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Summary

Forty-six samples were obtained from timbers at Hunwick Hall Farm. Of these, 40 were analysed by tree-ring dating, this analysis producing two site chronologies. The first site chronology, HWKASQ01, comprises 20 samples these having a combined overall length of 96 rings. These rings were dated as spanning the years AD 1402-97.

Interpretation of the sapwood would suggest that the roofs of the east range (north end) and the north range (east end) are constructed of timbers cut in the period AD 1501 – 26, though possibly not as part of one single felling. Three common joists in the first-floor frame of the east range, and a single joist in the carriageway entrance ceiling are very likely to have been felled during this time too.

A number of other samples, including two which were combined to make site chronology HWKASQ02 with a combined overall length of 62 rings, cannot be dated. It is possible, though not at all certain, that much of the first-floor frame of the east range is made up of timbers with different felling dates.

Keywords

Dendrochronology
Standing Buildings

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Introduction

Hunwick Hall Farm, Hunwick, near Bishop Aukland (NZ 189 324; Figs 1 and 2) is on the site of a medieval manor complex dating back, it is believed, to at least the latter half of the twelfth century. The present house, the former Hall, and its associated outbuildings are grouped round three-sides of an elongated courtyard, with the house to the south side, and the other buildings, currently used as barns, animal pens, and stores, to the north and east sides. There are no buildings to the west. A general plan of the site is shown in Figure 3.

On stylistic evidence, in the form of window and door openings, mullions and door-jambs, it is believed that some elements of the extant buildings date from the fourteenth century. While some other portions may belong to the fifteenth century, further substantial elements are probably of sixteenth-century date. There is also evidence for later, eighteenth and nineteenth-century, building activity. The buildings are listed as Grade II* and are on the English Heritage Buildings at Risk Register.

Sampling

Sampling and analysis by tree-ring dating of timbers from Hunwick Hall Farm were commissioned by English Heritage. This was requested to inform a proposal for the conversion of the farm buildings to residential use. For this purpose the sampling of a number of elements of the site was required:

The East range.

On stylistic evidence it is thought that the shell of this building dates to the first half of the fourteenth century. The position and height of the windows show that, as originally built, it was intended to be of a single story. It also appears to have been built as two separate rooms, the northern two-thirds now of four bays, and a southern one-third now of two bays.

At some point, however, a first-floor was inserted in the northern section, making it two storeys. It is believed that this was done in the late-fifteenth or early-sixteenth century, such an interpretation being based on the form of the roof which is stylistically of this date, representing a re-roofing, rather than an early fourteenth-century original. The southern third of the east range, although also re-roofed at the same time, was not floored and remains open from floor to ridge-beam.

The roof of the northern part of the east range consists of five truncated principal rafter trusses, with tiebeams and collars. The undersides of the principals flare out or expand as they reach the collars forming arched heads. The tiebeams are slightly cambered and have chamfered soffits. Each pitch of the roof carries double purlins, the lower ones trenched into the back of the principal rafters, the upper ones clasped between the collars and the common rafters above. Later still the roof was altered slightly by the insertion of slightly curved struts from tiebeams to principals, and short king posts above the collars. The two roof trusses of the southern third of the east range are identical in form, an illustration of a typical truss being given in Figure 4. The quality of the carpentry at Hunwick suggests that the east range was still of reasonably high status at the time of its re-roofing.

The floor frame of the northern part of the east range consists of three large east-west bridging beams, with smaller common joists between them. While the bridging beams and some of the common joists show some consistency in dimension and patina, most common joists show variability, many being smaller still, less well carpentered, replaced in modern softwood, or missing altogether. The variation in timber, and the presence of inserted modern supporting block-work piers, give the impression that, despite no clear evidence for it, this floor has seen considerable alterations and contains timber with different felling dates.

Also in the east range are a series of wooden lintels to door and window openings. It was believed that these might belong to the original early fourteenth-century build.

From these timbers a total of 24 core samples were obtained. Each core was given the code HWK-A (for Hunwick site "A") and numbered 01 - 24. Fourteen samples, HWK-A01 - 14, were obtained from the roof timbers of the northern part of the range, with a further ten samples, HWK-A15 - 24 being obtained from the most suitable bridging beams and common joist of the floor-frame, and the door and window lintels. Because of the unsafe nature of the southern third of the east range, and the prospect of the imminent collapse of the south gable, no samples were obtained from the two trusses in this area.

North range (east end).

The north range, generally of two stories, comprises structures of possibly three identifiable building phases, the easternmost of these appearing to be the earliest. The roof of this section has six truncated principal trusses of exactly the same type found in the northern section of the east range. The undersides of the principals again flare towards the collars, and the tiebeams are slightly cambered and chamfered on their soffits. This would again suggest that this portion of the building was of moderately high status. From these roof timbers a further 14 core samples were obtained, HWK-A25 - A38.

The first-floor frame of this section was in two halves, both comprising close-set north-south joists. Those in the east half comprise modern softwood beams and no samples were taken. The joists in the west half of the east end, whilst all being of oak and being of reasonable size, were derived from very fast grown trees. It was felt very unlikely that such timbers would provide satisfactory samples, that is cores with at least 54 rings, and these beams were not cored.

North range (central building).

Adjacent and west of the building described above is a further building, possibly, though not necessarily, of a different phase of construction. The east end of this central portion is taken up with an entrance, or "carriageway", opening, with a ceiling of close set, east - west joists. This may be the position of the original entrance into the courtyard. The upper floor of this section, and the rooms immediately to the west of the carriageway, are again roofed with truncated principal rafter trusses, four in number. Only part, about half, of the first-floor frame of the section immediately west of the carriageway opening remains. The first floor beams of the western half having been cut out.

It was seen that almost all the beams used in this central section of the northern range were made from very fast grown timbers. It was felt very unlikely that such timbers would provide samples with at least 54 rings. This was particularly clear in the cut-off stubs of first-floor joists still buried in the walls of the western half of this section. It was seen that, had it been possible to core these timbers, they would have provided samples with 25 - 30 rings.

Thus, from the available timbers of the central range, only eight further samples were obtained, HWK-A39 - 46, all of them from the ceiling joists of the carriageway opening.

North range (west building).

The western-most building of the north range is possibly, though again not certainly, of a third phase of building, possibly eighteenth or nineteenth century. Although not included in the sampling request it was examined but seen to contain only relatively modern softwood timbers.

Farm House (former Hall) (south range).

Although again not included in the initial request for sampling the opportunity was taken to make a brief examination of the timbers of the former Hall, now the house. Although the building does contain three large beams in the ceiling of the ground floor, these are all relatively modern softwood timbers. An examination of the roof-space was not made, it being understood that this had been replaced earlier, in the twentieth century.

Plans, Figures 5a-c, show the approximate positions of the timbers sampled. In these drawings, as in Table 1, trusses, frames, beams, and other timbers are numbered and identified on a north to south, or east to west basis, as appropriate.

The Laboratory would like to take this opportunity to thank the owner of Hunwick Hall, Mrs Bellarby, for her enthusiasm for this project and for being so accommodating during sampling. We would also like to thank Martin Roberts of English Heritage north-east office for his help and for allowing us to use his drawings and descriptions in the introduction to this report.

Analysis

Each of the 46 samples obtained was prepared by sanding and polishing. It was seen at this point that only two of the cores from the ceiling of the carriageway entrance, HWK-A39 and A40, had sufficient rings for satisfactory analysis, the other six having between 15 and 28 rings. These short samples were rejected.

The annual growth-ring widths of the useable 40 samples were measured, the data of these measurements being given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum *t*-value of 4.5 two site chronologies could be formed. The first site chronology comprises 20 samples, the relative position of these samples being shown, sorted by sampling location, in the bar diagram, Figure 6.

The samples were combined at these relative off-set positions to form site chronology HWKASQ01, with a combined overall length of 96 rings. This site chronology was then compared with an extensive range of reference chronologies for oak indicating a consistent match with a high number of these when the date of its first ring is AD 1402 and the date of its last ring is AD 1497. Evidence for this dating is given in the *t*-values of Table 2.

The second site chronology comprises two samples, cross-matching as shown in the bar diagram, Figure 7. The samples were combined at these relative off-set positions to form site chronology HWKASQ02, with a combined overall length of 62 rings. This site chronology was also compared with an extensive range of reference chronologies for oak but could not be dated.

The two site chronologies thus created, HWKASQ01 and HWKASQ02, were compared with each other and with the 18 remaining measured but ungrouped samples. There was, however, no further satisfactory cross-matching. Each of the 18 ungrouped samples was compared individually with a full range of reference chronologies, but there was no satisfactory dating.

Interpretation

Analysis by dendrochronology has produced two site chronologies. The first, HWKASQ01, comprises 20 samples with a combined overall length of 96 rings. These rings are dated as spanning the years AD 1402 to AD 1497. Whilst unfortunately, due to the loss of complete sapwood through its decay and removal, the precise dates of felling cannot be calculated, some indication of the probable felling date can be made.

The collective average last heartwood ring date on the 20 samples in site chronology HWKASQ01 is AD 1486. Assuming that all the dated timbers were cut as part of a single operation, and using a 95% confidence limit of 15 - 40 sapwood rings on mature oaks from this part of England, it is estimated that they would have a felling date in the range AD 1501 to AD 1526.

However, even if they had not been felled at exactly the same time, it would appear very likely that the dated timbers from each sampling area were felled at very similar times. For example, the timbers from the east range roof alone have an average last heartwood ring date of AD 1485. Using a 95% confidence limit of 15 - 40 sapwood rings on mature oaks from this part of England would give the timbers represented an estimated felling date in the range AD 1500 to AD 1525.

The timbers from the east range first-floor frame have an average last heartwood ring date of AD 1489. Using the same 95% confidence limit, 15 - 40 sapwood rings, would give these timbers an estimated felling date in the range AD 1504 to AD 1529.

The timbers from the north range (east end) roof alone have an average last heartwood ring date of AD 1484. Using the same sapwood estimate as above would give these timbers an estimated felling date in the range AD 1499 to AD 1524. The timber from the carriageway entrance has an estimated felling date in the range AD 1503 to AD 1528. It will be seen that all estimated felling date ranges are contemporary.

The second site chronology, HWKASQ02, comprises two samples with an overall combined length of 62 rings. This site chronology cannot be dated. The relative positions of the heartwood/sapwood boundaries on each, however, suggest that the timbers represented, both common joists of the floor frame of the east range, were felled at the same time.

Conclusion

Interpretation of the sapwood would suggest that, although there is some variation in the relative position of the heartwood/sapwood boundary, as perhaps seen on sample HWK-A04, the dated material represents timbers, if not of a single phase of felling, then at least of very closely related set of fellings. It is estimated that these fellings took place some time in the first quarter of the sixteenth-century.

Most of the dated timbers are from the roofs of the east range (northern part) and the north range (east end). These roofs are identical to each other and, while it cannot be proven that the timber for each was felled in exactly the same year, there is little reason to suspect that they are not both part of the same general phase of re-roofing.

Truncated principal trusses are a type found in a number of County Durham's more important late-medieval buildings. These include Crook Hall, Durham, dated by dendrochronology to AD 1468 (Howard *et al* 1992), Seaton Holme, Easington, dated to the early-sixteenth century (Howard *et al* 1988 unpubl), and Wheesoe Grange, Darlington (now demolished). The date obtained for the two roofs at Hunwick is generally similar to these, though, depending on the actual felling date, may be a late example of the type.

Three of the dated samples, HWK-A20, A21, and A23, are from the first-floor frame of the east range, all of them representing common joists. This would suggest that at least some of the timbers in this floor were felled in the early sixteenth-century as well.

However, a number of the floor timbers, five out of eight, remain undated. It will be seen from Table 1 that most of these have low numbers of rings, many of them having only 54, the minimum required for satisfactory analysis. As indicated above this floor is an area which appears to have seen a degree of alteration, and it is possible that many of the undated timbers are of different felling dates having been inserted into their present positions during relatively recent repairs. It is thus not possible to say with certainty that the whole floor-frame dates to the early-sixteenth century.

One of the dated timbers in site chronology HWKASQ01, represented by sample

HWK-A39, is from the ceiling of the carriageway entrance and may indicate either the date that this was originally constructed, or closed by a new ceiling. However, given that only one timber out of eight beams sampled is dated, this interpretation is not certain and some caution might be expressed.

It may be worth noting that several of the samples in site chronology HWKASQ01 cross-match with each other with high *t*-values, figures in excess of *t*=14, 18, and even 20 being seen. Such values would strongly suggest that the timbers represented, mostly from the roof of the east range, were at least growing very close to each other. Indeed, given that some of these high *t*-values are between timbers of the same truss, often principal rafters, and that similarities between such timbers was seen at the time of sampling, it is likely that such timbers were derived from the same tree. This is seen to a lesser extent in some of the timbers from the roof of the east end of the north range, and from the floor-frame.

The second site chronology, HWKASQ02, comprises two samples with an overall combined length of 62 rings. This site chronology cannot be dated. The relative positions of the heartwood/sapwood boundaries on each, however, suggest that the timbers represented, both common joists of the floor frame of the east range, were felled at the same time.

Neither of the two samples from window or door lintels of the east range has dated. It was hoped that sampling these might indicate the original construction date for the east range, but this cannot be done. Again, both samples have low numbers of rings.

It will be seen from Table 2 that the material from Hunwick, perhaps not unexpectedly, cross-matches very well with reference chronologies made up of material from other sites in the north-east of England. This would suggest that the material used at Hunwick and these other sites come from the same general area, again not unexpectedly.

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Table 1: Details of samples from Hunwick Hall

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	East range roof					
HWK-A01	Tiebeam, truss 1	80	4	AD 1409	AD 1484	AD 1488
HWK-A02	East principal rafter, truss 1	54	no h/s	AD 1415	------	AD 1468
HWK-A03	West principal rafter, truss 1	54	h/s	------	------	------
HWK-A04	Tiebeam, truss 2	64	2	AD 1434	AD 1495	AD 1497
HWK-A05	West principal rafter, truss 2	57	no h/s	AD 1408	------	AD 1464
HWK-A06	East principal rafter, truss 2	72	4	------	------	------
HWK-A07	Tiebeam, truss 3	60	7	------	------	------
HWK-A08	East principal rafter, truss 3	54	h/s	AD 1427	AD 1480	AD 1480
HWK-A09	West principal rafter, truss 3	59	5	AD 1427	AD 1480	AD 1485
HWK-A10	West principal rafter, truss 4	83	h/s	AD 1407	AD 1489	AD 1489
HWK-A11	East principal, truss 4	87	h/s	AD 1402	AD 1488	AD 1488
HWK-A12	Tiebeam, truss 4	72	h/s	------	------	------
HWK-A13	West lower purlin, truss 3 – 5	54	h/s	AD 1432	AD 1485	AD 1485
HWK-A14	West lower purlin, truss 2 – 3	55	h/s	------	------	------
	East range first-floor					
HWK-A15	Common joist 3, bay 3	62	2	------	------	------
HWK-A16	East-west bridging beam 1	65	2	------	------	------
HWK-A17	Common joist 4, bay 3	55	h/s	------	------	------
HWK-A18	East-west bridging beam 2	74	h/s	------	------	------
HWK-A19	Window lintel	58	no h/s	------	------	------
HWK-A20	Common joist 7, bay 1	56	h/s	AD 1434	AD 1489	AD 1489

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	East range first-floor					
HWK-A21	Joist 5, bay 1	55	4	AD 1440	AD 1490	AD 1494
HWK-A22	Door lintel	57	h/s	------	------	------
HWK-A23	Joist 4, bay 1	55	6	AD 1441	AD 1489	AD 1495
HWK-A24	Joist 3, bay 1	54	h/s	------	------	------
	North range – east end roof					
HWK-A25	North principal rafter, truss 1	54	h/s	------	------	------
HWK-A26	South principal rafter, truss 1	56	3	AD 1434	AD 1486	AD 1489
HWK-A27	Collar, truss 1	54	h/s	------	------	------
HWK-A28	North principal rafter, truss 2	55	h/s	AD 1428	AD 1482	AD 1482
HWK-A29	South principal rafter, truss 2	54	h/s	------	------	------
HWK-A30	Collar, truss 2	55	h/s	------	------	------
HWK-A31	North principal rafter, truss 3	56	no h/s	AD 1411	------	AD 1466
HWK-A32	South purlin, truss 2 - 3	56	6	AD 1435	AD 1484	AD 1490
HWK-A33	South purlin truss 4 - 5	54	12	AD 1444	AD 1485	AD 1497
HWK-A34	North principal rafter, truss 4	57	no h/s	AD 1416	------	AD 1472
HWK-A35	Tiebeam, truss 4	54	3	AD 1434	AD 1484	AD 1487
HWK-A36	Collar, truss 4	54	h/s	------	------	------
HWK-A37	North principal rafter, truss 6	54	h/s	------	------	------
HWK-A38	Tiebeam, truss 6	55	h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Carriageway entrance					
HWK-A39	Joist 4	58	7	AD 1438	AD 1488	AD 1495
HWK-A40	Joist 6	54	16	------	------	------
HWK-A41	Joist 3	nm	---	------	------	------
HWK-A42	Joist 1	nm	---	------	------	------
HWK-A43	Joist 2	nm	---	------	------	------
HWK-A44	Joist 5	nm	---	------	------	------
HWK-A45	Joist 7	nm	---	------	------	------
HWK-A46	Joist 9	nm	---	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
nm = sample not measured

Table 2: Results of the cross-matching of site chronology HWKASQ01 and relevant reference chronologies when first ring date is AD 1402 and last ring date is AD 1497

Reference chronology	Span of chronology	*t*-value	
Kepier Hospital, Durham	AD 1304 – 1522	10.7	(Howard *et al* 1996)
Witton Hall, Witton Gilbert, Co Durham	AD 1395 – 1475	8.9	(Howard *et al* 1996)
Seaton Holme, Easington, Co Durham	AD 1375 – 1489	8.5	(Howard *et al* 1988 unpubl)
Old Durham Farm, Durham	AD 1390 – 1619	7.9	(Howard *et al* 1995)
The College, Cathedral Precinct, Durham	AD 1364 – 1531	7.3	(Howard *et al* 1992)
Trinity House, Newcastle	AD 1397 – 1524	7.1	(Howard *et al* 2002)
East Midlands	AD 882 – 1981	7.1	(Laxton and Litton 1988)
England	AD 401 – 1981	5.3	(Baillie and Pilcher 1982 unpubl)

Figure 1: Map to show general location of Hunwick

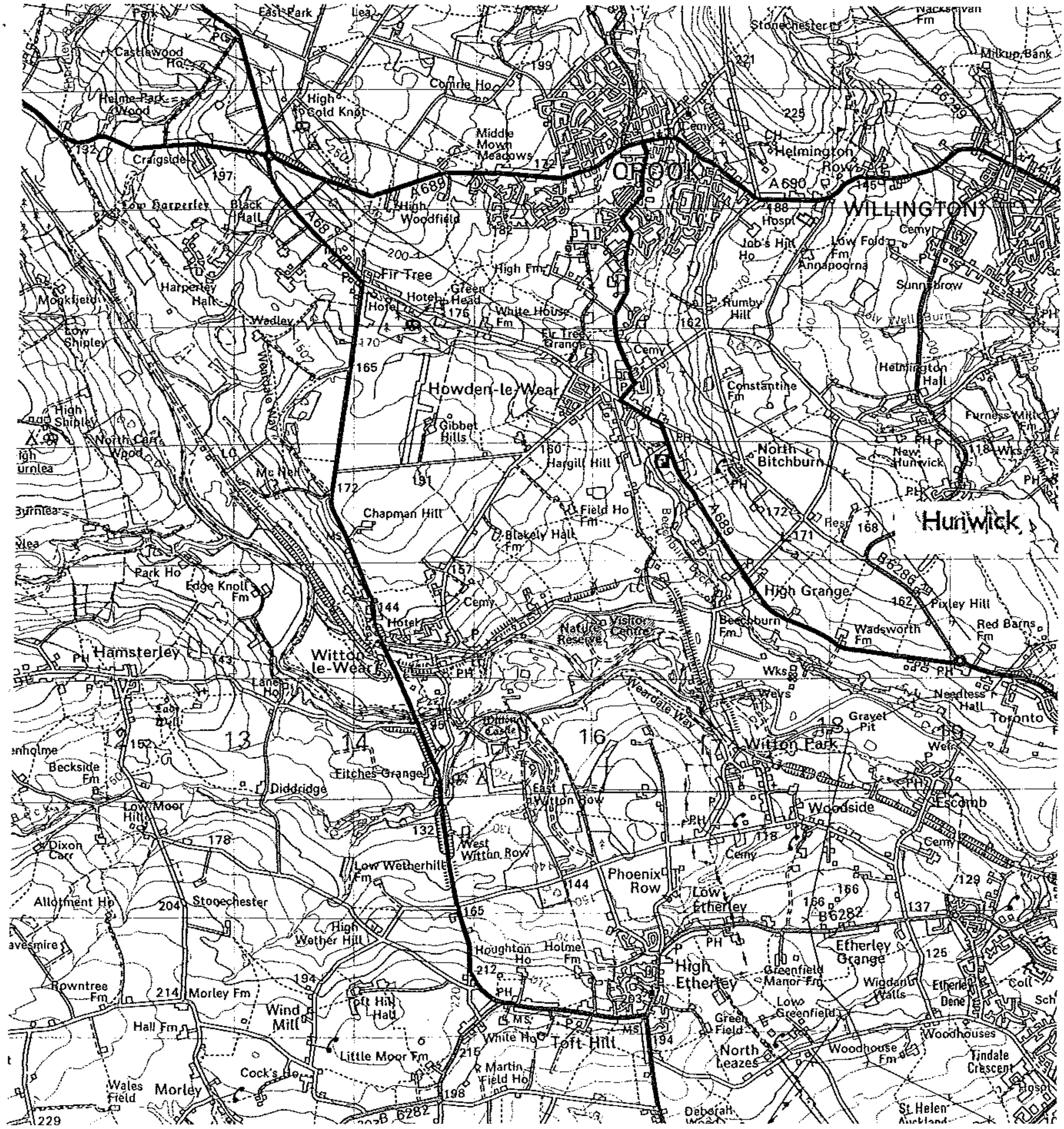


Figure 2: Map to show specific location of Hunwick Hall

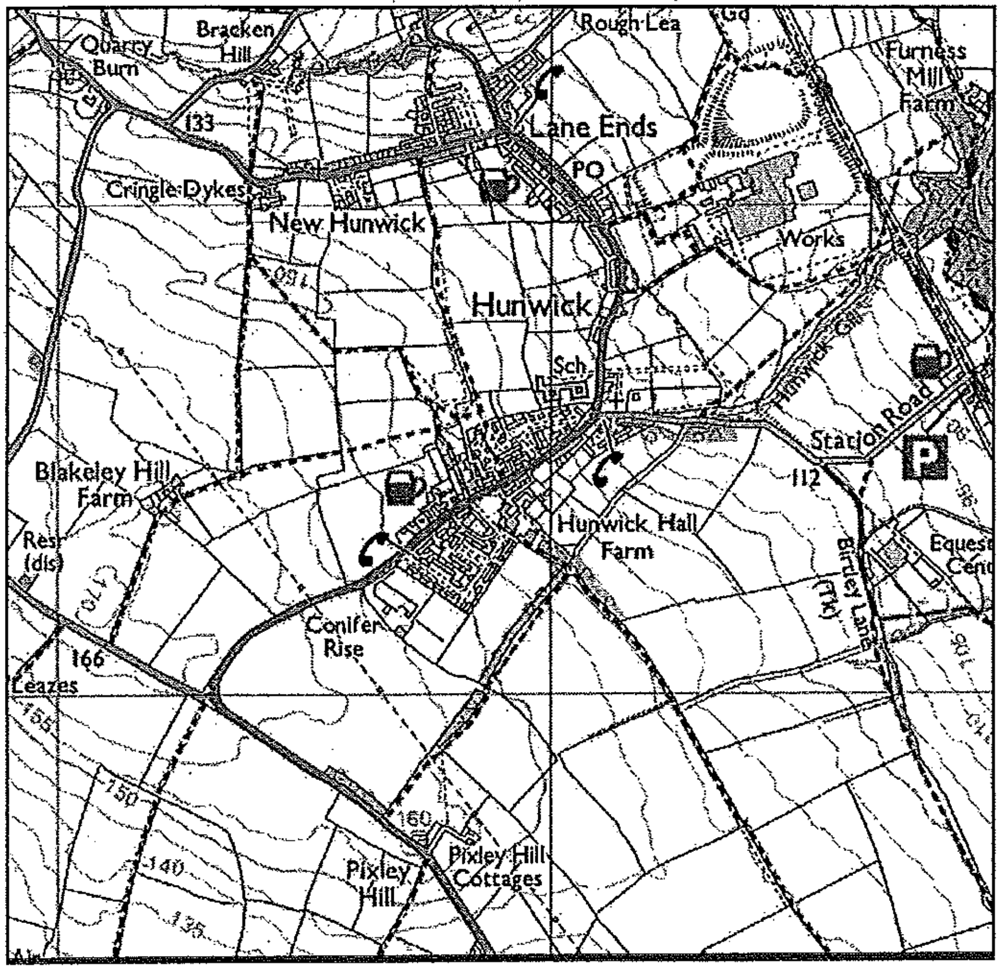


Figure 3: General plan of Hunwick Hall showing areas of sampling

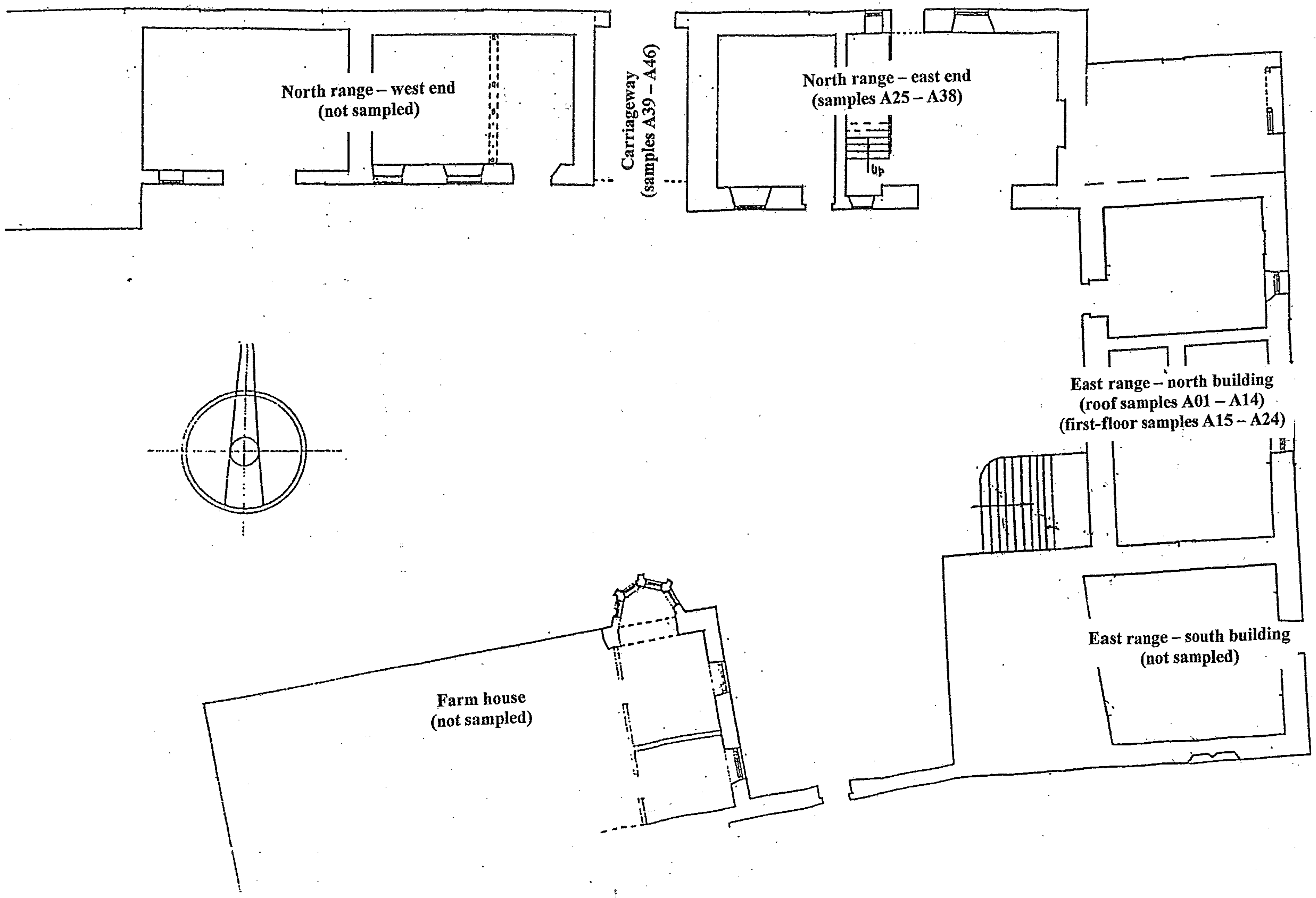


Figure 4: Illustration of a typical truss from the roof of the East range

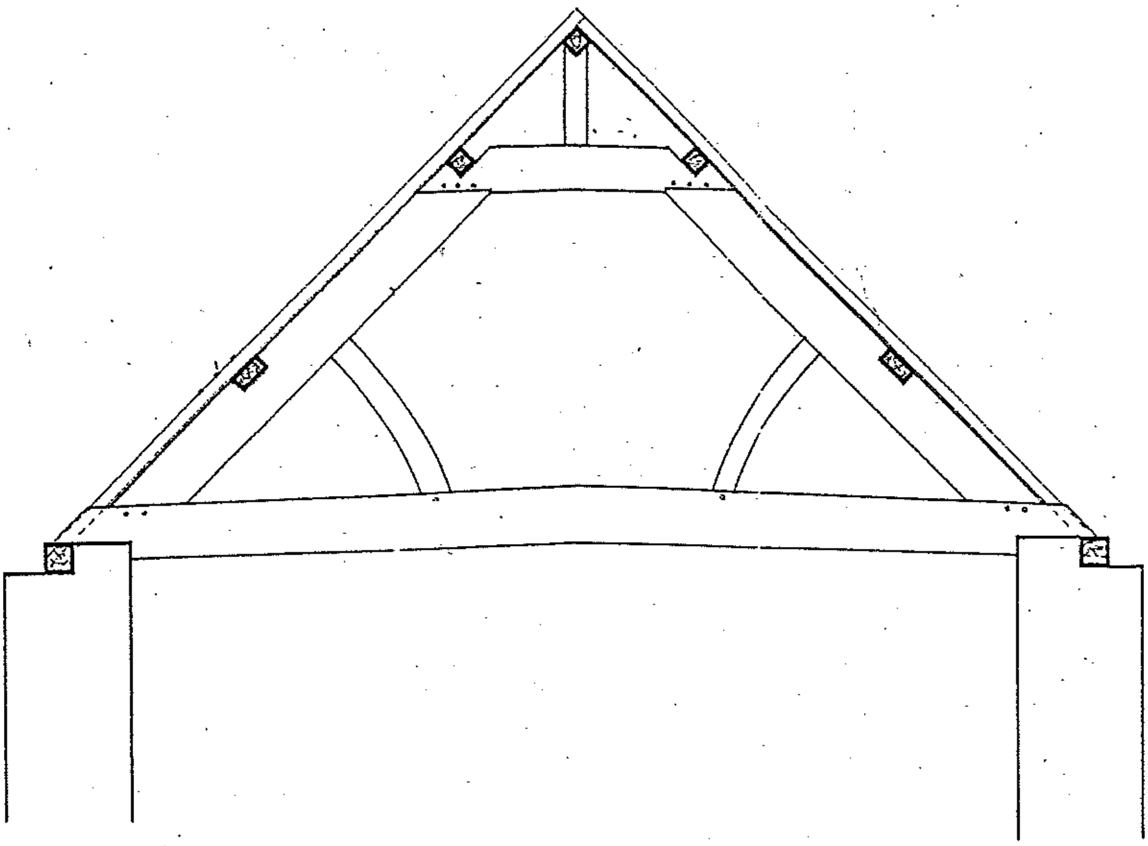


Figure 5a: Plan to show approximate location of sampled timbers in the roof of the East range

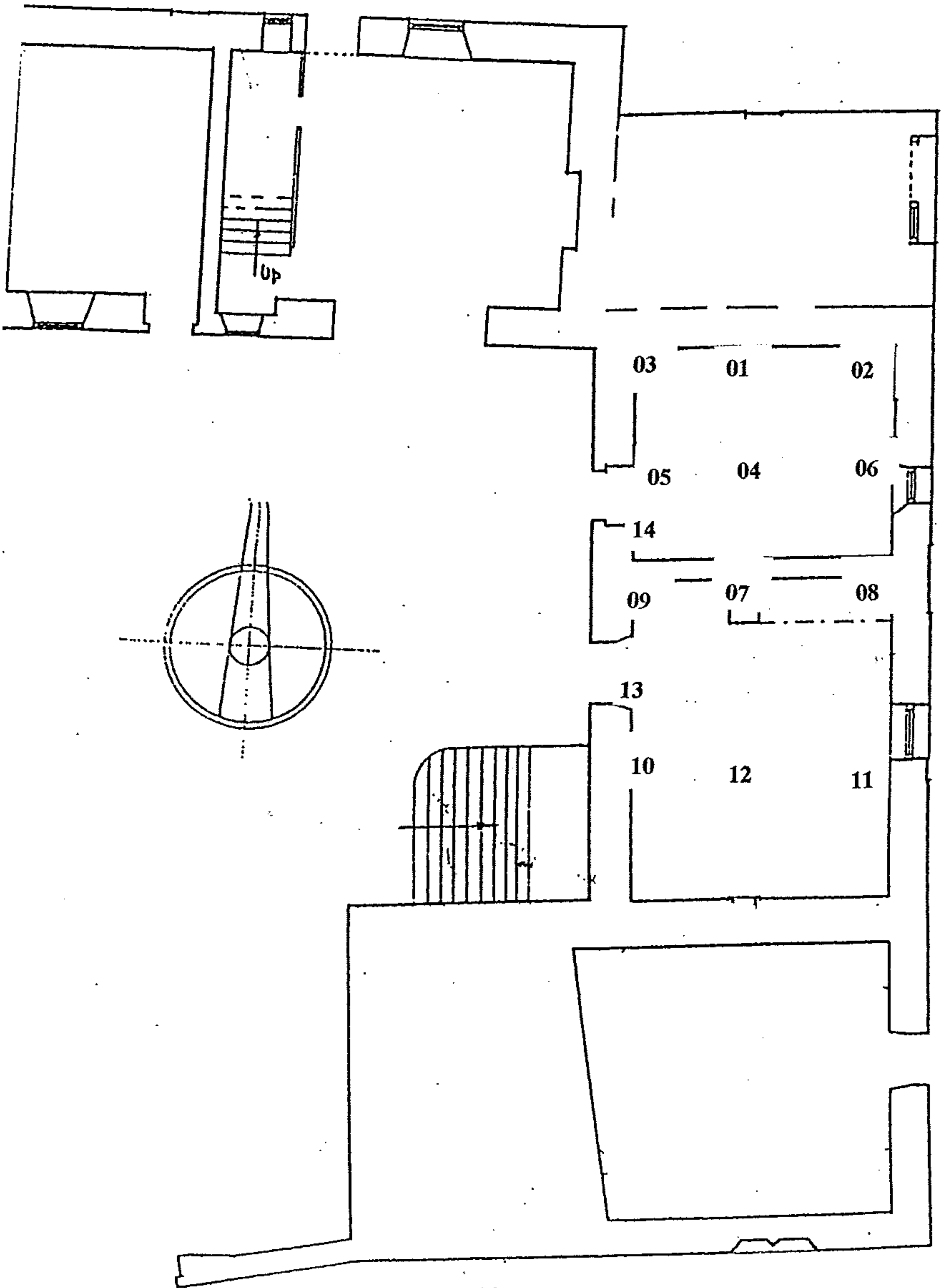


Figure 5b: Plan to show approximate location of sampled timbers from the first-floor of the East range

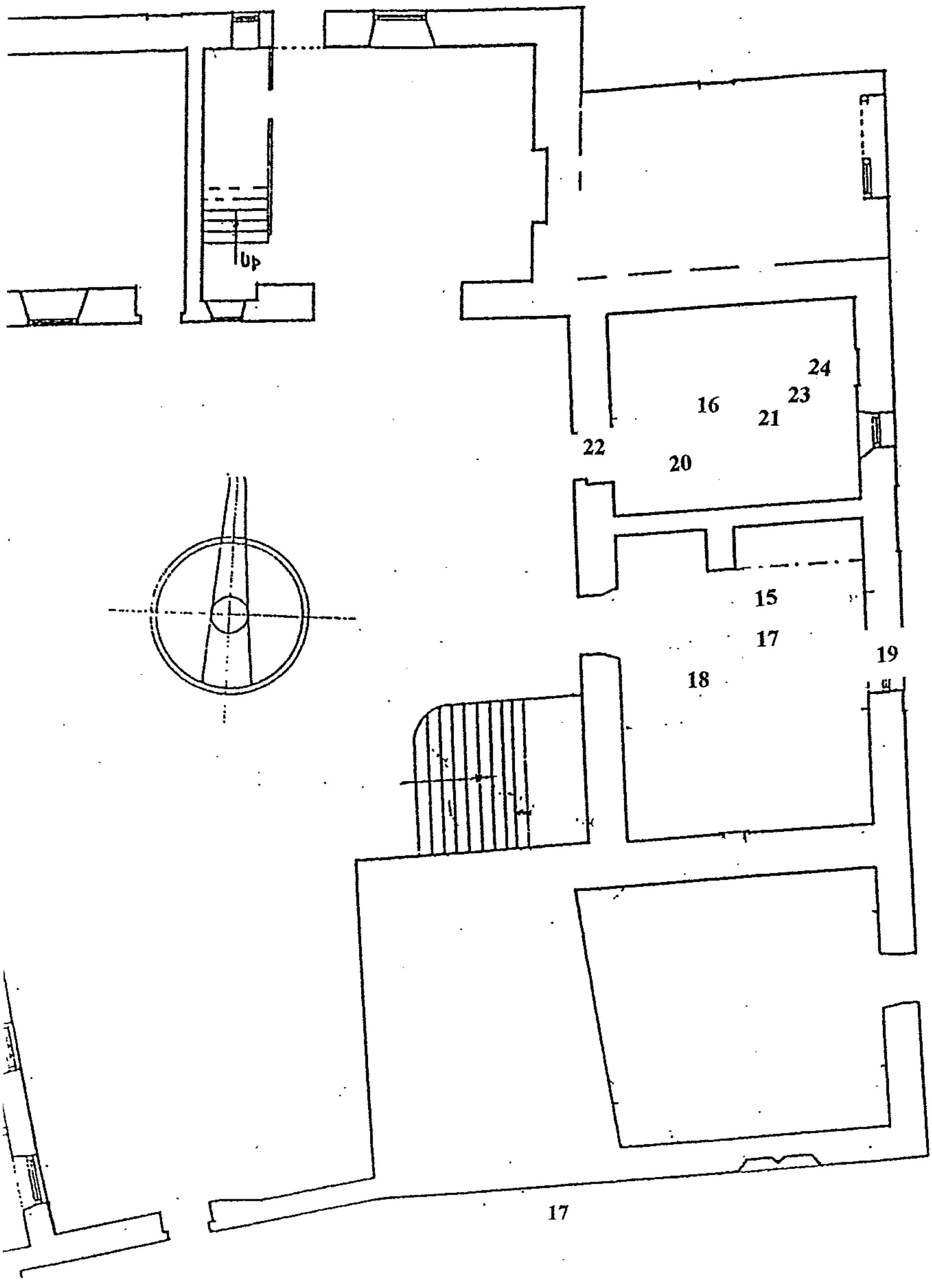


Figure 5c: Plan to show approximate location of sampled timbers from the North range (east end) and the carriageway

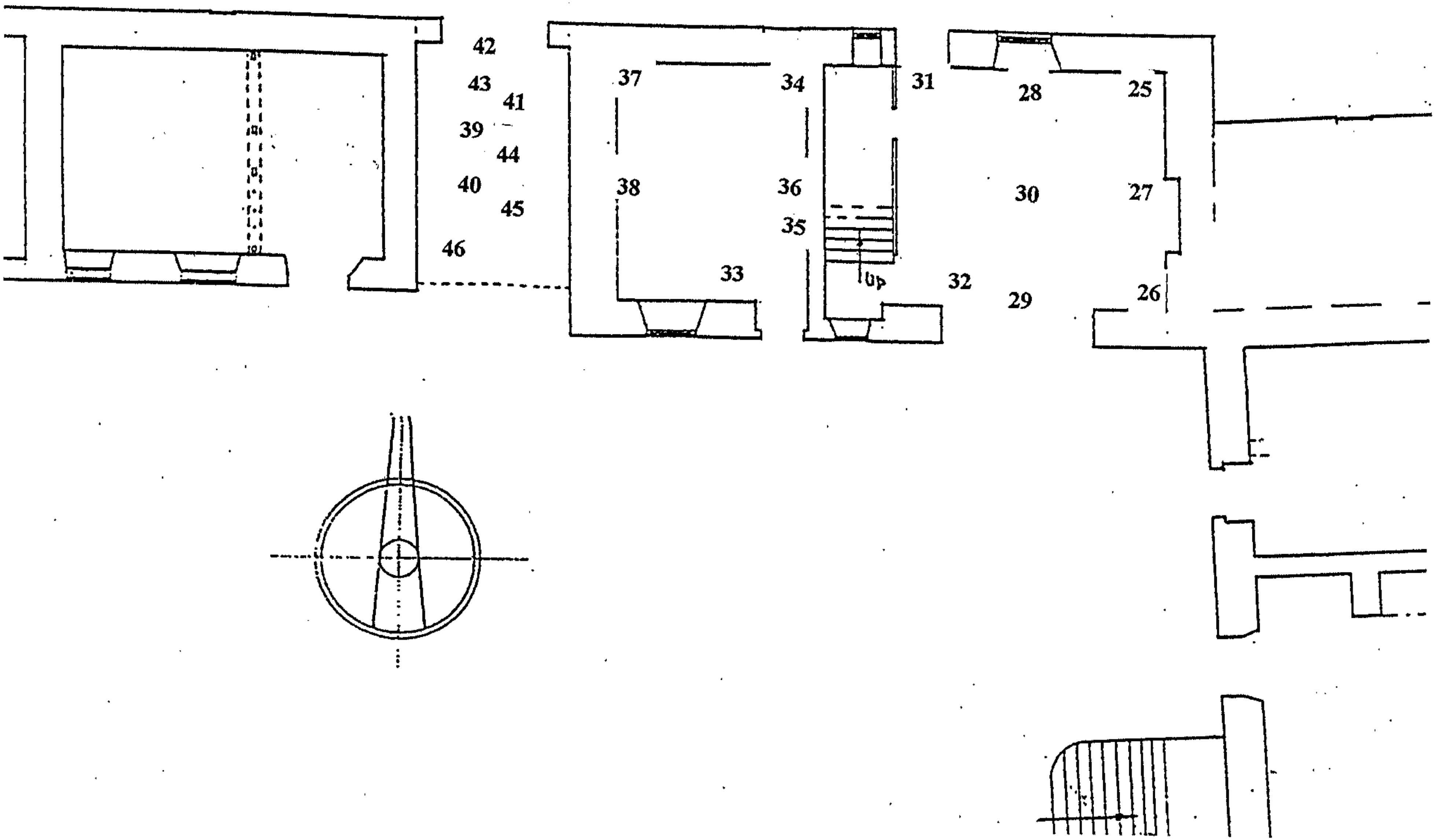
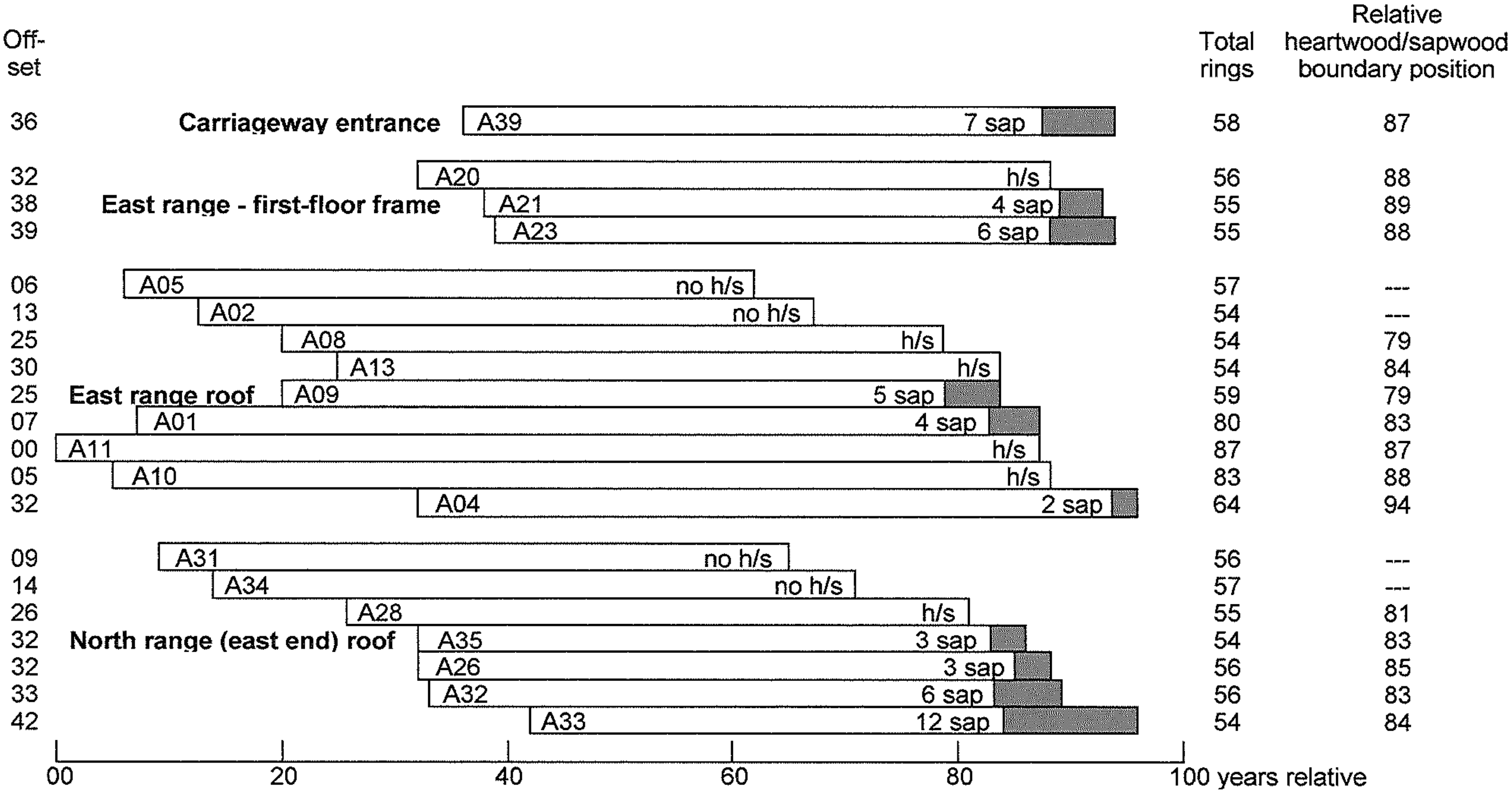
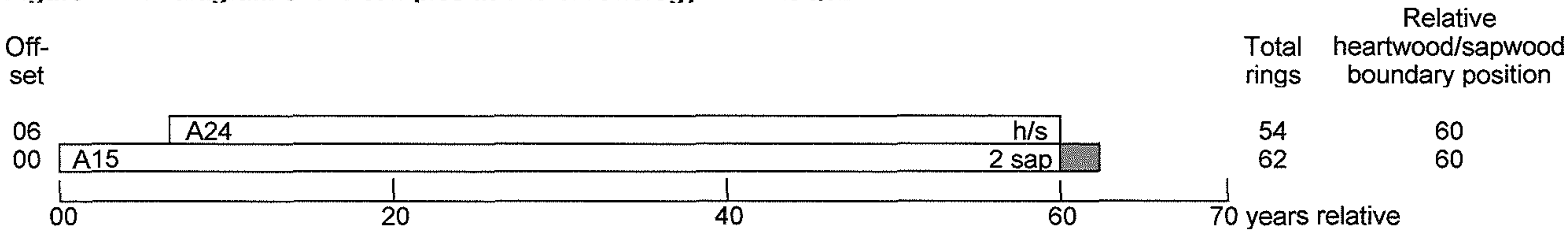


Figure 6: Bar diagram of the samples in site chronology HWKASQ01



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 7: Bar diagram of the samples in site chronology HWKASQ02



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Data of measured samples – measurements in 0.01 mm units

HWK-A01A 80
315 271 271 229 331 438 416 415 376 433 332 393 315 324 380 361 361 220 344 395
467 303 322 383 292 299 308 223 325 312 200 187 230 232 204 214 211 212 208 208
185 239 305 321 283 279 250 270 352 300 225 240 224 254 251 223 200 190 215 275
197 188 162 154 171 159 216 211 201 180 126 145 162 112 209 261 185 199 164 185
HWK-A01B 80
288 256 292 312 322 392 439 433 404 438 283 378 303 358 367 396 329 220 328 409
434 297 326 358 307 309 290 265 312 318 205 178 246 202 204 232 224 209 191 188
186 245 303 326 309 233 268 268 338 293 234 233 210 254 250 226 193 225 222 242
209 189 181 129 169 159 243 220 194 187 140 110 159 106 211 270 187 198 170 187
HWK-A02A 54
421 437 404 380 329 370 341 365 394 352 367 229 317 395 444 320 323 343 277 292
279 257 290 313 208 188 257 215 213 226 210 216 196 211 179 241 317 319 276 290
257 283 363 281 239 241 216 270 229 213 193 214 234 255
HWK-A02B 54
408 441 404 386 304 382 351 359 386 385 364 257 329 424 437 320 319 359 292 298
287 248 312 306 213 193 229 216 206 228 229 193 192 216 169 235 315 310 294 278
246 284 353 289 229 236 211 274 234 230 197 199 197 286
HWK-A03A 54
137 240 180 230 249 329 291 167 264 213 146 135 108 109 98 123 127 176 121 101
148 159 131 162 144 135 146 163 148 177 185 168 130 103 125 103 116 101 121 109
124 141 140 120 121 122 102 116 93 129 130 115 131 114
HWK-A03B 54
141 242 184 235 243 320 222 199 232 218 136 138 108 111 97 118 121 172 140 107
151 152 139 161 153 132 146 161 138 183 189 156 139 126 138 105 115 107 120 122
128 143 130 117 120 127 109 107 100 113 128 123 134 113
HWK-A04A 64
310 471 485 539 425 398 464 527 397 480 561 531 288 359 293 318 317 339 353 273
505 281 402 284 218 234 331 385 466 472 427 337 411 440 417 500 565 384 179 180
163 390 422 261 285 258 226 251 240 220 359 292 264 388 178 218 156 101 75 118
170 180 226 220
HWK-A04B 64
309 472 477 560 449 422 426 570 392 507 534 486 261 368 287 317 295 327 346 257
494 293 385 301 205 258 328 368 464 479 413 339 425 453 426 504 553 380 185 179
181 395 398 257 303 284 233 233 233 274 340 282 238 402 185 237 143 99 80 124
157 197 195 180
HWK-A05A 57
246 302 334 376 456 475 483 471 297 262 213 186 216 146 120 111 173 107 66 141
317 405 323 271 211 191 299 261 181 175 159 157 191 211 181 167 254 185 114 162
165 195 167 156 141 127 135 83 97 80 57 80 97 93 87 95 98
HWK-A05B 57
241 282 370 419 464 470 436 436 272 270 221 192 246 155 139 110 167 122 91 103
318 424 332 275 243 194 289 244 178 187 166 150 191 209 179 174 245 187 112 165
177 193 170 154 146 125 149 81 89 83 62 82 85 86 95 106 89

HWK-A06A 72
349 319 375 332 406 459 500 379 362 403 333 286 331 216 401 259 294 311 236 296
241 301 334 361 263 240 309 167 221 191 99 74 50 30 40 56 74 78 86 94
109 126 136 119 116 111 138 129 166 160 131 138 80 59 72 58 70 58 66 69
84 96 88 85 90 73 71 74 93 99 100 104
HWK-A06B 72
322 324 411 319 393 480 488 376 368 402 361 296 321 224 395 274 292 307 237 294
240 303 334 377 240 234 333 171 228 186 104 70 45 32 47 46 62 97 77 102
98 127 125 127 99 127 136 124 160 165 141 134 83 65 78 52 72 70 65 67
73 96 95 94 77 73 67 85 105 89 84 126
HWK-A07A 60
333 281 456 377 368 376 465 377 392 506 304 351 421 313 277 262 261 328 380 400
346 355 416 412 405 326 323 234 279 241 321 410 321 331 308 275 252 244 264 322
271 289 421 355 342 250 158 133 177 202 252 275 233 250 250 179 159 163 204 275
HWK-A07B 60
331 295 478 368 371 379 456 368 405 497 305 342 426 328 265 264 267 325 390 394
335 344 432 408 406 336 318 240 278 223 336 408 326 318 302 277 258 241 264 337
263 279 435 380 336 226 157 137 173 206 248 267 237 250 212 214 153 164 187 226
HWK-A08A 54
160 298 358 254 266 288 167 268 277 256 293 186 246 267 285 212 288 288 272 288
285 301 323 332 312 333 300 265 220 238 242 193 196 221 185 235 204 146 71 71
84 114 84 107 115 92 80 139 182 219 226 180 222 315
HWK-A08B 54
155 295 366 245 268 273 175 259 261 276 270 172 247 264 297 206 291 269 303 279
258 327 302 348 285 321 313 257 220 250 230 197 221 223 175 219 206 154 76 88
83 113 83 136 95 85 93 150 183 217 206 191 240 234
HWK-A09A 59
151 283 322 267 267 283 167 259 281 261 243 203 247 268 299 218 293 275 296 287
262 328 307 348 295 321 310 266 199 267 233 218 217 223 179 225 200 152 86 75
115 109 72 104 111 100 80 149 179 225 237 212 228 224 164 114 210 259 179
HWK-A09B 59
188 309 327 277 270 271 162 259 269 273 251 208 236 263 294 216 292 282 290 276
269 331 307 347 287 318 313 266 209 249 234 202 218 209 174 229 202 143 97 75
89 107 83 102 113 98 77 143 178 214 195 198 237 262 160 116 211 268 183
HWK-A10A 83
393 390 539 603 468 476 375 346 359 407 392 346 259 295 270 344 353 352 319 275
394 433 460 371 337 424 355 409 357 352 335 331 251 263 182 181 185 240 194 175
215 230 193 234 260 254 292 288 254 277 313 236 185 203 227 200 238 231 191 206
226 300 223 201 205 102 130 94 192 172 140 182 158 155 163 113 117 164 166 215
228 143 155
HWK-A10B 83
427 411 551 564 501 467 385 335 365 395 353 347 254 276 276 347 335 365 294 290
409 429 471 401 346 396 362 382 386 349 357 322 243 210 232 172 177 234 197 191
214 231 178 220 265 270 315 242 245 285 322 238 168 212 236 211 208 236 194 214
242 253 217 217 201 99 110 110 179 204 149 163 168 169 181 96 122 164 181 235
203 144 143
HWK-A11A 87
396 587 457 287 285 227 253 320 323 365 419 524 485 473 306 252 216 188 213 139
131 105 152 90 59 122 294 384 301 273 207 184 288 251 186 159 166 175 191 206
177 167 248 190 118 156 166 200 167 156 137 137 128 84 98 81 79 79 77 95

96 90 93 83 67 96 95 83 90 87 49 35 31 56 56 55 65 70 53 52
47 67 63 47 47 48 61

HWK-A11B 87

443 581 481 270 287 216 243 283 349 395 446 474 498 470 295 279 199 185 222 141
125 107 151 95 62 112 258 386 320 268 206 196 281 253 192 166 174 171 187 208
183 161 248 194 114 155 170 191 159 155 116 135 133 85 101 81 76 78 73 97
85 106 97 81 72 94 103 92 88 97 45 35 35 48 59 57 58 76 58 49
51 67 61 55 40 53 61

HWK-A12A 72

176 165 162 283 353 207 177 98 51 92 133 136 141 335 314 358 359 347 321 312
303 358 324 345 181 188 345 288 217 297 363 315 297 158 153 153 146 160 135 132
111 135 94 70 126 346 514 433 348 265 205 309 274 235 167 194 175 201 208 171
158 255 159 134 136 165 192 172 192 219 191 206

HWK-A12B 71

162 176 318 335 205 175 86 72 79 145 136 139 333 321 359 366 343 327 312 328
360 317 352 174 177 348 270 238 269 365 303 289 182 163 121 167 155 149 126 111
146 106 64 164 323 499 435 349 250 231 318 252 227 161 184 158 210 186 168 169
230 186 118 150 169 185 184 217 188 196 176

HWK-A13A 54

351 292 308 285 257 306 316 211 188 235 212 211 227 205 213 193 185 188 231 327
309 297 250 244 274 335 285 207 235 229 312 210 232 187 196 226 275 188 188 181
142 167 152 233 222 172 188 131 145 167 87 201 273 194

HWK-A13B 54

358 262 287 281 249 318 300 216 186 245 227 208 224 210 217 181 231 190 236 306
322 294 276 249 278 363 306 212 235 213 276 235 219 207 202 204 280 214 194 170
135 175 172 227 218 202 175 115 128 152 90 246 260 219

HWK-A14A 55

174 218 118 121 168 204 302 311 286 310 240 278 260 346 213 408 347 187 179 249
140 180 252 275 350 403 428 227 296 313 388 287 189 180 265 278 162 185 244 243
199 165 324 271 267 222 334 203 277 316 258 284 202 153 188

HWK-A14B 55

172 212 110 106 155 178 323 266 257 271 242 279 251 300 161 374 292 171 211 257
210 158 251 279 346 485 517 313 299 297 377 281 230 188 276 289 189 260 285 246
203 157 323 267 269 208 329 164 273 318 260 290 186 174 141

HWK-A15A 62

226 167 141 126 171 103 123 168 149 140 207 227 205 202 239 287 319 260 196 155
136 132 132 181 202 146 161 149 170 174 254 249 205 318 400 315 283 290 363 182
177 191 159 132 165 126 108 102 146 159 152 173 193 119 303 289 276 288 198 212
198 223

HWK-A15B 62

248 196 172 114 171 100 134 170 148 141 204 213 212 197 225 289 339 255 201 140
132 141 121 198 202 142 162 146 159 175 245 245 210 324 402 318 287 290 351 189
185 195 159 164 165 118 118 123 130 172 138 215 200 130 297 278 284 300 189 228
184 232

HWK-A16A 65

183 135 116 141 114 116 121 103 139 157 211 265 277 190 230 221 184 200 154 123
166 136 145 186 209 234 161 172 186 195 149 284 307 240 190 174 229 233 178 216
217 204 194 173 149 190 167 192 195 204 175 179 144 170 134 214 212 180 163 152
222 185 165 173 235

HWK-A16B 65
160 134 121 133 103 107 110 104 156 144 180 246 324 192 213 213 165 198 145 130
153 138 132 184 218 244 167 185 185 199 172 279 288 239 193 172 204 255 193 194
217 189 192 170 170 196 157 190 210 202 181 173 153 157 133 219 214 173 162 147
179 169 189 179 226
HWK-A17A 55
95 123 103 120 243 189 256 195 185 266 139 361 123 279 249 226 201 216 490 372
230 133 131 171 268 113 155 206 226 211 293 294 313 279 145 121 120 102 77 99
85 68 68 114 121 168 215 212 182 239 293 252 243 220 247
HWK-A17B 55
106 110 94 124 250 192 241 202 180 269 135 359 141 245 261 242 194 216 492 337
232 135 137 177 248 131 160 201 239 203 291 295 316 290 139 125 117 100 77 101
78 70 67 109 132 170 217 223 177 253 278 315 213 250 248
HWK-A18A 74
380 345 340 254 391 380 307 363 377 451 374 400 340 389 332 266 155 95 132 104
121 121 153 142 153 140 130 153 176 173 84 119 128 136 144 211 222 288 389 263
334 342 254 240 277 246 238 207 200 240 230 247 251 211 172 204 144 154 137 165
203 227 233 176 161 192 158 206 169 145 240 100 165 159
HWK-A18B 74
403 381 372 228 391 328 345 292 358 425 380 398 342 387 334 281 154 89 126 105
119 120 157 141 159 140 124 144 187 168 100 109 131 125 142 208 226 290 394 260
325 344 247 237 278 263 211 211 197 229 225 240 251 207 181 207 147 154 140 153
213 218 241 176 158 205 160 240 136 212 141 101 170 179
HWK-A19A 58
138 183 124 209 144 149 300 178 159 172 116 158 153 234 160 272 214 111 115 151
172 158 164 156 329 359 292 209 359 351 374 325 357 255 253 156 165 157 256 377
258 265 386 233 197 100 96 141 179 248 179 261 147 188 134 190 67 118
HWK-A19B 58
140 181 127 202 154 148 297 166 166 134 157 160 145 221 177 246 218 103 122 157
176 159 149 167 290 336 308 197 345 365 358 325 373 245 237 177 162 165 238 373
271 290 375 222 191 116 94 138 187 235 208 247 142 198 137 158 86 118
HWK-A20A 56
266 240 227 169 102 124 169 250 139 254 244 308 188 278 255 242 245 276 300 236
308 236 266 255 242 180 176 199 233 178 184 192 119 278 268 273 226 238 140 126
130 166 290 256 225 231 139 157 90 100 149 188 206 245 178 184
HWK-A20B 56
295 271 203 169 100 124 170 249 140 245 278 286 211 272 264 241 263 271 302 205
335 242 272 273 236 182 190 215 215 176 184 174 164 262 278 258 223 230 136 141
127 183 268 222 238 230 134 161 94 110 130 177 208 212 224 161
HWK-A21A 55
316 267 253 241 288 296 196 289 225 241 264 268 345 225 331 211 269 275 221 195
179 218 209 175 203 171 148 269 255 274 204 251 153 122 123 166 302 226 261 241
125 153 80 120 153 167 204 201 230 162 110 77 59 89 132
HWK-A21B 55
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190 206 213 173 201 169 142 277 255 274 220 237 136 143 145 170 283 228 219 275
153 135 86 108 171 156 206 207 231 186 84 57 93 117 174

HWK-A22A 57
831 835 503 696 420 569 495 437 245 220 312 365 277 319 304 229 305 309 289 392
455 451 333 358 361 328 338 218 224 205 201 265 242 220 205 222 252 298 240 255
261 71 108 137 132 165 233 191 180 267 214 226 228 209 187 284 296
HWK-A22B 57
821 833 492 712 426 556 508 430 233 250 284 384 257 326 296 231 292 331 281 386
433 453 345 329 373 341 346 200 205 205 214 260 232 251 189 201 268 294 281 203
286 66 112 139 121 166 229 197 185 256 212 224 245 203 221 222 285
HWK-A23A 55
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214 221 177 190 169 137 264 269 283 213 248 142 140 133 183 252 213 241 243 141
171 78 108 157 144 223 212 236 151 110 84 129 148 191 219
HWK-A23B 55
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219 213 197 185 172 145 261 224 297 231 250 131 142 130 202 282 216 250 234 128
146 96 126 145 167 202 215 215 146 132 83 135 141 181 252
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127 154 167 166 200 230 194 336 422 316 255 349 373 186 168 215 276 259 135 113
107 115 144 175 269 273 219 166 313 304 298 248 189 226
HWK-A24B 54
124 177 242 146 217 198 191 210 249 274 315 273 207 148 137 132 136 197 171 144
130 177 138 160 244 208 195 345 403 310 295 306 371 161 181 189 253 281 166 138
112 111 164 172 245 268 201 214 317 295 235 312 188 207
HWK-A25A 54
122 198 142 213 101 211 185 212 295 346 229 244 244 193 155 136 142 113 95 116
102 176 143 113 152 157 146 145 134 192 155 154 140 167 168 183 140 126 122 103
131 111 127 114 126 129 135 111 127 135 106 118 134 139
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108 165 135 126 155 161 159 161 143 183 148 154 142 161 171 187 154 141 147 100
110 109 104 122 135 118 133 129 134 127 110 122 140 136
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257 248 277 243 299 223 226 216 222 215 223 188 206 224 264 192 198 155 159 177
157 220 229 200 170 113 144 138 108 252 278 168 159 228 231 223
HWK-A26B 56
179 179 156 184 187 115 186 131 111 135 135 131 124 119 120 181 153 213 228 222
234 246 278 262 303 213 235 211 227 226 227 184 204 215 269 205 192 174 140 179
152 232 201 182 193 138 134 158 104 232 260 173 165 186 152 181
HWK-A27A 54
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148 97 78 123 162 193 208 157 150 144 80 119 110 92
HWK-A27B 54
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145 86 91 124 146 198 224 142 131 120 74 113 106 85

HWK-A28A 55
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229 299 257 294 307 220 254 209 247 223 188 230 211 184 225 209 143 75 76 95
118 95 103 103 100 99 154 178 205 204 206 236 240 166 172
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228 304 250 295 312 219 263 206 235 239 209 189 212 193 202 219 132 84 70 91
111 75 103 117 107 93 151 181 210 203 192 222 262 190 164
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263 321 420 355 300 322 259 235 263 245 309 291 271 398 431 334 251 160 125 191
238 259 241 231 245 241 217 209 154 190 193 175 178 182
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502 302 371 399 307 270 269 247 339 364 400 368 376 426 389 439 326 295 257 273
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231 262 273 210 278 246 180 220 165 181 192 177 175 180
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315 314 281 125 222 220 212 254 285 193 238 250 248 266 197 196 117 115 177 185
178 170 148 172 147 146 132 174 172 167 193 223 137 151 169
HWK-A30B 55
340 322 345 309 305 265 275 278 227 218 189 232 232 222 243 248 359 219 250 269
260 325 245 178 216 235 218 216 251 194 203 246 257 269 212 199 119 119 171 186
172 173 145 161 143 155 124 174 166 179 205 232 138 151 171
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374 448 396 419 377 377 368 338 259 227 228 183 208 272 207 193 196 241 206 222
236 239 222 245 256 264 225 245 188 232 245 225 245 223 211 211
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467 471 467 448 401 421 432 409 228 306 272 355 361 346 273 294 402 463 498 420
356 442 398 416 370 375 358 341 266 211 246 186 176 285 201 182 215 256 175 246
255 248 237 250 251 260 237 249 167 218 243 222 245 236 210 227
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278 368 307 217 246 201 412 353 374 394 328 320 448 426 421 448 450 205 193 198
280 270 276 278 278 221 230 248 211 352 264 229 399 184 236 151
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218 211 363 361 418 432 532 404 467 470 469 246 378 289 340 305 308 375 271 497
285 374 296 213 223 242 388 360 374 388 333 338 437 429 423 445 489 218 196 199
278 278 275 277 276 222 233 250 215 340 271 238 391 191 229 146
HWK-A33A 54
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402 424 343 346 342 386 363 389 179 181 156 386 402 270 297 271 226 254 227 277
341 277 233 206 189 233 159 106 100 110 140 203 242 250
HWK-A33B 54
504 495 353 381 371 350 331 322 329 339 389 291 282 292 284 274 305 309 367 371
407 417 336 360 339 399 360 400 170 175 170 368 376 268 351 231 233 229 267 197
356 295 230 209 190 221 147 102 107 109 142 189 231 242

HWK-A34A 57
345 343 348 337 354 339 341 368 371 369 314 323 388 352 308 315 324 281 300 288
239 267 310 309 181 245 204 206 207 204 218 194 192 184 228 319 318 303 244 257
285 351 307 217 247 215 271 217 229 188 208 217 254 203 191 146 142
HWK-A34B 57
339 351 320 339 367 329 342 358 381 368 322 320 399 384 299 320 333 280 296 291
245 264 301 305 181 247 200 216 202 206 222 186 216 163 241 297 348 285 258 272
288 349 287 222 231 221 262 233 232 206 204 235 247 204 196 179 140
HWK-A35A 54
291 289 287 300 286 213 207 225 195 223 224 206 215 206 214 171 231 301 343 299
271 246 282 357 304 321 237 219 242 238 232 230 217 219 239 236 203 207 234 176
168 212 205 190 180 121 128 168 102 222 254 190 193 177
HWK-A35B 54
293 288 277 300 286 219 208 222 205 218 219 199 221 218 199 182 245 295 350 295
281 258 279 363 307 324 234 217 248 239 234 232 208 210 250 247 208 209 229 186
154 221 207 180 170 124 131 130 115 235 256 217 220 184
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335 244 234 250 270 200 220 279 370 215 318 352 300 302 267 258 295 273 249 230
278 254 274 240 281 274 226 263 310 375 341 284 310 225
HWK-A36B 54
277 248 275 294 217 254 319 387 348 274 313 231 299 264 316 303 253 369 297 356
300 257 263 207 274 195 200 329 350 210 328 332 303 287 304 256 279 261 251 244
283 274 272 257 274 286 215 262 320 366 341 282 310 234
HWK-A37A 54
347 305 329 324 249 263 204 271 204 213 353 305 341 306 257 259 210 269 200 216
317 360 210 331 333 311 302 278 256 290 301 299 284 254 304 261 266 244 267 251
302 369 345 294 298 229 297 267 328 291 249 359 309 359
HWK-A37B 54
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309 363 206 327 351 297 310 261 265 291 319 301 277 266 276 278 249 248 263 274
318 377 347 272 320 225 274 278 306 306 259 325 301 364
HWK-A38A 55
125 261 272 98 166 94 176 69 160 71 196 313 386 266 65 108 94 79 171 140
138 93 56 49 37 58 95 266 186 121 293 143 100 233 145 189 106 351 244 110
237 241 237 83 200 80 115 229 113 192 139 233 197 162 170
HWK-A38B 55
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148 94 58 43 38 77 89 255 197 133 289 131 128 228 141 184 109 342 247 94
237 260 218 78 202 74 120 241 110 178 147 239 194 156 175
HWK-A39A 58
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283 220 271 268 311 248 254 199 215 321 357 329 303 348 172 186 184 332 283 289
283 295 215 266 143 185 194 280 241 217 193 151 126 69 86 72 101 130
HWK-A39B 58
306 257 255 308 320 326 350 364 258 381 300 290 375 340 339 313 487 366 312 360
249 255 256 277 317 260 233 210 210 344 353 343 286 342 169 191 183 323 300 276
308 298 188 250 166 189 216 278 227 242 183 157 116 66 82 84 91 150

HWK-A40A 54
224 269 236 269 222 204 113 163 174 206 140 182 123 135 229 291 312 359 291 365
214 210 197 256 190 211 173 137 113 130 136 101 117 155 244 296 212 231 231 283
232 232 250 304 223 111 116 209 291 440 368 310 332 382
HWK-A40B 54
240 263 250 274 201 190 116 183 178 187 142 217 99 95 221 293 325 354 280 353
213 215 204 237 186 220 157 142 128 151 110 111 120 169 233 289 232 218 258 273
237 209 262 297 213 115 112 217 298 477 365 308 324 387

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.

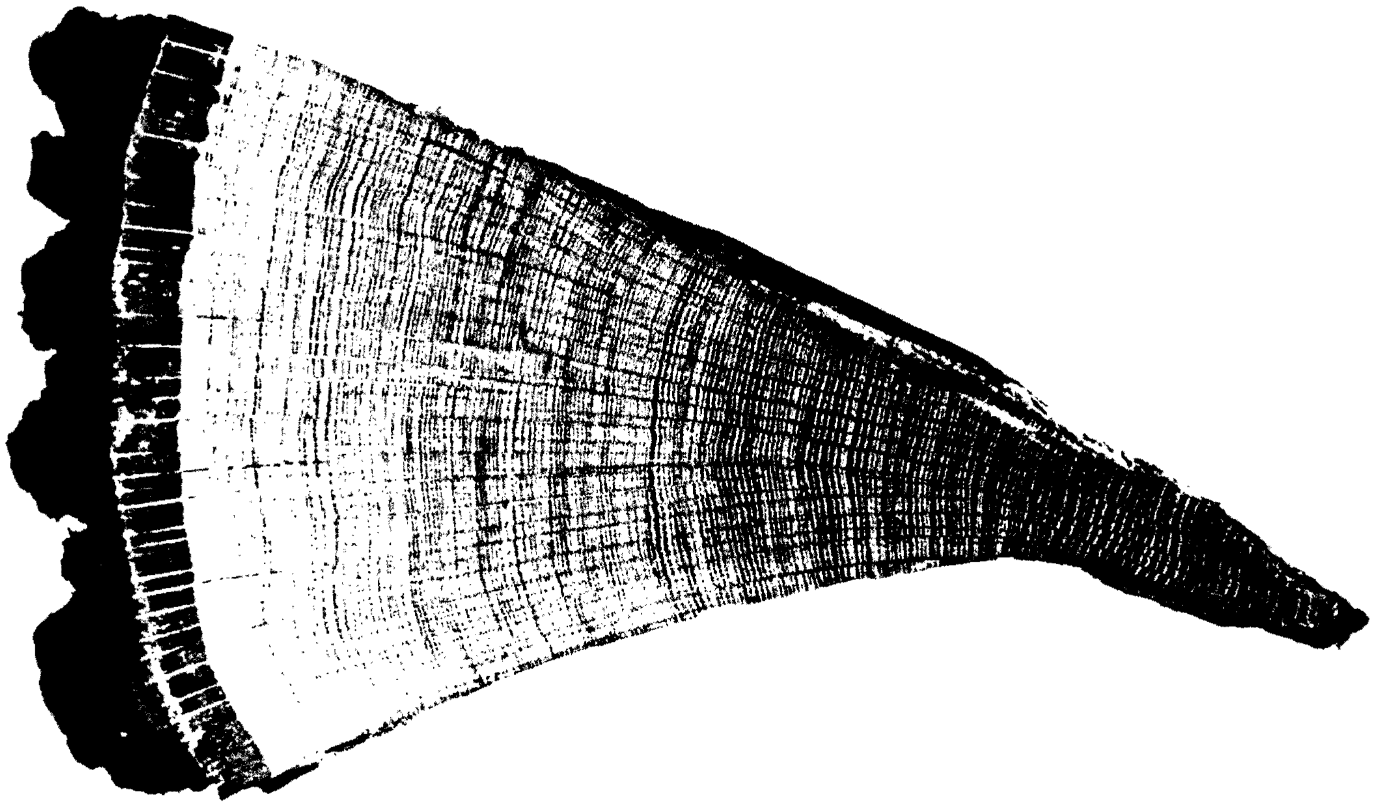


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

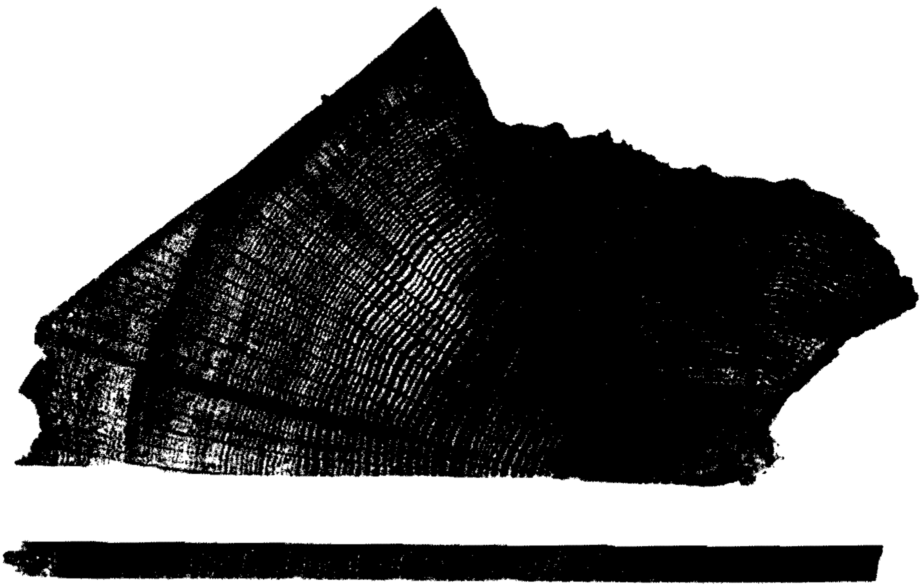


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

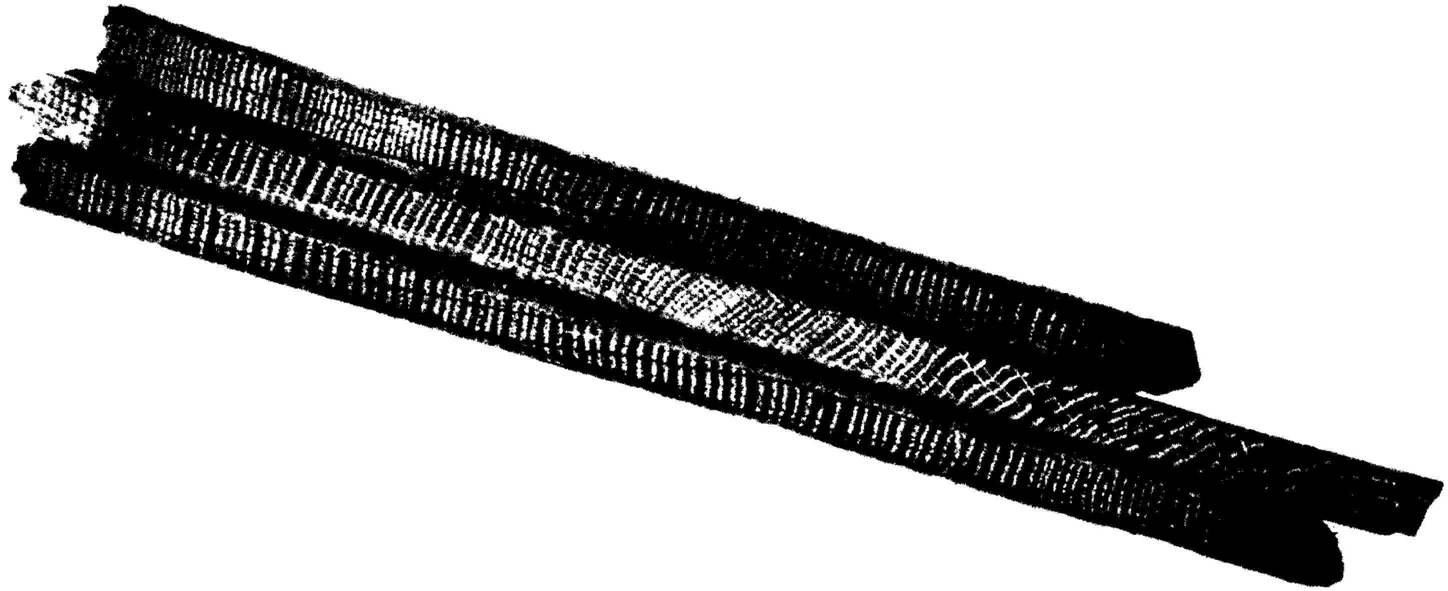


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

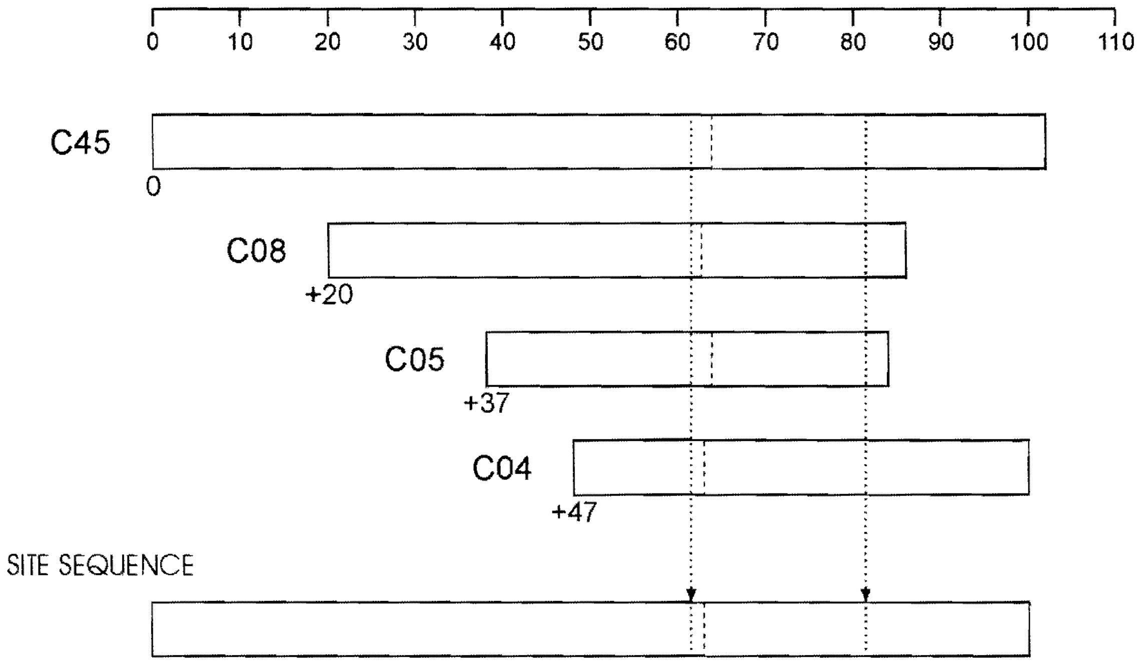


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

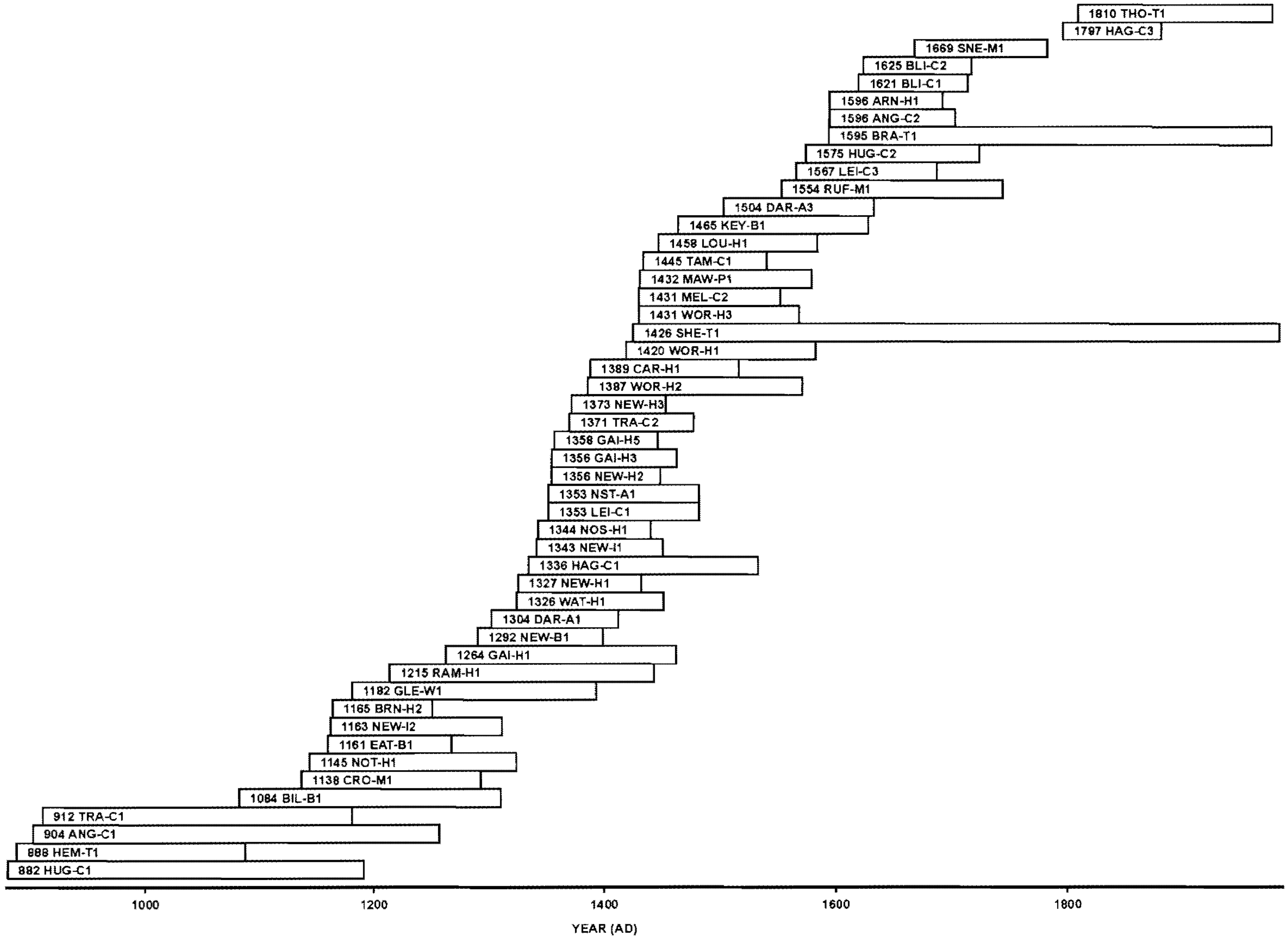
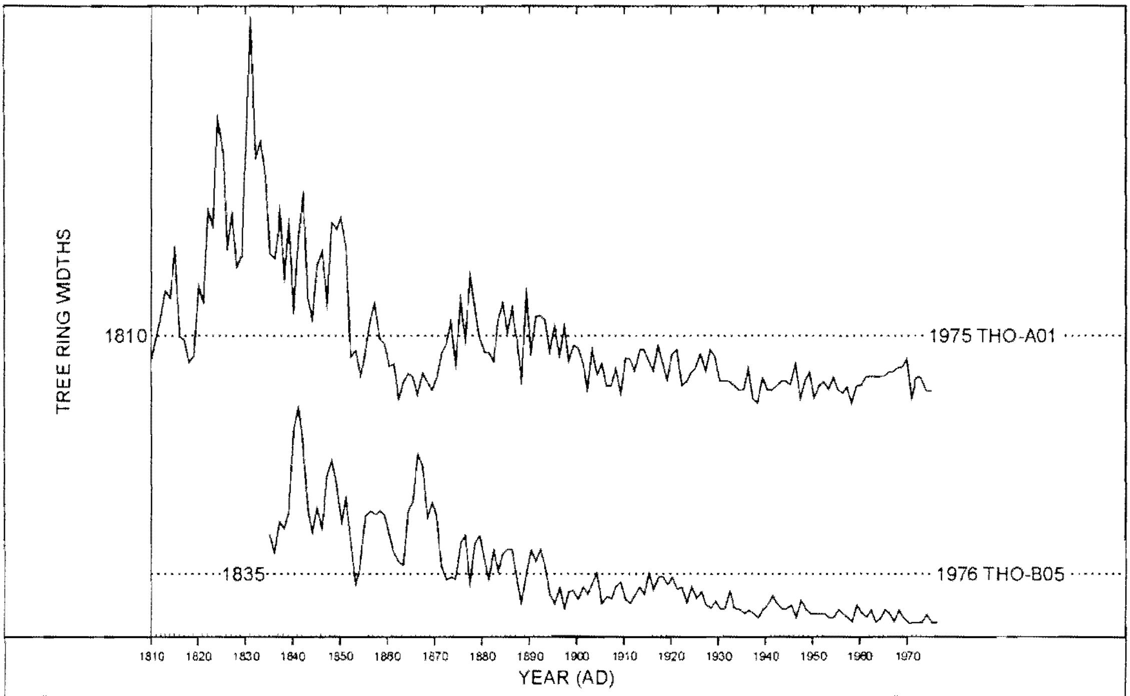


Fig. 6 Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

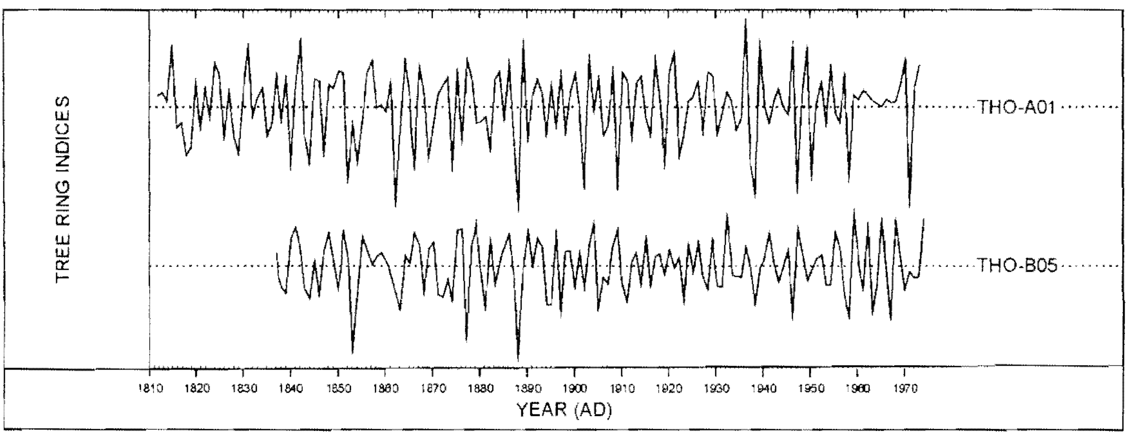


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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