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Tree-Ring Analysis of Timbers from White Hart Yard, 10-16 Cloth Market, Newcastle Upon Tyne, Tyne and Wear

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Summary

Samples were taken from timbers in both the front (roof, ground-floor and first-floor ceiling beams) and rear ranges of this building. Analysis undertaken on 31 samples resulted in 27 of these grouping to form site sequence NWCDSQ01. This site sequence contains samples from all areas sampled, and spans the period AD 1391-1529.

Prior to tree-ring analysis being carried out, this building was thought to date to the first half of the sixteenth century. It was uncertain, however, whether the ranges were contemporary or of slightly different dates. Dendrochronological dating has shown that the timbers from the rear-range roof were felled in AD 1527, with those from the ground and first-floor ceiling beams and the roof of the front range being felled two years later in AD 1529.

Keywords

Dendrochronology
Standing Building

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Introduction

The White Hart Yard site (Fig 1; NZ 246641), comprises one and one-half medieval burgage plots in one of the best-preserved sections of the pre-nineteenth century town. Development has grown from the front range along both sides of the plot around a central lane, closed to the rear (east) by the incursion of nineteenth-century Grey Street. It is thought to have originally been constructed in the sixteenth century, but was refronted in the late eighteenth century.

Front Range

This range consists of three storeys and four bays, with the third bay being a vehicle entrance to White Hart Yard (Fig 2). At ground-floor level, the bay to the left of the yard entrance has several large, close-set ceiling beams. The whole of the first floor is one large four-bay room, divided by heavy ceiling beams, between which are close-set joists with trilobe mouldings and elegantly run-out stops. The roof of this range is a ridge-braced kingpost and tiebeam roof structure. The sequence of carpenters' marks beside the ridge brace mortices on the king posts suggests that the roof is *in situ*. This part of the building has been dated on stylistic grounds to the first half of the sixteenth century.

Rear Range

This is a two-storey, four-bay wing. It is described as having similar heavy first-floor ceiling beams to those of the front range (English Heritage 2001), but at the time of the inspection and sampling these were no longer visible. It has a ridge-braced kingpost and tiebeam roof, of slightly cruder construction, but otherwise identical to that of the front range. A similar, if not identical date in the first half of the sixteenth century is suspected.

The Laboratory would like to thank Martin Roberts of English Heritage for his advice during assessment and John Nolan of Northern Counties Archaeological Services who provided Figures 2–15.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage to inform the forthcoming conversion and restoration works, and to contribute to the establishment of a regional roof typology. By dating these ranges it was hoped to accurately date the fireplace, door jamb, and floor-joist moulding, by association.

Sampling

Core samples were taken from 35 oak beams, and each sample was given the code NWC-D (for Newcastle, site 'D) and numbered 01–35. Eleven samples were taken from ground and first-floor ceiling beams of the front range (NWC-D01–11), 12 from the roof structure of the front range (NWC-D12–23), and 12 from the rear-range roof (NWC-D24–35). The position of all samples was noted at the time of sampling and has been marked on Figures 3–15. Further details relating to the samples can be found in Table 1. Ceiling beams and roof trusses have been numbered from north to south (front range) and from east to west (rear range).

Analysis and Results

Four samples (NWC-D01, NWC-D24, NWC-D26, and NWC-D29) had too few rings to be dated securely, and so were rejected prior to measurement. The remaining 31 samples were prepared by sanding and polishing, and their growth-ring widths were measured; these measurements are given at the end of the report. Usually the ring widths of each sample are measured twice, with these two sequences of measurements then matched together to form an average sequence. When more than one core is taken from a single timber, each sample is measured once only, with all sequences from this timber again matched together to form an average sequence. In the case of NWC-D30 two core samples were taken, one of which had 60 rings and one had 30 rings. When these two sets of sequences were matched together at the relevant offset they formed an average sequence of 63 rings. These samples were then compared with each other using the Litton/Zainodin grouping procedure (see appendix).

Twenty-seven samples matched each other with a minimum *t*-value of 4.5, and were combined at the relevant offset positions to form NWCDSQ01, a site sequence of 139 rings (Fig 16). This site sequence was then compared to a large number of relevant reference chronologies for oak, indicating a consistent match when the date of its first ring is AD 1391 and of its last measured ring is AD 1529. The evidence for this dating is given by the *t*-values in Table 2.

Attempts to date the remaining four samples by comparing them individually to the reference material were unsuccessful, and these samples remain undated.

Interpretation

Analysis of 31 samples taken from timbers in the front and rear ranges of White Hard Yard, Newcastle, has resulted in the construction and dating of a single site sequence. Site sequence NWCDSQ01, of 139 rings, contains 27 samples, and spans the period AD 1391–1529.

Nine samples are from ceiling beams of the ground and first floors in the front range. Of these, seven have complete sapwood and a last measured ring date of AD 1529, the felling date of the timbers represented. The other two dated samples taken from the ceiling beams have similar heartwood/sapwood boundary ring dates. The average of these is AD 1502 which, taking into account sample NWC-D03 having a last measured ring date of AD 1527 with incomplete sapwood, allows an estimated felling date to be calculated for the two timbers represented to within the range AD 1528–42, consistent with a felling date of AD 1529.

All 12 samples from the roof timbers of the front range were successfully dated. Of these, three have complete sapwood and a last measured ring date of AD 1529, the felling date of the timbers represented. Five other roof timbers have heartwood/sapwood boundary ring dates consistent with a single felling. The average of these five heartwood/sapwood boundary ring dates is AD 1505, which, allowing for sample NWC-D23 having a last measured ring date of AD 1528 with incomplete sapwood, calculates to an estimated felling date for the five timbers represented to within the range AD 1529–45. The remaining four roof samples do not have the heartwood/sapwood boundary ring and so an estimated felling date range cannot be calculated for them. However, by adding the minimum expected sapwood rings (15) to the last measured ring dates of AD 1461 (NWC-D14), AD 1467 (NWC-D18), AD 1497 (NWC-D21), and AD 1504 (NWC-D22), this would provide *terminus post quem* dates of AD 1476, AD 1482, AD 1512, and AD 1519, respectively.

Six of the samples taken from the timbers of the rear-range roof are included in site sequence NWCDSQ01. Of these, four have complete sapwood and a last measured ring date of AD 1527. The average heartwood/sapwood boundary ring date of the other two roof timbers is AD 1506 which, given that sample NWC-D35 has a last measured ring date of AD 1524 with incomplete sapwood, allows an estimated felling date range to be calculated for the two timbers represented of AD 1525–46, consistent with a felling date of AD 1527. In calculating felling date ranges, this Laboratory uses the estimate that 95% of mature oak trees from this area have between 15–40 sapwood rings.

Discussion

Prior to the tree-ring analysis, the front and rear ranges had been dated to the first half of the sixteenth century on the basis of roof type and similarity to other dendrochronologically-dated roofs in the area, such as Kepier Hospital, West Range, Durham (AD 1522; Howard *et al* 1996) and the Rigging Loft, Trinity House, Newcastle (AD 1524; Howard *et al* 2002). However, it was uncertain whether the two ranges were contemporary or, if not, what difference in date there was between them.

Tree-ring dating has shown that the roof of the rear range is constructed from timbers felled in AD 1527, two years earlier than the front range roof and ceiling beams, which are built of timbers felled in AD 1529.

With the success of the dendrochronological dating, we now have precise dates for the roof and floor structures of the front range and roof of the rear range. In addition, the dating of the ceiling beams provides dating evidence for the type of moulding seen on these beams, information which might prove useful in other buildings. The design of fireplace and door jamb type seen at this building can now also be precisely dated by association with the dated timbers. The dating evidence of type of roof construction found here will be added to that already known and assist in the refinement of the roof typology for this area.

All 27 dated samples had matched each other to form a single site sequence. This suggests that the dated timbers from which this building was constructed were all from the same woodland source.

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Table 1: Details of tree-ring samples from White Hart Yard, 10–16 Cloth Market, Newcastle upon Tyne

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Front Range Ground-floor ceiling beams						
NWC-D01	Beam 1	NM	--	----	----	----
NWC-D02	Beam 2	68	17	1449	1499	1516
NWC-D03	Beam 3	81	22	1447	1505	1527
NWC-D04	Beam 4	72	22C	1458	1507	1529
NWC-D05	Beam 5	75	23C	1455	1506	1529
NWC-D06	Beam 6	74	22C	1456	1507	1529
First-floor ceiling beams						
NWC-D07	Beam 1	76	25C	1454	1504	1529
NWC-D08	Beam 2	64	25C	----	----	----
NWC-D09	Beam 3	63	21C	1467	1508	1529
NWC-D10	Beam 4	85	17C	1445	1512	1529
NWC-D11	Beam 5	83	25C	1447	1504	1529
Roof						
NWC-D12	East principal rafter, truss 1	51	15	1469	1504	1519
NWC-D13	West principal rafter, truss 1	58	h/s	1449	1506	1506
NWC-D14	East principal rafter, truss 2	71	--	1391	----	1461
NWC-D15	West principal rafter, truss 2	70	27C	1460	1502	1529
NWC-D16	Tiebeam, truss 2	93	21C	1437	1508	1529
NWC-D17	East principal rafter, truss 3	80	12	1437	1504	1516
NWC-D18	West principal rafter, truss 3	77	--	1391	----	1467
NWC-D19	Post, truss 3	75	26C	1455	1503	1529
NWC-D20	East principal rafter, truss 4	93	h/s	1414	1506	1506
NWC-D21	West principal rafter, truss 4	99	--	1399	----	1497

NWC-D22	East principal rafter, truss 5	69	--	1436	----	1504
NWC-D23	West principal rafter, truss 5	91	24	1438	1504	1528
<u>Rear Range</u> Roof						
NWC-D24	North principal rafter, truss 1	NM	--	----	----	----
NWC-D25	King post, truss 1	56	22C	1472	1505	1527
NWC-D26	South principal rafter, truss 2	NM	--	----	----	----
NWC-D27	King post, truss 2	65	15	1454	1503	1518
NWC-D28	Tiebeam, truss 2	60	21C	1468	1506	1527
NWC-D29	North principal rafter, truss 3	NM	--	----	----	----
NWC-D30	King post, truss 3	63	12	----	----	----
NWC-D31	King post, truss 4	74	h/s	----	----	----
NWC-D32	Tiebeam, truss 4	74	15C	1454	1512	1527
NWC-D33	South principal rafter, truss 5	56	12C	1472	1515	1527
NWC-D34	King post, truss 5	50	10	----	----	----
NWC-D35	Tiebeam, truss 5	86	15	1439	1509	1524

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

Table 2: Results of the cross-matching of site sequence NWCDSQ01 and relevant reference chronologies when the first-ring date is AD 1391 and the last-ring date is AD 1529

Reference chronology	*t*-value	Span of chronology	Reference
England	8.2	AD 401–1981	Baillie and Pilcher 1982 unpubl
Wales and West Midlands	7.5	AD 1341–1636	Siebenlist-Kerner 1978
Aydon Castle, Corbridge, Northumberland	10.5	AD 1424–1543	Hillam and Groves 1991
1–2 The College, Cathedral Precinct, Durham	7.9	AD 1364–1531	Howard *et al* 1992
Finchale Priory Barn, Brasside, Durham	7.2	AD 1449–1677	Arnold *et al* 2002
Nether Levens Hall, Kendal, Cumbria	7.1	AD 1395–1541	Howard *et al* 1991
35 The Close, Newcastle upon Tyne	7.0	AD 1365–1513	Howard *et al* 1991

Figure 1: Map to show the location of White Hart Yard, Cloth Market

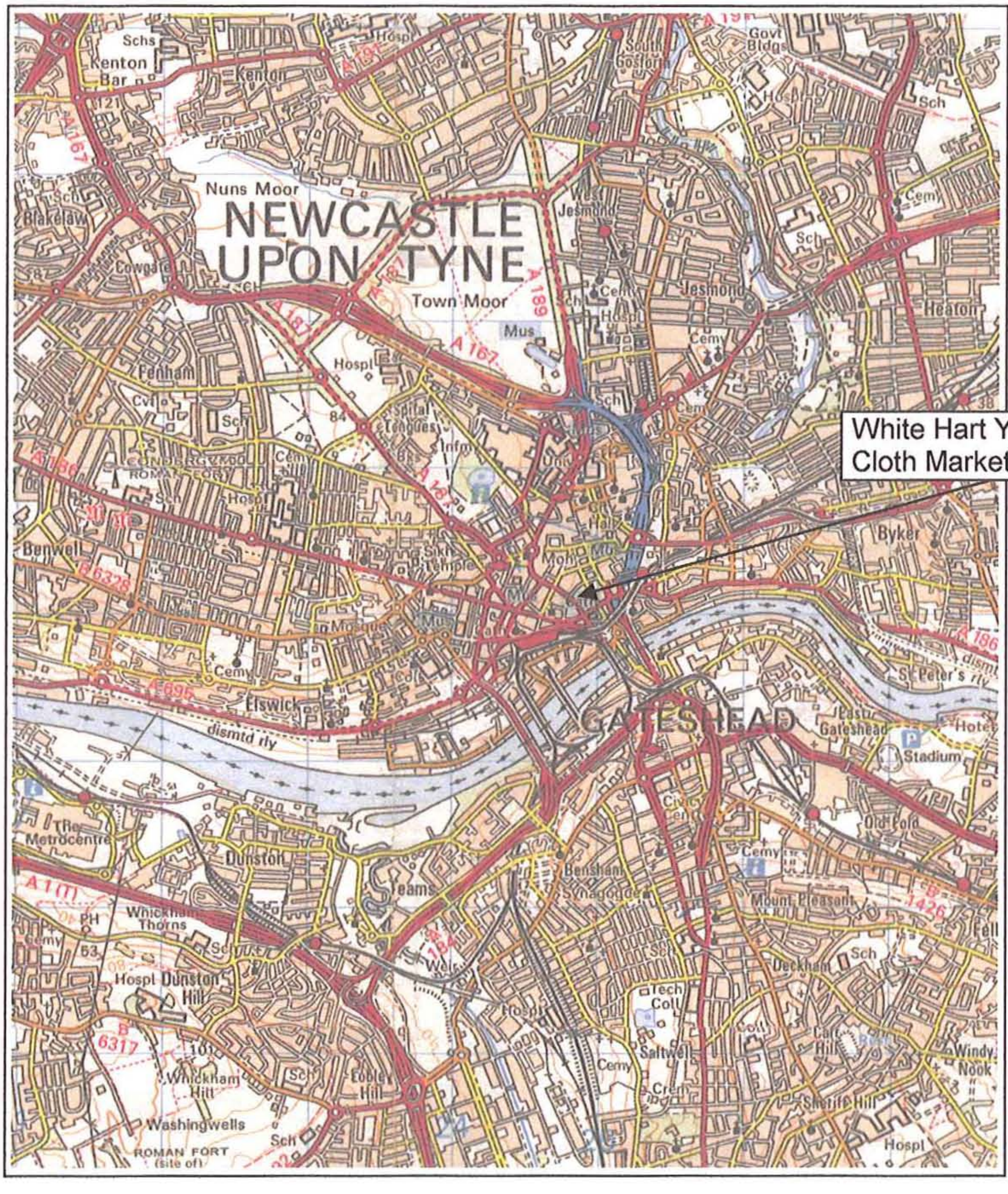


Figure 2: Plan of buildings in the complex, building under investigation outlined in red (Northern Counties Archaeological Services)

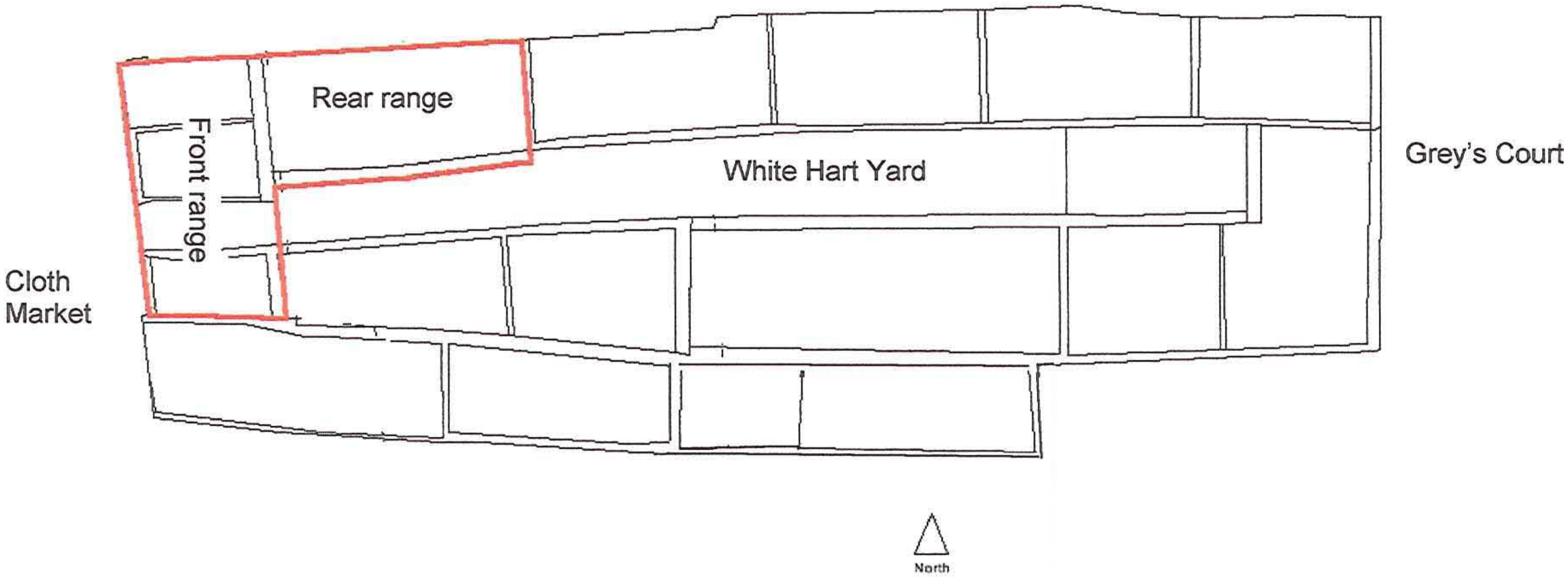


Figure 3: Ground-floor plan showing the location of samples NWC-D01-06 (Northern Counties Archaeological Services)

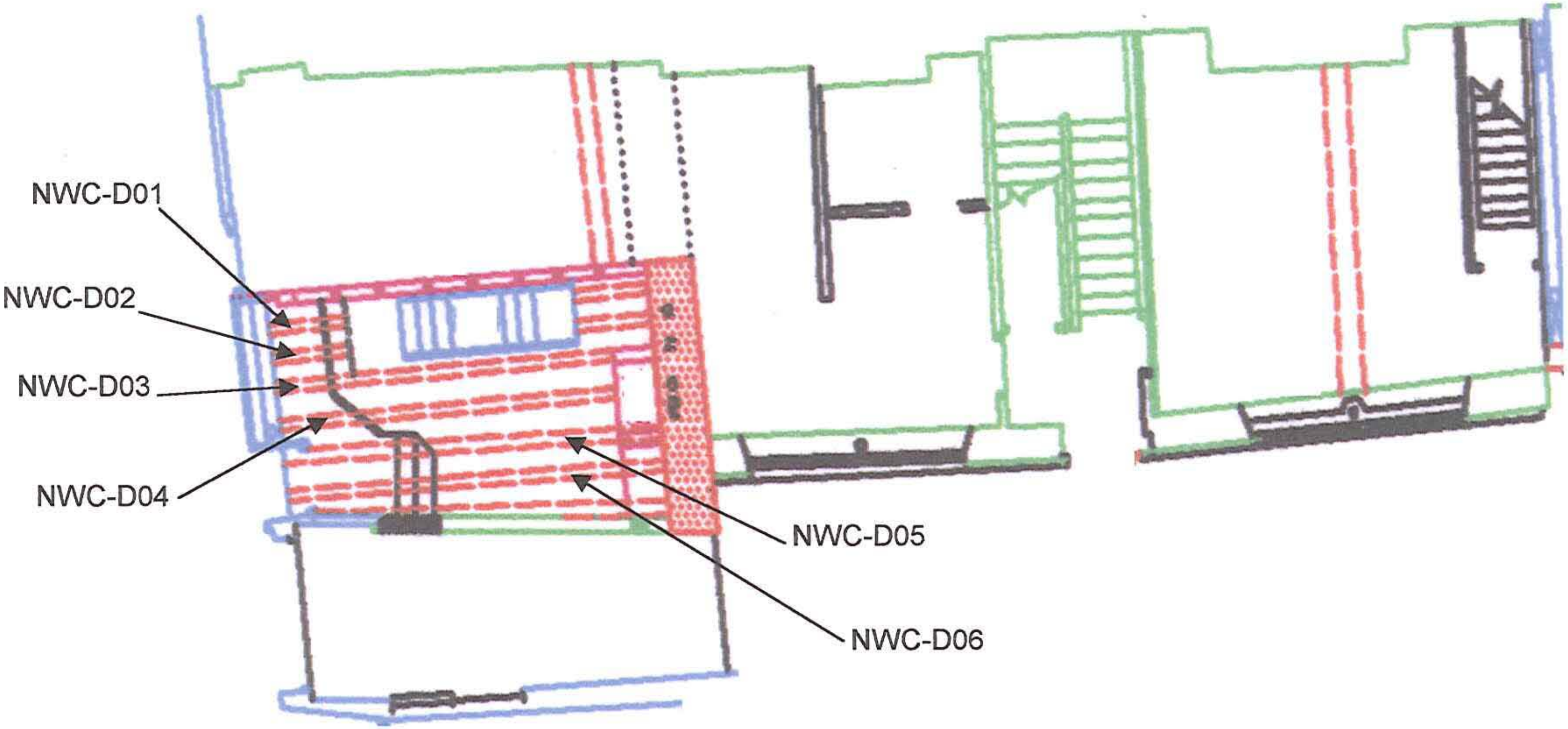


Figure 4: First floor plan showing the location of samples NWC-D07-11 (Northern Counties Archaeological Services)

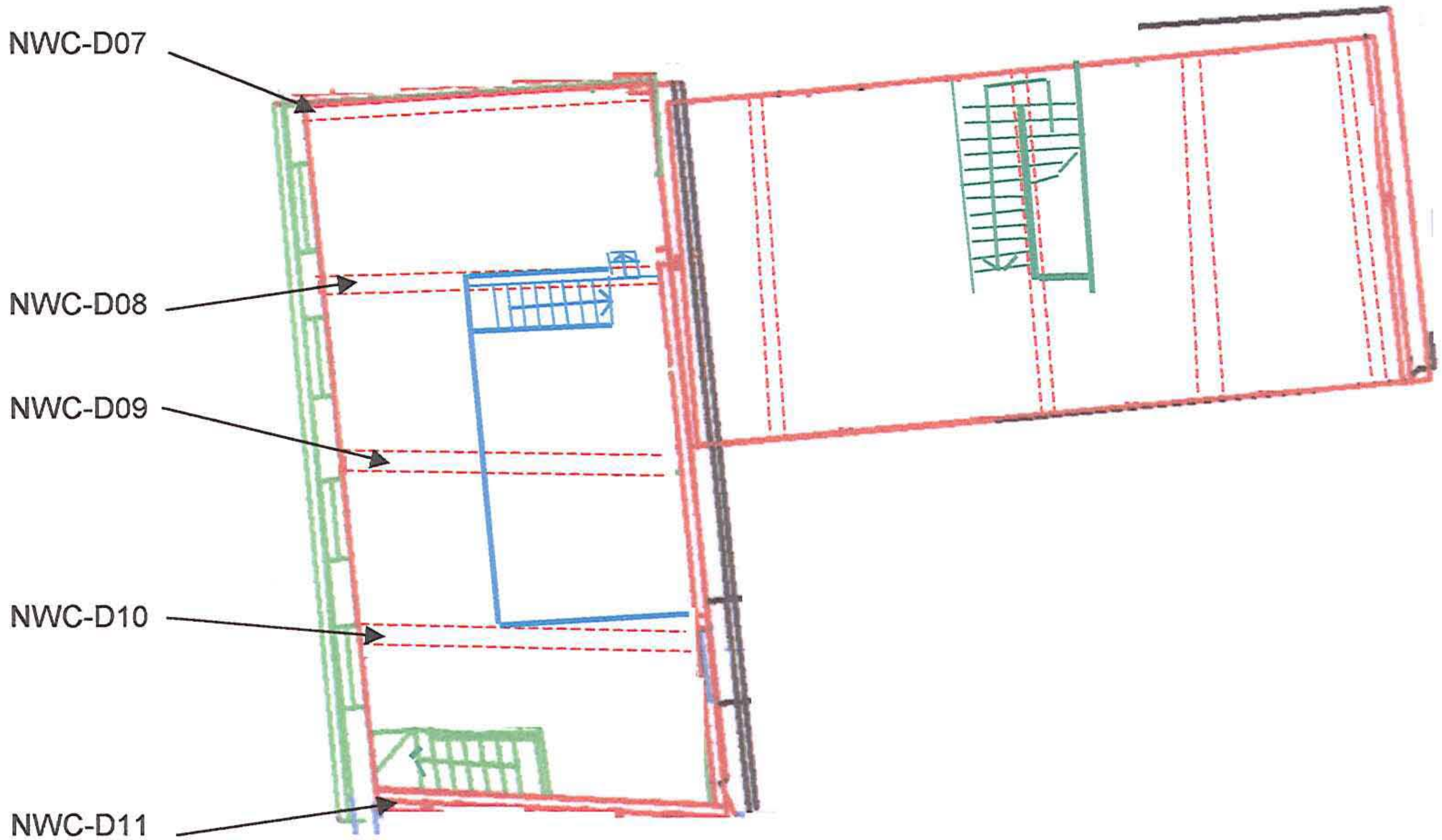


Figure 5: Attic plan showing truss numbering (Northern Counties Archaeological Services)

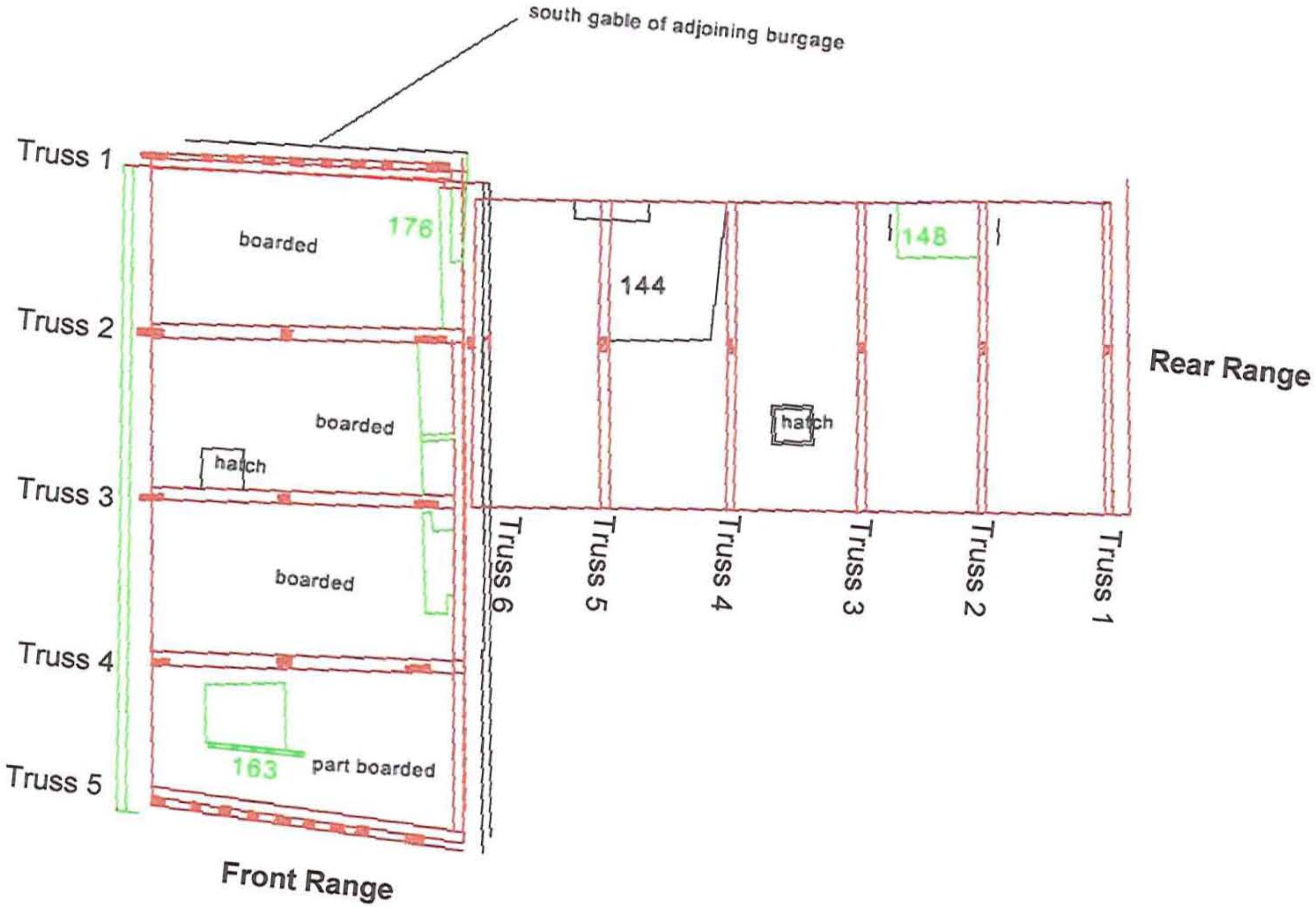


Figure 6: Front range; truss 1 (north face), showing the location of samples NWC-D12 and NWC-D13 (Northern Counties Archaeological Services)

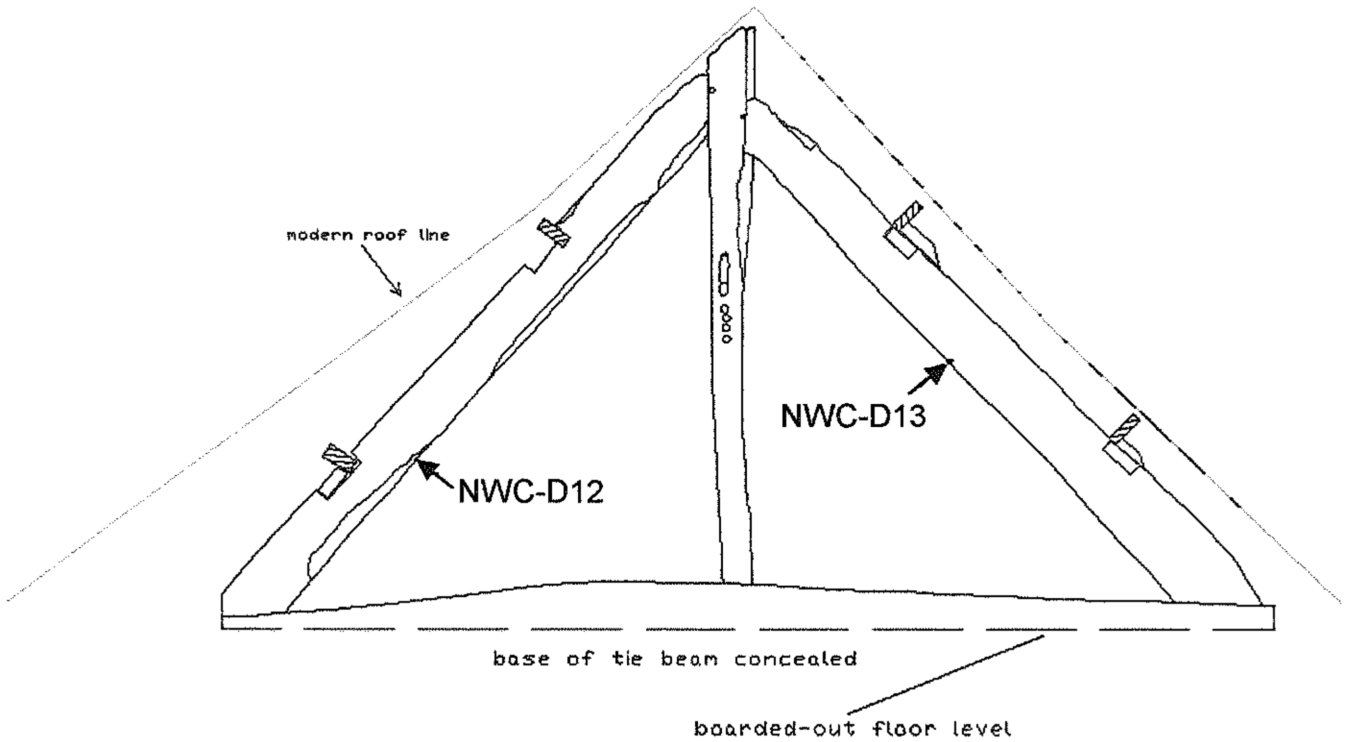


Figure 7: Front range; truss 2 (north face), showing the location of samples NWC-D14-16 (Northern Counties Archaeological Services)

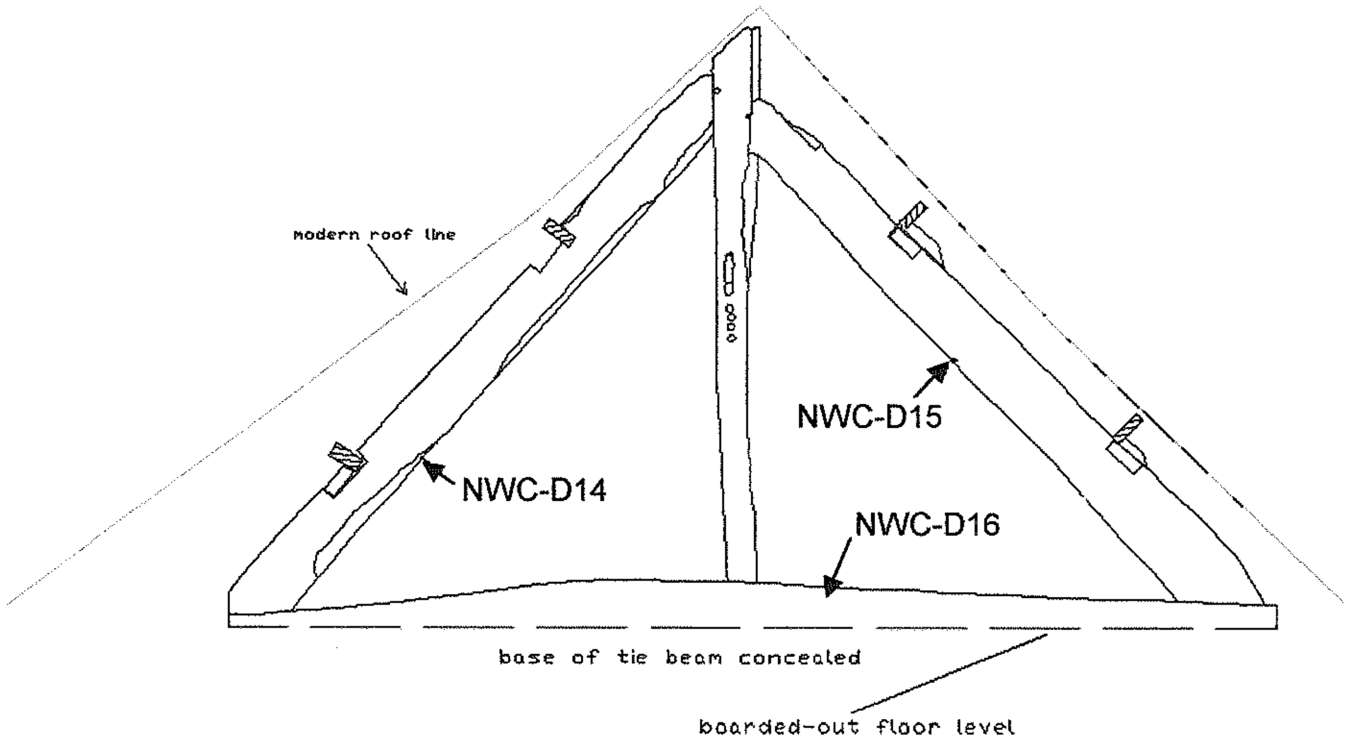


Figure 8: Front range, truss 3 (north face), showing the location of samples NWC-D17-19 (Northern Counties Archaeological Services)

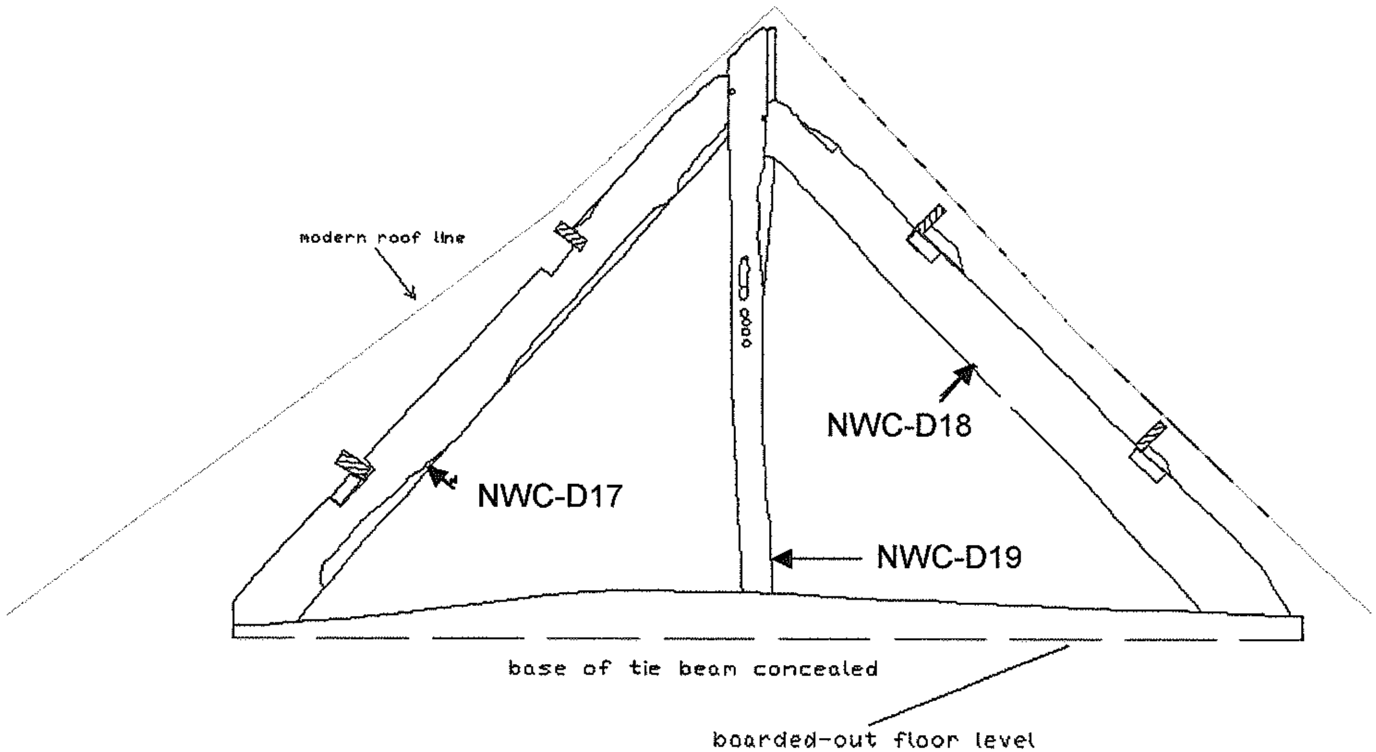


Figure 9: Front range; truss 4 (north face), showing the location of samples NWC-D20 and NWC-D21 (Northern Counties Archaeological Services)

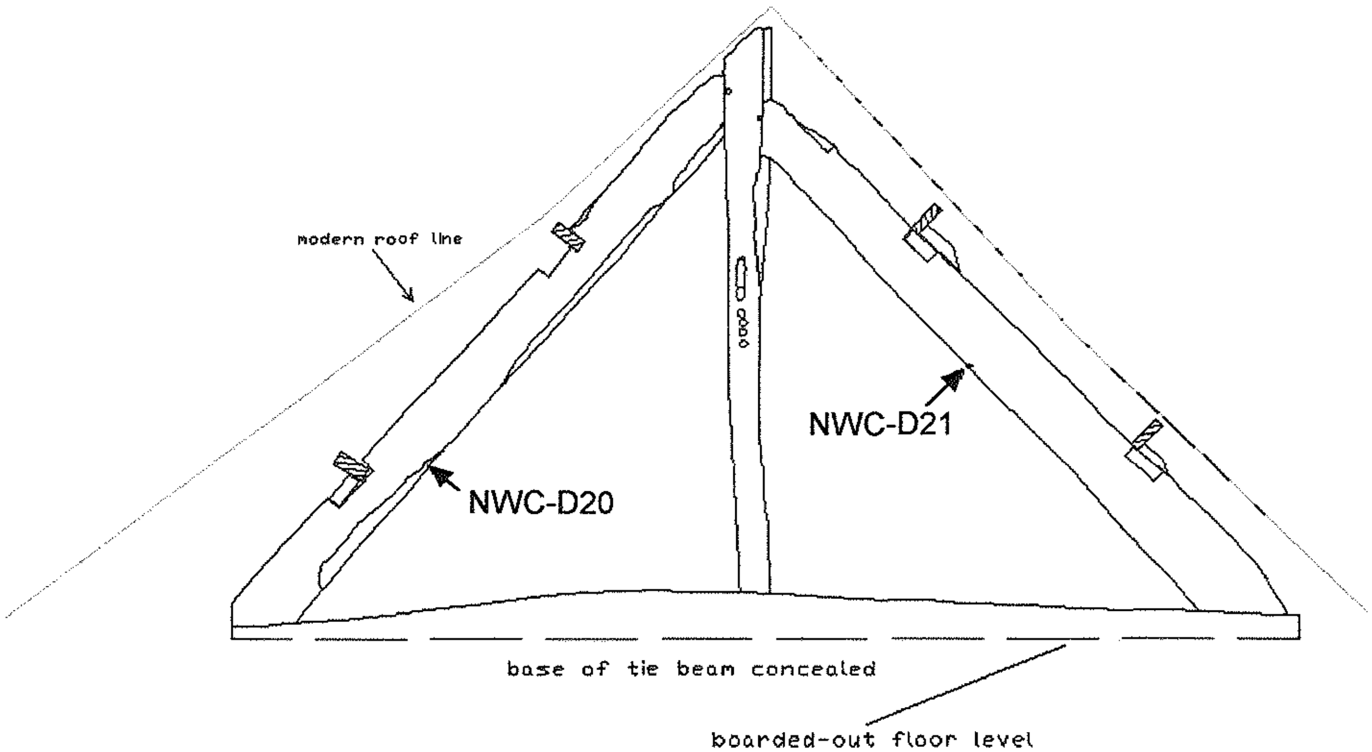


Figure 10: Front range (north face), truss 5, showing the location of samples NWC-D22 and NWC-D23 (Northern Counties Archaeological Services)

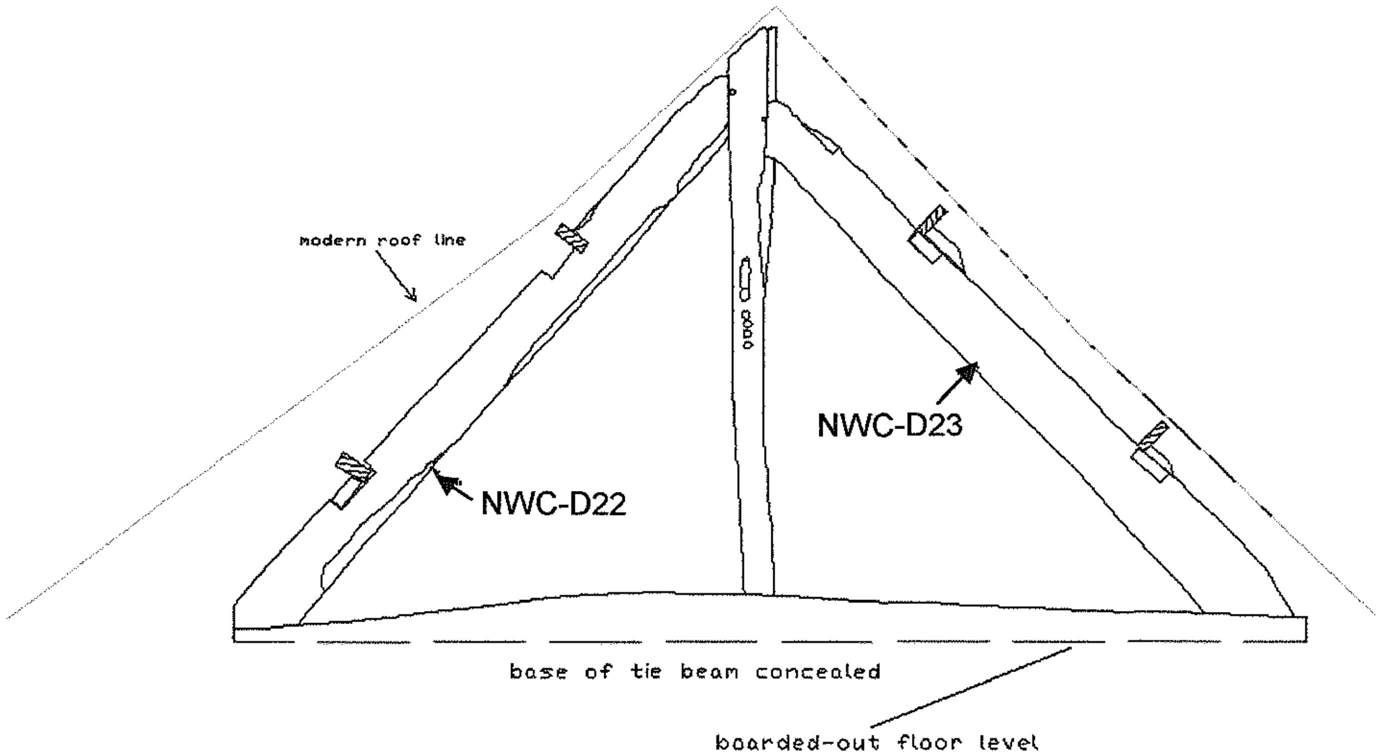


Figure 11: Rear range, truss 1 (west face), showing the location of samples NWC-D24 and NWC-D25 (Northern Counties Archaeological Services)

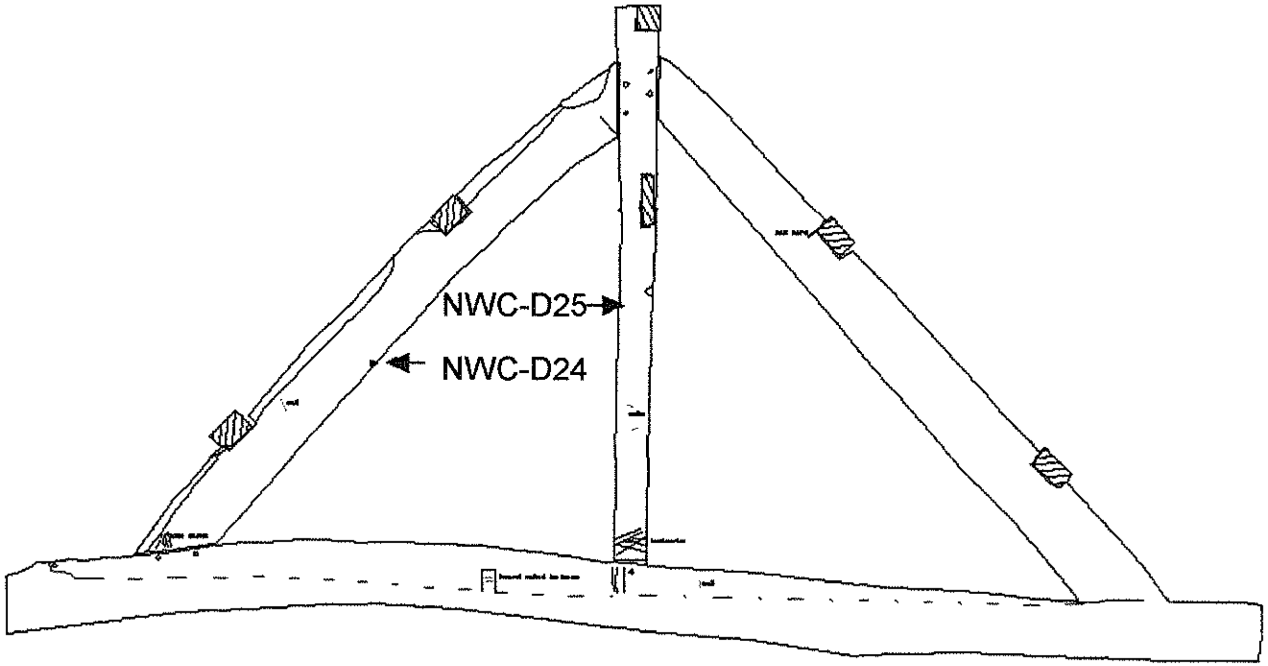


Figure 12: Rear range, truss 2 (west face), showing the location of samples NWC-D26–28 (Northern Counties Archaeological Services)

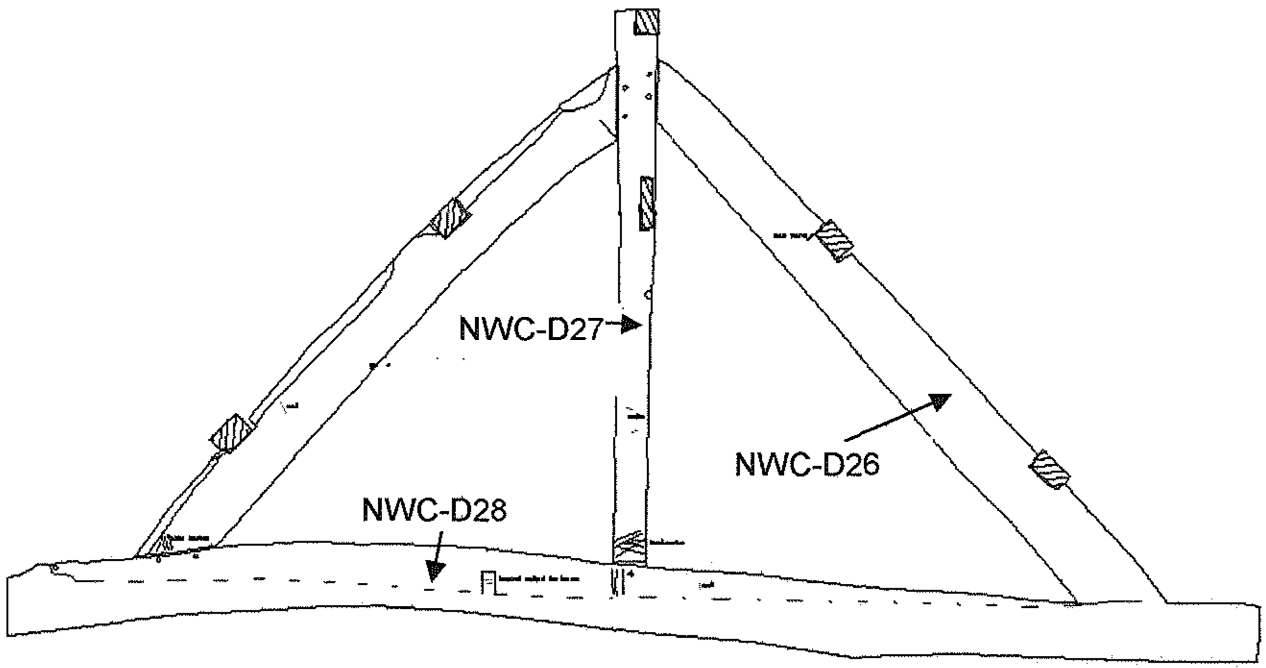


Figure 13: Rear range, truss 3 (west face), showing the location of samples NWC-D29 and NWC-D30 (Northern Counties Archaeological Services)

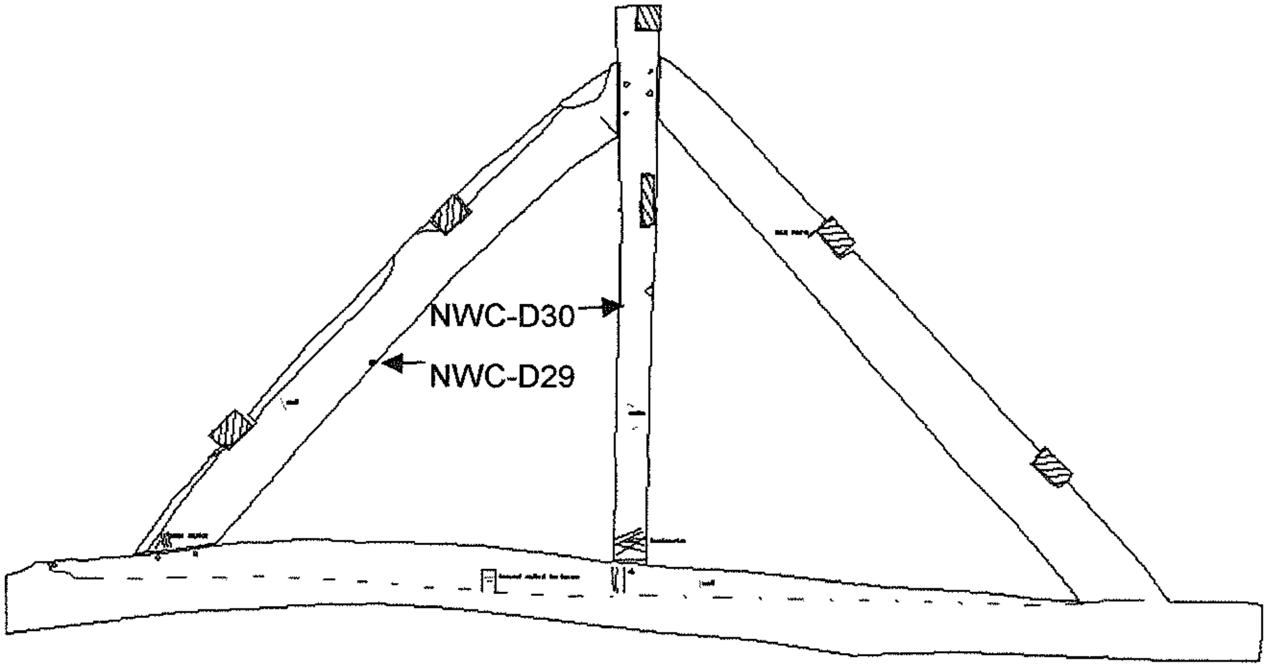


Figure 14: Rear range, truss 4 (west face), showing the location of samples NWC-D31 and NWC-D32 (Northern Counties Archaeological Services)

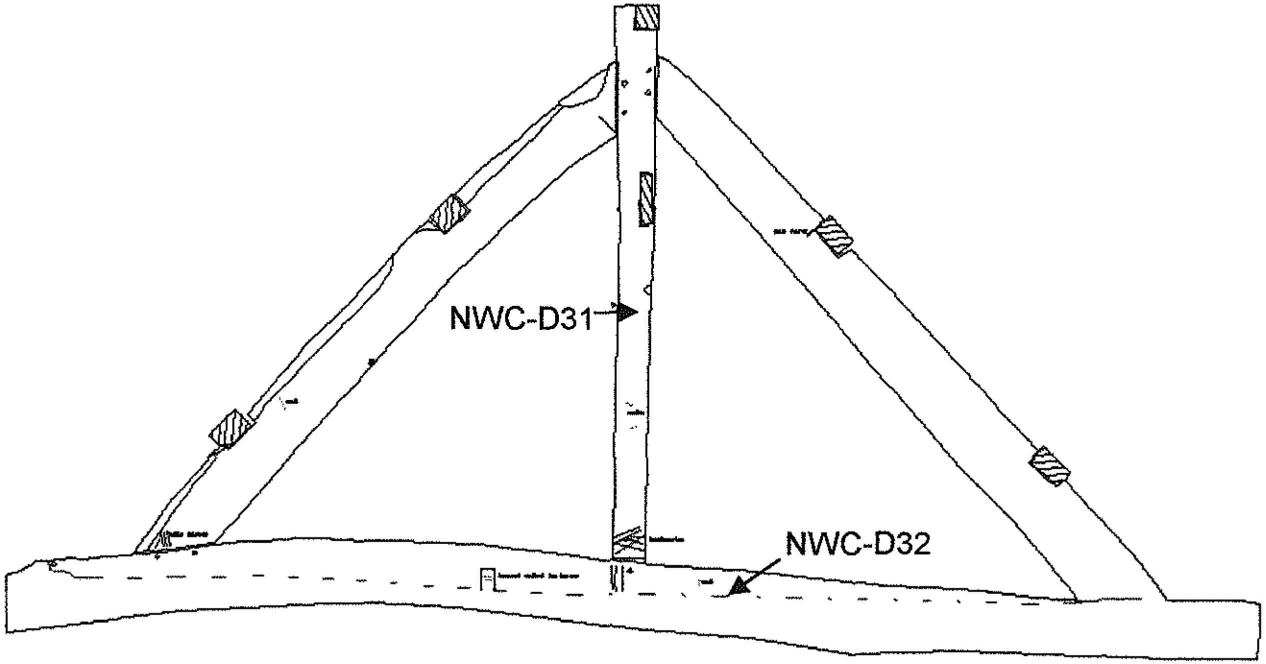


Figure 15: Rear range, truss 5 (west face), showing the location of samples NWC-D33-35 (Northern Counties Archaeological Services)

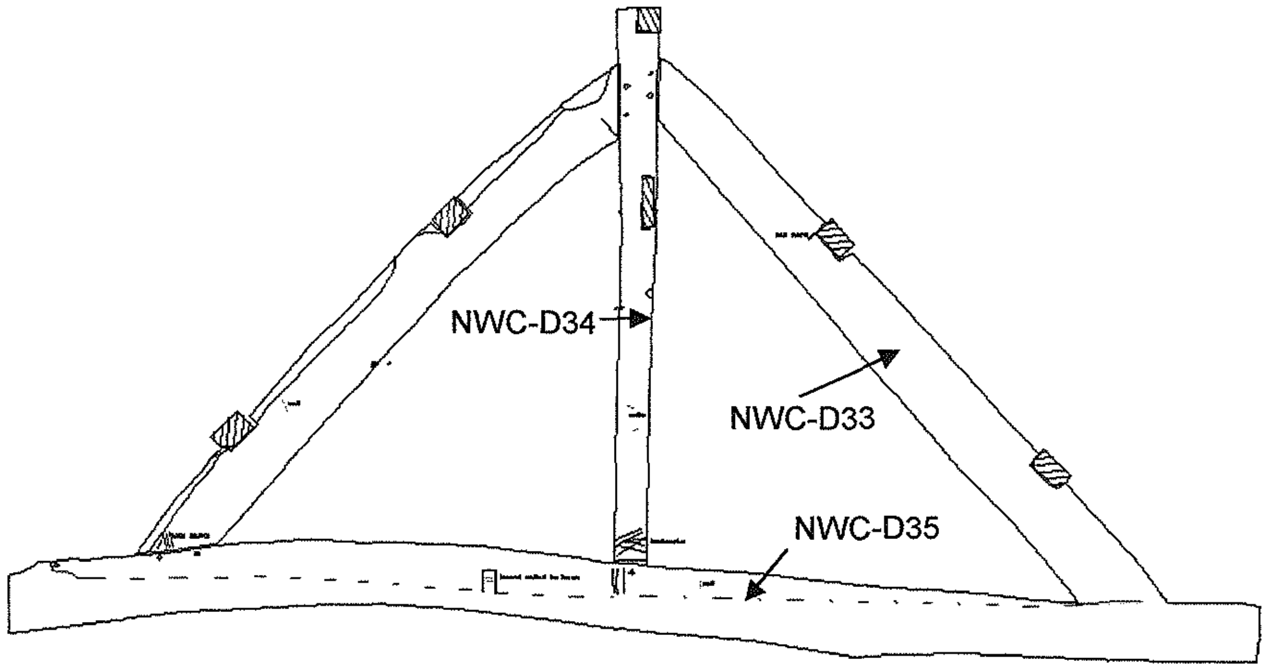
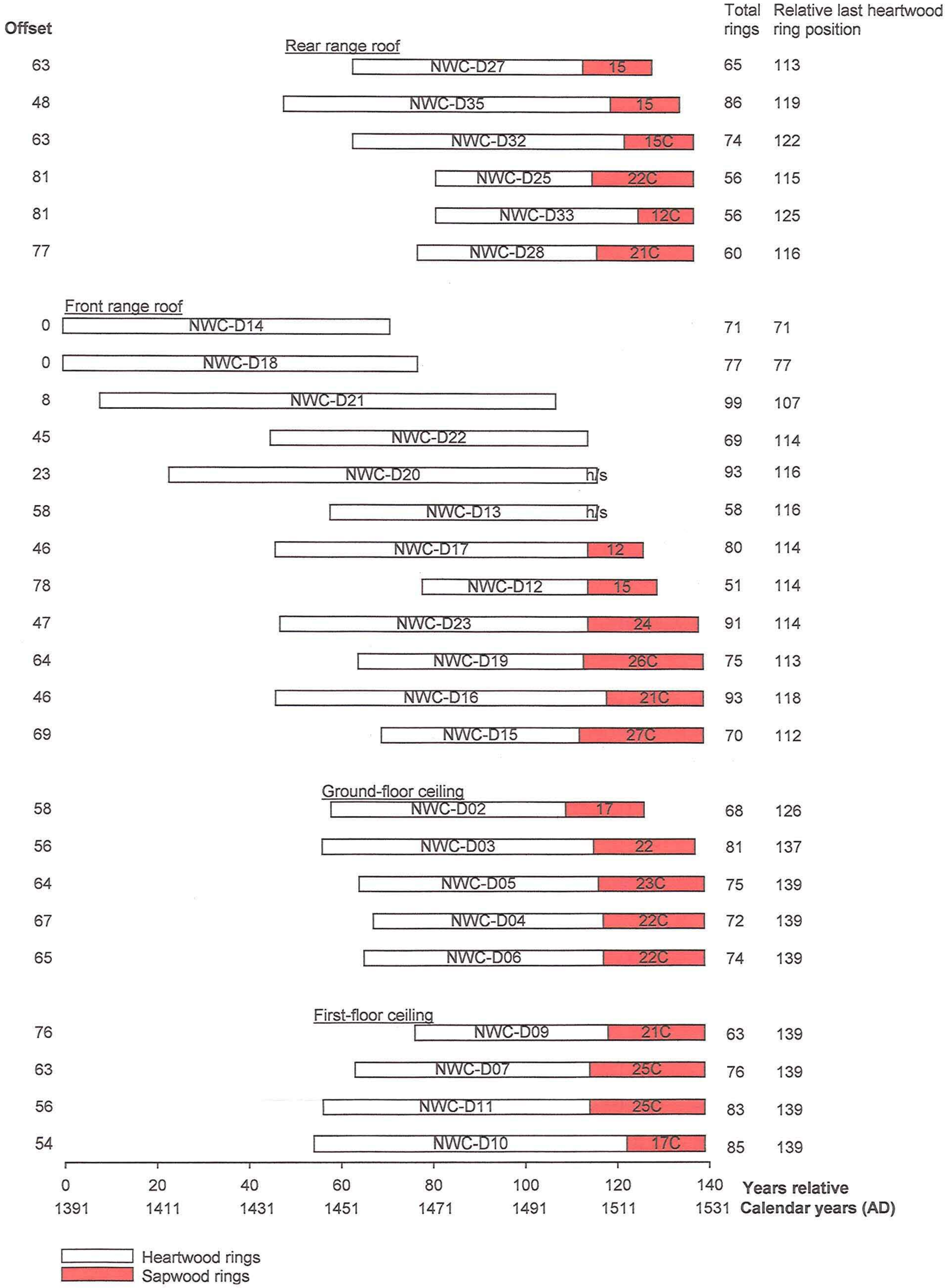


Figure 16: Bar diagram of samples in site sequence NWCDSQ01 sorted by area



h/s = the heartwood/sapwood boundary is the last measured ring
C = complete sapwood retained on sample, last measured ring is the felling date

Data of measured samples – measurements in 0.01mm units

NWC-D02A 68
375 360 394 284 319 385 268 326 354 349 284 318 267 271 316 266 228 293 300 393
302 285 326 330 278 199 219 237 191 262 281 227 262 277 232 157 190 223 303 250
240 219 184 163 155 113 141 235 140 107 190 171 126 134 95 150 147 185 180 210
208 166 191 184 171 168 167 166
NWC-D02B 68
354 371 366 279 316 367 290 318 353 358 283 339 288 270 318 269 225 292 302 396
308 290 328 320 276 201 216 239 198 258 296 226 255 279 233 159 194 210 304 247
240 213 178 168 152 124 139 237 133 119 184 169 133 133 100 144 148 178 186 210
195 176 196 172 185 162 166 166
NWC-D03A 81
114 206 227 184 181 166 135 150 142 166 150 130 119 137 109 151 116 122 138 152
194 194 152 195 168 141 177 234 237 256 285 225 240 269 252 297 286 245 272 355
437 341 269 288 242 312 187 239 241 328 214 252 287 184 150 98 112 181 162 173
112 199 201 177 170 143 139 127 124 129 114 163 142 114 110 110 109 152 128 132
157
NWC-D03B 81
122 193 205 183 177 169 141 177 138 181 141 123 116 132 109 152 110 110 148 143
210 216 164 183 195 143 181 226 251 244 274 240 248 260 253 303 285 254 265 355
430 345 266 287 241 321 182 236 247 318 225 254 289 177 149 97 112 165 162 179
114 196 187 185 172 143 134 139 130 120 114 161 146 114 114 107 108 143 140 127
158
NWC-D04A 72
238 204 183 175 213 317 367 274 353 417 425 333 377 303 298 275 297 348 218 294
284 324 252 250 207 246 251 214 221 320 228 240 192 203 196 184 163 163 251 182
161 176 218 122 144 133 241 180 171 123 159 159 113 107 135 178 121 166 172 188
188 194 177 165 195 152 125 156 208 246 182 144
NWC-D04B 72
164 193 186 185 209 309 368 275 356 433 430 343 377 328 295 260 299 361 232 295
275 347 275 250 201 241 237 230 221 301 245 231 185 211 201 188 156 163 266 183
158 174 220 127 146 128 242 188 171 134 156 162 129 116 149 147 130 167 164 188
192 229 141 189 184 126 128 143 184 253 175 154
NWC-D05A 75
320 447 425 435 365 467 360 320 328 346 301 373 386 355 335 288 260 367 296 328
399 253 292 275 258 274 257 311 225 205 136 163 194 137 192 187 222 271 220 165
171 210 130 138 146 192 113 90 60 95 129 162 142 175 208 168 125 151 163 143
126 113 107 116 104 75 78 74 62 74 78 74 108 91 97
NWC-D05B 75
316 465 432 420 352 491 359 334 336 347 304 367 404 358 309 299 268 384 311 405
401 237 291 265 265 268 262 319 241 189 144 159 198 126 197 192 216 276 201 182
170 214 125 138 150 185 117 94 60 96 128 170 138 165 218 162 138 138 172 149
119 117 110 114 113 69 78 70 57 79 75 82 114 98 97

NWC-D06A 74
222 322 302 259 328 327 294 237 261 231 263 418 449 379 396 348 297 223 225 382
229 300 181 211 161 184 155 205 129 176 193 166 138 154 184 147 198 134 143 161
187 174 99 100 124 108 118 110 186 156 130 107 147 140 125 104 123 181 116 171
120 77 133 104 108 95 88 105 104 127 120 127 102 125
NWC-D06B 74
235 324 297 189 337 330 286 243 255 228 271 407 463 376 411 351 300 241 224 364
223 309 181 217 163 175 173 209 135 175 196 165 136 150 187 147 195 146 140 168
197 177 96 106 118 125 114 112 181 155 130 110 148 143 112 114 124 176 127 175
115 87 116 115 109 94 73 128 90 127 131 122 104 113
NWC-D07A 76
408 322 446 504 486 430 411 344 368 448 344 346 411 464 514 371 391 355 344 281
233 317 373 322 323 334 265 354 391 336 260 218 268 353 253 250 265 238 217 206
163 203 277 186 186 202 160 138 137 110 152 136 185 145 172 171 139 129 107 104
133 116 159 158 148 166 136 107 144 122 135 101 113 137 119 124
NWC-D07B 76
369 324 500 483 505 404 413 355 374 425 334 360 407 470 518 361 396 357 333 274
254 310 376 335 311 354 262 343 381 340 262 228 272 349 260 263 256 241 230 202
179 193 274 175 187 197 155 137 133 105 152 126 174 144 174 174 133 138 92 109
128 131 153 149 143 167 140 121 142 120 138 101 104 122 108 109
NWC-D08A 64
424 451 454 505 448 377 380 292 217 251 251 269 292 340 247 265 322 350 263 342
406 409 333 206 227 208 168 168 121 202 299 241 154 229 238 154 162 125 76 59
41 24 44 49 60 68 63 71 58 67 91 88 88 127 113 87 67 49 55 78
91 85 117 144
NWC-D08B 64
440 545 527 517 411 351 366 257 197 229 256 269 290 337 251 263 321 348 259 319
408 401 331 212 220 195 189 165 124 198 297 232 166 229 240 158 154 122 67 61
48 31 43 47 59 63 60 67 55 82 102 90 88 131 100 93 59 53 52 76
95 87 107 167
NWC-D09A 63
390 389 377 336 387 347 358 353 448 381 421 343 519 357 368 477 446 396 381 336
405 308 307 295 249 255 252 255 287 342 299 231 280 314 210 186 152 243 223 216
204 184 246 227 209 201 189 186 169 195 163 152 234 177 137 124 105 117 139 136
122 125 98
NWC-D09B 63
395 391 377 331 390 351 344 351 439 371 429 336 527 355 367 475 446 406 366 351
393 309 333 291 265 252 251 274 277 350 305 237 280 298 214 202 157 261 228 219
193 190 246 230 213 211 167 192 175 209 146 154 236 179 131 132 102 117 132 124
142 125 107
NWC-D10A 85
392 346 395 381 403 364 459 406 351 401 417 448 365 336 373 378 327 346 292 208
248 261 261 298 214 240 227 197 206 155 207 208 218 198 200 165 176 185 146 153
145 155 198 190 181 128 131 111 133 190 252 298 206 210 268 223 151 150 171 284
271 300 197 213 205 189 180 200 202 198 138 158 183 170 210 169 97 107 113 146
133 160 100 96 125

NWC-D10B 85
417 357 385 349 395 366 443 411 337 392 423 443 366 334 373 382 320 349 290 210
248 262 265 310 223 233 229 199 197 155 212 211 220 202 204 169 175 172 147 144
148 156 200 192 179 131 120 120 132 194 243 291 212 190 263 226 164 143 179 275
265 309 199 212 209 184 184 197 195 183 158 167 176 170 184 177 108 101 120 143
141 141 102 100 127
NWC-D11A 83
258 433 312 281 351 374 314 357 338 434 454 427 384 356 293 324 341 306 313 320
362 337 316 303 300 243 156 180 201 232 213 189 238 177 201 233 207 198 181 209
259 193 160 156 94 115 84 107 140 220 158 106 150 133 102 107 92 150 177 170
128 115 111 112 95 72 80 72 99 92 73 83 107 92 102 88 76 97 77 91
84 68 81
NWC-D11B 83
244 471 263 264 360 371 306 363 340 410 422 427 380 339 297 309 330 319 303 316
355 335 318 308 288 241 154 171 203 209 217 192 229 178 191 242 210 196 177 206
250 201 159 156 104 107 100 98 139 209 148 118 143 127 99 109 97 148 177 176
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67 67 63
NWC-D12A 51
218 267 283 208 257 198 211 249 219 248 199 172 148 212 214 159 144 144 203 165
177 165 157 171 119 113 142 143 110 92 115 131 83 90 63 122 156 184 98 120
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NWC-D12B 51
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183 162 159 168 93 103 144 143 121 92 107 132 83 87 77 126 152 180 92 126
115 147 158 112 147 99 131 128 170 151 126
NWC-D13A 58
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227 251 342 276 289 327 360 319 323 347 341 251 237 310 289 194 223 226 299 209
236 193 177 231 165 124 225 203 151 125 158 210 125 129 107 168 141 164
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337 290 529 420 355 321 211 269 289 193 158 175 155 148 167 171 148 265 255 230
228 254 335 270 278 316 348 321 334 341 362 255 239 292 289 202 207 221 276 208
234 189 181 232 164 133 222 208 154 134 153 194 126 124 109 174 146 157
NWC-D14A 71
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173 236 187 146 220 187 157 166 180 201 213 162 170 199 167 141 187 158 141 120
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NWC-D14B 71
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NWC-D15A 70
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NWC-D16A 93
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NWC-D17A 80
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183 142 82 144 158 127 104 112 104 104 145 158 143 160 147 119 120 85 111 131
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NWC-D17B 80
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83 70 80 72 80 48 43 64 87 88 69 79 99 63 53 47 57 63 55 63
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NWC-D19A 75
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NWC-D20A 93
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227 198 179 203 256 283 195 168 144 179

NWC-D31A 74
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NWC-D33A 56
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NWC-D33B 56
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252 290 352 331 220 224 241 252 235 216 262 178 144 206 194 218 167 264 298 373
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NWC-D35A 86
212 284 364 343 404 355 354 261 337 353 286 261 391 311 334 331 222 305 299 262
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the 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 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 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 University of 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 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 to 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.

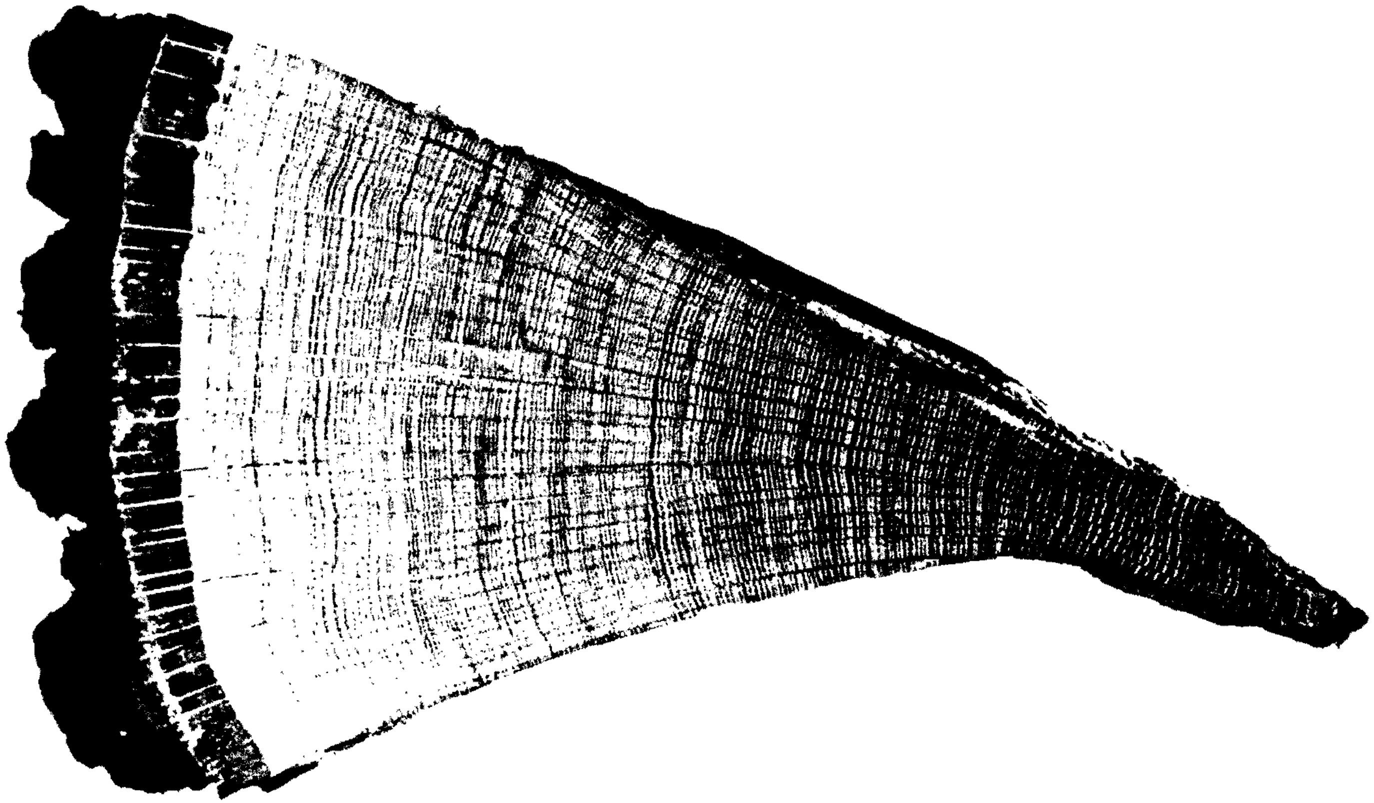

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

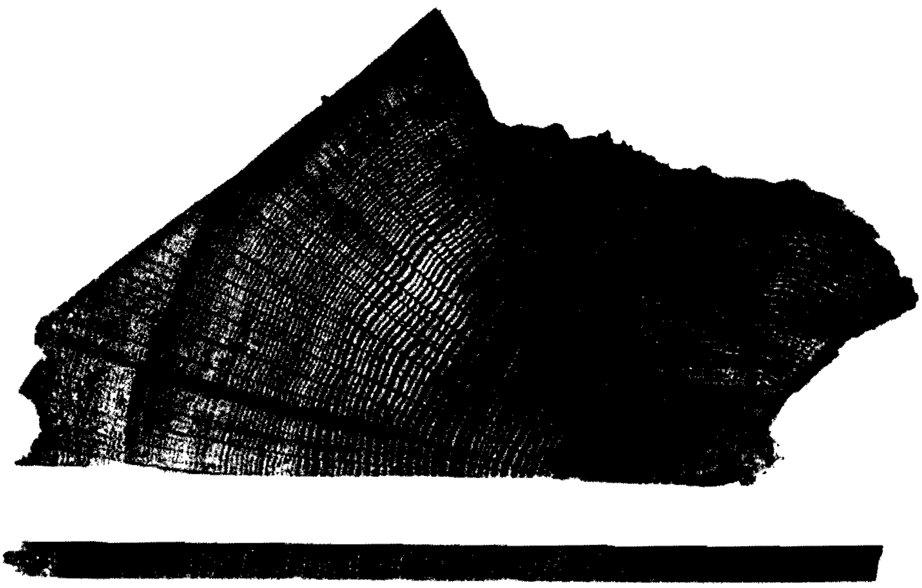

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig. 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 measure 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.

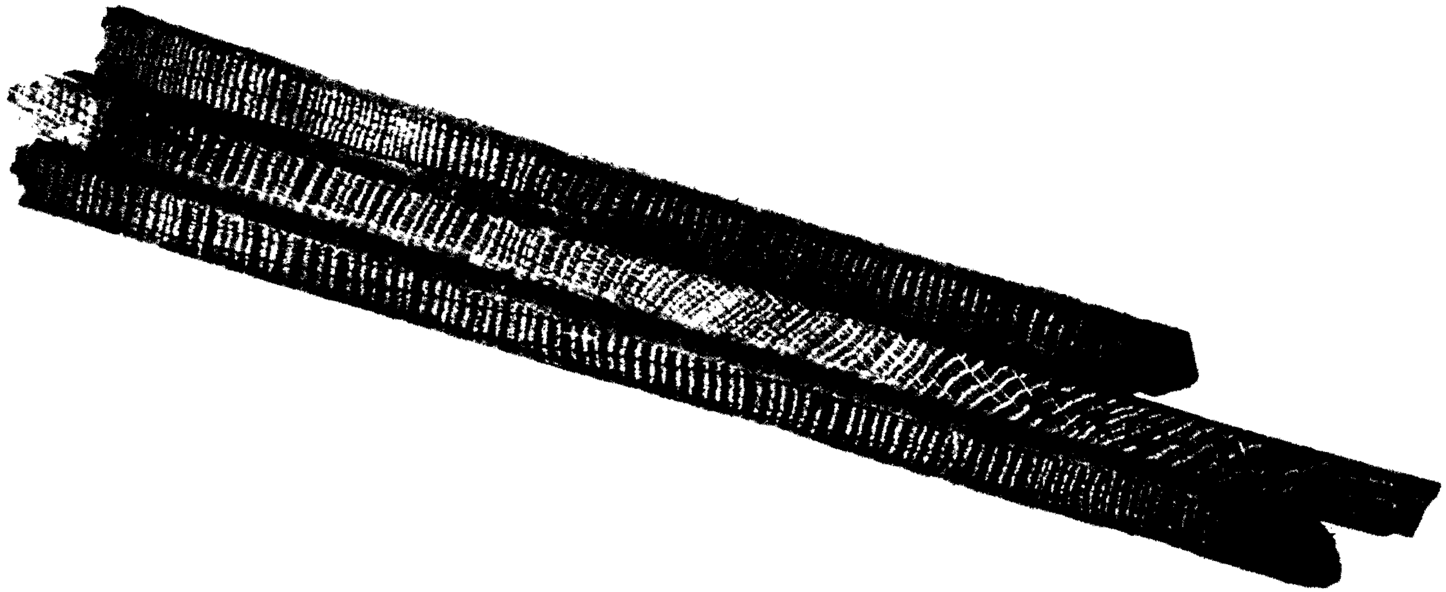

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 2; it is about 15cm long and 1cm 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.

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 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 3).

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 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 Fig 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 Fig 5. 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 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months 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 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 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 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, 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 *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

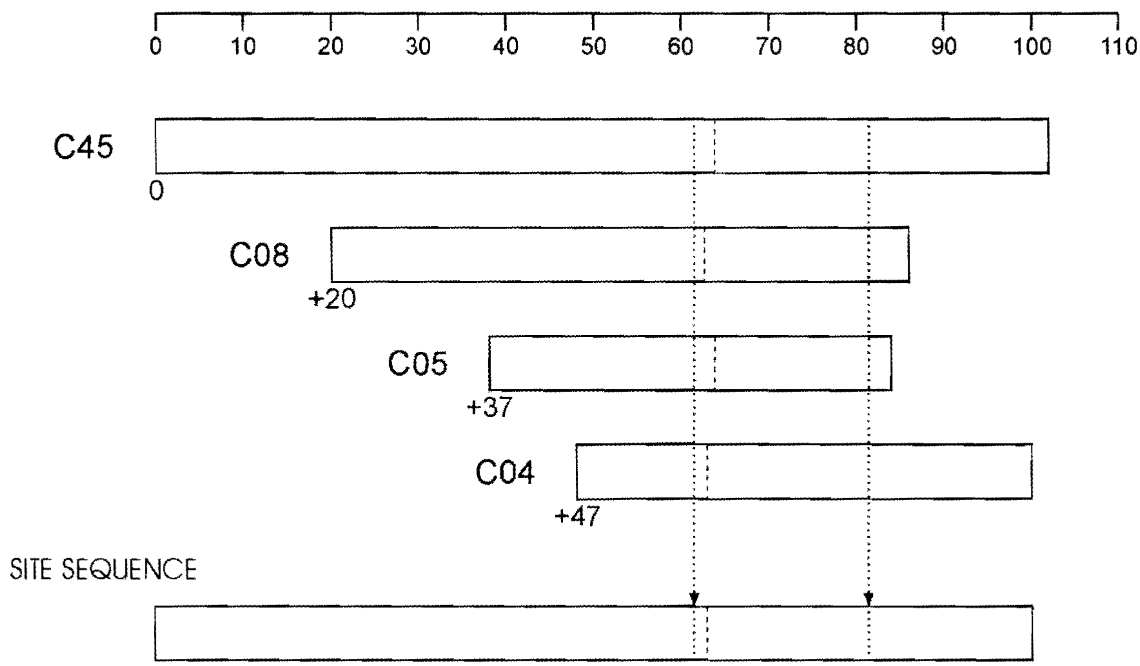

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 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 Fig 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 Fig 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 phenomena 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.

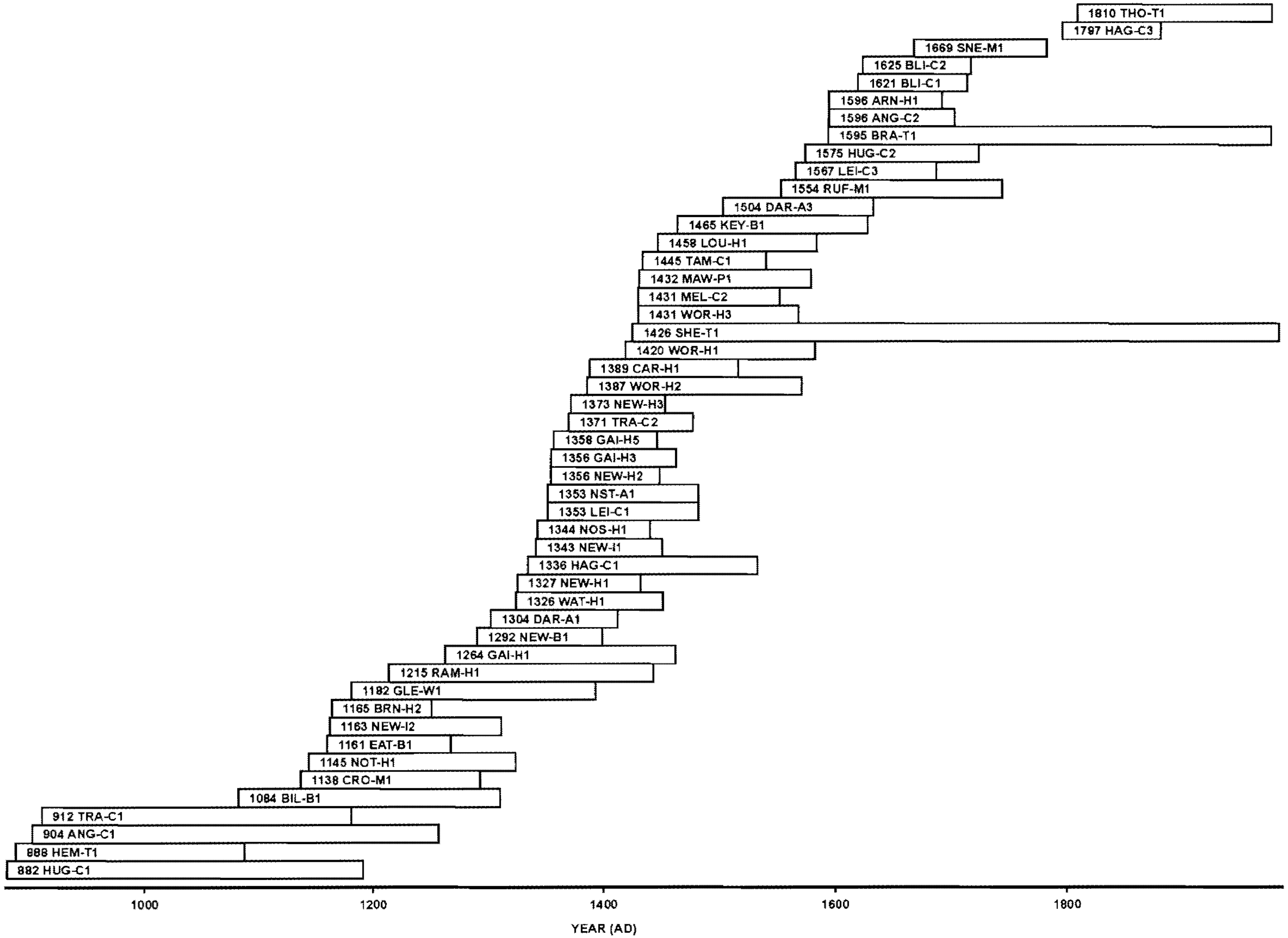

Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

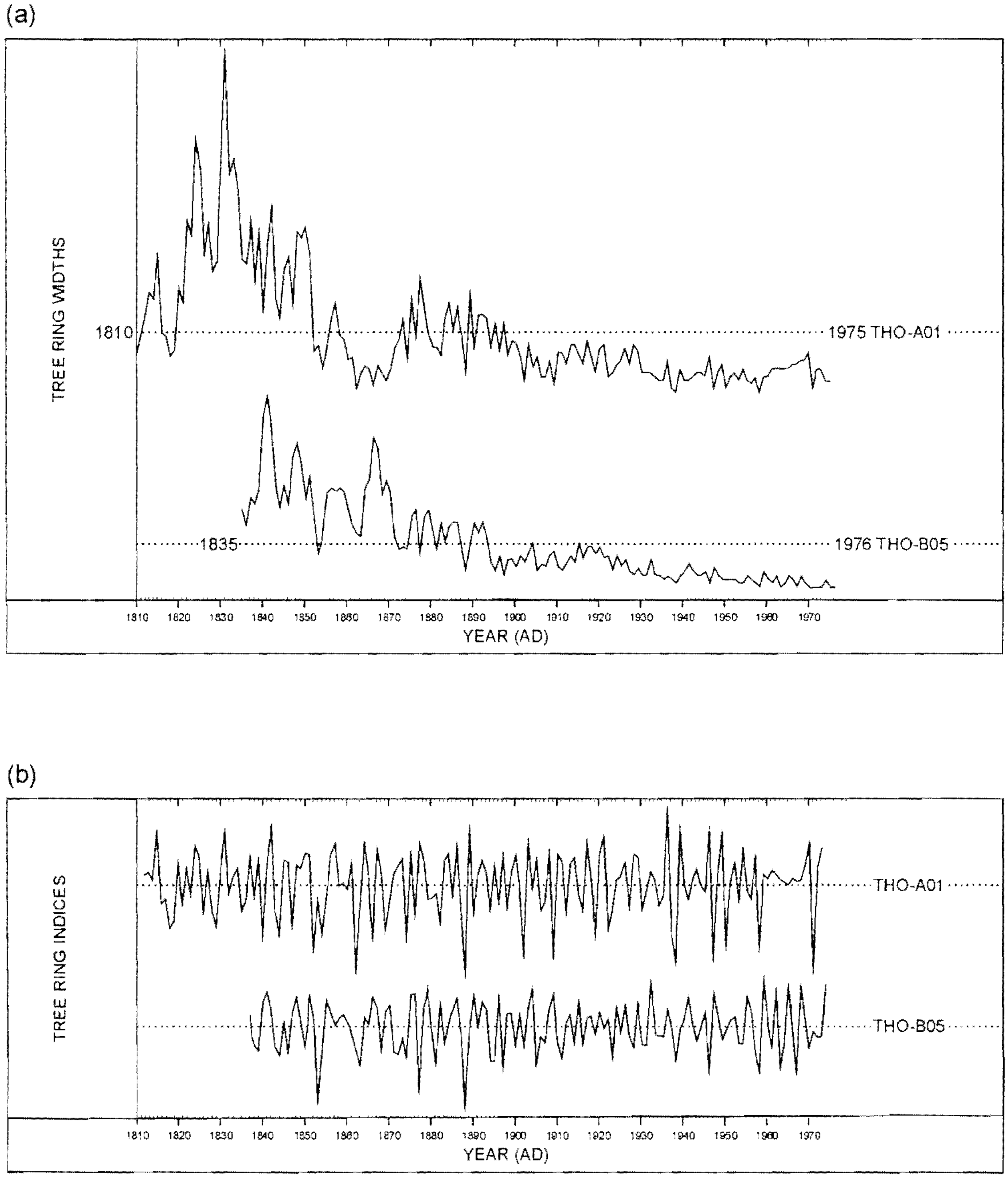

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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