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Scientific Dating

Broad Bottom Old Hall
Broad Bottom Lane, Mytholmroyd
Hebden Bridge
West Yorkshire

Tree-Ring Analysis of Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

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SUMMARY
Dendrochronological analysis was undertaken on core samples obtained from 21 oak timbers at Broad Bottom Old Hall, producing two site chronologies. The first site chronology, BBOHSQ01, accounts for 17 samples from both the hall and the east-range roof and is 168 rings long overall, these rings spanning the years AD 1361–1528. Interpretation of the sapwood on these samples suggests that the dated timbers to the hall were felled in, or about, AD 1464. The east-range roof also contains some timbers felled in, or about, AD 1464, and at least one timber that is potentially slightly earlier, but it also contains some timbers felled in, or about, AD 1528. The second site chronology is 70 rings long, BBOHSQ02, and comprises two samples from one of the trusses in the east-range roof, but this site chronology could not be dated. Two further samples remain ungrouped and undated

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
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ARCHIVE LOCATION
WYAAS Historic Environment Record
West Yorkshire Archaeology Advisory Service
c/o West Yorkshire Joint Services
Gildersome Spur Industrial Estate
Nepshaw Lane South
Morley
Leeds LS27 7JQ

DATE OF INVESTIGATION
2017–18

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INTRODUCTION

Broad Bottom Old Hall is a Grade II* listed building situated on the northern fringes of Mytholmroyd in the parish of Hebden Royd, West Yorkshire (Figs 1a–c). It is part of the Historic England Heritage at Risk team Marooned Manors Project, which aims to bring some historic residences on the Heritage at Risk register, including large farmhouses, manor houses, and yeoman's houses, back into use with grant-aid-support from Historic England.

Broad Bottom Old Hall is part of a complex of buildings of farmhouse, barns, and cottages. It is described in detail by Stell (1960; 1965) and also in brief in the Marooned Manors Project Plan (HE HaR team) and a short note by Rimmer and Taylor (HE September 2017). The summary information below is derived from these sources, as well as the entry in the National Heritage List for England (LEN 1279330).

It was originally a timber-framed double-aisled hall house with high and low wings, probably dating to the late-fourteenth or early fifteenth century and subsequently encased in stone in the sixteenth or seventeenth century. The construction of the hall house has previously been attributed to Randolph Draper who acquired the Broad Bottom estate in the late-fourteenth century (Ogden 1903). Following the death of Thomas Draper in AD 1573 the estate passed by marriage to the Sutcliffe family and in AD 1596 it was split between two brothers, William and Matthew Sutcliffe.

The remains of the hall house complex are fragmentary with neither wing surviving but two bays remain of what was once likely to have been a four-bay double-aisled structure (Fig 2; Stell 1965, fig 1), along with much of the encased timber frame and part of the cross passage. The eastern lower end of the hall, once containing the rest of the cross-passage and possibly a service end, has been lost to a later construction (Fig 2; Stell 1965, fig 1). At the west upper end of the extant hall, plank-and-muntin panelling remains to the lower part of the truss (truss IIII), with close-set vertical studs above and then a king post with braces (Fig 3a; Stell 1965 fig 1). The east extant truss (truss III) is also of king-post form (Fig 3b), and alongside the present fireplace which replaced the original open hearth in the eighteenth century is a thin, panelled fire-screen (Fig 3c). These two extant trusses carry double purlins to each pitch, which in turn carry the common rafters to the ridge. The northern aisle plate, with its curved braces from aisle posts to plate, appears likely to be original, unlike that to the south. The part of the building to the immediate east of the remains of the hall encompasses part of the former cross-passage but is now a store and a porch (Fig 2; Stell 1965, fig 1). Truss 1 is no longer extant but the middle (truss 2) and south gable (truss 3) trusses are also of king-post form, with truss 2 having short straight braces from tiebeam to king post (Fig 3d). These two trusses carry single purlins to each pitch of the roof, these in turn carrying common rafters.

SAMPLING

A dendrochronological study of the building was requested by Elisabeth Lewis, to obtain, if possible, independent dating evidence for the extant remains of this double-aisled timber-framed hall house. It was hoped that this would elucidate the historic development and inform significance and, hence, inform decisions relating to future development and management to secure the survival of Broad Bottom Old Hall and its removal from the Heritage at Risk register.

The assessment of dendrochronological potential noted that, whilst most of the timbers associated with the extant two bay remains of the hall probably related to the initial construction, some timbers were clearly later replacements. With the exception of the plank-and-muntin infill panelling, the timbers associated with the main hall structure were considered suitable for sampling and analysis, as were the timbers from the later, possibly eighteenth-century, rebuilding to the east side of the hall, referred to in this report as the east range. The plank-and-muntin panelling and the fire-screen timbers appeared generally to be derived from fast-grown trees and, hence, contained relatively few rings. This, combined with the way the individual elements were converted from the parent trees and the way they are joined with few exposed edges, meant that sampling was not considered feasible at present. However, it was noted that some of the boards in the fire-screen may warrant further investigation should the screen be dismantled at some point in the future to allow appropriate repairs to be undertaken.

Thus, from the suitable timbers of interest available, a total of 21 samples was obtained by coring. Each sample was given the code BBO-H (for Broad Bottom Old Hall) and numbered 01–21 (Table 1). Ten of these were from the hall, all sampled timbers appearing to be primary and associated with the original construction, and 11 being obtained from the roof of the east range. Some of these east-range roof timbers appeared to show some evidence, by way of ill-fitting joints and redundant mortices, of possibly being reused or reset.

The sampled timbers are located either on the plans provided, or on annotated photographs taken at the time of sampling (Figs 4a/b, 5a–c). In this report the front of the building is deemed to face site south, the rear to face site north.

ANALYSIS AND RESULTS

Each of the 21 samples thus obtained from Broad Bottom Old Hall was prepared by sanding and polishing and the widths of its annual growth rings were measured. The data of these measurements are given at the end of this report. All 21 series were measured and then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of two groups of cross-matching samples.

The first group comprising 17 samples from both the hall and the east-range roof, formed at a minimum *t*- value of 3.5, these cross-matching with each other as shown in Figure 6. These 17 cross-matching samples were combined with each other at their indicated offset positions to form BBOHSQ01, a site chronology with an overall length of 168 rings. Site chronology BBOHSQ01 was then compared to an extensive corpus of reference chronologies for oak, this indicating a consistent and repeated match with a high number of these when the date of its first ring is AD 1361 and the date of its last measured ring is AD 1528 (Table 2).

The second group, formed at a minimum *t*- value of 8.5, comprises two samples, both from the east-range roof, these cross-matching with each other as shown in Figure 7. These two cross-matching samples were combined with each other at their indicated offset positions to form site chronology BBOHSQ02, this having an overall length of 70 rings. Site chronology BBOHSQ02 was also compared to the reference chronologies for oak, but there was no satisfactory matching and these two samples must remain undated.

The two site chronologies thus created, BBOHSQ01 and BBOHSQ02, were then compared with the two remaining ungrouped samples, but there was no further satisfactory cross-matching. The two ungrouped samples were then compared individually with the full corpus of reference data, but again there was no further matching and these also remain undated.

INTERPRETATION

Hall

Eight samples representing timbers thought to be associated with the initial construction have been dated as constituents of site chronology BBOHSQ01. Three of these eight samples, BBO-H04, BBO-H09, and BBO-H10, retain complete sapwood, this meaning that they each have the last ring produced by the trees represented before they were felled. In each case, this last complete sapwood ring, and, thus, the felling of the trees represented, is dated AD 1464.

Four other samples, BBO-H01, BBO-H02, BBO-H06, and BBO-H08, retain some sapwood or at least the heartwood/sapwood boundary. This means that although they have lost some or all of their sapwood, it is only the sapwood that has been lost. The dates of their heartwood/sapwood boundary rings are compatible with a single felling, and the average heartwood/sapwood boundary ring on these four samples is dated AD 1442. Using the sapwood estimate of 15–40 rings (the 95% confidence interval) gives these timbers an estimated felling date in the range AD 1457–82. The dates of the heartwood/sapwood boundary on these four samples are very similar to each other and also very similar to those on the samples with complete sapwood, varying only by ten rings. As such, this is indicative of a group of timbers having been cut as part of a single episode of felling (although not necessarily at exactly the same time). There is, thus, little reason to suppose that these other timbers were not felled in, or about, AD 1464 as well, an interpretation supported by the high levels of cross-matching between some of the samples (eg BBO-H10 with complete sapwood matches BBO-H01 and BBO-H06 with *t*-values of 8.1 and 7.5 respectively).

The single remaining sample of this earlier phase, BBO-H07, does not retain the heartwood/sapwood boundary and it is, thus, not possible to estimate when the tree represented was felled as, in theory, the tree could have gone on growing for many years after its last extant heartwood ring date. However, given that this sample again cross-matches well with other samples of this group, it is likely to have come from the same general woodland area. As such, it is likely to have been felled as part of the same episode of felling in, or around, AD 1464.

East-range roof

The nine dated timbers indicate that this roof contains timbers felled at different times. Five of these were felled in the mid-fifteenth century, whilst the remaining four were all felled in the first half of the sixteenth century.

Mid fifteenth-century timbers

One of the samples, BBO-H15, in this earlier group retains complete sapwood, the date of this ring and, hence, the felling date, being AD 1464. Three other samples (BBO-H12, BBO-H13, BBO-H19) retain the heartwood/sapwood boundary ring, the average date of which is AD 1444, giving these timbers an estimated felling date in the range AD 1459–84. The dates of the heartwood/sapwood boundary on these three samples are very similar to each other, the sample with complete sapwood, and those on the samples from the hall range. Again, this suggests that these timbers were all cut as part of a single episode of felling in, or about, AD 1464. This interpretation is again supported by the overall levels of cross-matching between this group of timbers from the east-range roof and the hall.

The exception in this earlier group of samples from the east-range roof is BBO-H18. This sample retains some sapwood with the heartwood/sapwood boundary being dated to AD 1420, which is somewhat earlier than the other dated timbers from this group and the hall. Allowing for the same minimum/maximum sapwood estimate as above, 15–40 rings, would suggest that this timber was felled at some point between AD 1435 at the earliest and AD 1460 at the latest. Whilst this suggests that it may have been felled slightly earlier than the other fifteenth-century timbers, it is also possible that it is one of the timbers whose number of sapwood rings lies outside of the 95% confidence interval and, hence, it could potentially have been felled in the early AD 1460s.

Early sixteenth-century timbers

These comprise BBO-H11, BBO-H14, BBO-H16, and BBO-H17, of which sample BBO-H14 retains complete sapwood, in this case its last ring and, thus, the felling of the tree, being dated to AD 1528. The remaining three samples retain some sapwood or at least the heartwood/sapwood boundary. The average date of this heartwood/sapwood boundary is AD 1505, giving these timbers an estimated felling date in the range AD 1520–55. However, the heartwood/sapwood boundary dates on all four samples in this later group are very similar to each other, varying by only six years. This is again, consistent with a single phase of felling and is supported by the level of cross-matching between this group of timbers including a possible same-tree derivation for the timbers represented by BBO-H11 and BBO-H16 (t = 10.6). It is, thus, probable that all four trees represented were felled in, or about, AD 1528.

DISCUSSION AND CONCLUSION

It is clear from the analysis that Broad Bottom Old Hall contains a series of fifteenth- century timbers in both the hall and the roof of the east range, with all but one of these likely to have been felled as part of a single programme of felling in, or about, AD 1464. Those in the hall show no evidence of reuse and appear likely to be associated with the initial construction of the original timber-framed double-aisled hall house, thus, dating this phase of construction to shortly after felling in AD 1464. The timbers of this date found in the roof to the east range, representing common rafters and purlins, may well be reused in this roof given the nature of the construction here with evidence of ill-fitting joints and redundant features. The fact that they are the same date as those primary construction timbers in the hall suggests that it is a possibility they may have been salvaged from the demolition of the two easternmost bays of the hall house. The oddity is the wall plate used in this east range, which could have been felled some years before this AD 1464 felling date. It will be interesting to see if the building survey identifies any peculiarities with respect to this timber.

The east range roof also contains timbers which were probably all felled in, or about, AD 1528. None of these timbers, a principal rafter, a ridge, and two purlins, show any clear evidence of reuse. Thus, it is possible that they represent not only the primary construction phase of the east-range roof, but also the date at which the original four-bay hall was truncated.

As such, the dating evidence obtained from the dendrochronological analysis indicates that the extant part of the hall house is perhaps slightly later than previously thought, whilst the east-range roof is perhaps slightly earlier. This implies that the original four-bay hall house may have had a shorter life span than perhaps expected, having been built in AD 1464 and then truncated by building works in AD 1528. However, the building survey may further inform this interpretation, which is based solely on the dendrochronological evidence.

Although site chronology BBOHSQ01 has been compared with reference material from all parts of England, it shows the highest levels of similarity with reference chronologies from other sites in the surrounding areas, with various sites in West Yorkshire producing some particularly high *t*-values (Table 2). This remains true if sub-masters are produced for the fifteenth-century timbers and the sixteenth-century timbers. This suggests that the timber used at Broad Bottom Old Hall was from a relatively local regional source.

Four of the 21 samples obtained remain undated. BBH-O03 does contain a band of narrow rings where growth is supressed and the latter decades of BBO-H21 indicate some sort of growth release with the rings becoming increasingly wide. Both of these growth events are likely to hamper the chances of successful dating. It is very common in most programmes of tree-ring analysis to find that some samples remain undated for no apparent reason but this does not demonstrate that they are of a different date to the rest of the material. However, the fact that two of the undated, but cross-matched samples, BBO-H20 and BBO-H21, represent the two principal rafters of truss 3, the southern gable, of the east-range roof may be of note. Although these show no obvious differences in character compared with the dated timbers it will be of interest to ascertain from the building survey if there is any architectural evidence that may suggest that these are of a different phase of building activity.

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TABLES

Table 1: Details of tree-ring samples from Broad Bottom Old Hall, Mytholmroyd, Hebden Bridge, West Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Hall house					
BBO-H01	East brace, king post to ridge beam, east (III) truss	80	h/s	1361	1440	1440
BBO-H02	North post, east (III) truss	63	h/s	1379	1441	1441
BBO-H03	South post, east (III) truss	88	20C	------	------	------
BBO-H04	Tiebeam, east (III) truss	65	21C	1400	1443	1464
BBO-H05	West brace, north post to arcade plate, east(III) truss	60	no h/s	------	------	------
BBO-H06	North post, west (IIII) truss	78	3	1375	1449	1452
BBO-H07	South post, west (IIII) truss	71	no h/s	1364	------	1434
BBO-H08	Tiebeam, west (IIII) truss	41	h/s	1399	1439	1439
BBO-H09	East brace, north post - arcade plate, west(IIII) truss	93	25C	1372	1439	1464
BBO-H10	North purlin	83	20C	1382	1444	1464
	East range roof					
BBO-H11	Ridge beam, bay 1 (north bay)	82	14	1441	1508	1522
BBO-H12	Upper east purlin, bay 1	63	h/s	1386	1448	1448
BBO-H13	Lower east purlin, bay 1	50	h/s	1398	1447	1447
BBO-H14	West principal rafter, truss 2	67	22C	1462	1506	1528
BBO-H15	East common rafter 3, bay 2 (south bay)	65	21C	1400	1443	1464
BBO-H16	Upper east purlin, bay 2	84	h/s	1419	1502	1502
BBO-H17	Upper west purlin, bay 2	81	12	1436	1504	1516
BBO-H18	East wall plate, bay 2	58	10	1370	1420	1430
BBO-H19	East common rafter 7, bay 2	54	h/s	1384	1437	1437
BBO-H20	East principal rafter truss 3	48	no h/s	------	------	------
BBO-H21	West principal rafter, truss 3	70	10	------	------	------

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

Table 2: Results of the cross-matching of site sequence BBOHSQ01 and relevant reference chronologies when the first-ring date is AD 1361 and the last-ring date is AD 1528

Reference chronology	Span of chronology	*t*-value	Reference
All Hallow's Church, Kirkburton, West Yorkshire	AD 1306 –1633	11.9	(Arnold and Howard 2007)
Elland Old Hall, Elland, West Yorkshire	AD 1372 – 1574	10.7	(Hillam 1984)
Bramall Hall, Stockport, Greater Manchester	AD 1359 –1590	9.8	(Arnold and Howard 2013 unpubl)
Horbury Hall, Wakefield, West Yorkshire	AD 1368 –1473	9.7	(Howard *et al* 1992)
Westgate End House, Wakefield, West Yorkshire	AD 1377 –1567	9.7	(Arnold and Howard 2015)
The Great Tythe Barn, Bolton Abbey, North Yorkshire	AD 1350 –1518	9.7	(Arnold *et al* 2015)
Combermere Abbey, Whitchurch, Cheshire	AD 1363 –1564	9.3	(Howard *et al* 2003)
7–12 Church Street, Dronfield, Derbyshire	AD 1313 –1526	9.2	(Arnold and Howard 2014)
Ughill Manor, Bradfield, South Yorkshire	AD 1349 –1504	9.0	(Howard *et al* 1994)

FIGURES

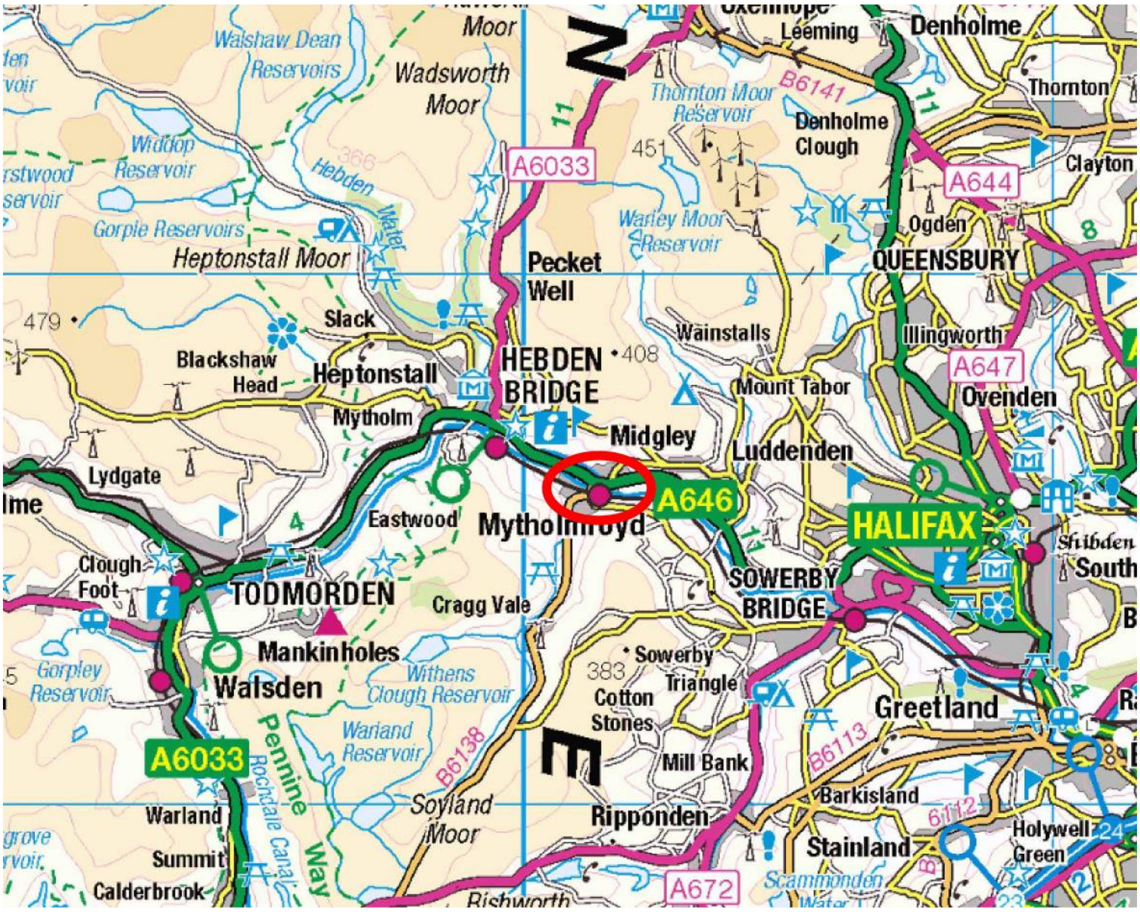


Figure 1a: Map to show the general location of Mytholmroyd. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

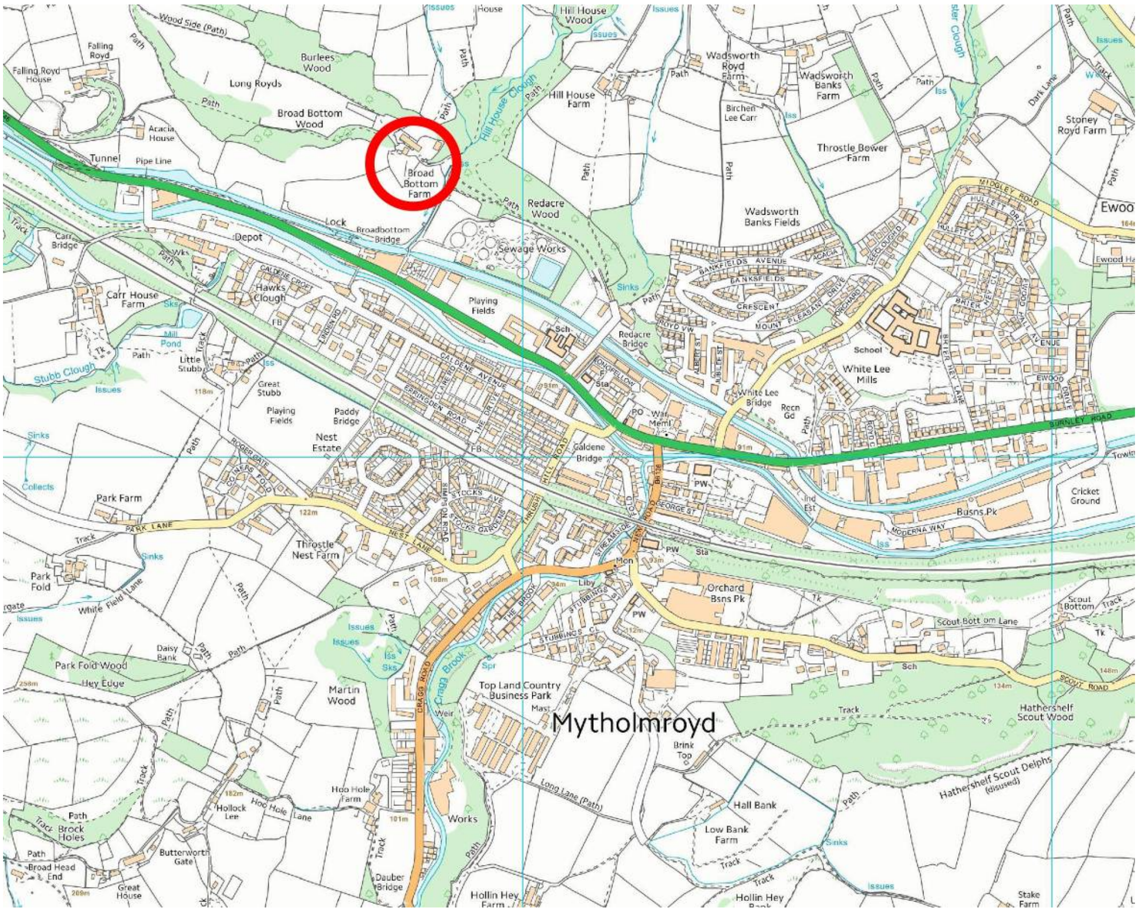


Figure 1b: Map to show the general location of Broad Bottom Old Hall. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

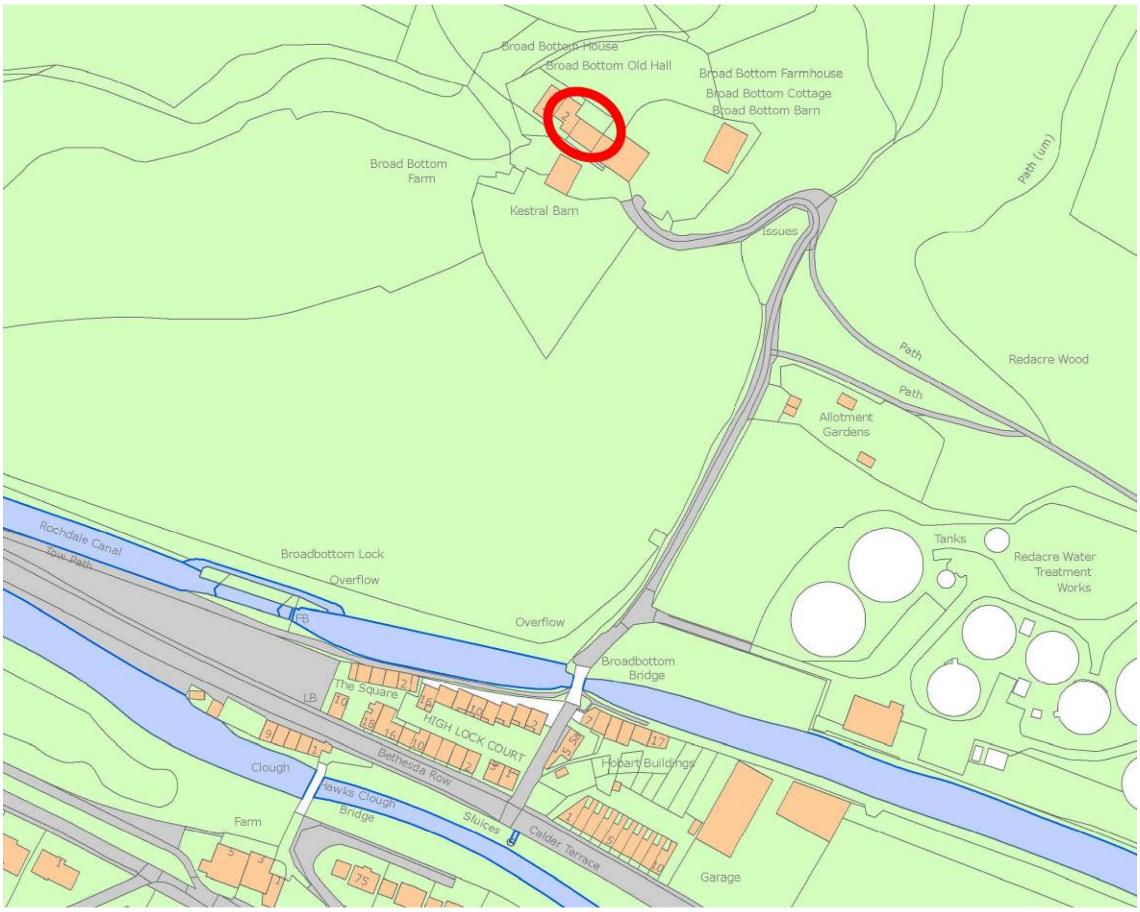


Figure 1c: Map to show the detailed location of Broad Bottom Old Hall. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

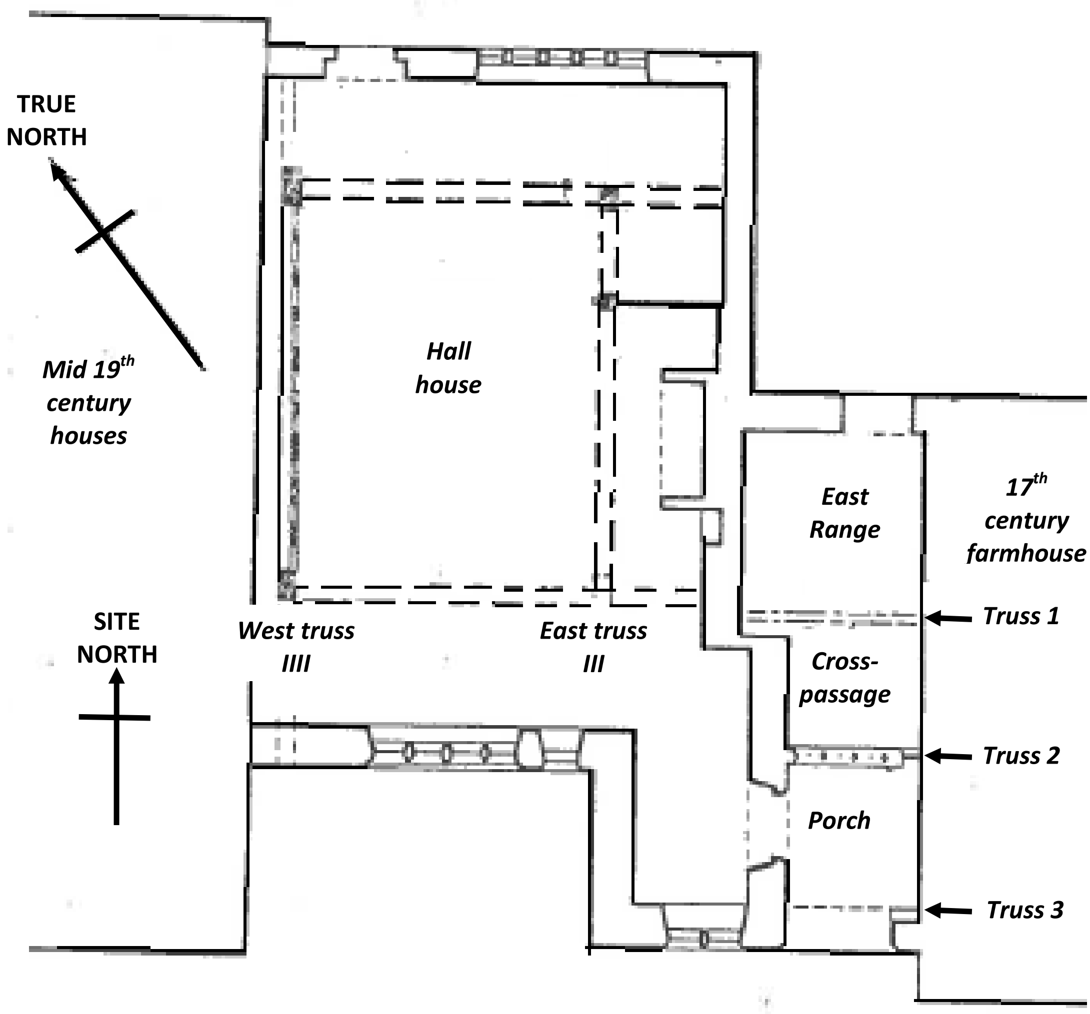
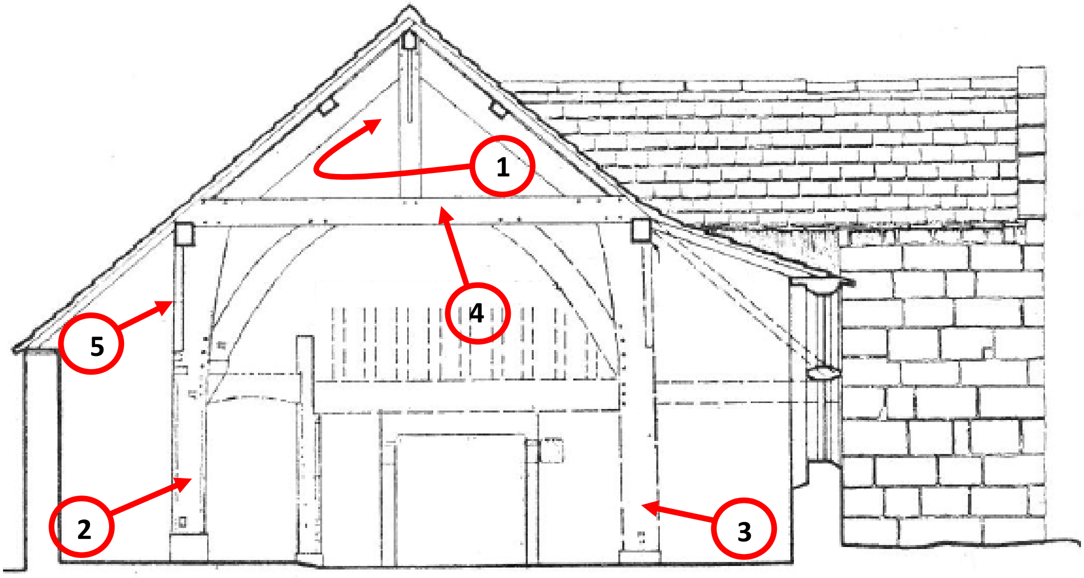


Figure 2: Plan of Broad Bottom Old Hall to show layout and arrangement of the trusses (after C F Stell 1965)

Figure 3a/b: View of truss III, the open east truss (top), and truss IIII at the high west, or dias, end (bottom) (photographs Robert Howard)

Figure 3c/d: View of the fireplace screen in the hall house (top) and the roof of the east range (bottom) (photographs Robert Howard)



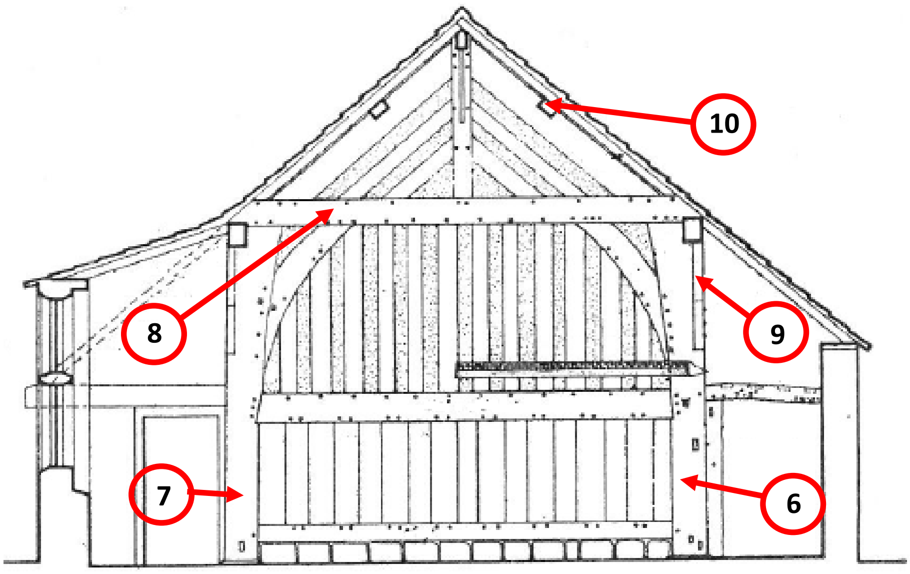
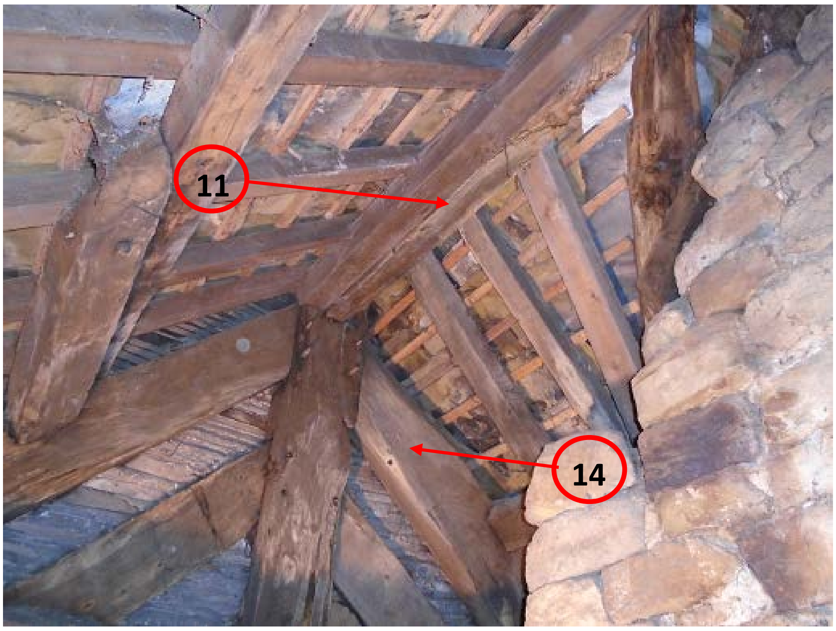


Figure 4a/b: Sections through the east (III) and west (IIII) trusses of the hall house with sampled timbers identified (after C F Stell 1965)



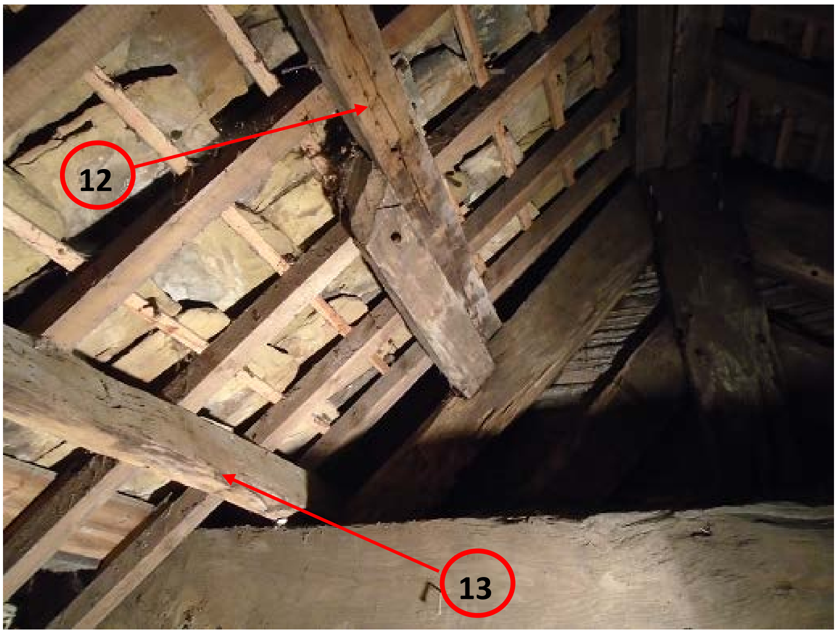


Figure 5a/b: Annotated photographs of the east-range roof with sampled timbers identified (photographs Robert Howard)

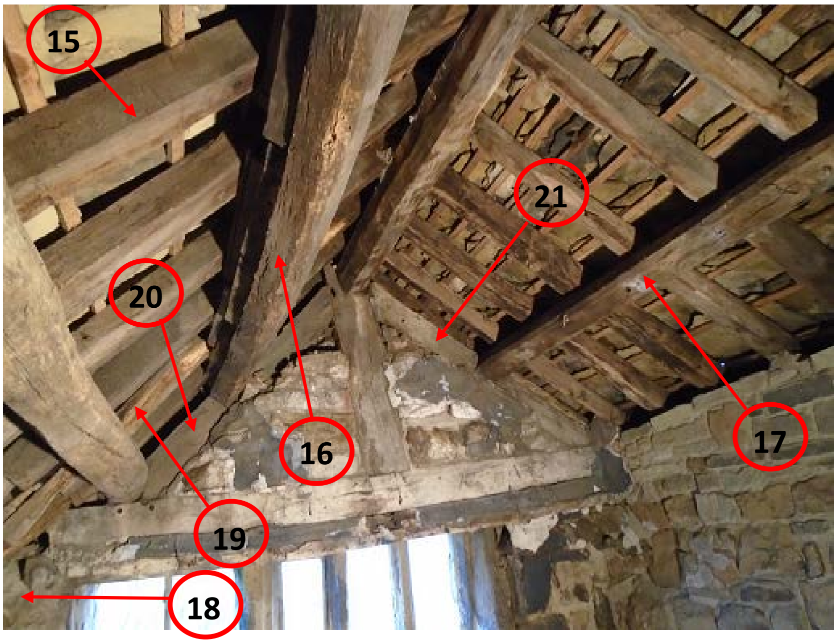


Figure 5c: Annotated photograph of the east-range roof to help identify sampled timbers (photograph Robert Howard)

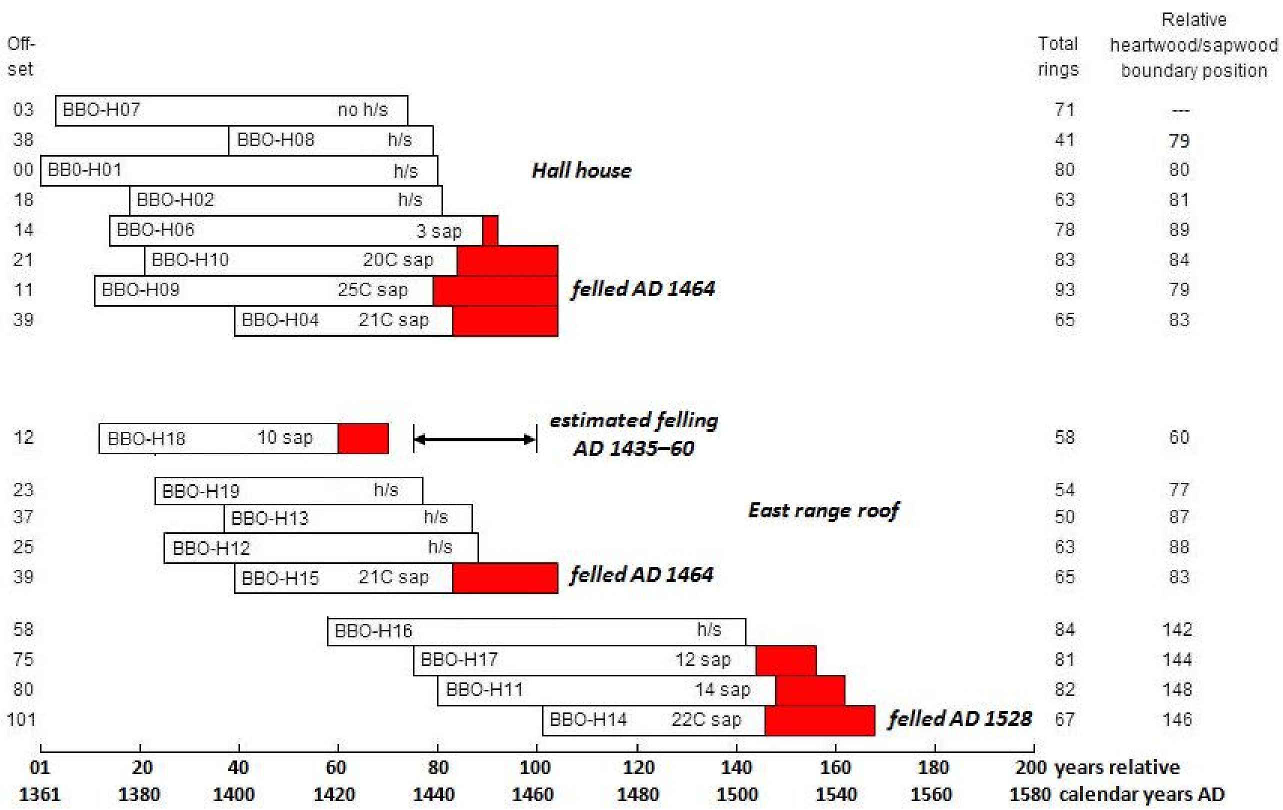


Figure 6: Bar diagram of cross-matching samples in site chronology BBOHSQ01

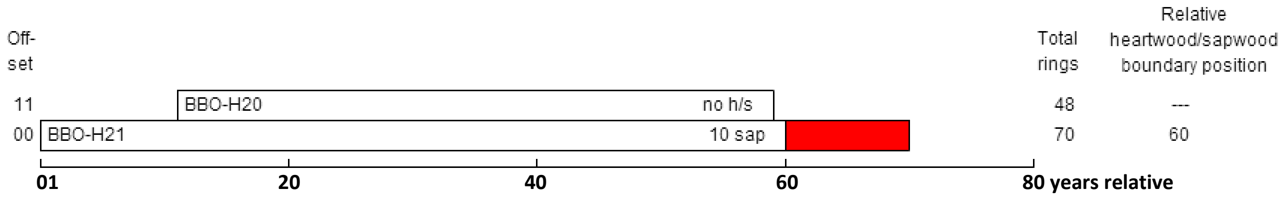


Figure 7: Bar diagram of cross-matching samples in site chronology BBOHSQ02

White bars = heartwood rings; red bars = sapwood rings; h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BBO-H01A 80
325 358 443 428 348 385 334 269 294 336 243 264 249 213 189 226 207 244 283 248
231 215 350 302 276 357 309 262 255 262 204 256 215 214 194 291 210 217 159 229
210 179 168 175 215 164 111 171 216 243 202 225 191 171 162 137 187 188 96 215
178 157 201 126 146 118 123 148 175 101 181 204 162 155 175 162 137 205 141 150
BBO-H01B 80
323 390 488 418 280 428 336 290 314 346 225 303 258 224 188 226 210 232 301 239
232 234 339 309 289 357 315 256 247 239 235 239 215 215 187 293 229 199 158 224
193 168 184 155 221 165 123 166 208 217 212 215 187 177 153 122 187 196 104 207
184 138 190 156 131 123 131 141 161 100 184 203 167 163 193 152 146 217 137 147
BBO-H02A 63
324 463 459 557 706 543 453 755 757 762 481 321 156 265 451 511 533 405 308 275
314 440 388 333 489 504 379 296 204 285 417 463 279 318 349 359 431 373 371 293
203 287 181 156 197 184 270 151 79 129 221 163 232 435 506 332 263 151 196 210
114 131 133
BBO-H02B 63
331 466 470 570 723 544 469 771 800 750 476 324 134 254 450 521 526 370 260 278
303 407 393 315 464 521 369 287 207 284 401 477 287 316 351 360 424 369 371 287
203 290 192 150 190 194 261 146 87 135 211 162 229 452 496 340 263 156 178 230
100 125 137
BBO-H03A 88
231 261 257 232 141 216 201 246 303 416 248 400 501 428 517 485 457 434 418 402
293 314 101 45 42 32 50 85 109 158 201 259 233 340 195 151 175 154 234 282
168 285 197 202 288 302 275 281 228 333 261 268 289 215 306 257 215 164 166 224
268 290 206 244 225 230 218 203 170 214 213 215 117 93 115 161 166 162 114 131
111 98 125 194 203 234 227 172
BBO-H03B 88
225 257 265 219 156 225 211 243 325 392 250 394 493 425 473 511 481 447 408 410
287 309 95 39 42 30 53 85 110 187 198 251 237 341 198 150 173 153 240 285
159 283 192 204 294 301 262 276 237 330 277 265 290 224 297 249 193 178 153 228
268 298 204 243 225 223 225 203 172 206 212 218 110 100 115 156 172 157 110 127
107 98 128 181 208 250 225 183
BBO-H04A 65
508 391 341 508 497 485 549 512 360 326 248 275 293 257 203 270 203 216 299 278
421 378 274 372 271 235 251 203 200 235 201 226 325 240 238 251 207 209 249 192
182 177 154 212 207 190 195 282 237 249 250 246 316 152 62 65 56 58 66 70
85 84 115 102 121
BBO-H04B 65
533 388 339 519 484 537 507 475 376 355 219 281 303 255 214 275 203 219 296 271
384 367 284 350 270 229 259 203 198 245 195 240 304 217 259 267 198 228 235 181
182 181 150 212 209 175 190 296 240 228 246 250 293 162 62 65 57 53 81 76
79 77 112 91 124
BBO-H05A 60
257 366 277 300 351 368 418 468 438 407 418 382 274 369 328 385 407 315 347 319
235 294 359 315 370 320 320 248 226 231 238 298 226 181 182 217 210 172 201 237
357 385 322 240 252 250 285 359 287 192 200 156 225 140 182 250 219 230 260 215

BBO-H05B 60
249 372 313 331 351 344 432 491 471 447 414 389 260 377 325 393 416 313 348 312
237 300 353 316 372 318 320 227 208 212 229 293 218 207 167 220 211 176 196 246
333 388 322 228 249 253 284 366 265 181 193 161 220 154 182 251 210 234 243 212
BBO-H06A 78
326 431 356 272 301 203 142 160 245 191 191 335 378 321 279 349 285 257 284 196
260 228 197 178 165 221 207 125 198 168 187 214 109 230 239 243 214 270 209 237
221 134 159 200 123 271 244 238 265 215 255 292 215 248 295 221 309 359 253 268
334 261 243 312 228 270 220 159 279 279 271 170 303 279 207 196 245 207
BBO-H06B 78
330 443 338 263 300 203 149 176 234 192 200 341 362 325 264 355 264 264 296 200
264 231 192 165 164 226 212 126 200 166 195 209 111 228 228 253 215 256 214 239
212 133 155 200 127 257 243 231 281 204 271 290 229 248 295 217 306 356 256 262
338 255 240 309 213 284 208 165 271 275 273 185 301 295 198 195 246 207
BBO-H07A 71
438 442 494 431 284 393 289 325 373 396 463 339 443 382 303 421 275 306 279 409
298 298 579 442 449 381 421 401 339 258 44 89 187 179 157 176 217 192 131 194
196 221 233 176 258 199 231 178 234 165 212 293 235 235 246 172 350 212 206 298
210 224 266 236 252 237 131 240 227 181 254
BBO-H07B 71
423 428 504 415 300 387 285 325 391 416 447 321 444 397 305 420 287 290 278 386
287 309 567 467 485 392 420 398 339 278 48 104 197 192 149 164 214 179 132 190
188 217 219 184 244 223 257 181 246 181 200 287 231 221 281 163 351 213 209 324
181 215 265 238 254 231 125 250 225 187 257
BBO-H08A 41
326 424 351 395 352 367 325 316 209 269 224 272 335 402 300 292 229 296 186 187
147 376 400 382 376 204 179 148 81 84 142 120 112 182 117 114 134 147 157 121
62
BBO-H08B 41
323 418 343 398 351 364 350 320 214 241 221 287 327 413 307 300 227 285 189 182
146 395 385 385 371 212 178 142 78 87 150 107 106 150 126 110 137 150 157 109
59
BBO-H09A 93
259 247 251 214 150 140 198 191 174 175 159 191 154 156 188 225 229 247 198 187
192 153 178 232 242 185 214 182 217 129 219 247 209 223 195 134 100 129 96 96
132 118 87 125 96 140 121 117 178 143 134 193 120 117 89 82 134 203 95 96
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233 173 143 139 267 159 134 121 178 188 149 165 126
BBO-H09B 93
260 238 256 216 145 142 199 203 175 171 173 183 153 156 192 216 217 249 200 180
185 177 211 219 234 174 232 167 225 146 209 247 205 221 192 128 118 129 95 96
137 109 84 139 92 146 121 111 200 145 132 182 123 117 84 84 146 191 89 87
195 107 76 115 109 146 135 125 98 150 84 108 128 117 87 92 115 115 129 170
228 171 134 129 260 155 140 138 156 193 150 166 128
BBO-H10A 83
254 291 312 214 332 293 264 196 219 182 189 171 181 194 234 216 217 196 217 282
216 269 224 239 179 150 210 182 217 210 210 189 185 173 178 156 202 124 262 194
143 217 168 181 144 112 162 164 157 228 269 204 170 184 187 170 203 159 164 153
140 200 221 172 127 150 105 125 117 156 170 175 181 187 256 187 166 153 212 174
250 250 235

BBO-H10B 83
238 323 322 206 332 293 271 210 221 189 176 164 171 179 235 207 224 189 230 283
219 255 200 239 178 139 214 191 217 226 214 183 187 173 176 151 215 117 258 192
155 205 155 193 156 100 164 168 146 251 273 205 162 184 183 174 210 162 179 151
140 195 203 168 136 140 107 124 118 150 184 165 181 185 274 181 166 150 212 164
256 257 240
BBO-H11A 82
83 66 141 146 96 46 48 58 60 78 103 109 94 92 83 145 97 72 75 161
134 120 119 87 103 176 108 135 155 205 148 103 122 182 268 173 146 142 202 207
195 107 108 116 155 188 271 185 157 168 121 93 75 109 143 193 159 145 173 137
90 104 89 140 120 113 84 79 157 128 165 154 137 121 120 129 153 146 129 140
170 187
BBO-H11B 82
84 65 143 142 99 46 42 61 59 83 92 108 98 88 83 141 99 71 73 151
129 127 120 80 101 188 103 135 153 210 143 107 121 178 266 166 132 139 197 205
191 100 117 115 153 189 276 186 152 153 114 102 78 111 135 197 167 143 176 142
81 105 92 114 121 112 79 81 159 115 171 159 150 105 115 148 148 139 137 137
171 187
BBO-H12A 63
184 178 100 64 77 285 200 282 232 216 275 182 235 205 241 219 186 244 242 228
159 123 128 104 85 85 91 94 85 116 112 124 117 91 150 142 133 171 125 111
133 146 146 143 103 143 198 165 157 169 146 129 151 115 85 98 93 98 129 95
82 96 111
BBO-H12B 63
180 172 102 65 87 280 175 287 237 203 276 199 237 203 249 228 206 240 254 232
160 117 132 103 89 81 95 94 84 115 110 125 122 95 139 149 135 168 132 108
131 146 148 146 104 136 185 155 162 160 137 128 160 97 93 93 93 104 134 93
85 96 112
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302 265 388 334 293 393 343 318 284 198 277 246 235 221 235 182 166 175 172 171
132 100 185 185 142 206 137 140 125 89 142 154 87 118 187 145 211 215 204 176
206 142 163 207 153 209 215 125 121 187
BBO-H13B 50
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139 100 195 161 139 210 150 132 132 86 127 156 89 118 187 142 210 210 198 181
200 145 153 209 149 214 215 117 125 197
BBO-H14A 67
413 356 318 302 387 514 382 376 472 282 278 158 163 400 578 525 242 365 238 324
164 259 412 214 255 347 300 234 310 44 55 42 93 82 92 100 110 143 90 62
70 75 110 90 181 167 157 285 179 212 201 174 131 98 98 81 88 65 62 89
97 100 121 121 96 76 133
BBO-H14B 67
413 354 306 301 401 512 378 360 476 283 284 173 151 383 564 542 250 345 215 331
150 279 376 228 239 318 287 240 279 60 42 42 99 81 96 125 117 134 92 64
68 87 103 89 175 171 151 275 179 231 197 154 162 101 98 78 84 68 60 91
106 96 119 106 95 81 124
BBO-H15A 65
334 302 308 347 351 373 351 262 325 263 217 251 282 281 277 284 207 231 215 171
214 235 178 196 159 149 167 184 276 307 234 219 260 187 209 204 215 196 203 179
186 219 165 217 257 146 134 140 84 125 117 151 142 153 132 123 171 150 140 124
165 182 207 142 167

BBO-H15B 65
344 329 283 367 349 360 355 264 326 253 226 250 273 275 253 303 192 215 214 153
191 200 178 201 139 157 176 171 276 331 264 209 265 185 212 215 212 201 185 176
173 214 168 220 268 150 135 147 87 106 110 162 146 135 132 126 162 151 126 143
171 175 206 159 173
BBO-H16A 84
130 223 211 212 232 114 121 108 57 93 149 116 242 137 116 146 137 119 158 146
121 121 150 113 220 182 169 110 121 97 134 139 158 204 180 155 147 249 164 121
153 213 171 184 149 139 148 229 198 174 239 242 189 128 148 162 268 240 176 173
201 171 207 113 123 215 209 232 319 194 158 198 100 96 70 107 123 165 160 134
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BBO-H16B 84
120 231 203 221 237 117 124 108 51 94 148 110 237 135 102 135 135 126 150 136
107 117 154 113 218 178 173 107 118 100 132 140 161 200 185 149 156 239 158 128
149 210 175 176 152 131 150 232 196 172 235 242 180 134 145 172 271 234 180 171
203 169 209 112 128 210 222 228 314 199 167 186 103 98 62 114 120 165 144 143
149 106 84 90
BBO-H17A 81
145 151 124 108 85 127 114 255 250 150 86 97 96 184 341 301 212 171 230 146
328 189 148 87 178 262 268 210 169 171 381 353 308 306 316 174 126 154 178 315
234 165 148 215 152 215 139 153 179 142 229 215 150 125 129 107 96 70 95 113
169 151 109 131 128 104 99 103 176 159 125 78 114 196 113 183 166 121 77 89
167
BBO-H17B 81
138 150 134 105 81 132 90 254 258 144 83 109 106 182 336 256 212 171 221 148
341 193 157 78 177 248 265 209 163 163 393 310 318 326 318 168 128 145 164 320
246 170 146 234 154 229 137 162 175 149 193 222 151 115 127 114 90 67 104 118
184 150 120 128 118 112 101 124 146 151 101 96 122 168 156 174 167 106 90 90
165
BBO-H18A 58
210 298 192 198 166 225 276 244 153 168 271 283 287 373 386 475 453 385 388 254
185 231 251 228 189 185 158 271 153 196 200 229 265 239 178 198 225 240 179 240
217 184 306 284 334 401 228 407 210 235 292 216 115 75 75 77 111 179
BBO-H18B 58
220 289 184 204 162 222 280 231 162 171 273 303 273 409 382 468 450 389 363 257
196 223 252 264 181 187 165 265 162 203 187 228 270 239 177 212 234 248 190 228
220 207 283 291 334 400 215 410 232 207 297 237 115 81 72 78 114 191
BBO-H19A 54
225 129 219 234 124 159 163 150 159 169 166 178 173 135 152 134 145 150 147 184
216 139 132 103 135 126 113 117 116 98 89 102 67 72 62 54 92 107 146 134
110 128 86 75 121 175 107 121 171 118 126 107 164 168
BBO-H19B 54
231 128 220 233 127 154 170 148 171 178 161 171 175 134 151 120 153 155 148 184
178 145 128 107 135 126 110 117 115 92 89 101 64 72 61 51 92 114 147 137
110 127 84 83 116 174 103 131 175 118 128 103 162 170
BBO-H20A 48
220 278 287 280 225 200 184 164 150 146 137 129 69 101 94 78 98 69 62 85
77 63 72 100 58 54 58 58 60 63 98 133 149 73 77 117 187 173 225 249
297 240 266 245 278 404 303 334
BBO-H20B 48
224 276 300 276 229 194 193 163 151 132 144 128 75 99 89 76 100 71 62 82
73 58 82 103 55 55 72 57 70 44 98 132 153 75 84 105 195 165 215 251
274 257 259 243 268 423 312 342

BBO-H21A 70
106 179 146 172 154 164 153 132 98 153 190 126 142 142 107 107 71 78 84 55
74 87 64 32 46 51 53 67 46 37 50 42 41 40 45 32 35 30 40 42
22 67 104 117 84 61 130 209 212 314 270 307 289 253 192 270 304 195 196 212
245 160 171 160 198 217 228 162 215 185
BBO-H21B 70
107 178 140 187 157 158 152 122 96 164 180 124 143 157 113 108 64 76 78 55
60 81 57 29 45 49 50 67 49 39 62 42 42 44 48 35 32 30 36 42
24 80 87 121 76 62 127 216 228 322 248 320 289 255 194 271

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 Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see

how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of

the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

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

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

corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

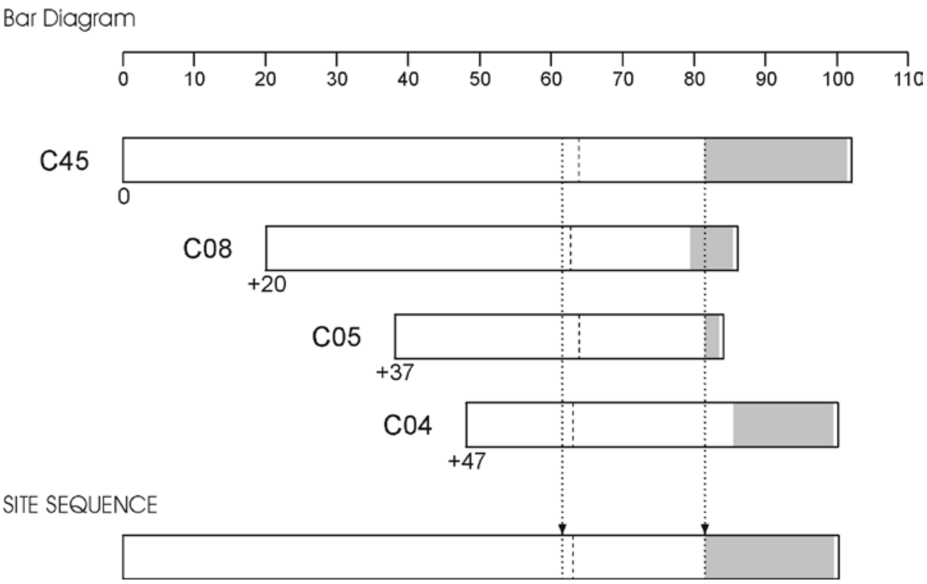


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

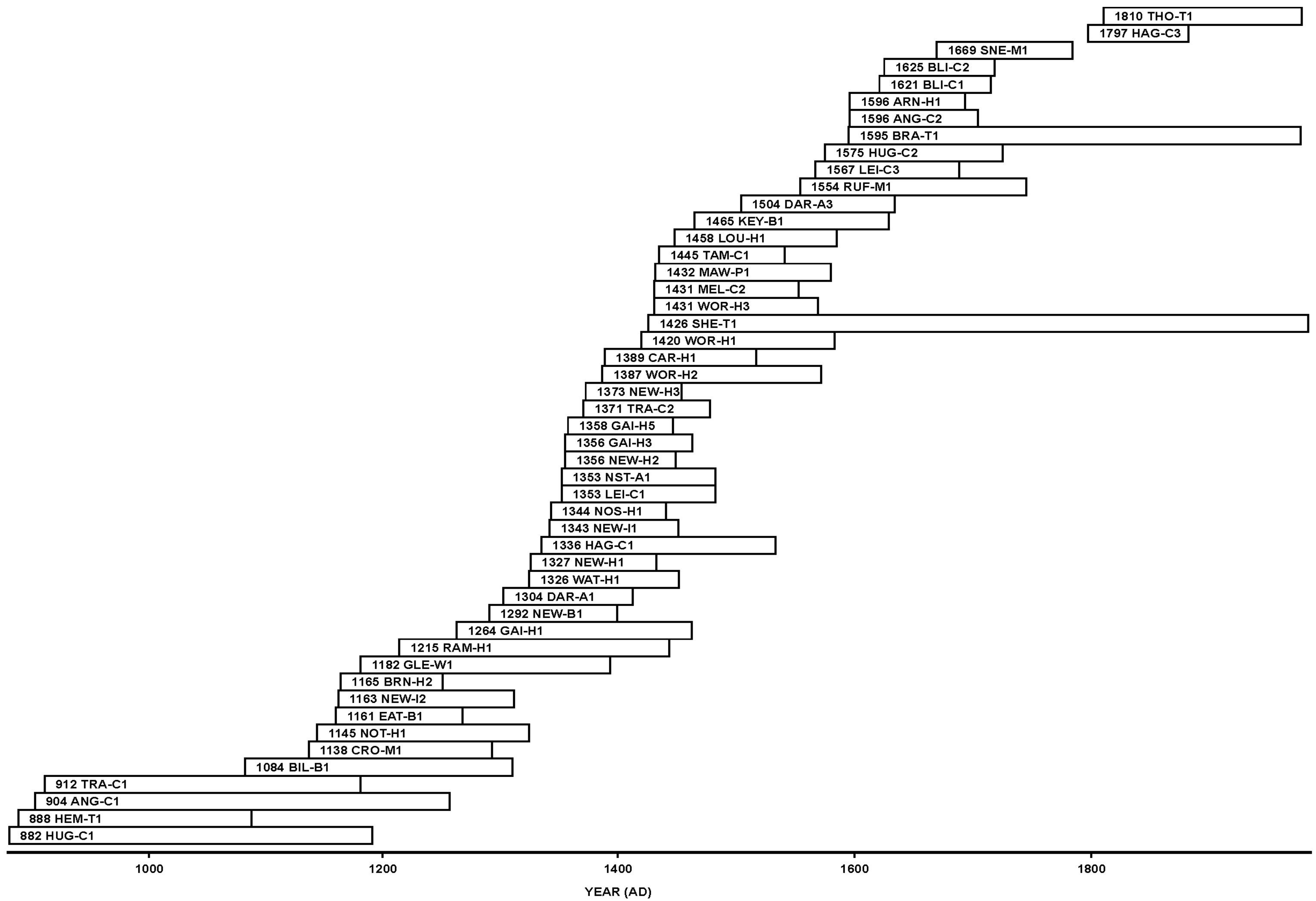
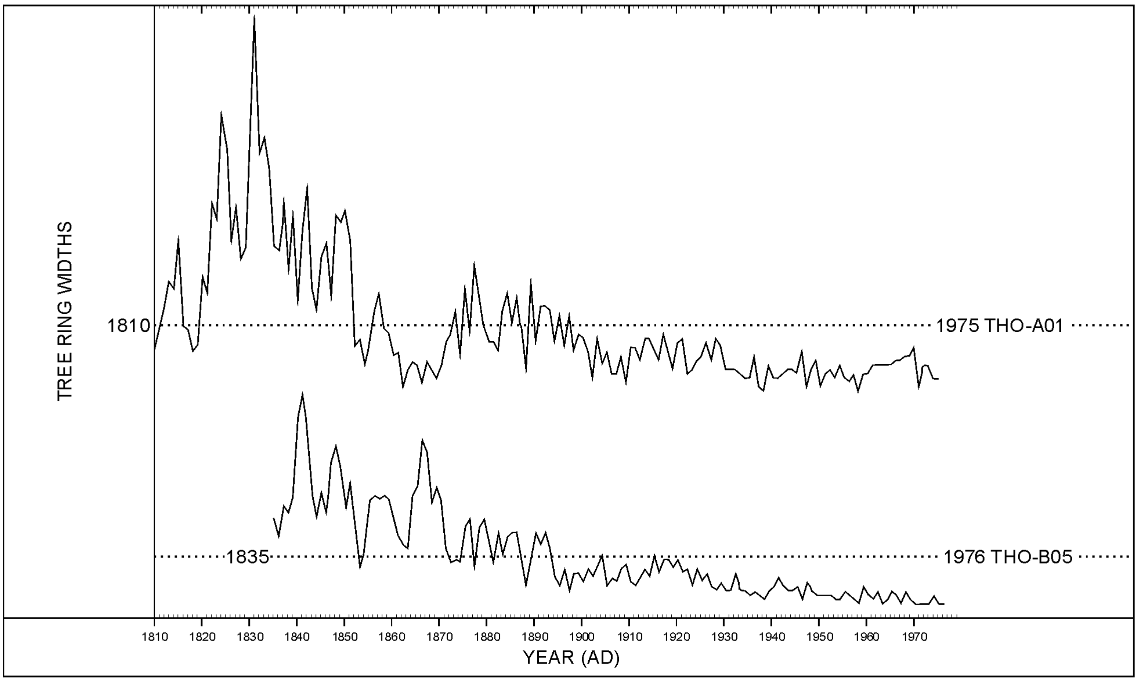


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

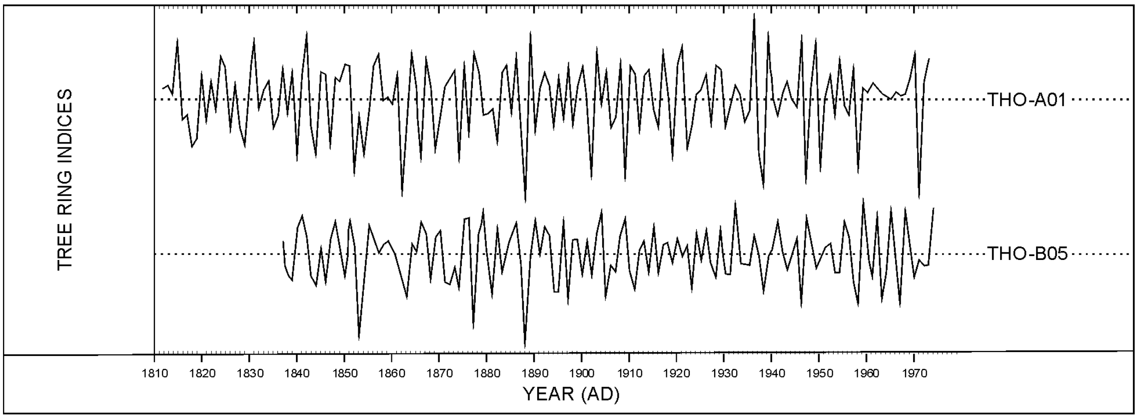


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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