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GOTHELNEY HALL, CHARLYNCH, NEAR BRIDGWATER, SOMERSET TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard, Matt Hurford and Cathy Tyers

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

GOTHELNEY HALL, CHARLYNCH, NEAR BRIDGWATER, SOMERSET

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SUMMARY

Dendrochronological analysis was undertaken on 31 of the 41 samples taken from a number of different locations within Gothelney Hall. This resulted in the production of eight site chronologies, each comprising between two and six samples, of lengths of between 61 and 174 rings. These eight site chronologies account for 26 of the 31 measured samples.

Only one site chronology, comprising three samples, could be dated. The timbers represented, floor joists of the solar attic, have an estimated felling date in the range AD 1426–51. The grouping of the other samples suggests the possibility that a number of different phases of felling may be represented.

Five measured samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold, Robert Howard, Matt Hurford, and Cathy Tyers

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to take this opportunity to Mr and Mrs Price, owners of Gothelney Hall, for their enthusiasm and support for this programme of tree-ring analysis, and for their generous hospitality during sampling. We would also like to thank both Marius Barran and Claudia Burn of Marius Barran, Architects, Dulverton, for their help in interpreting the possible phases of timberwork found here, and for the prompt provision, and use, of their plans and drawings in this report. Thanks are also due to Jenny Cheshire Historic Buildings Inspector, of English Heritage's Bristol office. Finally we would like to thank the Oxford Dendrochronology Laboratory, particularly Martin Bridge, for comparing the site chronologies to their reference database.

ARCHIVE LOCATION

Somerset Historic Environment Record
Somerset County Council
Taunton Castle
Taunton TA1 4AA

DATE OF INVESTIGATION

2008–10

CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Matt Hurford and Cathy Tyers
Dendrochronology Laboratory
Archaeology Graduate School
University of Sheffield
West Court, 2 Mappin Street
Sheffield S1 4DT
0114 2763146
m.hurford@sheffield.ac.uk
c.m.tyers@sheffield.ac.uk

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INTRODUCTION

Gothelney Hall, just to the west of Bridgwater in Somerset (Figs 1 and 2), is an impressive, Grade I listed, manor house, possibly the remains of a once larger complex of buildings, the presently extant structures now forming a U-shaped group round a courtyard open to the south. According to Penoyre (2005), Gothelney Hall may have been an example of a type characterised by small, square, halls with flat beamed ceilings and chambers above that were open to the roof.

The northern part of the west range comprises a tall house containing a solar and great chamber. This section is believed, on the basis of stylistic evidence, to be of later-fifteenth or early sixteenth-century date, and may have been built by Alexander Hody (a wealthy lawyer who is believed to have been in possession of the site by AD 1439), his widow, or perhaps his nephew. Most of the subsequent additions were probably made during the later period of the Hody family's ownership.

The front, or east, elevation of the northern part of the west range, has a two-storeyed porch attached to it which now gives access to the former cross-passage (a simpler, single-storey, porch is found attached to the rear elevation). To the left of the front porch is a tall embattled tower, with a spiral staircase within, and a room on its top floor distinguished by a three-light widow with perpendicular tracery. This stairs also gives access to the upper rooms. The central, double-height, ground-floor hall appears to have had rooms at each end, above each of which was another room at first floor level. On the second floor a great chamber, open to the roof, extended over the hall and the northern first floor room, while the second floor over the southern room formed a solar, also open to the roof. The great chamber was lit by two two-light windows on each side, while on the west there was a fireplace whose flue was bracketed out from the wall. There was also a garderobe and second, minor, stair tower containing other rooms, at the south-west corner of this northern range.

The roofs of the great chamber and solar, which are believed to be contemporary with each other, are both richly decorated, comprising between them twelve arch-braced main and intermediate trusses with three rows of cusped windbraces (Figs 4–6). It is thought that the roof of the great chamber would have been visible from the floor below. A variation in this roof form is seen in the two bays of the solar where the windbraces of the upper tier to both pitches are inverted (Fig 7). These spectacular roofs are now hidden in the attic, cut off from view by the insertion, it would seem, of a later ceiling to the upper rooms (Fig 8). The date of the insertion of the ceilings to the upper rooms, creating the attics, is unknown. Indeed, on the basis of subtle but important differences in the size, moulding, and spacing of the joists, it is believed that portions of the ceilings may have been inserted at different times. One effect of inserting this frame was to cut across and partially block the window openings of the great chamber (Fig 9).

Extending southwards from the solar end of the original house is a lower second, or southern, range, probably of sixteenth-century date, and probably intended for storage rather than domestic use. The roof here comprises three principal-rafter with tiebeam trusses. Running eastwards from the northern end of the main range is a further extension, known as the 'smoke house' or east range, comprising three bays of cruck trusses. This extension, probably also of the sixteenth century, contained kitchen and service rooms.

The most notable seventeenth-century insertion is a ribbed plaster ceiling in the northern ground-floor room. In the eighteenth century there was much internal refitting and sash windows were put into the east side of the great chamber. The porch and two-storeyed passage next to it appear to have been rebuilt in the early-nineteenth century.

SAMPLING

Sampling and dating by dendrochronology of the timbers at Gothelney Hall were requested by Jenny Chesher, Historic Buildings Inspector at English Heritage's Bristol office. The primary purpose of this programme of analysis was to support a reassessment of the structural development of the building to further inform an understanding of its phasing. An additional benefit of sampling for tree-ring dating was the contribution the data might make to the corpus of reference material available for this region, which, although now increasing due in particular to the efforts of English Heritage, is still under-represented.

With these aims in mind English Heritage requested assessment and appropriate sampling of several different areas. This was primarily focused on the hall/solar range and associated elements. This included: the roofs over the great chamber, solar, and garderobe; the three distinct sections of the attic floor frame along the length of the great chamber and solar; the lintels of the now blocked windows within the attic; the ceiling beams from the spiral stairs (Fig 10) and double-height dining room (Fig 11); and various door frames within this range. Sampling was however also requested for the roof and floor beams to the southern extension from the main range, as well as from the 'smoke-house' or east range off the northern end of the hall range.

From this extensive assemblage of timbers, a total of 41 oak timbers was sampled by coring. Each sample was given the code GTH-A (for Gothelney, site 'A') and numbered 01–41. Seventeen samples, GTH-A01–17, were taken from the frame of the hall attic, with a further three samples, GTH-A18–21, being obtained from the smaller number of accessible timbers in the floor frame of the solar attic.

From the roof of both the hall and solar range at total of 12 samples was obtained, GTH-A21–32, with two samples, GTH-A33 and A34, being taken from the window lintels now within the hall attic. Four samples, GTH-A35–8, were taken from the various doorways (a few doorway timbers proving unsuitable for analysis), with a final three samples, GTH-A39-41, being taken from the ceiling beams of the spiral stairs.

Unfortunately some areas included within the brief proved unsuitable for sampling. These included the roof of the garderobe, the timbers here not only being derived from fast-grown timbers, but also being of small scantling. As such, although a close inspection was made, it was thought that they were unlikely to provide suitable samples for reliable dating. The two ceiling beams of the double-height dining room also proved unsuitable. Not only were these timbers inaccessible in this room (nor were they visible when floorboards were lifted in an adjacent ceiling-level corridor), but it appeared that the beams were made up of several small applied coved and moulded pieces, few of which were apparently of any significant depth and likely to produce worthwhile samples. Nor were samples obtained from the roof and floor frame of the southern extension, or from the eastern, 'smoke-house', range, all the timbers of these elements being of elm. Although elm can occasionally be dated by tree-ring analysis, dating is usually only possible where large numbers of samples with high numbers of rings can be obtained. In the case of the material here, it was seen that the majority of the elm timbers were derived from very fast-grown trees with low numbers of rings. As such, it was felt that they would not provide useable samples.

The location of samples was noted at the time of coring and marked on the drawings kindly made available by Claudia Burns of Marius Barran, Architects. These illustrations are reproduced here as Figures 12–16. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

Each of the 41 samples obtained was prepared by sanding and polishing. It was seen at this point that 10 samples had very low numbers of rings and were rejected from this programme of analysis. The annual growth rings of the remaining 31 were, however, measured, the data of these measurements being given at the end of this report. The data of these 31 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

At a minimum value of t=4.5, eight different groups of cross-matching samples could be formed, accounting for 26 of the 31 measured samples, the samples of each group cross-matching with each other as shown in the bar diagrams (Figs 17–24). The samples of each group were combined at their indicated offset positions to form site chronologies GTHASQ01–SQ08.

All eight site chronologies were compared to an extensive range of reference chronologies for oak, this indicating a repeated cross-match and date for only one of them, GTHASQ04, with a first ring date of AD 1238 and a last measured ring date of AD 1411. The evidence for this dating is given in the t-values of Tables 2.

Each site chronology was compared with the other seven, and with the remaining five measured but ungrouped samples. There was however, no further cross-matching. Each of the five ungrouped samples was then compared individually with the reference chronologies, but again there was no cross- matching.

This analysis can be summarised as follows:

Sequence	Samples	Rings	Location	Date span
GTHASQ01	21, 22, 23, 24, 25, 27	112	Hall range roof	undated
GTHASQ02	3, 4, 5, 6, 7	84	Hall attic joists, bays 1 and 2	undated
GTHASQ03	8, 9, 10, 11	72	Hall attic joists, bay 3	undated
GTHASQ04	18, 19, 20	174	Solar attic joists	AD 1238–1411
GTHASQ05	37, 38	64	Attic doorways	undated
GTHASQ06	33, 34	73	'Attic' window lintels	undated
GTHASQ07	39, 41	66	Spiral stair ceiling	undated
GTHASQ08	12, 13	61	Hall attic joists, bay 4	undated
Ungrouped	5 samples			undated
Unmeasured	10 samples			----------

DISCUSSION AND CONCLUSION

Analysis of 31 measured samples from Gothelney has resulted in the production of eight site chronologies, only one of which, GTHASQ04, can be dated, its 174 rings spanning the years AD 1238–1411. This dated site chronology comprises three samples, all of them from the floor joists of the solar attic. None of the samples in this group retains complete sapwood, and it is thus not possibly to reliably indicate a precise felling date for the timbers represented. One of the samples in this group, however, GTH-A19, retains the heartwood/sapwood boundary, this being dated to AD 1411. Using a 95% probability of 15–40 sapwood rings the tree might have had would give the timber represented an estimated felling date in the range AD 1426–51, thus indicating the presence of material of a slightly earlier date than might have been anticipated.

Although, because they do not have the heartwood/sapwood boundary, the felling date range of the other two samples, GTH-A18 and A20, in dated site chronology GTHASQ04 cannot be accurately determined, there is little reason to suspect that the timbers they represent were not felled during this time span as well. The two samples have last measured, heartwood, rings dates of AD 1406 and AD 1376, which, using a 95% probability of a minimum of 15 sapwood rings, would mean that the respective timbers are unlikely to have been felled before AD 1421 and AD 1391. Furthermore, all three samples in site chronology GTHASQ04 cross-match with each other with values of t=6.8 and t=7.4, values high enough to suggest that the source trees grew close to each other in the same area of woodland. Had the trees been felled at different times, it is less likely that they would have been used in the same constructional element.

Although the other sampled timbers are undated, it is of interest to note from Table 1 and the bar diagrams that the samples do appear to fall into groups related to their sample location. The samples in site chronology GTHASQ01, for example, are all from the roof of the hall range, thus demonstrating that the timbers here, perhaps not unexpectedly given the similarity of design and structural integrity of the trusses, are all of one phase. Those samples in site chronology GTHASQ02 are all from the attic floor joists of bays 1 and 2, those in GTHASQ03 from the attic floor joists of bay 3, and so on. Where the samples retain it, the relative position of the heartwood/sapwood boundary suggests that the timbers of each group were cut as part of a single period of felling.

This grouping of the samples could be taken to support the view, based on subtle differences in their sizes and shapes, that the joists of the various bays of the hall and solar attics, along with other timbers, could be of different dates, though this cannot be proven by the results of this programme of tree-ring analysis. The inference is clearly that the timbers are unlikely to be of a single phase of felling from a single, closely related, group of trees. It is noticeable during analysis that while the cross-matching between the samples within each site chronology is sometimes very high, indeed high enough to suggest some timbers are derived from the same tree, there is no satisfactory cross-matching between site chronologies.

There are, for example, noticeably high *t*-values between samples GTH-A03 and A07 (t=11.9), between samples A04 and A07 (t=11.5), and between A21 and A22 (t=11.2). It is probable that the pairs of timbers represented were derived from single trees. Within site chronologies, other cross-matches in excess of t=6.0 and t=7.0 are also found. There are, however, no significant cross-matches between any of the eight site chronologies.

Thus, while at the moment tree-ring analysis has not been quite the dating success that might have been hoped, it may have given some support to the structural interpretation of the building in showing that timbers of different dates may be present.

Although mostly undated at the moment, the data obtained here may in due course play an important part in the development of a more robust regional reference corpus, at which point the felling date of these timbers may become known. Somerset is an area in which it has been difficult to find buildings with sufficient suitable timbers for analysis, with a large proportion of buildings being rejected as unsuitable. In this respect the material obtained from Gothelney is typical, although in this instance very disappointing, but it clearly provided a potentially important opportunity to extend the regional reference dataset, as well as the opportunity to aid the overall understanding of the development of this building.

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TABLES

Table 1: Details of tree-ring samples from Gothelney Hall, Bridgwater, Somerset

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Hall range attic floor joists						
GTH-A01	Bay 1, joist 2 (from east)	nm	h/s	------	------	------
GTH-A02	Bay 1, joist 8	nm	h/s	------	------	------
GTH-A03	Bay 1, joist 10	64	no h/s	------	------	------
GTH-A04	Bay 1, joist 11	55	no h/s	------	------	------
GTH-A05	Bay 1, joist 12	78	h/s	------	------	------
GTH-A06	Bay 2, joist 2	69	h/s	------	------	------
GTH-A07	Bay 2, joist 3	73	h/s	------	------	------
GTH-A08	Bay 3, joist 3	69	h/s	------	------	------
GTH-A09	Bay 3, joist 9	53	h/s	------	------	------
GTH-A10	Bay 3, joist 12	60	no h/s	------	------	------
GTH-A11	Bay 3, joist 14	58	no h/s	------	------	------
GTH-A12	Bay 4, joist 3	56	no h/s	------	------	------
GTH-A13	Bay 4, joist 4	48	no h/s	------	------	------
GTH-A14	Bay 4, joist 6	48	h/s	------	------	------
GTH-A15	Bay 4, joist 9	nm	h/s	------	------	------
GTH-A16	Main floor beam, bay 1	65	h/s	------	------	------
GTH-A17	Main floor beam, bay 4	nm	------	------	------	------
Solar range attic floor joists						
GTH-A18	East joist 2	92	no h/s	1315	------	1406
GTH-A19	East joist 3	131	h/s	1281	1411	1411
GTH-A20	East joist 4	139	no h/s	1238	------	1376

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Hall range roof timbers						
GTH-A21	Truss 1, east principal rafter	55	2	------	------	------
GTH-A22	Truss 1, west principal rafter	54	2	------	------	------
GTH-A23	Truss 3, east principal rafter	77	no h/s	------	------	------
GTH-A24	Truss 3, west principal rafter	71	h/s	------	------	------
GTH-A25	Truss 3, east upper arch brace	80	no h/s	------	------	------
GTH-A26	Truss 3, west upper arch brace	nm	---	------	------	------
GTH-A27	Truss 4, east upper arch brace	62	no h/s	------	------	------
GTH-A28	Truss 6, west principal rafter	nm	h/s	------	------	------
GTH-A29	Truss 10, west principal rafter	nm	---	------	------	------
GTH-A30	Truss 10, west wall post	56	h/s	------	------	------
GTH-A31	Truss 10, collar	55	no h/s	------	------	------
GTH-A32	Truss 11, collar	nm	---	------	------	------
GTH-A33	East window lintel at truss 6	70	h/s	------	------	------
GTH-A34	West window lintel at truss 6	72	h/s	------	------	------
Other attic timbers						
GTH-A35	Attic doorway, hall range to solar, west jamb	nm	---	------	------	------
GTH-A36	Attic doorway, hall range to solar, cill beam	nm	---	------	------	------
GTH-A37	Attic doorway, solar to stairs, east jamb	52	h/s	------	------	------
GTH-A38	Attic doorway, solar to stairs, west jamb	64	h/s	------	------	------
Ceiling to main spiral staircase						
GTH-A39	Main north-south beam	62	h/s	------	------	------
GTH-A40	North-west lateral beam	49	no h/s	------	------	------
GTH-A41	South-west lateral beam	66	h/s	------	------	------

nm = not measured

h/s = the heartwood/sapwood ring is the last ring on the sample

Table 2: Results of the cross-matching of site sequence GTHASQ04 and relevant reference chronologies when the first-ring date is AD 1238 and the last-ring date is AD 1411

Reference chronology	t-value	Span of chronology	Reference
Exeter Cathedral, Devon	7.4	AD 1137–1332	(Mills 1988)
Stockton Lovell Farmhouse, Fiddington, Somerset	7.4	AD 1271–1403	(Miles and Worthington 1999)
The George Inn, Norton St Philip, Somerset	7.2	AD 1290–1509	(Miles and Worthington 1998)
The Priory, Odiham, Hampshire	6.9	AD 1207–1448	(Miles and Worthington 2000)
Reading waterfronts, Berkshire	6.5	AD 1160–1407	(Groves *et al* 1997)
The Gatehouse, Holnicote, Somerset	6.3	AD 1243–1430	(Miles *et al* 2004)
Shapwick House, Shapwick, Somerset	6.1	AD 1268–1488	(Miles and Haddon-Reece 1996)
St Mary Magdalene Church, Twyning, Gloucestershire	5.9	AD 1251–1452	(Tyers 1996)

FIGURES

Figure 1: Map to show the location of Gothelney Hall

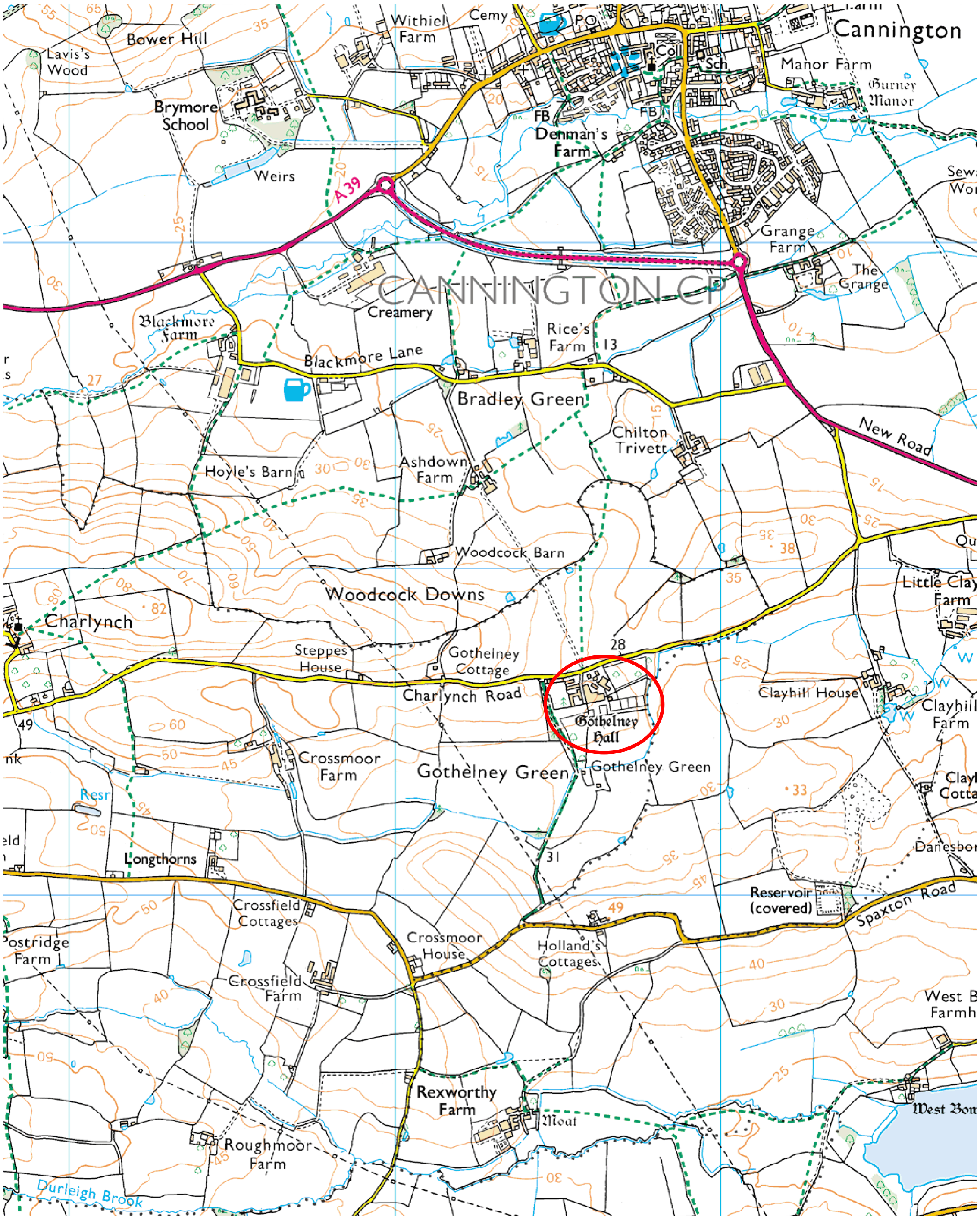


Figure 2: Map to show the location of Gothelney Hall

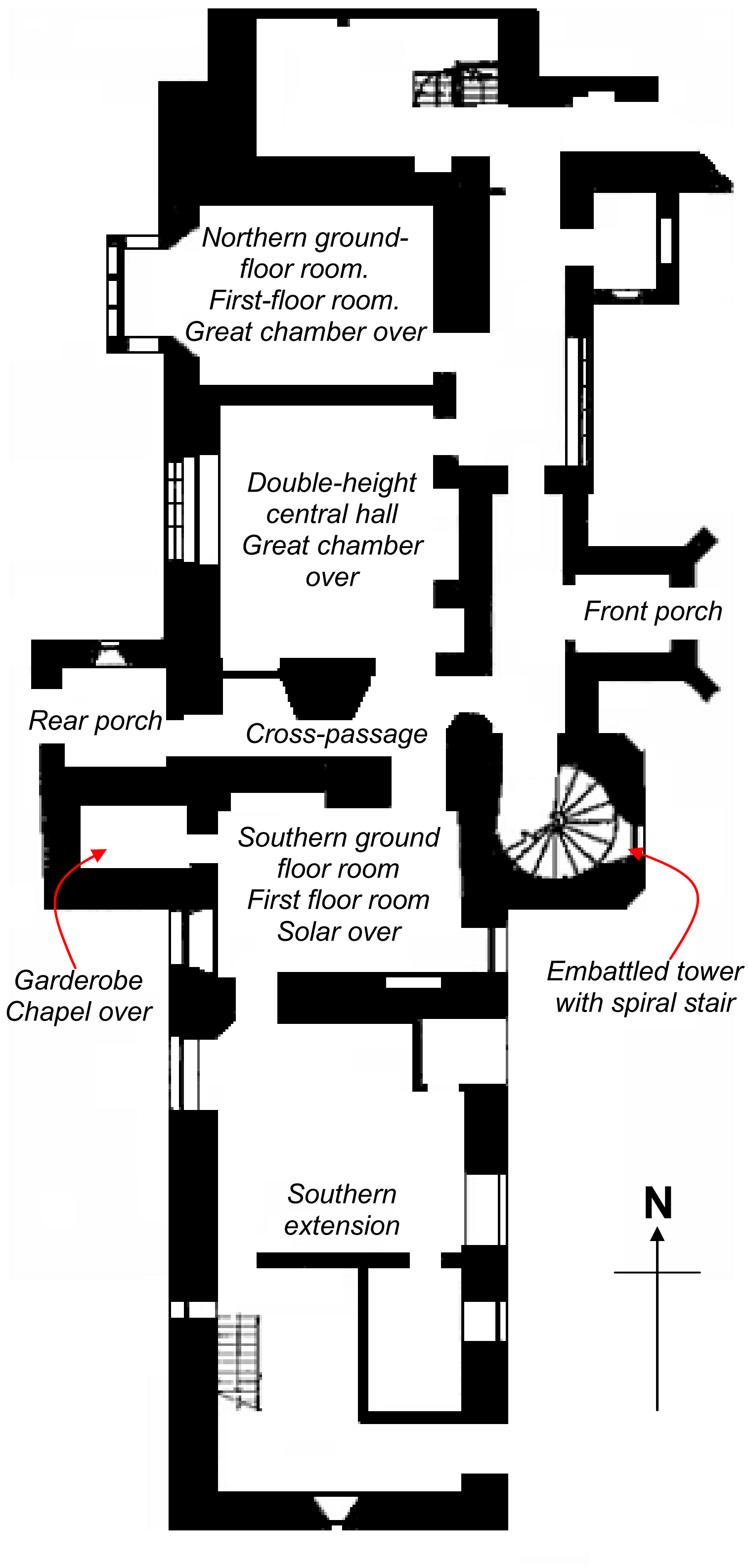


Figure 3: Basic plan of main west range (after Marius Barran)

Figure 4: The roof to the great camber, looking south to north

Figure 5: Detail of moulding to the wall plate

Figure 6 (left): Windbraces to the great chamber roof

Figure 7 (right): Windbraces to the solar roof showing inversion of the upper tier

Figure 8 The frame inserted to ceil the great chamber and form the attic floor

Figure 9: The attic floor frame cutting across a window of the great chamber

Figure 10: The ceiling of the main spiral staircase

Figure 11: View of the beams in the double height ground-floor room

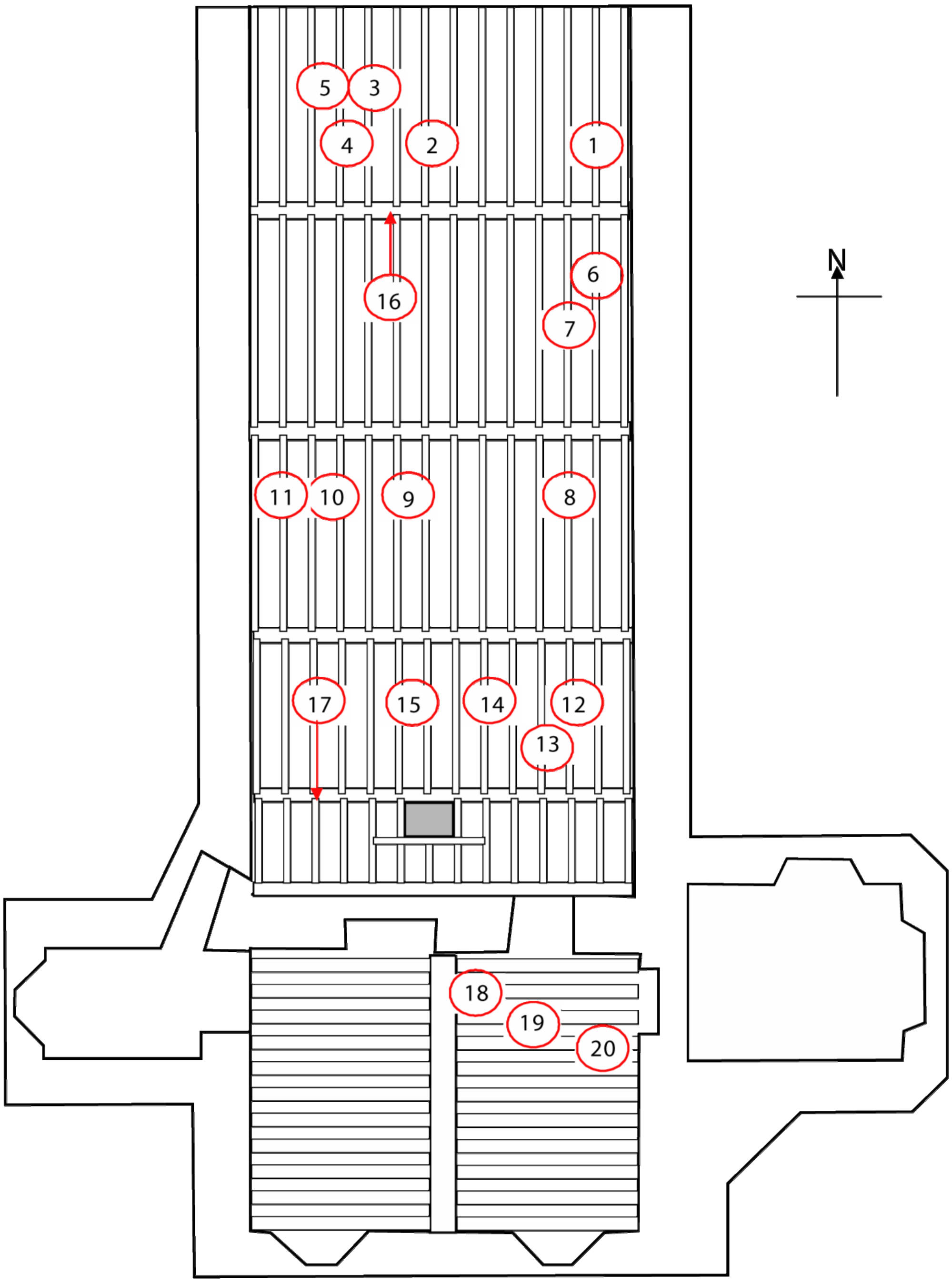


Figure 12: Plan of the attic to show sampled floor-frame timbers

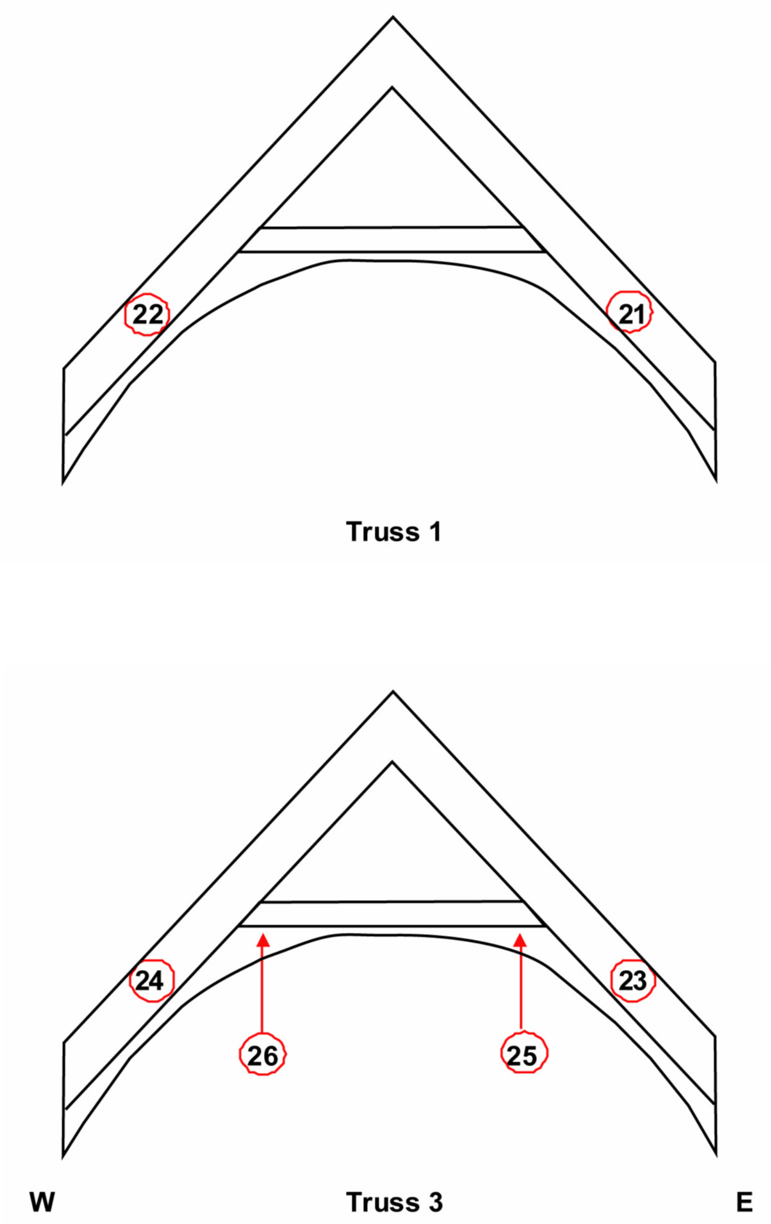


Figure 13a: Trusses of the great chamber roof to show sampled timbers (after Marius Barran)

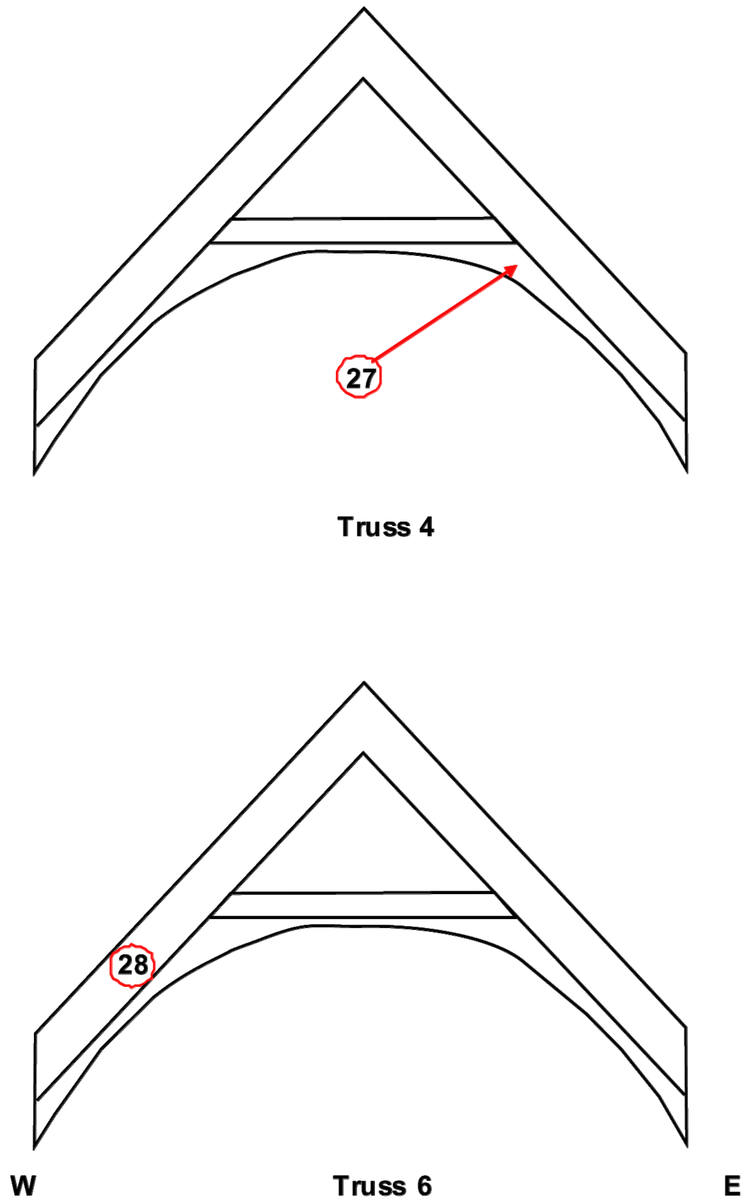


Figure 13b: Trusses of the great chamber roof to show sampled timbers (after Marius Barran)

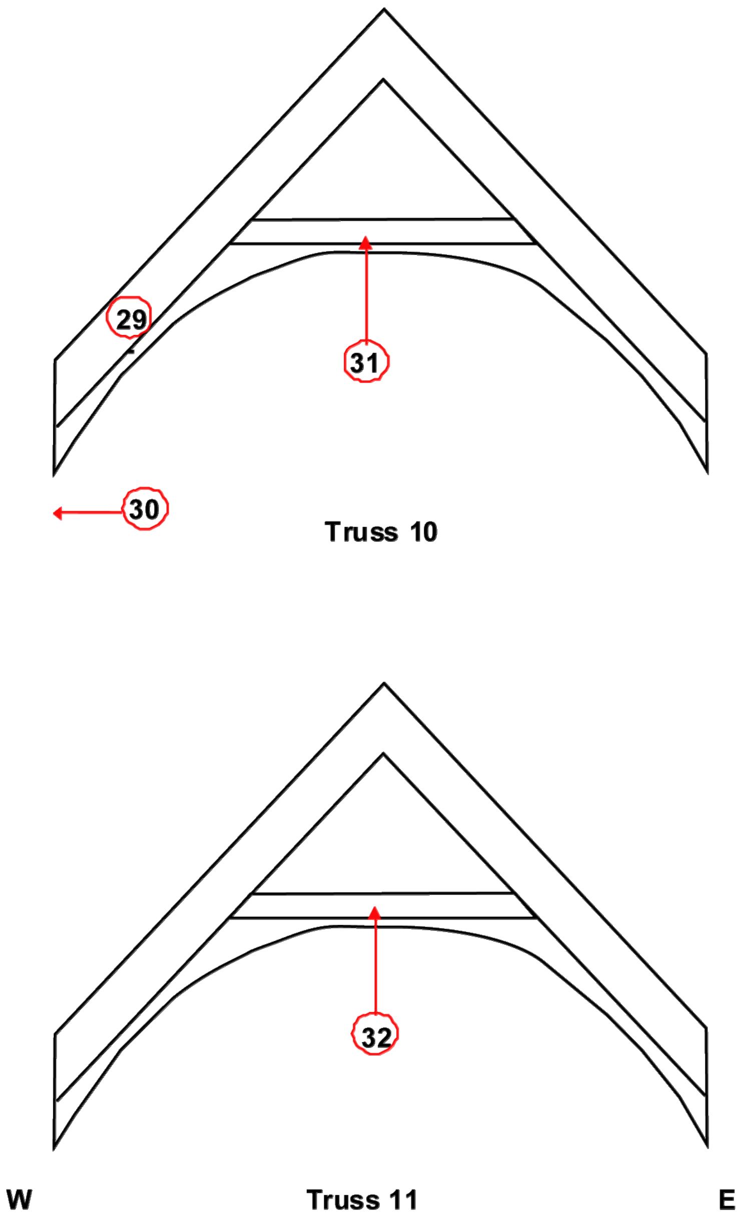


Figure 13c: Trusses of the solar roof to show sampled timbers (after Marius Barran)

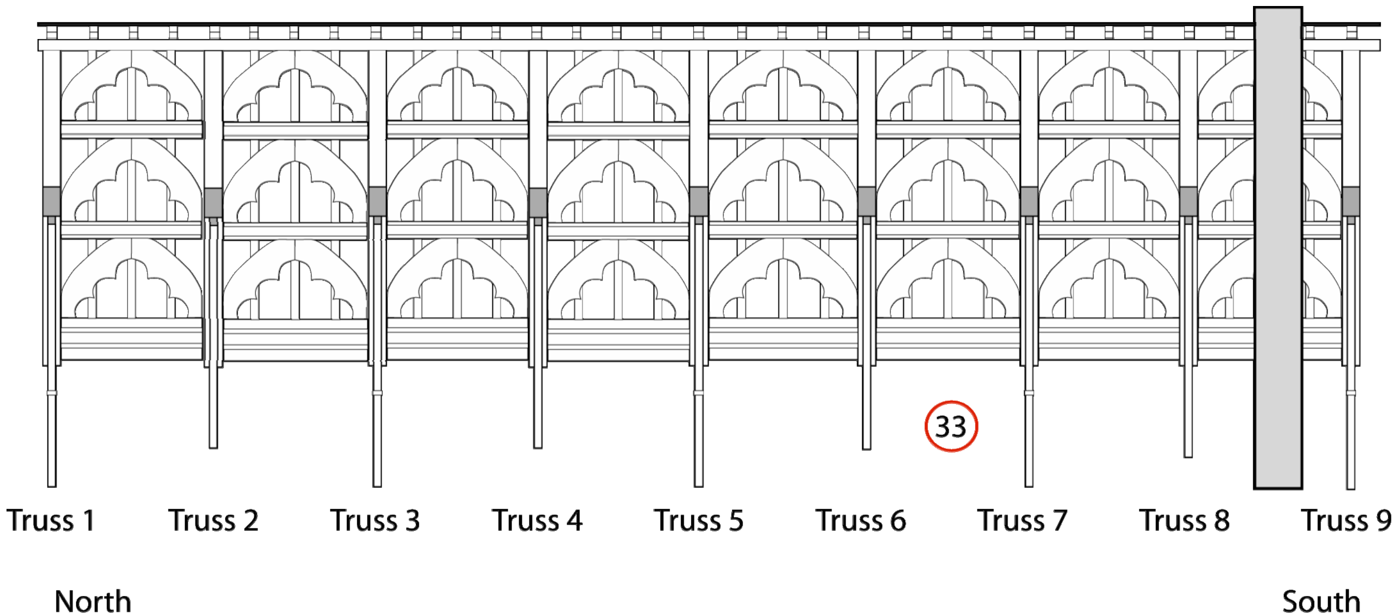


Figure 14a: Long section looking east to show sampled timbers (after Marius Barran)

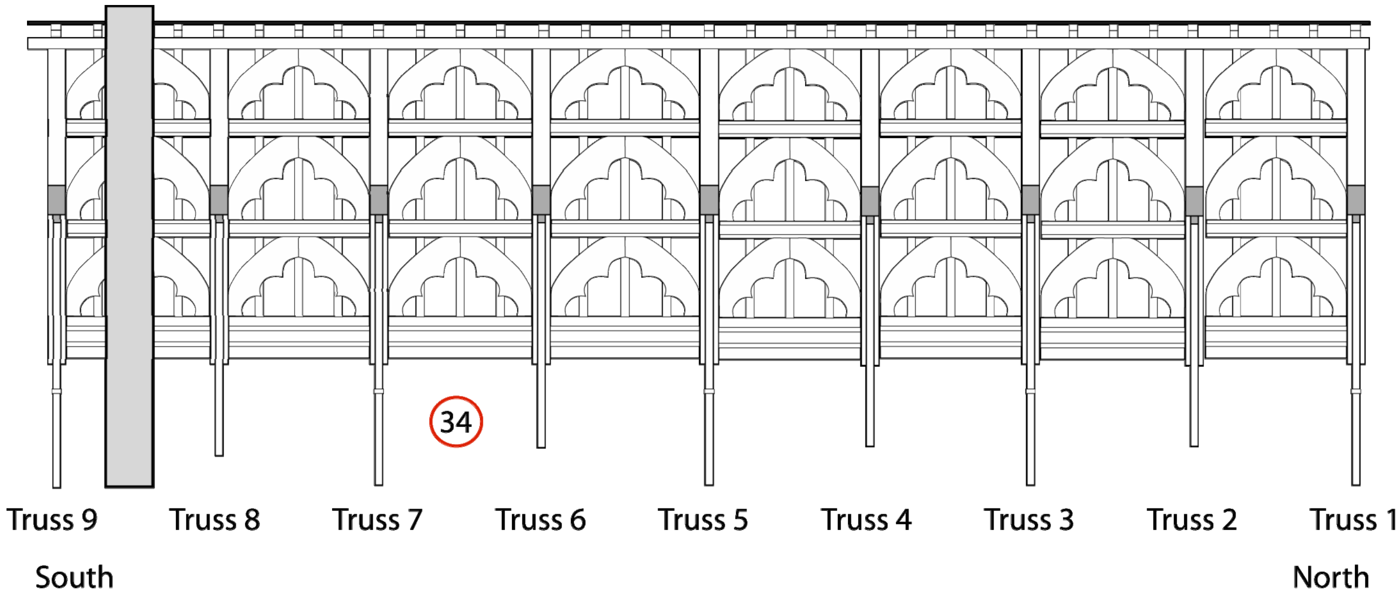


Figure 14b: Long section looking west to show sampled timbers (after Marius Barran)

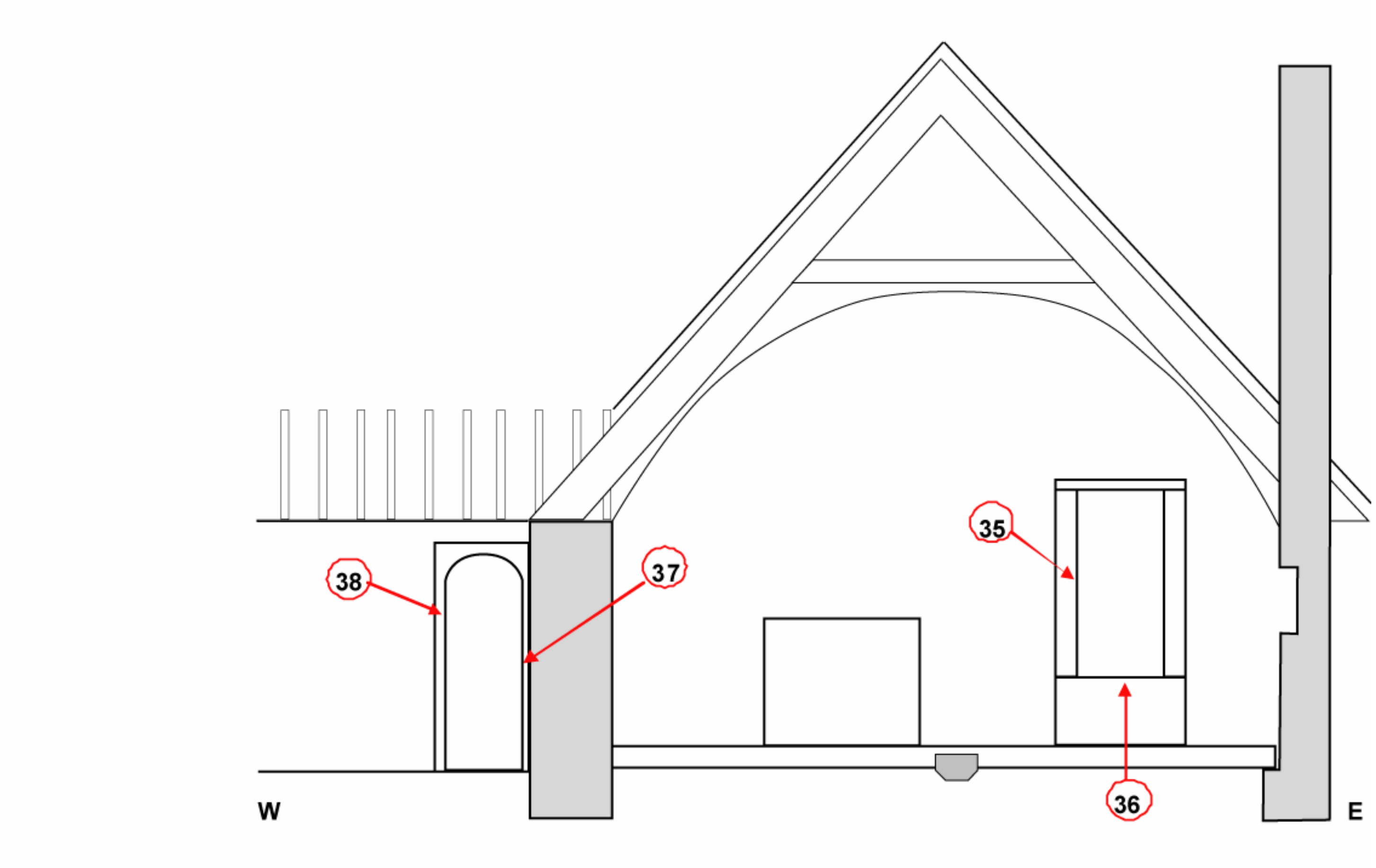


Figure 15: Section at attic level to show sampled door-frame timbers (after Marius Barran)

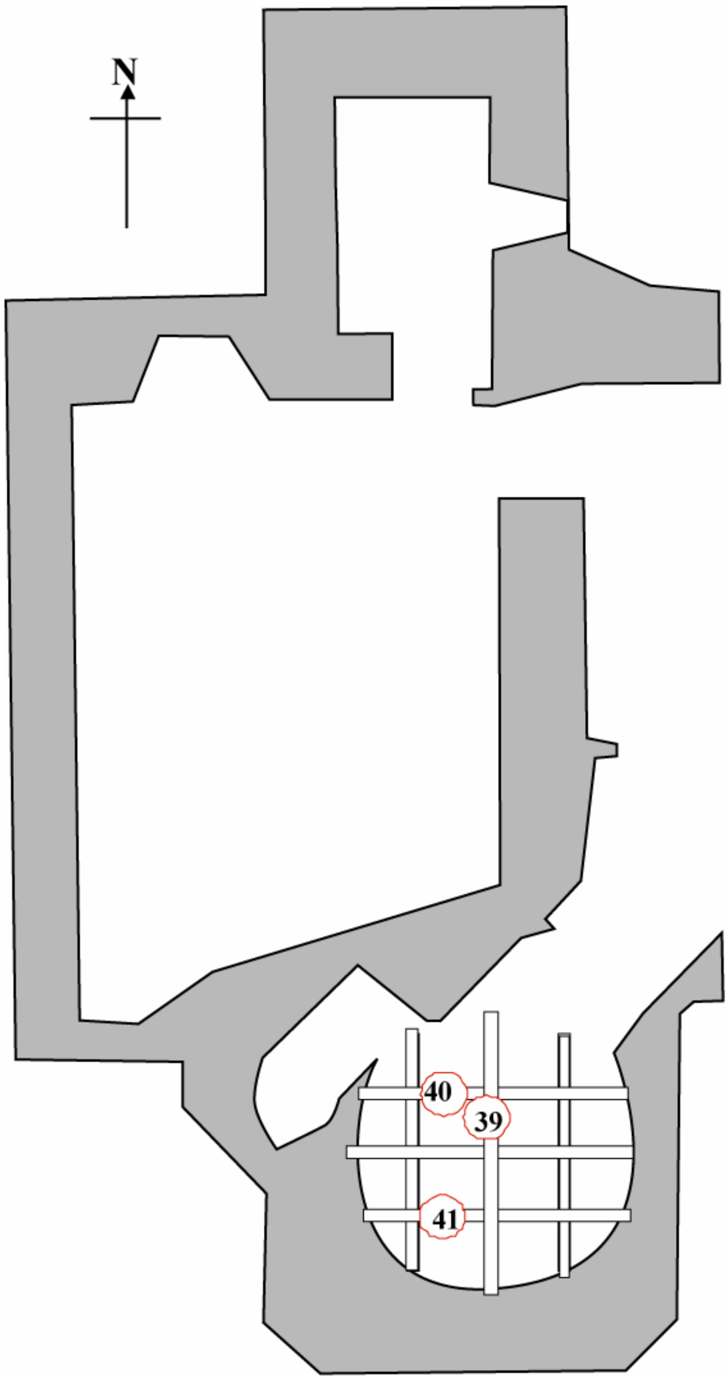


Figure 16: Simple plan of the ceiling to the main spiral staircase to show sampled timbers (after Marius Barran)

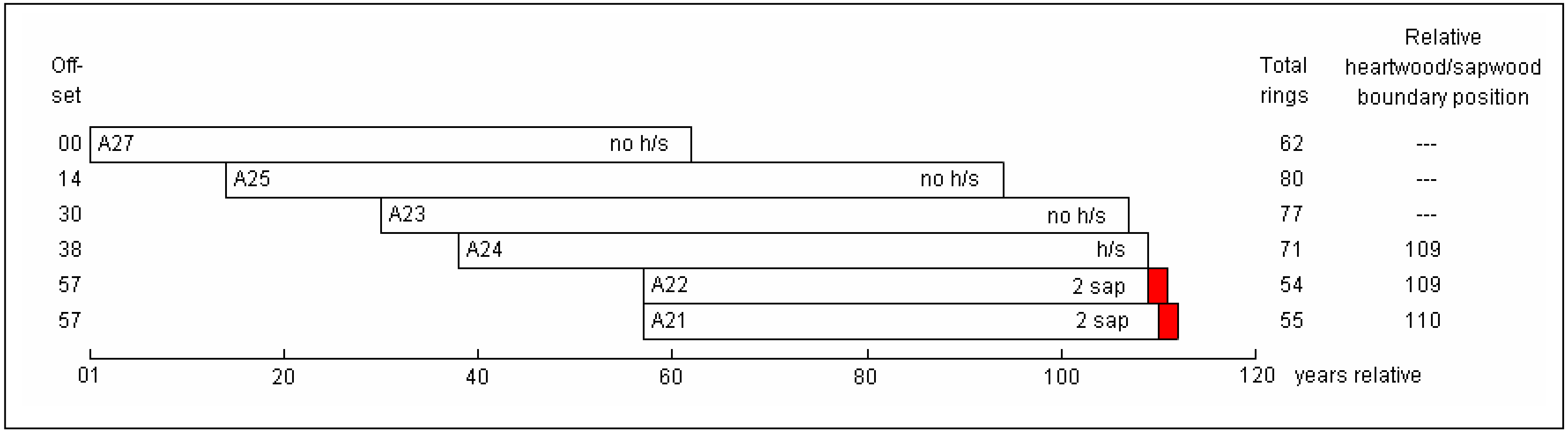
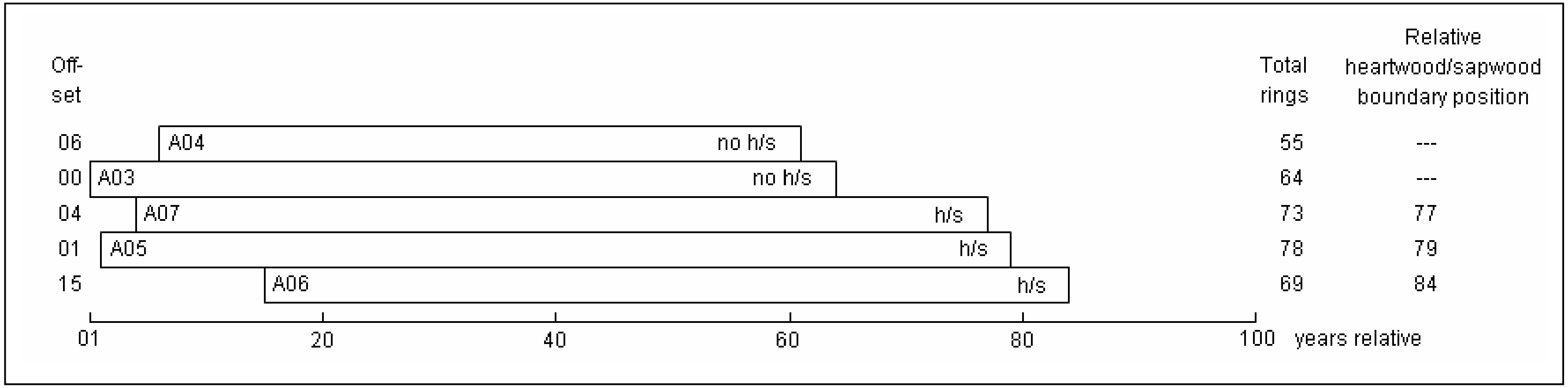


Figure 17: Bar diagram of samples in site chronology GTHASQ01



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 18: Bar diagram of samples in site chronology GTHASQ02

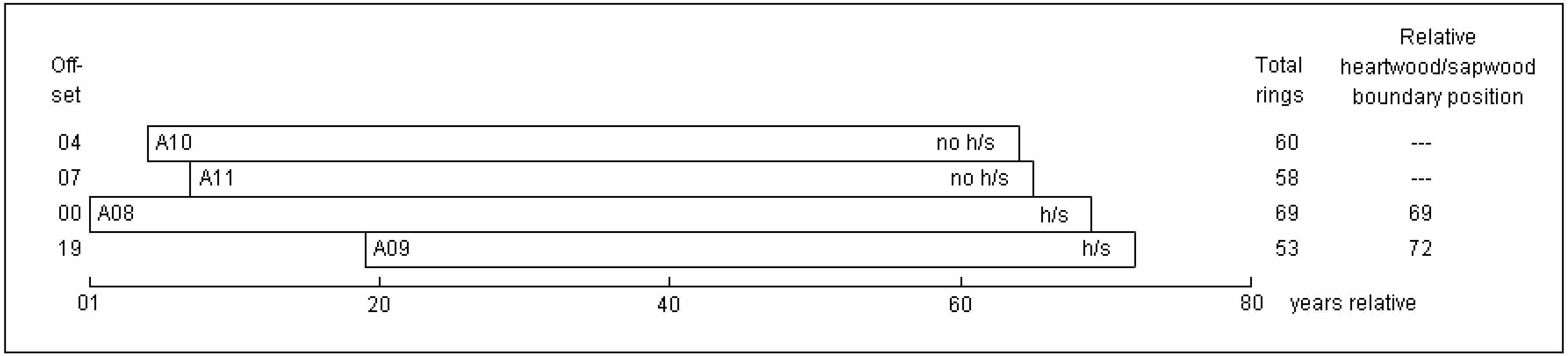
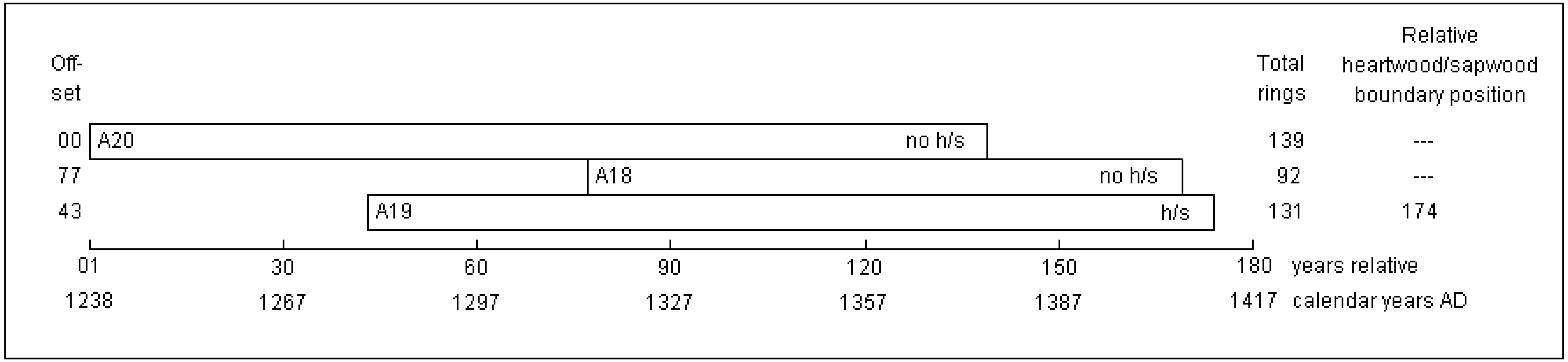


Figure 19: Bar diagram of samples in site chronology GTHASQ03



White bars = heartwood rings, shaded area = sapwood rings

h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 20: Bar diagram of samples in site chronology GTHASQ04

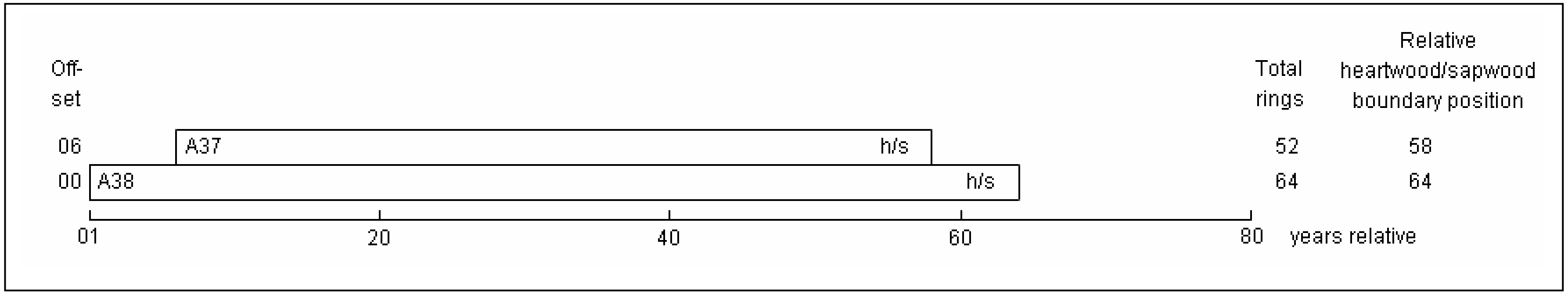
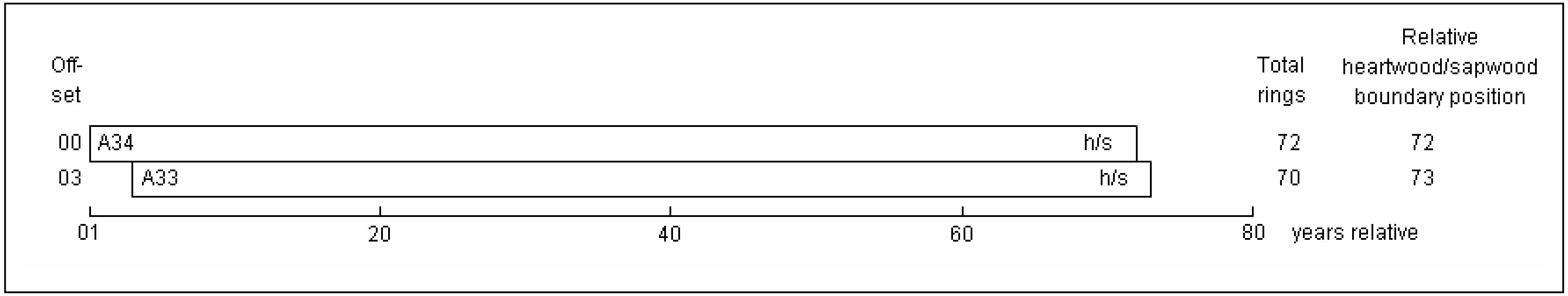


Figure 21: Bar diagram of samples in site chronology GTHASQ05



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 22: Bar diagram of samples in site chronology GTHASQ06

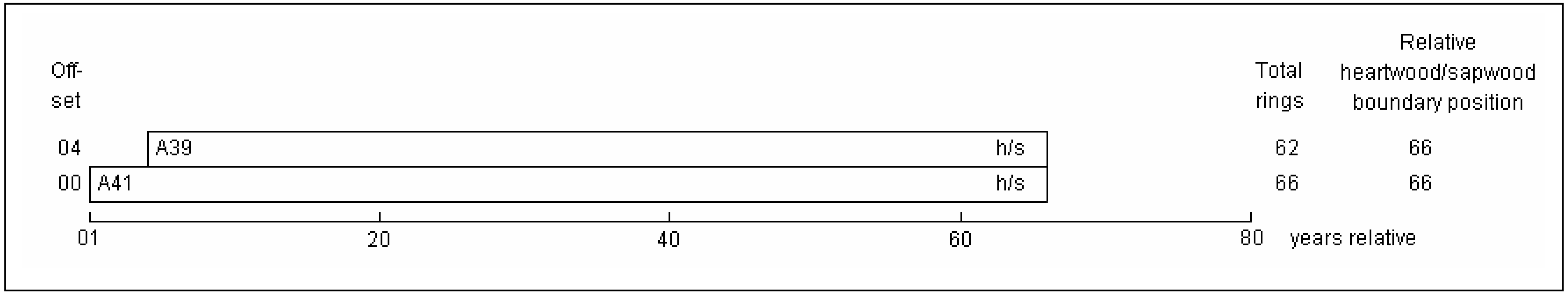
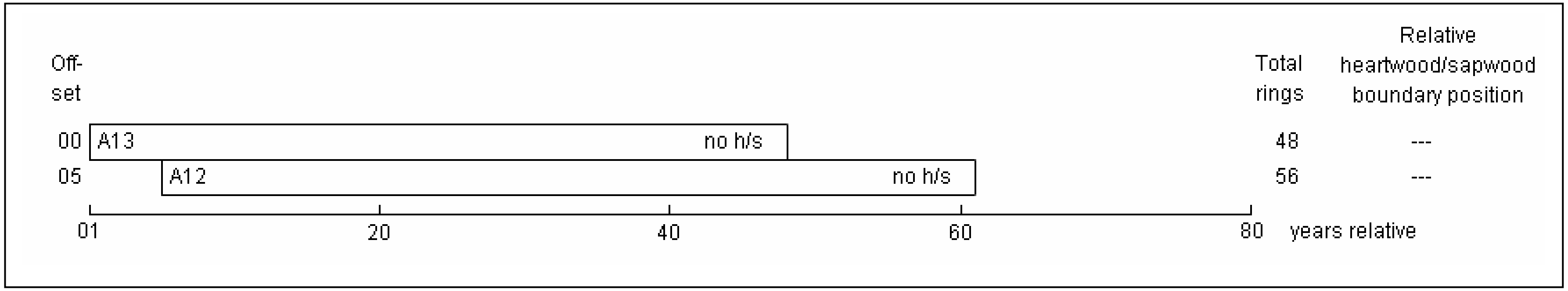


Figure 23: Bar diagram of samples in site chronology GTHASQ07



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 24: Bar diagram of samples in site chronology GTHASQ08

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

GTH-A03A 64
244 326 128 141 173 248 180 204 209 277 293 326 338 431 284 304 213 279 134 93
99 157 172 128 135 137 210 182 226 203 314 324 218 260 262 116 170 92 106 167
68 139 144 252 156 192 164 171 170 259 151 312 181 184 243 239 188 205 172 200
166 196 320 219
GTH-A03B 64
252 332 133 144 156 258 196 203 221 271 311 291 354 481 258 308 235 272 138 108
92 170 156 133 149 132 193 189 227 206 300 326 230 265 256 123 101 76 100 176
78 120 152 244 151 200 154 167 179 233 153 312 188 181 246 235 196 191 182 198
151 195 300 239
GTH-A04A 55
300 231 239 299 209 251 539 541 308 331 289 303 129 78 88 145 154 180 211 156
233 247 244 271 300 310 243 267 406 200 300 185 210 280 77 110 134 173 157 180
150 151 206 284 280 371 341 228 347 252 220 292 267 301 297
GTH-A04B 55
297 228 241 297 220 243 473 547 300 337 291 299 119 78 95 146 157 169 209 169
233 238 250 268 298 312 256 374 413 189 280 176 193 260 81 114 147 167 156 190
144 155 213 286 274 368 320 225 331 271 219 279 246 294 290
GTH-A05A 78
305 155 209 225 274 329 248 261 363 387 347 356 308 256 301 346 317 167 119 138
145 175 144 140 146 146 163 159 218 183 184 178 204 224 113 128 77 99 109 59
78 78 129 85 108 99 102 108 141 118 180 101 134 146 86 98 127 129 130 88
104 74 78 74 61 116 141 94 179 150 135 155 74 53 74 104 104 140
GTH-A05B 78
302 160 202 226 269 338 235 260 367 455 350 353 307 271 289 340 323 157 115 140
154 166 148 149 147 138 150 166 210 188 184 190 208 212 124 120 83 95 108 59
85 83 120 91 99 102 103 109 134 125 176 111 129 151 90 97 117 129 134 88
105 74 73 76 65 113 141 94 179 153 149 151 69 61 68 109 101 140
GTH-A06A 69
377 347 383 184 62 113 119 190 155 180 168 211 193 282 235 309 365 279 338 396
168 180 89 110 182 73 120 106 164 133 164 186 213 206 270 297 494 299 299 314
256 338 398 273 337 219 195 267 168 151 118 195 233 146 245 227 266 246 124 82
71 116 182 194 206 156 278 262 276
GTH-A06B 69
363 339 385 181 72 108 110 174 160 173 174 208 190 282 232 312 364 284 315 393
161 193 90 115 175 79 125 108 151 146 170 170 218 205 280 282 495 301 299 321
249 326 416 277 326 226 185 262 165 160 117 207 230 153 239 230 287 236 125 80
72 118 177 197 206 168 295 236 260
GTH-A07A 73
240 274 287 228 239 287 230 243 278 365 174 204 209 238 101 86 115 187 174 154
155 131 178 152 144 184 190 207 132 163 200 109 153 105 133 196 99 158 181 272
199 218 172 164 195 202 124 158 115 137 220 201 204 207 153 168 127 186 268 146
133 127 162 149 101 181 181 225 233 277 290 167 241
GTH-A07B 73
259 273 291 224 230 290 215 245 286 354 216 236 198 242 91 79 123 163 175 146
147 128 192 155 138 176 188 225 153 153 201 104 153 113 126 198 100 150 187 264
191 233 163 160 192 230 116 159 119 122 238 198 193 210 160 170 125 190 264 143
142 129 152 148 101 176 185 220 231 285 273 157 224

GTH-A08A 69
320 302 364 279 257 63 57 60 55 69 110 165 178 233 274 185 246 88 50 93
105 152 167 176 211 209 278 259 124 97 101 110 193 133 124 158 267 262 114 104
129 161 286 234 306 229 224 283 271 212 235 264 230 116 187 238 157 176 157 295
250 148 253 131 262 257 130 52 86
GTH-A08B 69
305 323 367 255 272 58 48 69 62 64 100 163 191 231 260 187 244 84 58 90
102 134 173 170 207 213 289 252 122 93 117 115 191 139 135 154 269 258 94 112
167 151 289 233 310 217 220 278 268 215 251 278 225 133 170 240 150 168 164 304
242 147 241 129 282 248 114 65 58
GTH-A09A 53
143 137 156 170 226 193 270 317 365 93 75 53 103 215 132 123 105 172 170 98
178 283 288 421 276 282 220 238 239 172 170 279 217 231 148 169 205 152 185 110
184 197 146 226 152 179 201 94 66 67 80 67 75
GTH-A09B 53
143 140 152 179 223 199 258 327 355 103 63 59 91 223 134 119 106 177 170 99
167 281 289 442 265 280 214 242 237 165 162 274 212 210 166 171 215 151 182 103
221 199 162 211 142 186 196 90 72 68 68 72 78
GTH-A10A 60
173 114 70 125 167 166 202 310 183 191 305 337 279 72 60 88 128 160 211 262
187 132 192 206 64 65 117 109 151 103 129 108 173 151 169 239 335 183 301 227
391 287 220 354 233 224 228 204 189 190 244 288 146 202 165 190 238 175 145 151
GTH-A10B 60
173 117 77 115 167 164 200 315 165 164 313 333 296 77 59 90 129 161 217 267
173 136 191 206 68 52 119 110 151 106 130 104 184 149 170 235 330 181 307 231
370 290 233 341 233 218 228 203 206 186 262 287 148 203 154 203 233 167 149 152
GTH-A11A 58
55 88 135 191 265 179 237 378 381 284 104 36 64 76 109 182 183 227 289 272
269 85 64 90 130 201 89 110 106 175 226 159 168 145 146 241 148 167 135 128
142 203 156 238 160 184 170 209 244 166 151 127 180 171 120 145 118 235
GTH-A11B 58
61 89 134 200 260 179 236 393 384 287 106 39 58 75 104 180 185 238 293 271
261 84 70 87 132 198 97 110 107 170 224 153 168 146 141 243 142 169 131 122
140 198 149 240 162 181 170 215 258 155 149 122 182 166 119 147 117 231
GTH-A12A 56
326 427 366 353 347 272 292 273 108 100 101 115 141 202 271 226 152 170 195 183
238 291 240 197 200 152 162 273 276 236 348 245 171 182 225 112 153 199 209 140
197 321 302 237 275 208 188 133 188 179 205 391 377 354 204 291
GTH-A12B 56
328 442 365 350 344 291 292 272 96 89 114 115 134 194 275 214 157 174 202 177
227 278 248 182 197 157 171 269 281 235 353 245 149 176 218 118 148 201 211 147
178 338 299 232 282 209 180 142 189 183 182 412 361 357 201 286
GTH-A13A 48
323 343 333 197 321 279 324 244 259 288 248 275 272 128 146 195 211 195 304 326
369 293 329 406 446 337 381 256 306 223 214 209 334 287 278 330 207 159 177 176
96 125 217 212 150 157 256 245
GTH-A13B 48
321 294 317 202 337 319 263 223 263 295 253 266 248 128 160 215 188 178 301 320
304 262 355 379 460 359 362 268 264 231 214 220 330 273 287 323 223 154 177 194
78 137 218 208 142 163 253 235
GTH-A14A 48
152 113 187 228 204 195 257 322 307 295 262 285 281 288 257 377 284 292 258 227
177 191 230 176 173 236 219 184 211 224 165 212 135 109 141 131 122 102 72 115

173 232 130 140 247 221 181 156
GTH-A14B 48
114 131 178 236 213 208 241 327 305 260 239 284 281 274 261 368 298 302 247 238
175 190 233 160 180 240 215 191 202 228 140 210 132 96 149 131 107 98 85 102
166 229 130 143 253 211 179 155
GTH-A16A 65
171 112 126 165 125 60 177 354 240 217 567 773 807 517 551 326 432 358 451 429
398 497 299 249 274 265 307 204 136 130 84 138 144 134 72 85 63 81 70 71
90 158 312 379 321 251 314 281 262 277 259 222 163 116 157 118 244 133 215 323
493 421 197 242 343
GTH-A16B 65
177 107 131 163 122 57 181 311 239 220 488 774 772 515 522 311 416 317 409 377
438 524 297 239 238 260 306 185 124 141 97 126 141 129 72 83 62 87 75 64
85 163 314 363 338 252 320 290 254 285 264 225 156 121 142 127 240 140 220 329
465 416 183 258 340
GTH-A18A 92
57 60 59 35 29 32 45 43 42 30 28 43 45 40 50 35 24 29 40 63
57 59 40 40 73 64 104 116 162 144 157 127 81 70 44 61 97 79 99 67
64 71 121 74 74 78 83 171 160 111 82 54 55 76 92 78 71 69 36 80
90 129 136 136 147 114 86 91 53 69 85 180 154 179 142 98 105 85 157 112
167 144 116 136 227 188 345 243 216 160 99 168
GTH-A18B 92
55 62 58 36 30 27 47 43 43 30 27 39 49 42 51 36 22 29 39 66
54 62 32 46 74 60 112 114 177 119 164 145 99 77 53 53 92 87 91 72
61 74 101 76 73 62 92 142 172 116 83 56 63 80 96 93 80 62 35 78
95 114 128 123 148 108 89 85 55 71 85 188 156 162 130 97 114 93 157 113
155 177 119 125 202 170 286 228 201 159 101 169
GTH-A19A 131
183 201 132 119 141 131 72 51 114 162 134 192 147 91 73 81 66 78 83 81
66 70 45 40 71 74 57 74 69 75 63 50 65 79 74 87 87 48 46 47
55 67 89 62 61 66 85 74 103 85 44 57 82 128 77 76 76 65 96 117
112 127 119 138 134 138 107 77 56 57 48 45 77 73 54 84 159 128 135 120
156 209 229 180 148 193 168 187 186 187 127 171 116 135 166 202 178 175 168 140
124 111 100 100 80 90 88 95 83 67 57 76 112 60 120 121 77 105 104 137
173 142 123 139 112 151 192 212 201 181 186
GTH-A19B 131
178 201 126 122 143 143 80 62 97 136 140 180 141 94 73 78 69 80 94 67
68 74 48 42 64 72 61 68 73 76 52 38 60 76 91 70 75 43 55 54
49 84 95 65 56 71 82 73 98 102 57 59 86 96 79 87 92 67 89 117
132 105 127 136 149 140 92 81 55 41 55 50 67 78 48 68 156 124 146 124
147 210 238 178 168 185 180 184 195 168 147 202 122 127 143 210 168 174 167 134
125 124 91 104 75 93 88 99 70 77 57 70 110 65 111 126 90 99 108 119
153 143 126 139 112 149 194 216 199 183 172
GTH-A20A 139
144 107 214 106 158 265 178 263 276 303 309 395 260 260 223 260 192 230 175 195
300 191 157 125 99 98 77 52 28 33 29 43 54 50 47 47 35 29 44 62
40 41 70 66 61 49 43 54 47 45 24 42 44 60 64 68 36 40 53 37
48 53 43 40 38 35 30 36 42 42 31 42 43 33 29 39 40 80 65 72
41 35 29 32 46 50 49 36 54 79 58 65 49 30 33 59 75 65 64 58
53 73 56 79 58 90 69 89 81 73 64 42 44 49 47 52 59 37 47 91
63 65 60 71 84 122 125 111 98 104 97 98 103 107 62 42 109 106 99
GTH-A20B 139
120 112 214 107 157 291 191 270 267 301 305 412 258 262 217 267 202 229 170 198

306 192 153 130 94 101 77 47 35 25 50 38 47 49 47 49 32 29 43 49
57 45 62 60 63 50 43 56 44 46 21 35 40 61 78 62 46 38 50 41
47 50 43 44 36 35 28 37 49 37 37 36 42 36 27 39 41 82 62 72
45 35 28 39 41 44 55 38 43 79 61 65 45 25 36 67 67 67 57 60
55 73 61 77 65 92 70 81 78 86 74 44 47 45 50 48 60 44 45 95
62 73 55 68 83 132 116 119 103 116 95 103 107 97 59 39 111 110 121
GTH-A21A 55
521 635 548 701 671 300 574 633 613 477 550 564 502 416 391 461 441 554 493 328
339 278 302 230 165 359 325 327 338 334 217 328 301 272 321 352 311 227 280 239
330 249 234 264 263 269 199 212 191 138 197 186 214 229 211
GTH-A21B 55
492 650 555 702 670 321 591 604 604 506 535 576 506 359 379 437 459 558 476 341
330 268 328 243 164 365 320 323 341 333 211 329 300 276 329 329 344 208 287 241
312 253 218 292 269 242 195 215 191 142 200 197 211 211 210
GTH-A22A 54
473 617 535 619 566 265 430 545 418 364 402 318 437 463 435 399 372 392 385 283
294 265 289 171 114 274 285 275 334 240 181 235 215 235 297 341 231 181 256 196
270 237 202 251 224 229 178 211 169 99 153 151 167 187
GTH-A22B 54
477 600 530 604 580 255 449 547 418 366 373 323 416 477 446 373 380 386 375 277
282 267 274 178 132 289 270 275 335 250 176 245 193 213 302 345 230 164 251 206
275 234 197 247 234 222 173 214 155 100 152 154 153 176
GTH-A23A 77
537 393 366 321 502 448 519 448 455 325 682 508 474 194 109 228 430 398 365 361
399 445 497 206 88 126 150 174 159 169 209 192 96 63 74 66 69 95 117 191
153 121 188 197 295 277 283 258 242 134 158 89 98 159 208 179 121 81 202 208
229 231 253 266 170 210 151 158 123 79 118 150 186 172 191 186 115
GTH-A23B 77
588 397 345 307 471 503 536 454 450 303 688 515 477 199 109 229 429 420 369 368
372 466 488 198 101 129 162 184 174 179 180 205 96 63 73 66 75 98 124 174
152 128 193 202 283 284 287 252 222 159 148 106 102 162 201 180 109 103 190 206
254 222 236 257 173 185 155 154 126 75 105 150 197 181 193 178 116
GTH-A24A 71
420 278 680 352 358 208 218 324 348 355 370 316 294 355 425 131 77 68 101 93
123 173 245 177 104 52 77 79 91 81 56 70 75 85 97 72 85 160 212 187
129 114 103 72 142 195 178 173 134 124 214 188 298 285 233 149 161 170 136 153
106 127 142 175 242 187 224 166 87 171 170
GTH-A24B 71
426 271 656 358 378 204 217 321 352 362 371 321 288 356 423 137 78 58 103 101
124 166 228 184 122 48 73 79 90 79 69 58 77 92 89 81 75 187 228 188
129 110 99 74 144 193 165 185 133 118 216 187 302 288 232 160 151 158 140 139
112 144 138 174 231 183 219 155 111 160 165
GTH-A25A 80
272 221 413 432 504 443 270 356 488 344 186 219 135 212 240 295 303 281 365 280
640 492 599 672 599 507 651 492 571 396 216 275 341 503 380 304 413 390 517 102
39 32 69 89 132 109 133 147 83 65 74 106 123 184 184 251 250 159 274 259
236 493 333 445 439 407 277 212 610 457 452 435 396 540 334 292 422 437 408 367
GTH-A25B 80
263 224 414 431 521 455 270 342 472 367 176 199 145 211 240 294 303 322 314 346
640 490 601 670 602 495 650 477 561 404 203 290 345 493 380 316 399 395 470 115
40 34 63 97 130 113 129 157 77 66 74 103 122 161 227 240 263 154 279 249
243 471 335 431 431 396 290 209 623 419 447 426 410 545 386 301 448 419 438 348
GTH-A27A 62

308 244 311 324 388 326 409 294 343 146 84 147 266 220 248 243 271 314 248 233
144 206 279 217 132 100 68 87 137 139 235 214 219 222 84 83 162 211 210 228
311 324 276 93 38 67 99 138 117 97 117 60 141 52 25 32 49 86 96 60
60 75
GTH-A27B 62
264 245 329 314 411 325 394 307 299 158 92 161 278 212 264 238 264 329 238 247
160 204 282 225 119 106 76 86 128 137 227 201 224 240 66 105 169 222 205 239
318 325 279 84 43 64 108 142 115 92 125 63 146 47 27 37 41 90 103 54
65 70
GTH-A30A 56
317 261 550 508 332 568 566 518 529 571 627 426 395 337 363 293 409 454 195 336
222 448 457 322 238 383 332 305 378 317 269 204 284 265 529 467 232 201 236 270
224 207 281 275 455 480 330 214 118 187 184 270 407 339 385 262
GTH-A30B 56
301 266 551 511 348 572 530 498 538 563 599 441 400 358 351 303 440 446 197 324
227 446 463 320 246 401 341 278 387 326 300 212 290 277 508 469 212 206 240 292
224 211 259 315 413 456 347 206 116 186 167 276 409 337 392 252
GTH-A31A 55
445 464 462 637 492 565 492 481 436 488 559 454 528 671 656 506 558 454 451 260
286 344 282 365 68 44 70 99 114 109 209 232 343 307 388 519 313 251 354 135
184 130 49 70 59 70 135 165 190 149 200 152 138 251 201
GTH-A31B 55
464 440 467 633 498 602 508 442 392 507 570 477 513 660 663 514 554 458 457 259
295 339 280 371 63 51 78 88 121 107 217 222 336 312 397 517 304 251 362 127
187 135 40 69 62 72 140 154 183 154 191 160 135 264 193
GTH-A33A 70
458 453 481 381 474 570 639 517 540 286 377 256 449 441 310 333 390 443 359 221
339 366 462 376 316 352 226 165 186 222 195 184 194 220 218 185 167 129 152 133
146 126 112 155 164 91 80 112 77 106 154 133 141 114 135 201 140 161 229 168
158 180 181 202 163 160 202 223 171 180
GTH-A33B 70
444 453 482 368 468 581 645 517 530 299 362 265 412 449 326 311 418 458 324 223
348 380 467 371 330 340 226 159 179 219 206 183 191 230 224 185 173 127 155 131
143 120 122 147 162 96 72 101 88 129 135 147 132 115 136 206 137 162 210 165
154 181 201 193 155 157 202 210 197 174
GTH-A34A 72
494 558 594 505 465 546 482 563 648 558 424 558 344 377 212 239 371 150 152 214
302 294 191 277 437 742 587 385 418 429 180 209 234 205 161 195 183 194 150 178
79 86 93 101 131 167 140 123 116 125 120 85 131 148 100 156 65 61 75 84
94 116 163 144 158 161 150 166 147 179 142 150
GTH-A34B 72
517 548 585 475 462 547 504 546 622 550 415 568 332 351 185 248 366 144 149 219
309 298 193 285 430 739 589 377 422 422 184 210 236 211 158 190 186 202 145 184
71 85 92 102 122 155 162 130 125 111 131 85 117 158 95 144 69 62 84 83
87 132 143 167 157 161 147 166 159 167 132 167
GTH-A37A 52
244 213 225 189 211 257 234 198 145 128 243 330 283 257 404 413 264 229 243 267
284 257 214 212 258 209 193 150 113 100 102 191 214 245 326 184 206 323 251 317
241 108 116 137 185 155 174 235 191 210 315 242
GTH-A37B 52
233 225 222 192 204 243 227 205 143 121 257 331 278 267 410 407 284 221 245 263
277 248 221 214 260 224 200 160 86 111 117 185 213 248 318 186 213 313 261 310
245 112 127 134 173 161 170 232 195 209 322 236

GTH-A38A 64
228 135 137 144 165 84 172 205 193 152 194 199 147 173 133 129 136 173 146 119
186 164 175 205 146 134 204 256 222 281 332 263 233 269 209 285 216 383 317 299
349 253 227 366 302 397 377 96 70 129 242 192 195 290 227 221 350 225 304 265
189 224 353 243
GTH-A38B 64
209 162 152 148 183 95 164 203 193 168 195 192 148 170 135 130 134 167 149 124
187 157 186 196 147 141 214 235 233 285 317 264 241 262 216 278 222 378 327 300
351 236 240 360 301 387 376 88 78 129 233 190 173 261 228 243 354 228 299 234
193 240 340 241
GTH-A39A 62
273 227 172 149 168 215 230 200 215 143 146 134 174 182 169 155 128 176 185 203
228 206 139 120 94 110 135 121 138 159 129 127 110 136 162 141 157 185 210 170
209 213 238 181 278 267 220 176 189 198 209 219 215 214 140 189 158 141 142 179
194 221
GTH-A39B 62
283 209 193 137 187 196 235 208 212 148 137 144 155 190 170 145 140 166 200 208
220 193 160 108 92 111 141 121 148 150 136 114 120 134 151 140 160 185 206 173
211 209 232 179 285 254 228 177 178 204 205 237 231 206 152 195 156 130 141 170
209 237
GTH-A40A 49
319 238 276 190 337 284 275 361 450 376 344 350 291 291 290 305 244 226 222 232
307 260 304 261 341 296 331 240 263 266 218 192 218 155 139 112 124 187 168 184
192 182 203 243 202 244 223 254 299
GTH-A40B 49
306 233 290 195 327 279 266 361 399 366 337 383 290 295 290 298 229 231 232 260
298 244 301 284 389 278 379 262 277 248 230 195 239 153 131 97 138 211 175 185
188 177 209 211 188 253 202 233 289
GTH-A41A 66
279 264 177 198 175 140 192 154 160 175 139 140 145 135 142 134 137 155 133 150
105 126 141 149 199 178 133 110 94 110 117 100 120 125 119 97 111 135 147 127
156 187 193 143 196 205 210 178 272 258 254 175 164 181 228 234 198 182 152 190
152 141 116 166 160 188
GTH-A41B 66
277 264 190 186 181 152 180 145 145 175 155 145 141 140 133 136 142 144 142 152
107 128 148 146 183 184 138 110 95 107 146 98 113 135 117 87 111 144 142 131
149 195 189 151 199 204 208 177 275 270 250 173 163 173 237 230 198 185 145 195
155 133 123 168 157 182

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

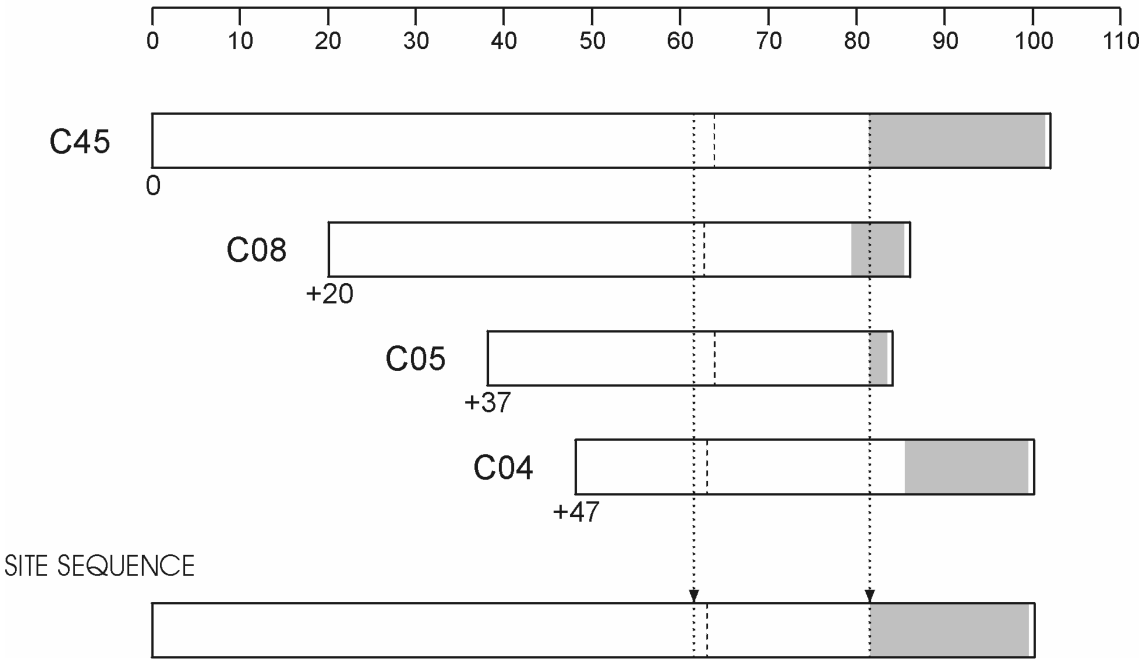


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

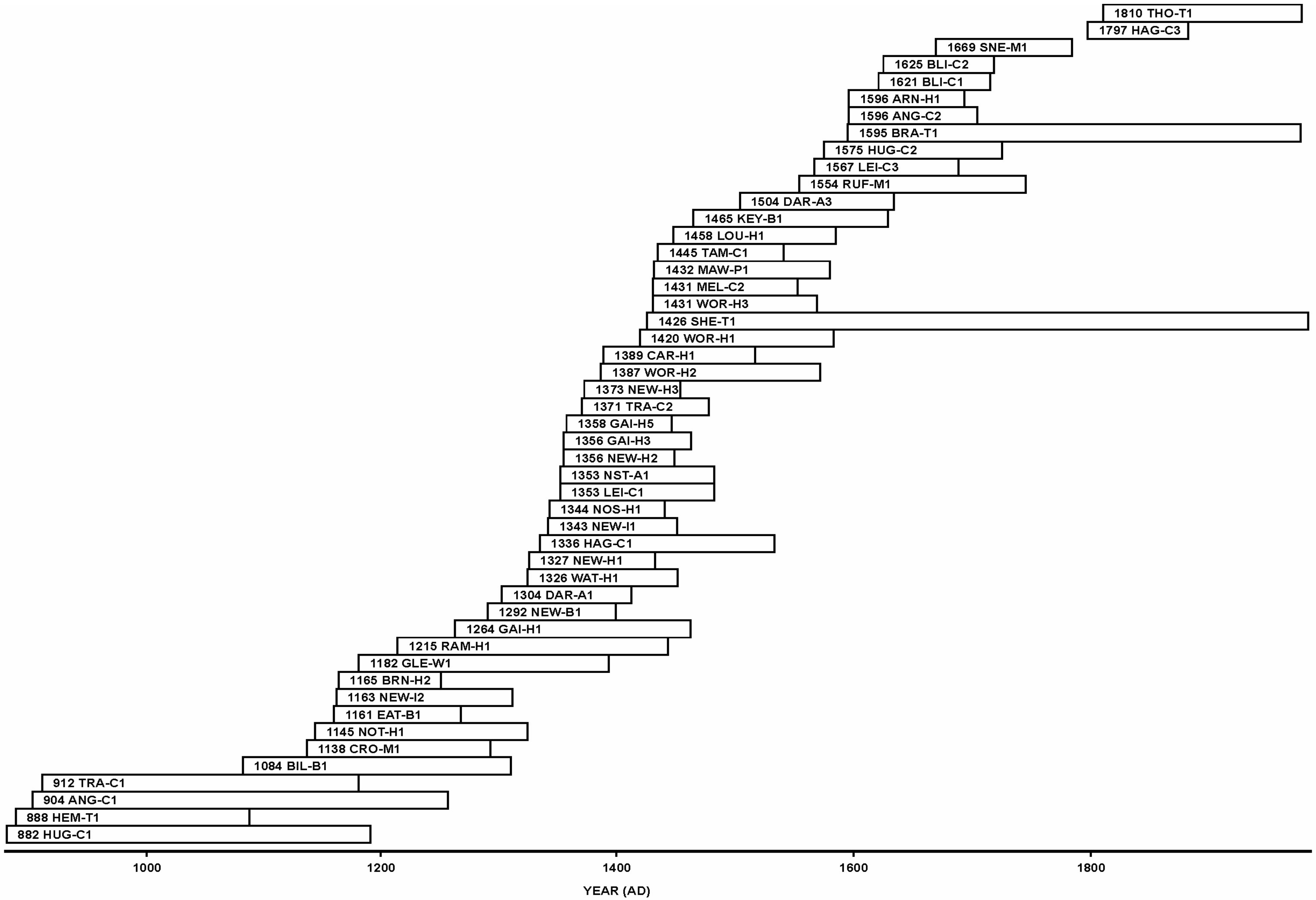
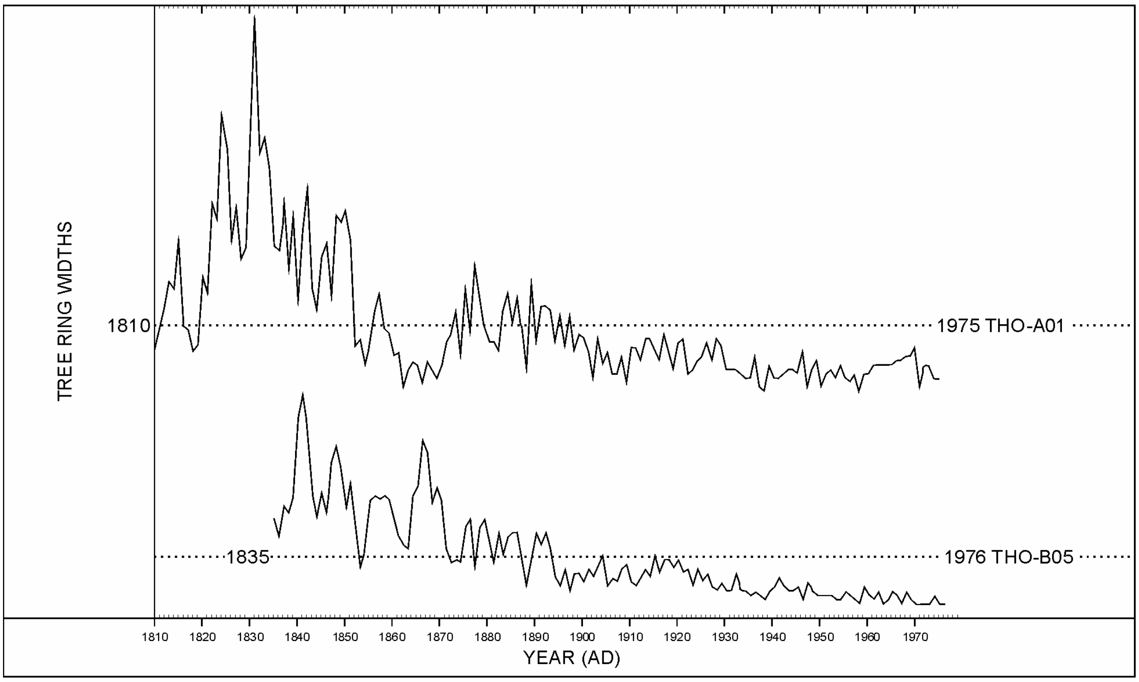


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

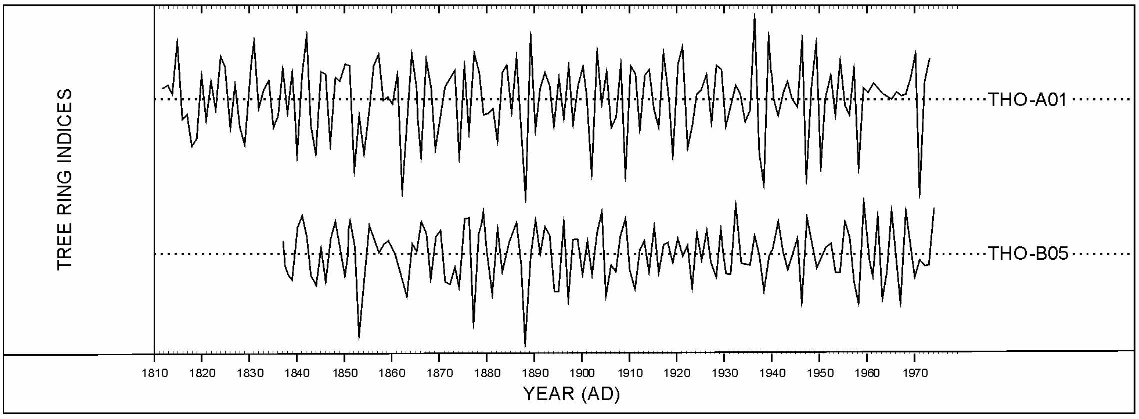


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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