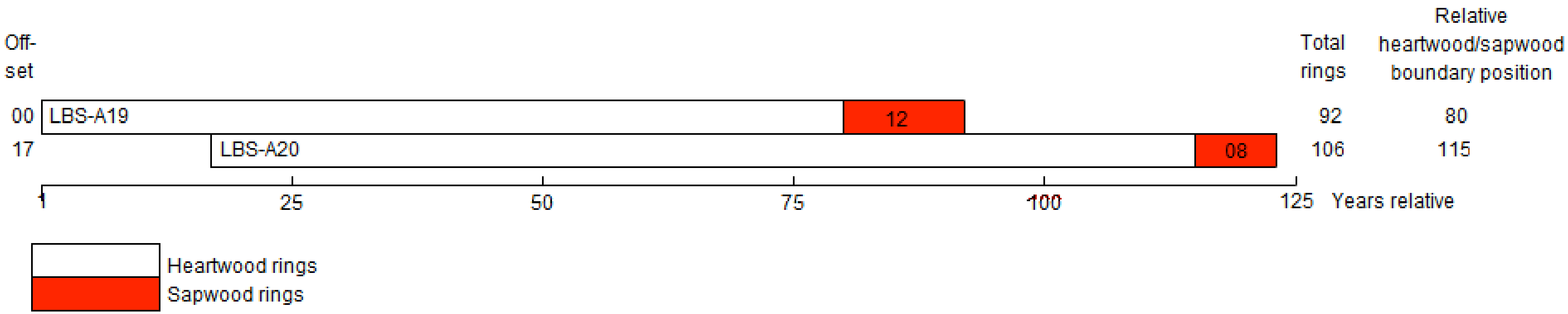


Figure 29: Bar diagram of samples in undated site sequence LBSASQ05

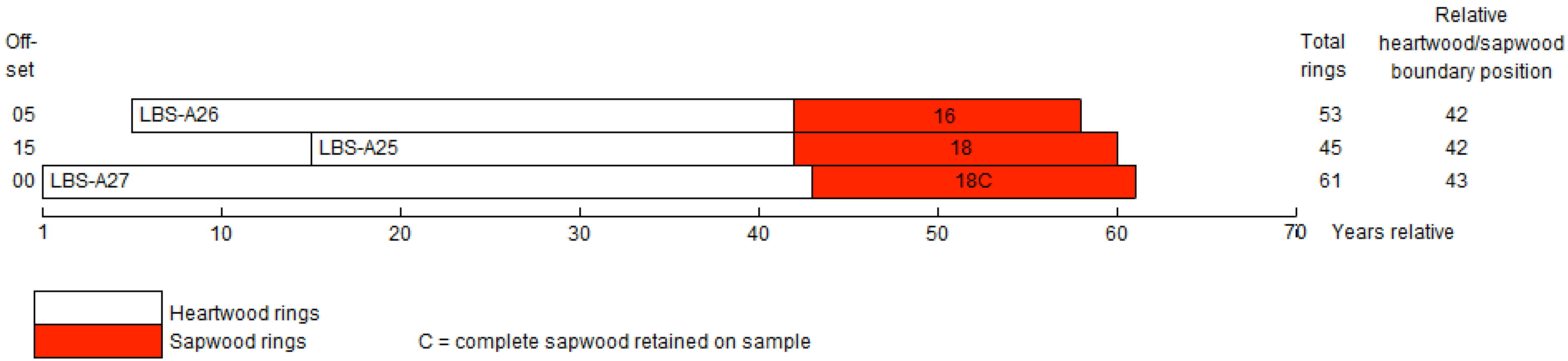


Figure 30: Bar diagram of samples in undated site sequence LBSASQ06

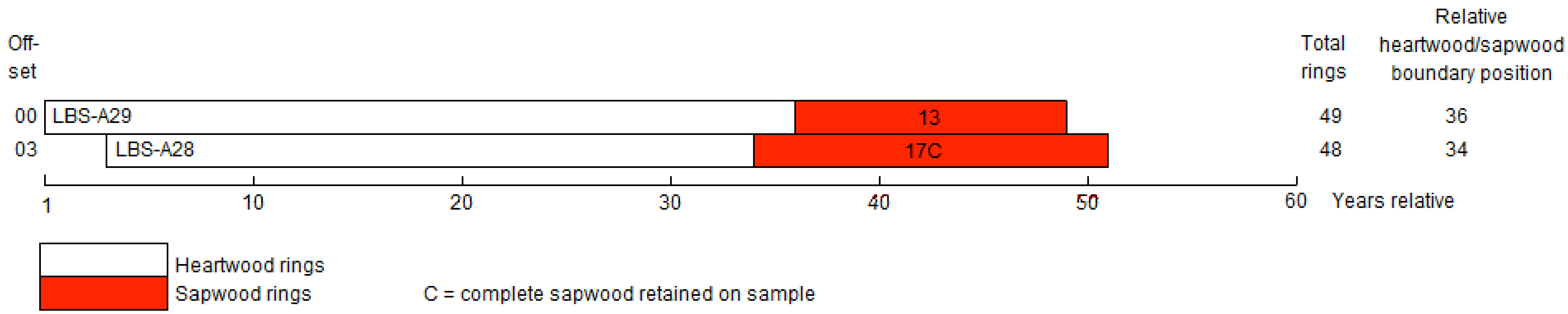


Figure 31: Bar diagram of samples in undated site sequence LBSASQ07

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LBS-A01A 74
333 273 254 243 228 235 203 247 277 273 278 286 226 247 195 184 218 225 204 256
270 256 275 187 183 166 180 185 171 160 41 32 31 34 36 34 39 23 28 41
46 54 84 76 88 131 139 153 163 137 144 187 195 179 54 81 85 129 124 50
69 107 128 153 141 118 170 145 151 171 175 145 235 162
LBS-A01B 74
330 304 247 229 235 239 200 225 282 286 276 277 233 247 206 184 221 234 220 255
277 246 270 189 199 168 179 185 162 166 47 28 32 32 33 33 40 31 28 38
36 61 79 71 92 130 149 146 174 133 150 184 201 173 67 71 83 126 123 53
82 99 116 151 130 106 193 136 155 166 175 149 233 165
LBS-A02A 46
164 169 99 54 59 67 48 84 65 49 45 62 67 97 148 104 110 173 98 134
128 119 181 160 165 133 63 75 78 102 121 88 170 176 222 271 209 194 264 220
241 211 200 176 172 200
LBS-A02B 46
165 171 103 48 62 67 46 86 60 47 47 62 77 97 144 101 115 168 93 135
121 122 174 168 159 126 76 69 76 101 116 92 170 161 190 282 195 202 281 223
243 203 193 154 180 195
LBS-A03A 74
229 156 208 239 222 152 108 216 211 290 272 134 166 144 118 138 207 239 241 153
211 195 162 202 189 180 250 164 128 115 127 204 125 145 124 114 139 153 142 151
145 141 157 113 103 127 147 142 118 102 119 104 141 99 96 92 86 82 76 86
85 105 95 95 100 99 85 75 95 96 91 105 100 88
LBS-A03B 74
227 160 201 238 224 154 105 216 211 294 275 130 161 146 118 140 207 239 246 149
212 192 162 203 191 180 251 170 126 119 128 199 125 143 122 121 137 143 143 153
143 143 155 113 112 156 145 137 124 96 115 103 137 98 107 79 95 76 75 87
89 106 94 91 103 95 83 79 97 91 99 102 106 106
LBS-A04A 53
208 346 196 249 317 307 299 276 414 298 313 311 268 405 322 425 359 273 310 280
284 244 251 213 38 47 34 40 35 57 66 61 57 77 70 111 167 228 213 304
236 266 310 284 353 397 362 323 83 92 88 129 191
LBS-A04B 53
228 288 228 251 305 311 324 259 401 289 333 316 278 401 320 434 358 267 311 281
273 248 239 205 42 43 34 38 32 58 69 55 60 80 75 109 171 219 221 293
235 264 309 285 358 396 378 339 85 90 84 140 147
LBS-A05A 77
256 264 277 227 202 234 200 275 283 244 264 261 238 205 207 234 183 230 274 269
309 303 297 309 213 193 252 282 242 327 291 352 344 230 238 192 204 185 188 192
70 51 55 58 61 72 70 51 51 74 61 91 124 145 144 161 153 172 195 166
176 225 246 231 74 67 65 109 99 103 167 192 172 162 156 142 221
LBS-A05B 77
286 280 273 224 188 227 204 273 282 251 268 261 232 207 207 237 181 230 275 274
309 303 296 310 209 197 257 284 237 350 300 351 344 224 239 201 199 188 179 183
64 48 60 54 64 71 68 54 49 71 63 89 138 136 140 162 153 176 192 167
177 226 247 228 76 66 65 106 112 98 162 193 163 165 153 182 195
LBS-A06A 142
22 18 23 21 45 43 53 73 78 66 83 68 73 71 69 78 74 79 56 57

62 34 38 31 40 29 27 19 20 16 25 24 38 57 53 55 48 44 87 70
53 58 50 37 20 32 45 140 152 175 146 145 142 130 134 170 176 133 106 129
135 147 181 85 89 76 85 107 115 186 153 124 164 111 91 117 107 89 76 112
113 95 133 109 93 110 106 107 122 133 174 129 118 114 134 102 75 91 78 67
71 56 74 60 81 82 69 67 59 49 61 51 44 73 58 55 74 58 53 57
66 60 58 62 56 67 70 74 75 78 84 78 82 64 111 96 80 87 75 86
72 66
LBS-A06B 142
24 16 21 21 51 37 53 72 77 68 76 65 75 70 71 77 78 82 54 58
54 38 41 27 38 31 25 17 19 18 24 26 37 53 45 56 51 49 84 71
59 58 47 36 19 31 45 144 153 170 147 139 146 122 135 171 151 132 101 135
133 147 179 84 91 75 86 102 125 195 152 126 134 106 91 106 107 83 84 96
107 105 121 126 93 112 107 111 126 139 142 126 117 135 124 89 73 80 74 63
63 59 71 61 87 73 72 68 50 53 56 50 47 66 57 60 74 59 58 56
73 66 57 59 83 62 68 76 73 78 74 84 77 84 98 101 79 90 84 94
85 88
LBS-A07A 68
136 170 180 195 194 224 207 180 247 179 192 263 168 185 169 194 229 231 244 199
159 189 163 141 153 199 182 284 221 226 217 217 212 161 228 320 387 318 399 383
159 169 130 161 189 309 377 326 239 239 170 225 251 174 144 142 150 175 185 144
164 162 152 162 178 165 260 287
LBS-A07B 68
146 176 190 185 200 226 207 174 244 180 201 260 171 183 167 196 230 227 261 180
155 189 167 150 168 183 183 279 232 218 209 222 190 161 222 337 394 329 395 378
157 189 130 157 191 301 377 324 223 265 165 219 247 179 145 149 143 170 188 140
170 158 147 160 164 165 267 276
LBS-A08A 127
407 418 399 229 306 267 326 334 332 331 312 428 377 426 299 264 267 300 306 281
296 344 266 197 250 277 296 268 251 347 250 316 253 361 299 249 215 235 274 222
242 273 271 289 357 302 203 246 300 227 208 202 237 265 234 204 239 199 217 210
185 219 226 205 185 168 141 148 163 152 76 90 133 191 177 149 199 163 101 92
145 223 241 206 142 128 179 179 192 180 140 144 131 150 127 153 190 181 188 123
75 68 105 135 124 143 161 119 103 81 64 99 108 129 135 145 148 211 183 144
178 157 165 119 155 109 72
LBS-A08B 127
362 409 419 208 300 278 323 328 335 328 310 438 375 415 313 277 254 291 356 266
296 345 269 198 262 271 304 262 248 347 257 318 247 348 307 255 240 230 262 230
236 289 274 295 371 282 212 251 308 226 219 185 248 260 241 207 239 178 231 206
201 225 218 201 196 163 151 152 166 158 63 103 137 184 177 153 197 162 96 107
135 231 230 198 163 143 180 184 192 161 152 152 138 162 126 153 196 179 166 150
72 82 103 127 130 156 165 97 103 73 79 90 129 151 133 132 141 236 188 131
156 175 167 146 147 124 66
LBS-A09A 100
321 313 258 287 213 270 260 248 335 222 243 175 253 198 157 176 164 135 159 155
196 138 167 233 200 137 194 193 175 148 160 198 227 245 216 252 188 207 194 161
163 197 232 361 247 238 257 299 239 139 138 140 178 159 157 201 232 133 164 162
188 178 204 122 121 156 179 164 185 160 144 150 148 156 160 183 160 159 193 133
164 106 118 110 133 123 106 104 91 107 115 137 149 146 198 192 269 257 175 247
LBS-A09B 100
301 303 233 297 214 240 260 253 332 237 261 175 236 197 158 171 168 140 156 169
192 145 172 223 205 154 199 189 168 156 165 194 236 252 208 252 188 187 185 164
173 202 220 360 255 219 261 293 234 133 138 141 190 160 168 198 221 142 167 154
182 181 204 131 120 159 183 162 189 159 150 148 154 154 153 194 151 158 202 129

161 112 122 102 130 127 101 106 90 108 119 135 143 151 189 192 272 250 175 259
LBS-A10A 88
351 326 382 319 325 439 409 301 322 439 371 320 253 348 260 227 116 176 266 271
216 481 297 296 441 313 309 298 330 510 266 206 221 130 93 108 155 223 435 257
203 266 178 171 211 161 253 242 161 149 165 260 251 264 159 164 200 224 242 159
260 352 278 315 185 88 153 224 214 220 174 194 150 230 135 156 215 246 406 256
222 383 501 279 175 141 149 72
LBS-A10B 88
357 326 394 346 336 414 400 304 329 443 375 324 254 346 267 228 104 190 277 257
220 479 303 289 447 285 322 298 324 513 295 213 210 127 94 110 147 230 428 267
202 265 187 165 209 164 267 233 155 151 165 261 241 269 166 165 191 219 231 159
260 367 277 309 184 96 162 218 220 228 178 189 145 244 129 154 214 241 407 251
226 379 505 294 192 142 146 93
LBS-A11A 105
265 303 385 327 303 386 330 266 258 262 289 250 263 381 304 335 189 273 238 179
164 172 176 201 229 245 232 250 328 311 171 205 298 213 196 166 265 354 281 262
327 271 235 235 290 295 262 264 371 353 313 330 297 280 200 223 296 351 269 225
243 258 165 201 191 218 284 214 214 329 388 270 247 268 217 206 220 194 189 211
215 186 230 216 124 195 238 201 189 178 177 162 136 124 139 146 165 167 176 168
258 257 184 148 164
LBS-A11B 105
312 320 377 336 317 375 330 261 273 246 317 248 256 385 315 325 185 243 255 175
160 173 198 200 214 244 214 260 302 286 175 186 272 217 188 175 250 349 288 257
318 271 246 222 301 292 260 273 361 347 307 330 293 274 198 231 290 354 267 220
255 250 150 199 186 238 272 215 227 364 377 273 250 268 229 191 222 185 190 217
215 187 258 182 126 203 240 202 190 180 170 178 127 139 128 166 173 174 144 170
241 254 178 151 163
LBS-A12A 106
249 290 231 302 346 267 375 418 443 497 475 503 214 238 293 380 360 330 380 383
478 446 358 394 328 290 356 380 388 303 346 282 224 306 264 323 274 238 317 216
202 173 262 218 187 159 157 178 154 164 196 149 180 217 187 100 138 188 128 119
116 143 179 161 177 171 184 184 159 157 148 139 128 187 144 150 160 138 106 81
84 152 228 173 171 181 186 102 95 125 193 233 181 144 183 187 172 190 179 150
130 121 189 109 173 200
LBS-A12B 106
267 292 223 308 348 267 383 412 456 493 480 499 224 235 302 365 358 334 389 380
473 452 365 411 343 301 366 396 361 308 349 293 210 312 261 318 275 238 318 209
207 173 258 219 185 158 160 174 156 169 190 150 187 202 192 114 133 181 137 114
117 146 173 173 158 181 177 194 150 154 132 139 125 188 156 156 156 136 113 77
82 150 222 160 178 178 186 103 88 134 189 228 180 150 174 190 168 205 161 133
137 132 152 111 184 205
LBS-A13A 96
204 178 181 196 192 192 175 278 236 224 261 211 213 102 142 176 218 198 175 196
191 111 123 145 214 169 191 139 151 152 178 191 156 126 124 125 136 138 158 188
153 154 138 66 116 100 138 118 114 134 88 103 75 86 112 122 139 141 110 132
166 132 125 148 162 168 135 148 54 46 36 59 60 41 29 49 43 46 40 48
46 53 63 63 48 56 47 35 45 61 98 105 127 114 126 87
LBS-A13B 96
277 199 186 187 193 185 178 258 220 226 290 216 225 102 142 182 238 190 162 229
184 107 114 138 210 201 187 142 140 163 182 189 155 116 131 124 142 129 155 179
168 151 138 70 120 106 139 125 116 135 91 107 75 86 112 116 125 139 108 138
168 134 125 159 163 172 137 151 52 48 46 59 59 40 33 53 42 47 42 44
45 55 63 59 60 49 49 27 53 57 93 105 123 119 121 100

LBS-A15A 83
223 255 195 266 200 205 156 144 166 132 141 178 139 181 180 138 114 136 165 132
140 106 158 152 138 187 168 182 157 144 124 124 129 110 136 117 141 111 111 133
146 139 140 160 156 152 123 119 150 138 122 115 120 153 113 136 126 149 172 152
125 137 158 135 148 111 137 119 136 176 115 107 97 144 119 148 136 143 128 160
160 155 174
LBS-A15B 83
208 267 175 269 210 207 148 129 193 153 136 173 140 197 185 164 124 148 171 123
141 120 161 168 135 194 170 185 161 141 128 132 134 107 137 113 143 103 111 128
145 143 141 159 152 146 115 116 146 136 126 116 122 148 125 146 130 146 173 151
123 145 162 144 135 115 137 129 131 160 132 106 103 136 124 142 132 146 124 166
144 165 194
LBS-A16A 100
333 459 271 316 210 334 264 268 273 297 302 279 289 378 253 287 330 260 400 395
341 308 305 218 226 260 335 253 294 253 263 409 405 335 274 325 420 230 243 239
251 275 203 220 316 301 220 218 238 300 201 300 215 261 253 296 245 298 250 262
204 173 187 166 194 197 168 224 206 179 156 135 151 182 151 176 186 173 142 157
133 63 110 131 143 120 121 108 140 223 158 110 119 136 135 134 103 133 108 140
LBS-A16B 100
374 472 254 312 210 347 250 262 269 297 294 272 331 373 262 270 335 258 403 396
336 307 292 210 216 260 328 251 257 248 272 392 407 332 277 302 402 202 244 240
242 278 185 231 319 310 204 219 240 297 202 307 175 254 264 286 233 296 262 245
212 184 185 163 193 217 162 212 205 178 162 151 161 181 155 177 186 179 151 149
128 74 104 130 146 132 101 120 142 211 174 91 118 141 131 134 100 139 109 137
LBS-A17A 79
361 293 336 309 303 223 220 181 209 150 153 162 205 173 181 265 250 142 53 103
169 177 156 189 238 214 156 79 110 132 129 139 133 103 178 202 133 168 176 178
175 151 151 143 125 202 238 190 157 123 154 153 153 140 181 186 250 200 210 178
124 156 125 141 202 215 199 162 297 279 186 143 180 207 208 250 184 157 172
LBS-A17B 79
358 298 335 317 298 225 220 186 220 143 149 165 213 175 182 252 261 142 60 93
173 173 153 189 245 211 157 78 110 129 132 136 136 102 181 196 136 162 175 190
172 147 147 145 126 206 234 190 156 129 156 153 150 133 184 175 253 197 206 182
142 160 123 141 203 213 199 161 291 299 182 144 160 201 209 263 189 144 214
LBS-A18A 150
283 228 287 285 260 285 234 274 308 215 218 188 141 156 204 234 243 199 153 191
171 146 172 155 155 111 112 111 148 122 162 174 114 133 148 141 130 114 105 131
138 145 157 167 139 111 176 153 177 148 168 186 141 162 125 164 167 155 134 128
132 118 105 139 118 100 136 135 106 119 137 138 99 102 85 97 156 122 127 102
119 113 163 132 124 122 179 151 122 108 124 91 97 111 124 129 117 95 102 110
100 112 87 137 106 89 122 133 146 139 146 112 99 90 101 84 85 102 85 93
69 67 52 60 94 101 118 91 104 93 77 66 73 68 93 93 76 68 110 101
85 73 97 86 95 96 79 74 77 92
LBS-A18B 150
282 231 284 273 277 270 252 240 314 214 197 169 161 149 207 231 249 203 157 187
182 141 173 154 154 124 119 117 151 125 151 161 127 137 137 134 132 113 113 125
145 136 156 164 139 110 170 164 174 155 149 201 143 163 133 156 173 156 139 122
132 120 107 143 117 102 132 131 100 119 136 142 93 103 86 104 147 118 121 102
121 106 148 132 121 126 176 152 118 112 123 97 91 100 126 128 113 91 105 105
103 112 85 145 109 82 122 140 147 137 147 109 99 93 100 96 79 102 79 90
74 66 51 65 91 102 110 104 101 93 77 63 78 64 92 94 83 60 115 89
92 73 91 88 95 91 83 79 78 93
LBS-A19A 92

299 336 427 350 222 257 203 224 261 196 174 204 223 290 343 257 238 214 196 167
132 180 234 211 206 182 205 201 187 236 251 281 247 194 161 163 239 198 135 145
150 146 125 183 206 205 315 192 187 148 153 187 179 155 173 152 135 256 179 158
152 155 182 168 173 179 179 205 185 250 204 159 172 107 137 196 192 208 171 145
149 135 113 107 120 234 304 175 154 150 162 133
LBS-A19B 92
312 435 373 355 243 257 222 245 250 198 167 202 216 296 344 263 229 219 190 169
133 179 235 213 206 182 215 213 182 240 273 281 250 201 164 183 226 192 129 140
156 144 128 186 207 209 299 182 184 137 151 186 178 152 179 152 140 255 170 155
156 155 181 171 176 173 180 207 181 250 205 164 167 103 141 197 189 199 176 145
157 135 100 114 113 227 304 174 153 140 159 130
LBS-A20A 106
255 257 275 220 286 261 244 253 195 246 231 223 239 264 259 232 260 202 207 250
230 158 157 253 256 213 180 161 190 187 196 225 201 215 277 242 292 284 229 210
267 226 173 152 149 211 155 171 200 244 227 162 222 198 194 242 164 143 159 193
154 110 130 136 188 176 151 169 208 251 162 139 135 125 175 123 137 144 136 114
108 112 147 137 136 114 117 150 142 153 131 153 195 138 98 106 66 111 127 162
111 120 139 112 100 86
LBS-A20B 106
253 260 280 222 290 255 244 251 198 238 232 234 232 268 265 227 265 203 192 246
234 159 154 247 257 217 169 161 192 187 198 218 208 213 249 235 295 294 225 204
274 224 171 152 148 206 156 175 196 242 234 163 217 200 189 245 163 143 158 194
154 113 125 133 190 175 156 170 212 254 162 135 136 128 169 125 136 142 138 115
105 117 142 138 133 114 124 155 140 146 135 157 185 146 99 99 70 108 127 159
108 135 139 102 112 78
LBS-A21A 104
276 280 191 225 262 273 232 265 272 212 233 221 165 189 230 231 264 163 165 203
217 195 256 245 359 274 303 215 228 325 285 253 277 237 266 231 235 272 228 149
93 109 82 60 74 103 98 112 135 142 113 157 139 202 202 183 152 161 152 153
158 89 38 71 55 69 88 92 125 108 99 154 132 144 129 136 151 150 164 146
161 179 152 172 133 97 166 189 158 174 249 181 199 181 163 164 164 138 142 162
163 140 127 139
LBS-A21B 104
273 265 169 217 250 277 241 276 264 213 240 213 167 174 232 233 257 164 164 204
214 197 253 246 362 275 305 211 233 321 265 274 286 235 270 222 239 274 227 156
90 101 88 61 64 111 110 111 136 133 111 156 141 202 198 184 157 157 152 157
163 86 41 63 53 68 100 79 126 106 105 151 131 142 128 137 152 148 161 158
159 182 148 176 141 90 172 183 160 170 254 182 203 193 159 164 166 147 134 154
169 138 132 130
LBS-A22A 63
192 174 168 221 256 236 120 54 113 158 178 253 272 262 266 154 294 194 171 174
148 183 174 160 200 193 136 151 130 206 167 208 136 233 261 266 220 182 255 216
240 230 203 197 210 186 222 118 50 46 49 51 44 70 100 95 86 108 121 46
74 75 87
LBS-A22B 63
169 183 177 211 250 227 102 44 124 151 178 261 294 281 292 175 278 169 170 184
186 176 174 169 202 187 143 154 136 214 171 206 142 231 258 256 210 189 244 224
256 222 201 196 222 188 228 121 65 38 48 50 47 75 86 85 96 96 118 51
78 71 91
LBS-A23A 74
200 284 230 294 226 320 308 337 345 246 286 331 328 273 303 258 288 326 284 305
426 365 288 226 235 277 308 203 204 186 219 258 192 181 261 357 354 333 393 465
286 253 114 142 209 200 250 330 421 417 312 244 261 220 194 144 126 139 230 398

354 175 141 208 225 159 146 218 175 190 228 278 134 189
LBS-A23B 74
187 272 231 280 222 314 291 319 350 241 277 322 326 279 295 266 288 312 290 311
422 343 294 220 238 269 324 201 203 187 242 260 192 182 262 355 359 340 400 463
283 260 112 142 213 216 255 292 420 420 306 248 263 204 163 139 104 150 205 388
340 177 130 214 214 155 155 208 171 196 242 275 140 182
LBS-A24A 70
279 458 556 486 503 391 364 301 257 215 220 179 163 123 101 126 171 134 159 156
170 195 295 290 258 308 336 390 268 245 295 318 328 335 335 391 314 364 293 218
211 212 167 162 181 237 246 187 233 156 229 210 237 143 134 129 151 131 130 131
136 132 127 154 62 85 106 115 111 136
LBS-A24B 70
280 427 531 491 487 373 365 297 255 214 219 198 164 132 100 130 176 130 151 159
172 196 298 279 250 306 336 373 264 245 311 324 337 359 388 369 312 376 271 197
235 214 170 165 173 235 242 193 225 169 216 195 219 141 151 139 148 115 134 148
132 137 130 150 64 82 101 115 110 129
LBS-A25A 45
314 183 260 373 283 360 345 323 372 266 333 303 229 233 249 253 251 302 229 229
217 264 118 68 71 64 86 76 82 87 75 97 102 131 150 85 122 125 144 183
219 242 217 174 226
LBS-A25B 45
304 182 275 355 273 354 339 321 378 264 343 302 228 233 256 242 257 296 248 229
212 267 120 74 63 67 88 69 83 83 78 93 103 131 151 83 125 121 139 186
227 257 216 171 235
LBS-A26A 53
192 185 211 191 208 191 182 194 232 186 224 136 223 218 216 234 200 197 185 192
213 178 163 185 178 170 167 192 192 182 200 215 124 64 45 62 66 64 57 71
59 69 96 88 100 75 92 89 111 162 222 217 209
LBS-A26B 53
200 187 206 177 182 191 183 196 239 184 213 145 218 215 223 236 222 197 190 192
220 181 159 184 177 165 163 208 183 179 186 210 119 69 52 55 63 67 56 68
66 72 97 96 93 75 89 99 107 149 231 221 203
LBS-A27A 61
90 76 99 95 90 160 163 205 209 346 323 310 286 355 336 377 237 403 304 325
436 566 512 565 464 488 419 309 336 356 339 420 451 507 476 436 499 462 120 87
97 131 131 146 133 150 172 187 259 247 131 144 152 105 143 218 235 237 217 193
249
LBS-A27B 61
77 79 91 97 92 134 171 209 211 343 323 328 296 351 336 382 241 398 304 320
437 549 503 552 458 471 424 312 338 350 338 420 452 518 476 466 488 458 124 80
112 134 127 145 155 146 230 190 221 238 124 141 157 99 156 210 238 236 220 203
228
LBS-A28A 48
412 485 382 333 405 406 251 318 394 457 455 446 353 430 413 329 329 347 320 352
304 301 274 334 336 417 294 264 104 102 41 49 58 69 114 140 156 151 112 139
167 178 187 250 257 251 167 183
LBS-A28B 48
440 505 383 332 399 404 241 328 393 462 447 457 351 430 413 330 331 344 311 368
326 302 284 320 333 423 285 275 101 103 29 55 55 70 118 138 158 153 110 143
160 180 190 240 266 238 170 176
LBS-A29A 49
359 337 395 395 472 423 367 419 407 340 417 484 514 459 506 409 444 415 328 322
350 308 355 368 395 378 346 372 386 362 340 122 87 42 57 55 70 114 135 164

146 128 151 182 172 198 284 316 319
LBS-A29B 49
359 341 396 400 466 422 371 395 417 345 407 488 508 467 509 408 439 415 330 324
356 303 360 365 406 380 348 384 390 371 340 126 90 51 43 54 65 117 136 166
155 128 153 176 162 207 286 318 312
LBS-A30A 50
207 184 301 319 191 279 189 245 300 258 233 330 216 189 217 197 167 162 184 197
178 208 233 195 183 171 130 157 174 192 168 192 159 191 178 130 136 140 169 144
173 125 218 346 175 137 121 138 198 211
LBS-A30B 50
203 194 312 306 192 280 190 241 305 262 229 327 212 190 222 193 170 162 180 200
172 210 236 182 188 169 138 153 172 200 163 187 155 186 178 113 140 139 174 142
173 122 231 341 176 128 135 120 191 198
LBS-A31A 51
454 402 391 289 511 361 376 293 198 303 333 225 235 229 304 242 180 310 356 277
254 202 161 149 127 128 134 99 95 127 108 96 110 141 165 140 147 127 114 116
134 145 106 101 84 114 109 135 95 150 187
LBS-A31B 51
411 404 394 289 507 372 379 289 202 304 351 235 237 225 308 241 168 326 373 276
251 199 154 147 126 142 123 113 99 124 109 103 102 131 155 146 153 122 108 120
126 139 105 113 76 116 122 121 96 141 193
LBS-A32A 54
124 132 141 103 87 76 79 102 110 98 101 131 133 112 120 106 114 122 153 145
143 115 92 127 125 97 121 159 123 111 99 148 115 121 144 173 187 122 102 67
59 134 137 135 86 62 42 41 39 28 26 40 36 41
LBS-A32B 57
192 222 182 175 137 153 142 130 147 125 180 150 95 123 139 99 138 185 181 199
184 136 176 127 81 87 101 106 128 105 91 136 150 121 117 119 113 112 167 160
164 100 108 138 121 99 133 163 121 128 107 162 138 123 146 172 178
LBS-A33A 57
170 134 123 209 242 145 178 159 206 160 160 167 159 159 166 136 104 151 135 88
130 133 97 141 134 178 222 161 118 107 74 53 67 71 77 92 82 90 97 132
133 114 122 147 112 117 104 124 132 116 153 125 144 131 178 225 128
LBS-A33B 57
183 169 137 210 241 144 166 146 218 152 171 152 177 157 160 134 108 130 127 77
147 129 106 131 138 199 230 161 123 104 69 60 67 75 81 90 88 77 95 133
123 110 130 143 114 118 104 119 142 110 138 129 146 132 184 216 124

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

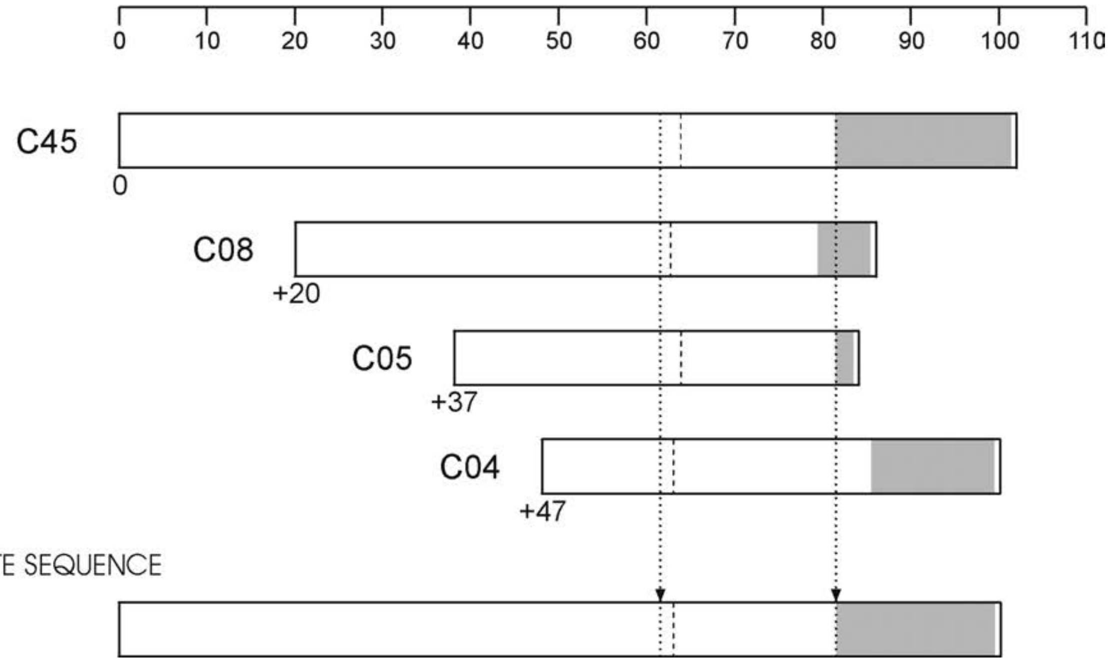


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

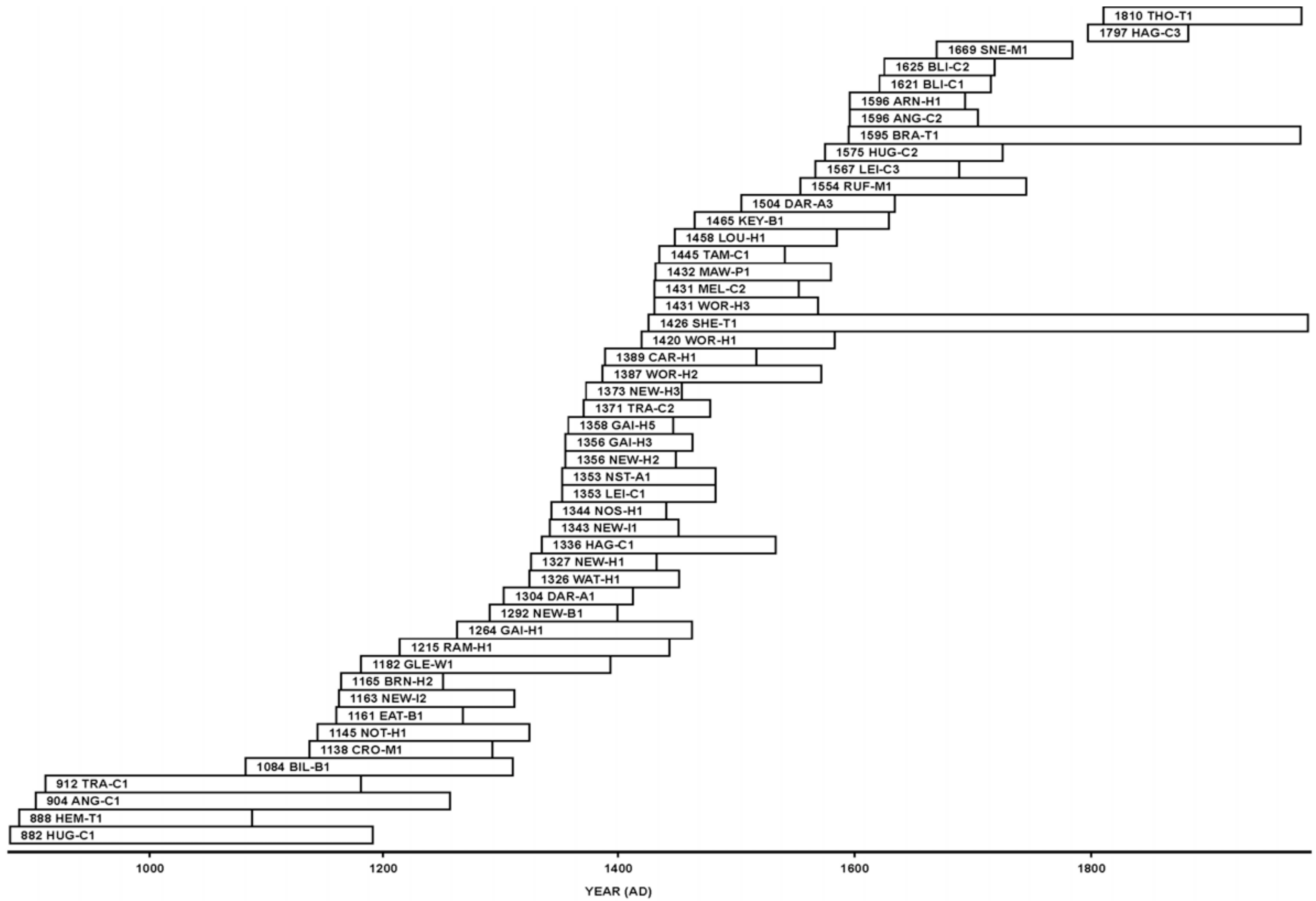
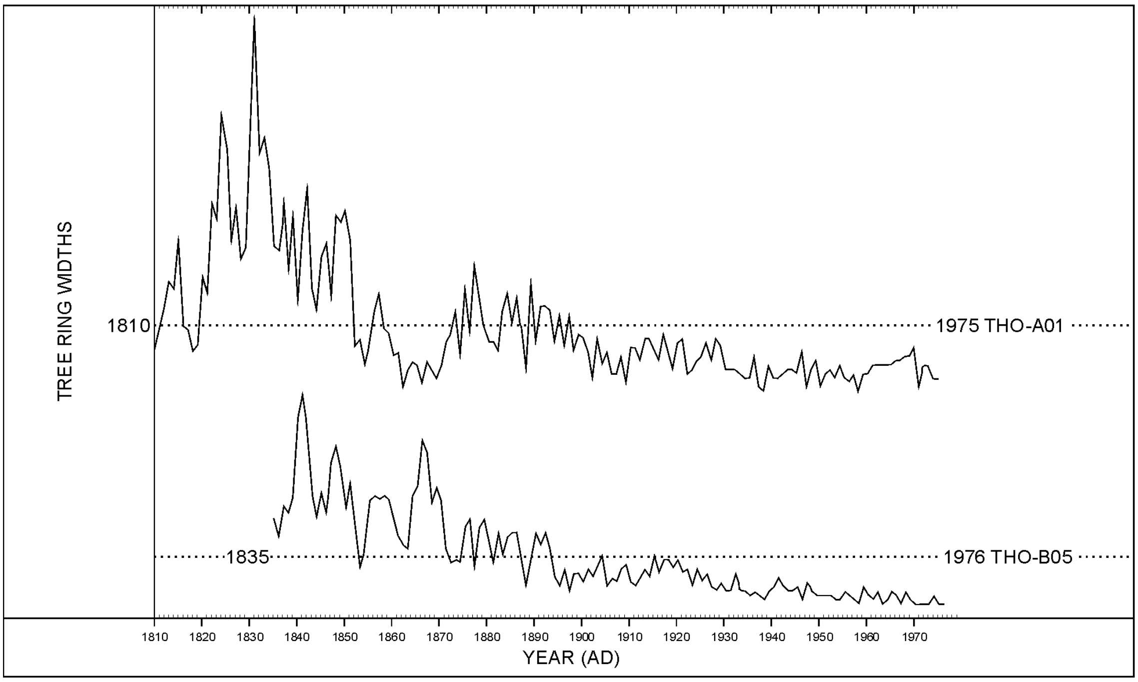


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

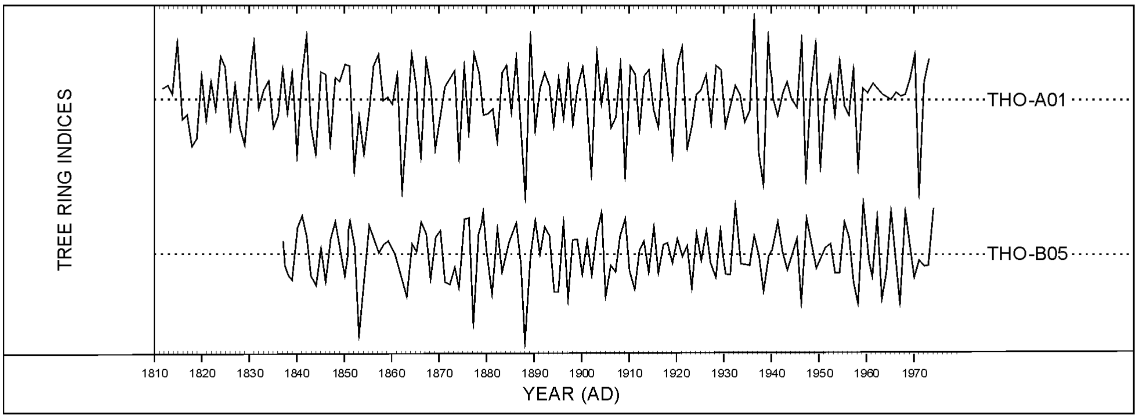


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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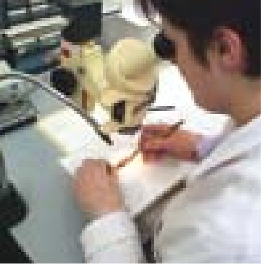 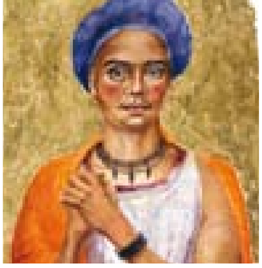    

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