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TRERICE, KESTLE MILL, CORNWALL
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Matt Hurford, Alison Arnold, Robert Howard and Cathy Tyers

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SUMMARY

Dendrochronological analysis was undertaken on 31 of the 35 samples taken from three different roofs at Trerice, Kestle Mill: the Great Hall, the West Wing, and the Great Chamber. This resulted in the production of two site chronologies, TRCESQ01 and TRCESQ02. These comprise 28 and 3 samples with overall lengths of 169 rings and 115 rings respectively. The first site chronology can be dated as spanning the years AD 1394–1562, whilst the second site chronology is undated.

Interpretation of the sapwood and the heartwood/sapwood boundary on the dated samples indicates that the timbers from all three roofs are likely to represent a single programme of felling, probably dated to the early AD 1570s, with the possible exception of one timber that may have been felled over a decade earlier. The dendrochronological results therefore support the suggestion that the Great Hall, the Great Chamber, and the West Wing were constructed as part of the scheme of works commissioned by Sir John Arundel IV, High Sheriff of Cornwall, between AD 1570–3.

CONTRIBUTORS

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

ACKNOWLEDGEMENTS

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CONTACT DETAILS

M Hurford and C Tyers
Dendrochronology Laboratory, Archaeology Graduate School, The University of Sheffield, West Court, 2 Mappin Street, Sheffield, S1 4DT
Tel: 0114 276 3146. Email: m.hurford@sheffield.ac.uk, c.m.tyers@sheffield.ac.uk

A J Arnold and R E Howard
Nottingham Tree-Ring Dating Laboratory, 20 Hillcrest Grove, Nottingham, NG5 1FT
Tel: 0115 9603833. Email: roberthoward10@hotmail.com, alisonjarnold@hotmail.com

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INTRODUCTION

The grade I* listed manor house of Trerice, Kestle Mill, Cornwall (SW8411258475; Figs 1–4) has fifteenth- and sixteenth-century origins. The earliest phase, potentially associated with Sir John Arundel I (died AD 1471), is thought to have comprised a tower house with a low block, which was extended early in the sixteenth century by a two-storey range, elements of which form the current south-west range. The main north-east E-plan range is thought to have been built by Sir John Arundel IV, High Sheriff of Cornwall, in AD 1570–3. It comprises a central porch to screens passage, a hall to the left and services to the right, and an open cloister walk at the rear, with a projecting polygonal stair tower giving access to a long gallery over. This range abuts the earlier south-west range comprising the Great Chamber and West Wing, which is thought to have been mostly rebuilt during the same time that the north-east facing range was being constructed. The northern service end of the main north-east range, with the exception of the lower two floors of the outer walls, was demolished in *c* AD 1860 and rebuilt in AD 1954. The rear elevation was also remodelled in the twentieth century (Listed Building Description).

The focus of this investigation is three elements of the building complex believed to have been constructed by Sir John Arundel IV. These are: the roof over the Great Hall (Fig 5) comprising seven trusses with cranked collars and principal rafters and threaded purlins; the roof over the West Wing (Fig 6) comprising three trusses with cranked collars and principal rafters and threaded purlins; and the roof timbers over the Great Chamber (Fig 7) which consists of 24 scissor-braced frames with collars, with evidence for an earlier phase comprising two collars embedded in the ceiling just beyond the entrance hatch (Eric Berry pers comm). These roofs are all thought likely to date to the very early AD 1570s, as the plaster overmantle of the Great Hall dates to AD 1572 and that of the Great Chamber to AD 1573, with the West Wing appearing to have been mostly rebuilt at the same time (Listed Building Description).

SAMPLING

Analysis by dendrochronology at Trerice, specifically the roofs over the Great Hall, the West Wing, and the Great Chamber, was requested by Francis Kelly, 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 this important building complex. In addition it was hoped that this analysis would enhance the understanding of the stylistic dating evidence in the county. A further potential benefit of the dendrochronological investigation was the contribution of the data to the corpus of reference material available for this currently under-represented area. This investigation also formed part of the English Heritage funded dendrochronological training programme for the first author.

In order to address these objectives, a total of 35 timbers was sampled by coring. Each sample was given the code TRC-E (for Trerice, site 'E') and numbered 01–35. Thirteen samples, TRC-E01–13, were taken from the roof of the Great Hall. A further four samples, TRC-E14–17, were obtained from the small number of timbers available in the roof of the West Wing. Sampling was restricted in this roof, as it contained only six original oak timbers, with two of these, the cut-off remains of collars, being unsuitable for analysis, as they were derived from fast-grown trees and had less than the minimum of number of rings necessary for reliable analysis. The remaining timbers of this roof were of modern softwood. Finally, 18 samples, TRC-E18–35, were taken from the roof of the Great Chamber. Sampling was restricted to rafters and braces, as the collars proved inaccessible for coring. The two collars located beneath the scissor braces which were thought to potentially represent an earlier phase of construction could not be sampled, as there was the risk that the vibrations generated during coring would damage the plaster ceiling below.

The location of samples was noted at the time of coring and marked on the drawings provided by Nigel Thomas, Senior Archaeologist, Cornwall County Council, these being reproduced here as Figures 8–28. Further details relating to the samples can be found in Table 1, in which the timbers have been located and numbered following the scheme on the drawings provided.

ANALYSIS AND RESULTS

Each of the 35 samples obtained was prepared by sanding and polishing. It was seen at this point that four samples, TRC-E02, E15, E20, and E29 had an insufficient number of rings for reliable dating, and so these samples were rejected from this programme of analysis. The annual growth rings of the remaining 31 samples were measured, the data of these measurements being given at the end of this report. The data of these 31 samples was then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing two groups to be formed at a minimum value of t=3.9, the samples of each group cross-matching with each other as shown in the bar diagrams (Figs 29 and 30). The minimum t-value is low, but within the main group of 28 samples a sub-group of four timbers is readily identified that produce lower intra-site cross-matching than the rest of the large group. However, as this four-timber site sequence can be dated independently, and as it produces a low but significant t-value with the 24-timber mean, it was decided to amalgamate them.

Both site chronologies, TRCESQ01 and TRCESQ02, were compared to an extensive range of reference chronologies for oak, this indicating repeated cross-matches and dates for one of them. The evidence for the dating of TRCESQ01 is given in Table 2.

This analysis can be summarised as below:

Site chronology	Number of samples	Number of rings	Date span (where dated)
TRCESQ01	28	169	AD 1394–1562
TRCESQ02	3	115	undated

INTERPRETATION

Roof over the Great Hall

The roof over the Great Hall is represented by 12 dated samples in site chronology TRCESQ01 (Fig 29). None of these 12 samples has complete sapwood and it is thus not possible to calculate a precise felling date for the timbers represented. However, five of the samples did retain their heartwood/sapwood boundary ring, the average date for this being AD 1544. Using the 95% confidence limit of 15–40 sapwood rings appropriate for mature oaks in this part of England, an estimated felling date in the range of AD 1559–84 can be calculated for these timbers. The heartwood/sapwood boundary on these five timbers varies by 18 years. This, combined with the overall level of cross-matching (*see below*), suggests that these timbers are likely to represent a single felling programme with the timbers felled at the same time, or possibly over a short period spanning a small number of years.

The remaining seven dated samples have no trace of sapwood and thus it is not possible to calculate their likely felling date ranges. The dates of their last measured rings vary from AD 1463 to AD 1531 which, as the level of cross-matching implies that all dated timbers from the Great Hall roof form a coherent group, suggests that some of these timbers represent the inner sections of long-lived trees. This, combined with the fact that they appear integral to the roof structure with no evidence for reuse or insertion, suggests that it is likely that they were part of the same felling programme dating to AD 1559–84.

A full complement of sapwood was present on one of the dated timbers from this roof, TRC-E06, but, due to its highly friable nature, the outer 20–25mm was lost during coring. Generally this would be used to suggest a narrower felling date range that that produced above using the average heartwood/sapwood boundary date. However in this instance TRC-E06 appears to be anomalous. The average ring width of 1.41mm suggests that approximately 14–18 sapwood rings were lost, indicating a felling date of *c* AD 1556–60. This only just overlaps the earlier end of the estimated felling date range indicated above and, bearing in mind the overall level of cross-matching between the material from all three roofs (*see below*), suggests that either its outermost sapwood rings are significantly narrower than the average ring width implies, or that this timber was potentially felled slightly earlier than the majority of the material.

Roof over the West Wing

The roof over the West Wing is represented by three dated samples in site chronology TRCESQ01 (Fig 29). None of these three samples has complete sapwood and thus again it is not possible to calculate a precise felling date for the timbers represented. However, two of the samples did retain their heartwood/sapwood boundary ring, which varies in date by seven years, indicating that they are likely to represent a single programme of felling. The average date for the heartwood/sapwood boundary is AD 1542. Using the same sapwood estimate as above, an estimated felling date in the range of AD 1557–82 can be calculated for these timbers. This estimate can be truncated to AD 1563–82, as the outermost measured ring on sample TRC-E16 dates to AD 1562.

The remaining dated sample has no trace of sapwood and thus it is not possible to calculate its likely felling date range. The date of its last measured ring is AD 1485, which is considerably earlier than the other two dated samples. Again, taking into account the overall level of cross-matching and the lack of evidence for reuse or insertion, it appears most likely that this timber represents the inner section of a long-lived tree, and that its felling is coeval with the two other dated timbers from this roof.

In this instance it is possible to suggest a potential further refinement to the estimated felling date range of AD 1563–82, due to the presence of bark edge on the timber from which sample TRC-E16 was obtained. Due to its friable nature, the outermost 10–15mm of sapwood was lost during coring. The average ring width of 1.13mm indicates that this represents approximately 9–13 rings which would suggest a felling date of *c* AD 1571–5. This clearly lies within the estimated felling date range based on the average heartwood/sapwood boundary date, and it is therefore possible that the dated timbers from the West Wing roof were actually felled in this period spanning only a few years in the early AD 1570s.

Roof over the Great Chamber

The roof over the Great Chamber is represented by 13 dated samples in site chronology TRCESQ01 (Fig 29). As none of these samples has complete sapwood, a precise felling date for the timbers represented cannot be calculated. However, 11 of the samples did retain their heartwood/sapwood boundary ring, the average date for this being AD 1547 which, using the sapwood estimate as above, gives an estimated felling date in the range of AD 1562–87 for these timbers. The heartwood/sapwood boundary on these timbers varies by 20 years. This, combined with the overall level of cross-matching (*see below*), suggests that these timbers are likely to represent a single felling programme, with the timbers felled at the same time or possibly over a short period spanning a small number of years.

The remaining two dated samples have no trace of sapwood and thus it is not possible to calculate their likely felling date ranges. The dates of their last measured rings vary from AD 1509 to AD 1523. The level of cross-matching within the dated timbers from the Great Chamber roof is such that it suggests that they are a clearly coherent group. Hence, bearing in mind the lack of evidence for reuse or insertion, it seems likely that these two timbers were part of the same felling programme of AD 1562–87.

Again it is possible to suggest a potential refinement to this estimated felling date range of AD 1562–87, due to the presence of bark edge on the timber from which sample TRC-

E18 was obtained. Due to its friable nature, the outermost 15–20mm of sapwood was lost during coring. The average ring width of 1.25mm indicates that this represents approximately 12–16 rings, which would suggest a felling date of *c* AD 1571–5. This clearly lies within the estimated felling date range based on the average heartwood/sapwood boundary date, and it is therefore possible to that these timbers were actually felled in this period spanning only a few years in the early AD 1570s.

DISCUSSION AND CONCLUSION

Prior to tree-ring analysis being undertaken at Trerice, the roofs were generally believed to be part of the work commissioned by Sir John Arundel IV, during the period AD 1570–3. The basic tree-ring results indicate that the timbers from the roof of the Great Hall were probably felled in the period AD 1559–84, those from the West Wing in the period AD 1563–82, and those from the Great Chamber in the period AD 1562–87, thus providing broad support to the view that Sir John Arundel IV was responsible for the building work in these areas.

The overall level of cross-matching, including a range of *t*-values in excess of 7.0, between the dated timbers from all three roofs is such that it suggests a common woodland source. In addition, there are two notably high *t*-values which imply that timbers utilised in different roofs may have been derived from the same tree: TRC-E01and E16 (t = 11.2) from the Great Hall and West Wing; TRC-E09 and E22 (t = 15.7) from the Great Chamber and Great Hall. This evidence, combined with the overall heartwood/sapwood boundary date variation of 20 years, suggests that it is likely that all of the dated timbers represent a single felling programme occurring sometime in the AD 1560s to AD 1580s, with the possible exception of one sample, TRC-E06 (*see above*). However, based on the evidence of the amount of sapwood, including bark edge, lost during sampling from two cores (TRC-E16 and TRC-E18), it is possible to suggest that this main programme of felling may have occurred, either in one year or over a small number of years, in the early AD 1570s. This would clearly provide further support for Sir John Arundel IV having commissioned this programme of building works.

Table 2 includes some of the highest *t*-values obtained, and thus demonstrates the greatest degree of similarity, with reference chronologies during the dating of TRCESQ01. This clearly includes reference chronologies from the South East and West Midlands regions, amongst a number from the South West region. Previous analyses of sites in the South West region (eg Tyers 2004b; Groves 2005; Arnold and Howard 2007) have noted strong similarities with some reference chronologies from western counties, in particular. However, the most consistent and widespread cross-matching is found with a wide range of reference chronologies from the south-west, thus suggesting that the Trerice material is likely to have been derived from relatively local woodlands.

Site sequence TRCESQ02 incorporates the only three measured but undated samples, all from quartered timbers. Notably high *t*-values exist between these three samples (9.8, 13.8, and 12.2), suggesting that they are likely to have been derived from the same tree. The lack of conclusive cross-matching with TRCESQ01 and reference chronologies may well be due to a series of periodic growth retardation events in the first half of the sequence. Thus, although on structural evidence there is no reason to suppose that these timbers are of a different date to the rest of the Great Chamber roof, the dendrochronological evidence can neither confirm nor refute this supposition.

The successful dating of these three roofs should add to the overall understanding of the development of this building complex, as well as providing additional information for stylistic dating in this county. The production of a well-replicated, relatively long dated site sequence, TRCESQ01, is a valuable addition to the local network of reference chronologies and will no doubt prove of use in future analyses in this area.

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TABLES

Table 1: Details of tree-ring samples from Trerice, Kestle Mill, Cornwall

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof above the Great Hall						
TRC-E01	Truss 1 north principal	90	--	1413	----	1502
TRC-E02	Truss 1 collar	nm	--	----	----	----
TRC-E03	Truss 1 south principal	84	--	1408	----	1491
TRC-E04	Truss 2 south principal	80	--	1424	----	1503
TRC-E05	Truss 3 north principal	88	--	1396	----	1483
TRC-E06	Truss 3 collar	87	4c	1456	1538	1542
TRC-E07	Truss 3 south principal	81	--	1446	----	1526
TRC-E08	Truss 4 south principal	83	h/s	1459	1541	1541
TRC-E09	Truss 4 north principal	119	h/s	1438	1556	1556
TRC-E10	Truss 5 collar	90	--	1442	----	1531
TRC-E11	Truss 6 north principal	56	--	1408	----	1463
TRC-E12	Truss 7 collar	152	h/s	1394	1545	1545
TRC-E13	Truss 7 north principal	69	2	1472	1538	1540
Roof remains over the West Wing						
TRC-E14	Truss 2 east principal	88	--	1398	----	1485
TRC-E15	Bay 3 east upper purlin	nm	--	----	----	----
TRC-E16	Truss 3 east principal	110	17c	1453	1545	1562
TRC-E17	Bay 4 east upper purlin	71	2	1470	1538	1540
Roof over the Great Chamber						
TRC-E18	Truss 5 east brace	72	4c	1488	1555	1559
TRC-E19	Truss 5 west rafter	102	h/s	1448	1549	1549
TRC-E20	Truss 7 west rafter	nm	--	----	----	----
TRC-E21	Truss 7 east brace	76	h/s	1476	1551	1551
TRC-E22	Truss 8 west rafter	88	--	1436	----	1523
TRC-E23	Truss 9 east rafter	91	h/s	1454	1544	1544
TRC-E24	Truss 9 west rafter	96	--	----	----	----
TRC-E25	Truss 13 east rafter	77	h/s	1478	1554	1554

TRC-E26	Truss 14 east rafter	83	--	1427	----	1509
TRC-E27	Truss 15 east rafter	80	--	----	----	----
TRC-E28	Truss 16 west rafter	94	h/s	1460	1553	1553
TRC-E29	Truss 17 east brace	nm	--	----	----	----
TRC-E30	Truss 17 east rafter	85	h/s	1456	1540	1540
TRC-E31	Truss 17 west rafter	109	h/s	----	----	----
TRC-E32	Truss 18 west rafter	89	h/s	1447	1535	1535
TRC-E33	Truss 18 east brace	68	6	1476	1537	1543
TRC-E34	Truss 19 west brace	101	h/s	1442	1542	1542
TRC-E35	Truss 19 east brace	80	h/s	1473	1552	1552

nm = not measured
h/s = the heartwood/sapwood ring is the last ring on the sample
c = complete sapwood exists on the timber but all or part of the sapwood has been lost from the sample during coring

Table 2: Results of the cross-matching of site sequence TRCESQ01 and relevant reference chronologies when the first-ring date is AD 1394 and the last-ring date is AD 1562

Reference chronology	*t*-value	Span of chronology	Reference
Farmers Club, Widemarsh Street, Hereford	8.9	AD 1313–1617	(Tyers 1996)
Chalgrove Manor, Chalgrove, Oxfordshire	8.5	AD 1355–1503	(Howard *et al* 2000 unpubl)
Roscarrock, near St Endellion, Cornwall	8.0	AD 1373–1500	(Tyers 2004a)
Newnham Hall Farm, Newnham Murren, Oxfordshire	7.7	AD 1414–1551	(Arnold and Howard 2006 unpubl)
49/50 Quarry Street, Guildford, Surrey	7.6	AD 1341–1583	(Arnold and Howard 2005 unpubl)
Castle Close, Eardisley, Herefordshire	7.4	AD 1367–1530	(Tyers 2005)
Pendennis Castle, near Falmouth, Cornwall	7.2	AD 1358–1541	(Tyers 2004b)
The Old Mansion, Clarendon, Wiltshire	7.2	AD 1315–1625	(Tyers 1999)
Brookgate Farm, Plealy, Shropshire	7.2	AD 1362–1611	(Miles 1993)
St Martin's Church, Looe, Cornwall	7.0	AD 1445–1580	(Arnold *et al* 2006)

FIGURES

Figure 1: Map to show the location of Trerice, Kestle Mill (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

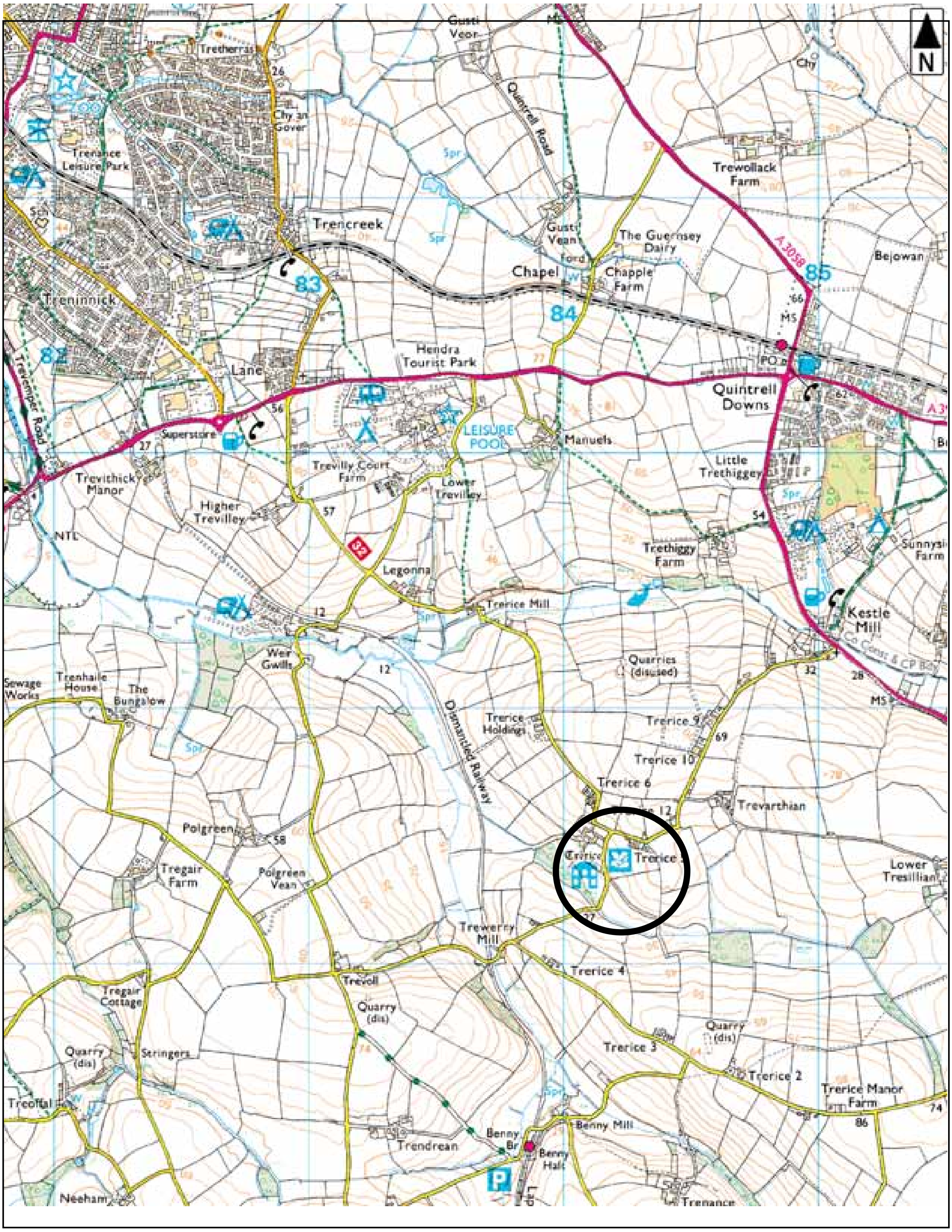


Figure 2: Map to show the location of Trerice, Kestle Mill (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 3: General view of the front north-east range of Trerice viewed looking west

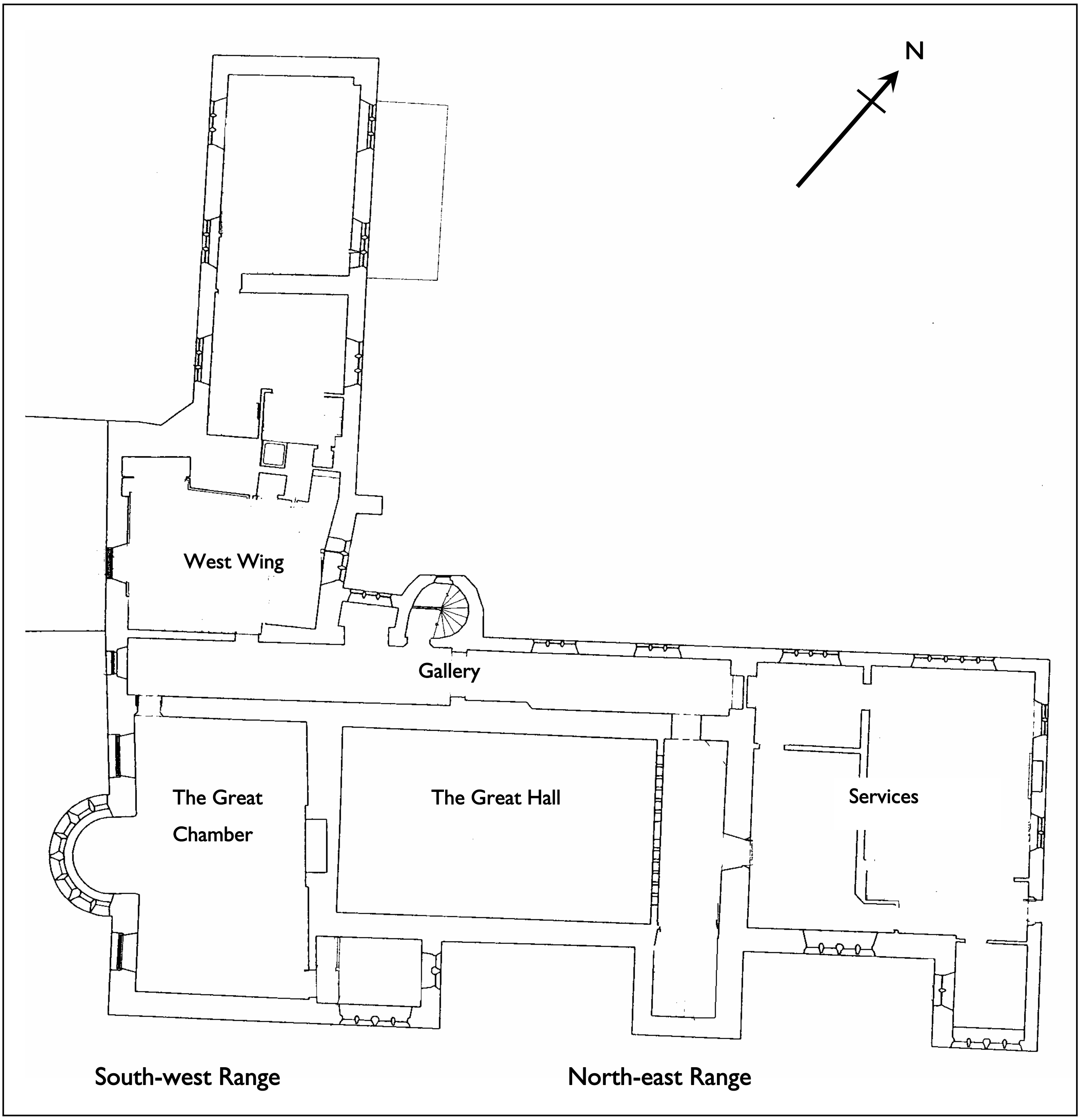


Figure 4: General plan of the south-west and north-east range

Figure 5: Roof timbers over the Great Hall viewed looking south-west

Figure 6: The east principals of Trusses 2 and 3 of the roof over the West Wing viewed looking south-east

Figure 7: Roof timbers over the Great Chamber viewed looking south-east

Figure 8: Plan showing the truss numbering scheme and the locations of samples TRC-E15 and E17 (based on a drawing provided by Nigel Thomas)

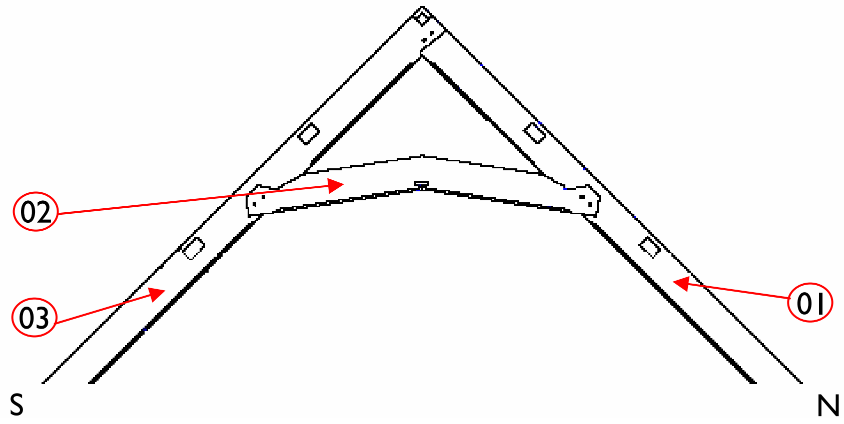


Figure 9: The Great Hall sample locations truss 1 (based on drawings provided by Nigel Thomas)

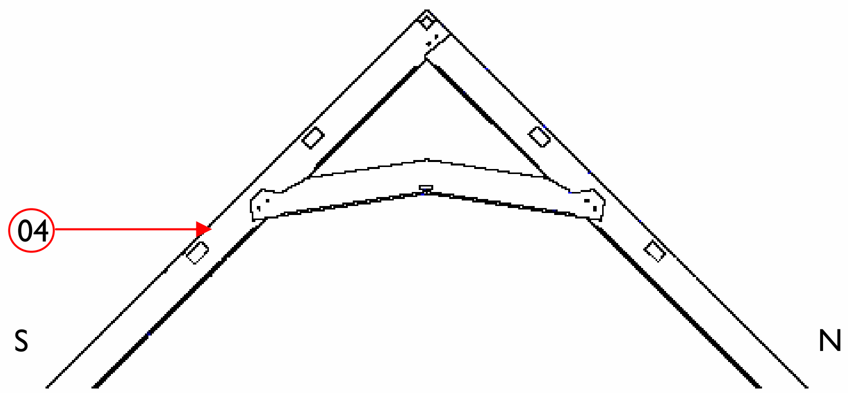


Figure 10: The Great Hall sample locations truss 2 (based on drawings provided by Nigel Thomas)

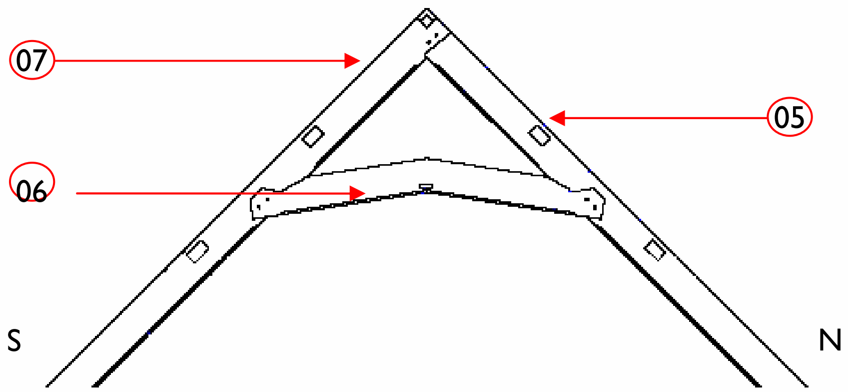


Figure 11: The Great Hall sample locations truss 3 (based on drawings provided by Nigel Thomas)

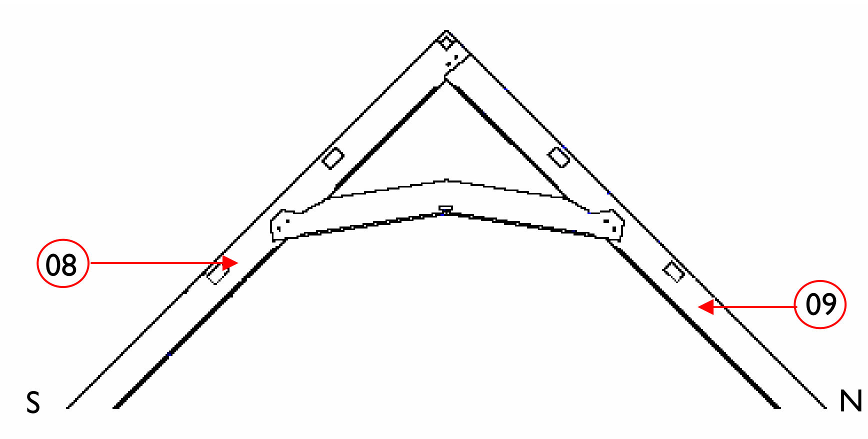


Figure 12: The Great Hall sample locations truss 4 (based on drawings provided by Nigel Thomas)

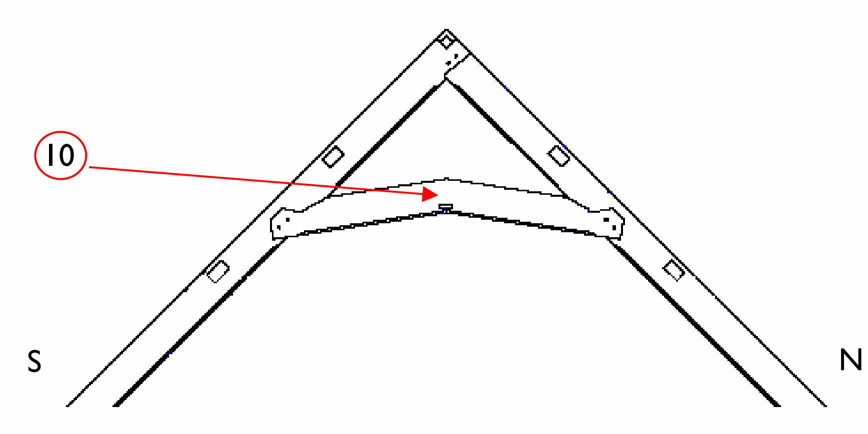


Figure 13: The Great Hall sample locations truss 5 (based on drawings provided by Nigel Thomas)

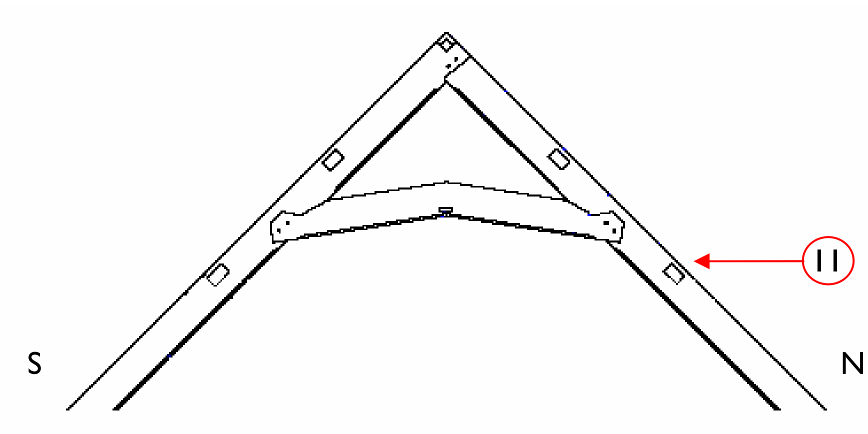


Figure 14: The Great Hall sample locations truss 6 (based on drawings provided by Nigel Thomas)

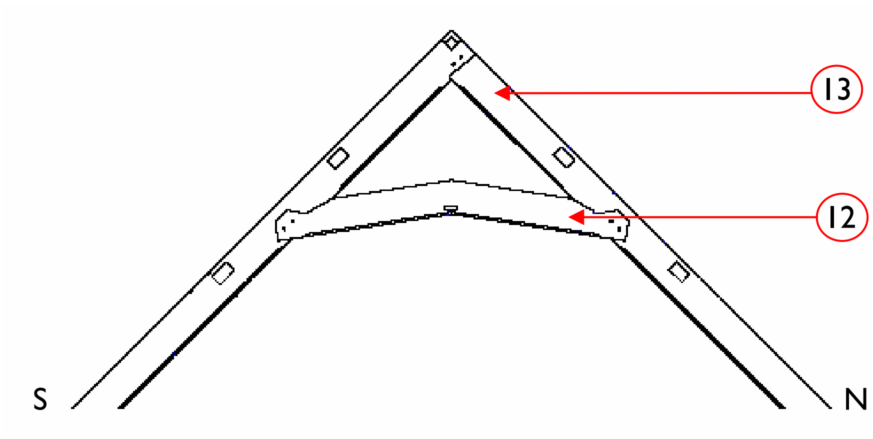


Figure 15: The Great Hall sample locations truss 7 (based on drawings provided by Nigel Thomas)

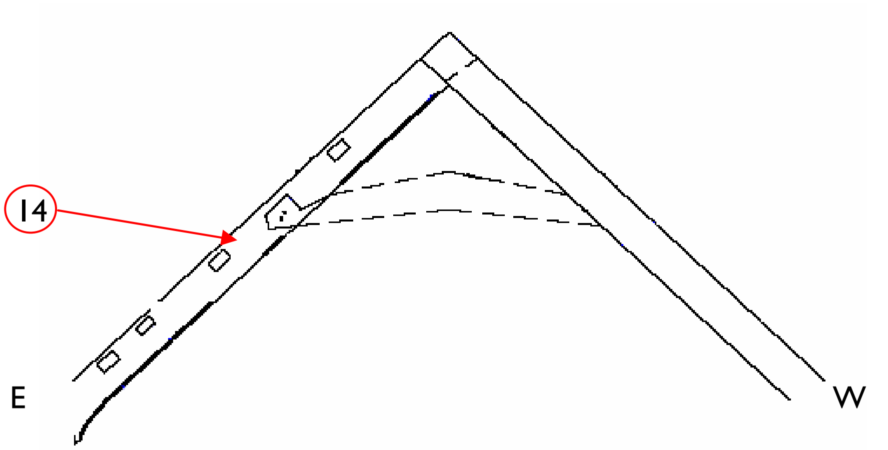


Figure 16: The West Wing sample locations truss 2 (based on drawings provided by Nigel Thomas)

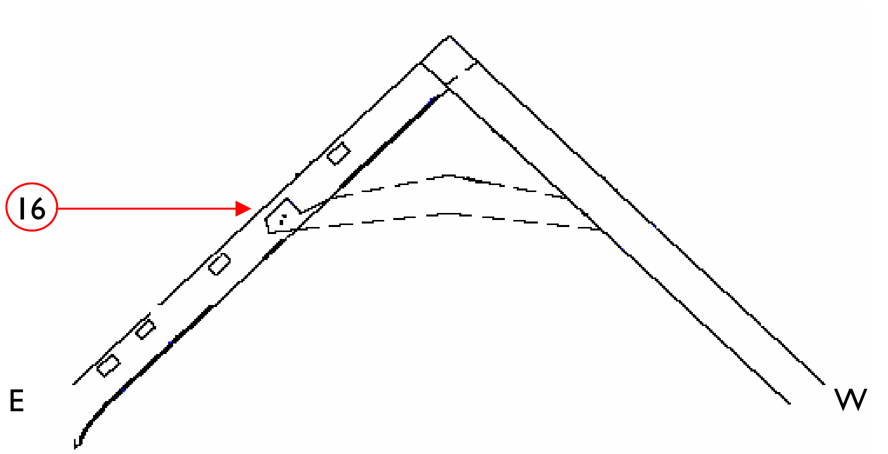


Figure 17: The West Wing sample locations truss 3 (based on drawings provided by Nigel Thomas)

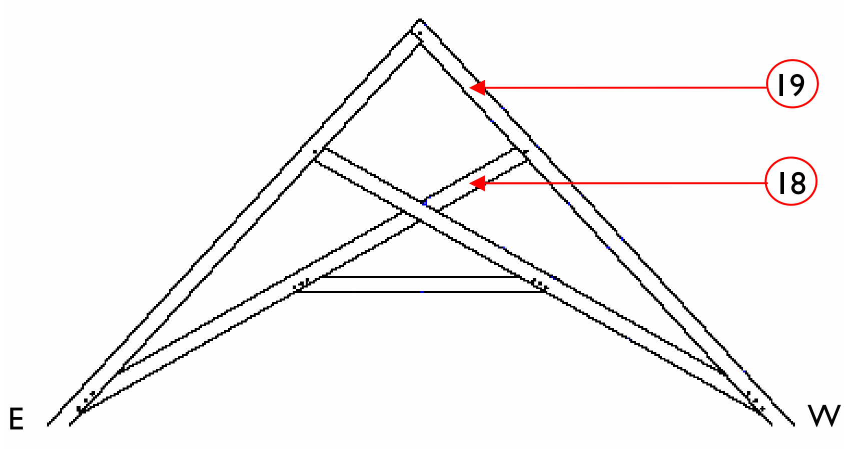


Figure 18: The Great Chamber sample locations truss 5 (based on drawings provided by Nigel Thomas)

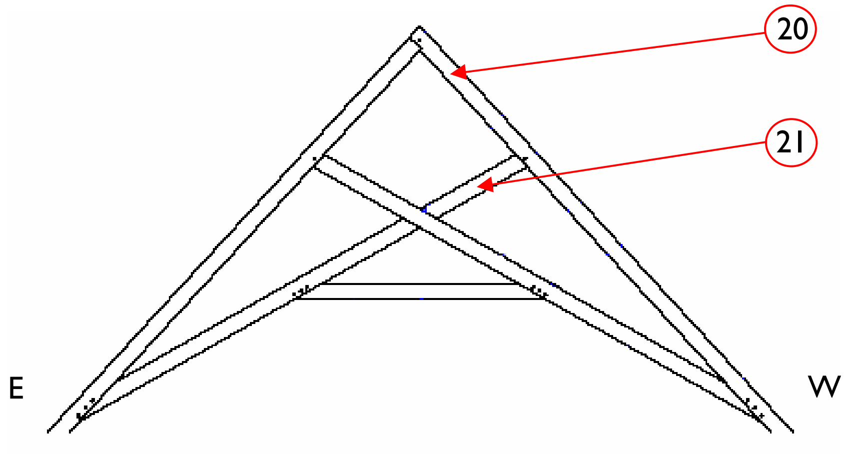


Figure 19: The Great Chamber sample locations truss 7 (based on drawings provided by Nigel Thomas)

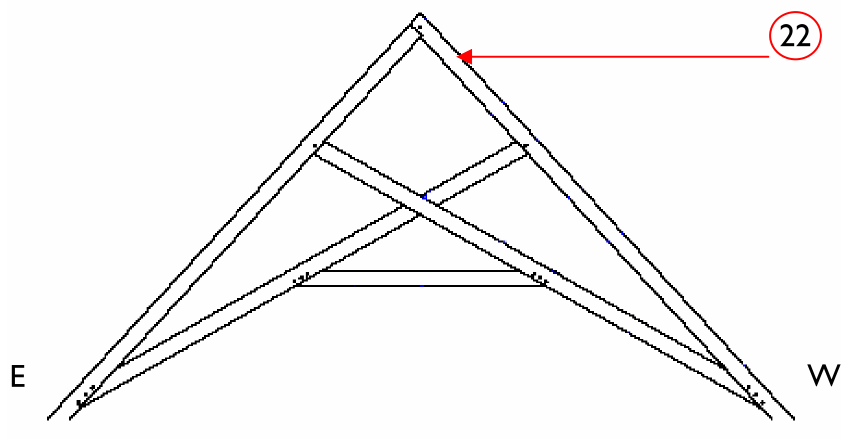


Figure 20: The Great Chamber sample locations truss 8 (based on drawings provided by Nigel Thomas)

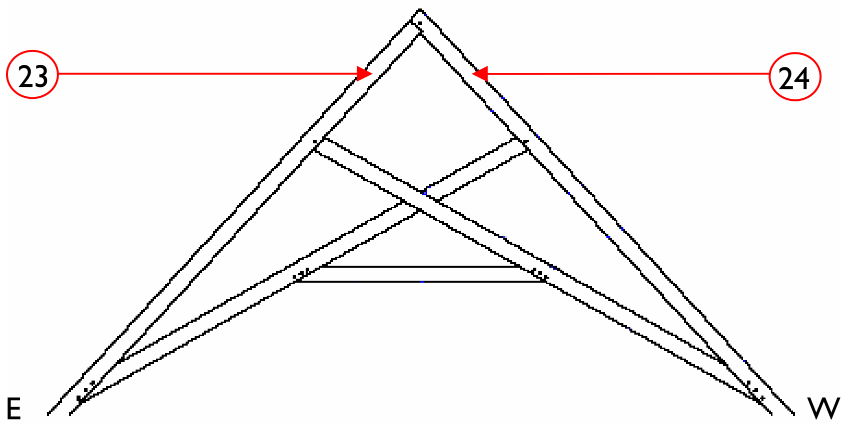


Figure 21: The Great Chamber sample locations truss 9 (based on drawings provided by Nigel Thomas)

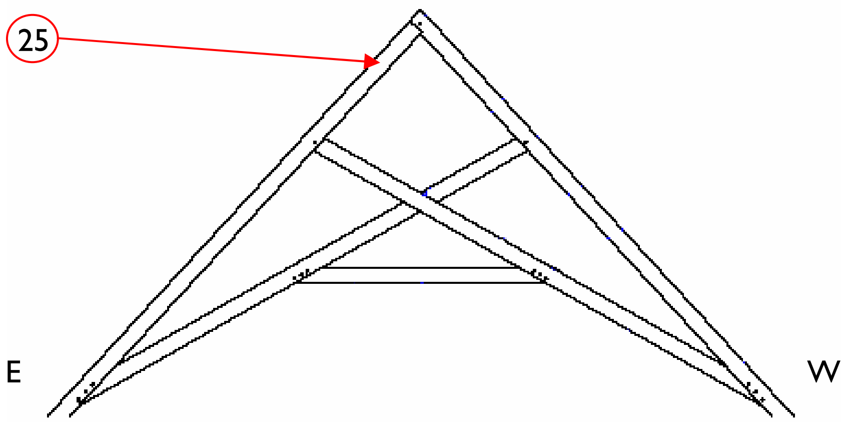


Figure 22: The Great Chamber sample locations truss 13 (based on drawings provided by Nigel Thomas)

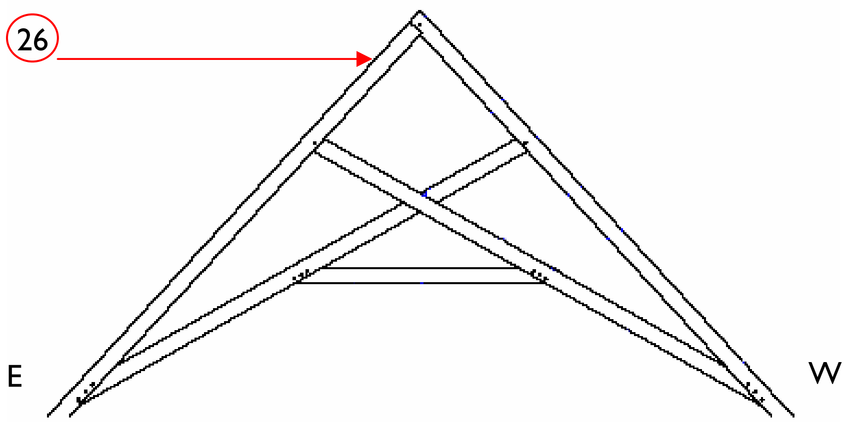


Figure 23: The Great Chamber sample locations truss 14 (based on drawings provided by Nigel Thomas)

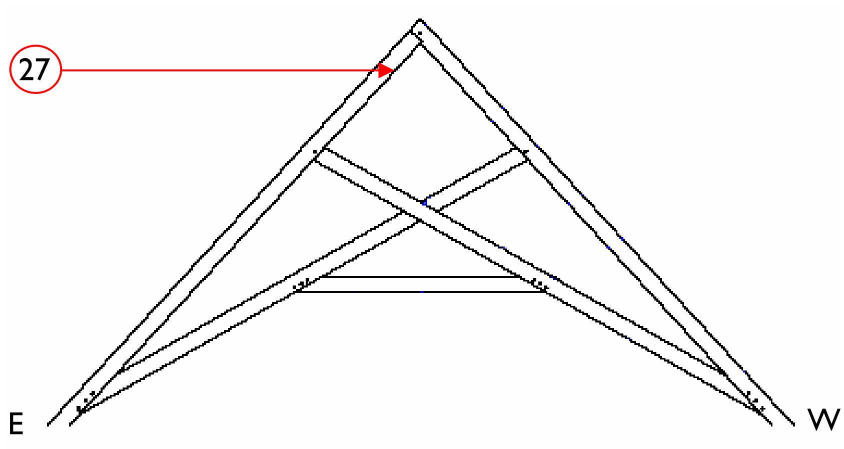


Figure 24: The Great Chamber sample locations truss 15 (based on drawings provided by Nigel Thomas)

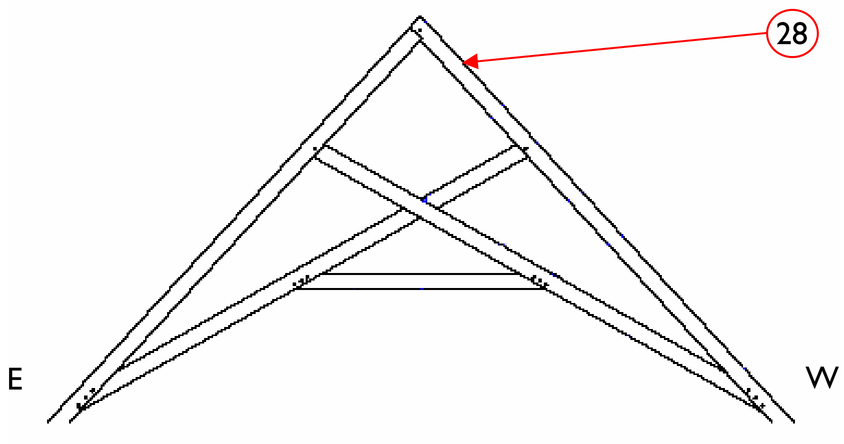


Figure 25: The Great Chamber sample locations truss 16 (based on drawings provided by Nigel Thomas)

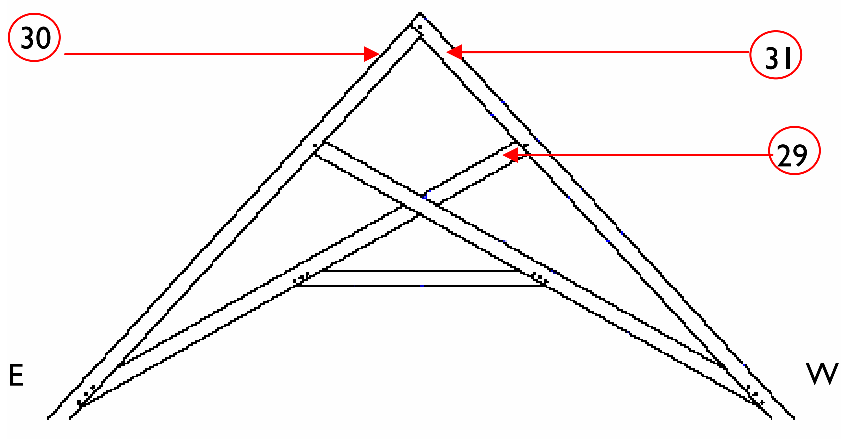


Figure 26: The Great Chamber sample locations truss 17 (based on drawings provided by Nigel Thomas)

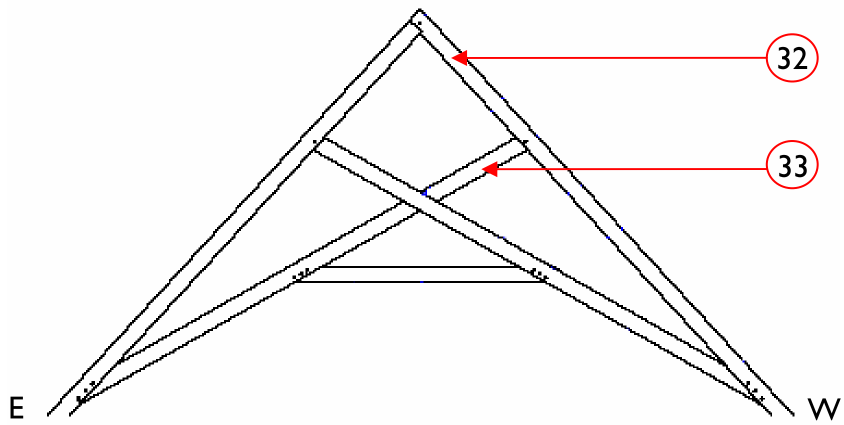


Figure 27: The Great Chamber sample locations truss 18 (based on drawings provided by Nigel Thomas)

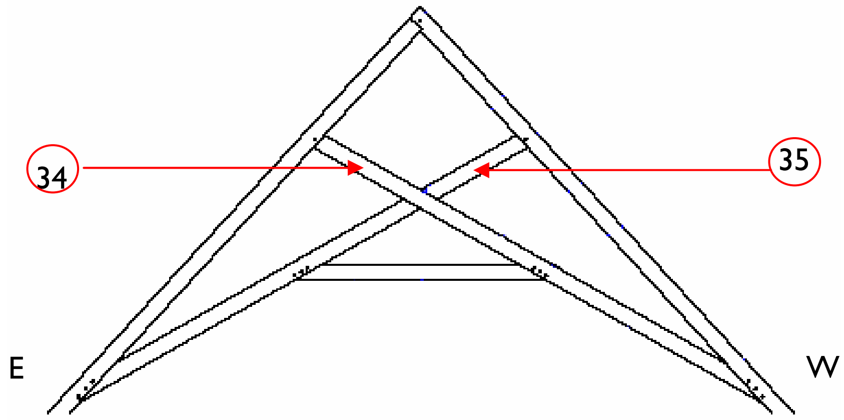
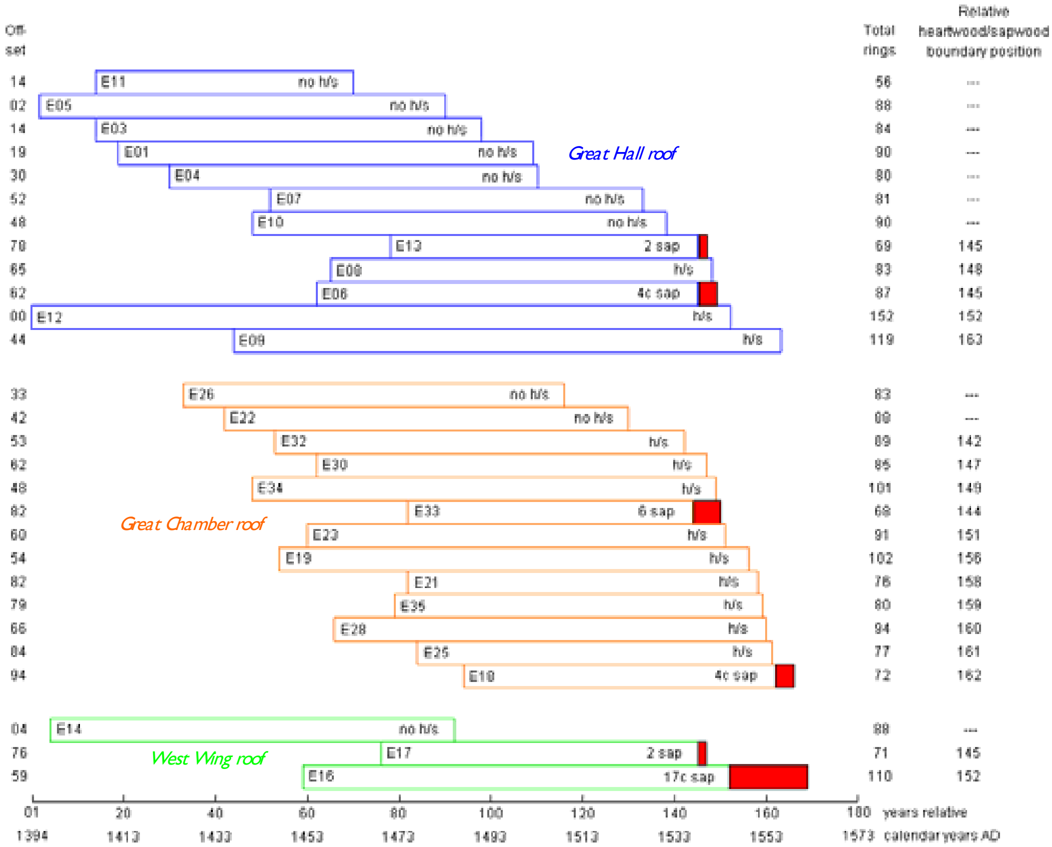
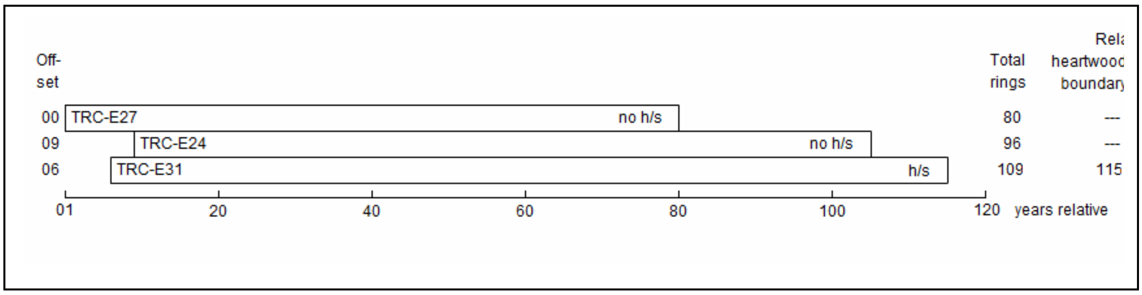


Figure 28: The Great Chamber sample locations truss 19 (based on drawings provided by Nigel Thomas)



White bars = heartwood rings;
filled bars = sapwood rings
h/s = the last ring of the sample at the heartwood/sapwood boundary
c = complete sapwood exists the timber but all or part of the sapwood has been lost from the sample during coring.

Figure 29: Bar diagram of the samples in site chronology TRCESQ01



White bars = heartwood rings
h/s = the last ring of the sample at the heartwood/sapwood boundary

Figure 30: Bar diagram of the samples in site chronology TRCESQ02

DATA OF MEASURED SAMPLES

measurements in 0.01mm units

TRC-E01A 90
485 621 500 370 411 316 251 486 278 292 454 381 293 217 198 287 286 271 323 307
301 197 254 200 198 264 195 300 318 240 192 137 90 122 165 146 238 148 195 176
148 153 129 125 139 125 92 92 118 153 194 148 160 123 95 81 158 216 211 200
264 234 157 99 103 108 98 115 154 106 95 118 126 192 181 145 232 290 160 113
119 237 263 224 153 122 171 174 218 235
TRC-E01B 90
456 594 506 404 348 302 256 464 302 280 480 404 299 213 206 257 308 271 313 325
270 208 258 182 212 271 206 315 330 249 226 127 100 122 143 156 214 155 196 176
152 156 134 112 135 128 81 102 104 157 190 143 174 137 92 82 170 187 207 184
282 243 174 113 114 90 107 109 152 95 91 120 119 194 200 167 224 292 177 109
126 242 282 254 169 138 175 200 213 235
TRC-E03A 84
237 316 356 315 414 402 385 430 278 198 168 173 338 278 214 358 240 204 123 112
265 386 321 340 335 283 244 297 214 271 226 258 325 457 354 351 345 217 234 290
280 428 319 295 261 198 185 205 324 237 226 166 117 173 161 200 212 140 210 139
121 141 224 200 170 195 206 283 279 237 221 284 310 200 171 192 233 143 186 139
179 179 212 86
TRC-E03B 84
293 319 365 302 413 399 384 425 276 198 171 169 334 288 218 358 257 200 127 123
234 344 313 337 355 288 257 283 226 270 230 271 339 458 360 360 338 214 229 298
275 428 322 284 271 196 188 192 331 242 208 155 109 149 165 217 205 168 203 149
130 148 216 204 171 191 210 261 273 236 228 291 314 204 174 192 231 147 183 148
176 190 225 108
TRC-E04A 80
569 382 269 293 463 309 318 349 592 493 451 420 246 348 315 237 286 280 327 276
212 202 251 262 174 248 170 202 195 178 268 205 269 299 351 282 314 309 274 308
226 249 279 232 241 248 303 221 175 247 214 328 273 183 209 236 233 313 292 280
168 92 130 116 129 119 129 141 117 151 172 247 405 192 181 322 241 182 211 300
TRC-E04B 80
522 349 275 238 457 299 316 347 564 484 439 398 267 309 324 252 273 254 298 284
221 202 238 269 179 254 158 202 191 186 266 226 285 290 360 287 306 310 273 318
232 290 289 239 238 247 302 221 192 254 228 309 277 173 211 221 236 305 290 307
167 96 125 127 130 108 137 129 129 174 173 247 383 186 183 324 253 185 241 304
TRC-E05A 88
163 154 187 113 109 63 106 91 105 79 123 153 173 141 104 96 157 118 186 210
220 327 499 312 451 354 382 538 449 464 392 360 446 478 420 292 455 437 459 426
262 445 365 261 259 283 230 274 275 329 374 347 345 353 286 312 320 238 386 268
287 290 296 186 237 215 238 262 190 208 271 179 230 234 276 209 174 196 158 209
222 160 212 242 196 280 249 221
TRC-E05B 88
163 133 153 121 114 70 104 79 94 72 127 146 172 150 110 87 155 125 184 206
216 302 498 329 427 349 390 539 423 515 388 364 454 432 405 296 506 433 476 436
251 437 366 261 256 286 232 279 271 318 394 350 349 339 287 303 327 244 375 288
281 285 303 179 253 216 214 266 204 190 258 201 247 208 271 204 184 203 147 215
212 177 199 238 196 270 255 262
TRC-E06A 87
221 208 194 129 184 128 157 184 162 215 196 160 160 146 101 110 90 129 116 140

135 126 145 147 189 207 199 182 187 172 225 237 183 153 122 133 107 150 156 172
205 138 124 124 156 134 143 154 146 131 126 144 175 178 139 140 134 125 146 113
91 103 141 153 132 100 132 118 108 97 120 73 85 86 96 121 104 78 111 131
147 120 116 89 103 102 117
TRC-E06B 87
215 211 184 101 173 112 157 189 167 226 158 157 157 143 109 116 95 122 95 149
145 120 150 151 187 217 187 189 169 179 231 237 190 146 119 137 113 146 136 165
196 133 120 133 151 135 141 170 132 129 129 155 182 170 137 147 132 117 153 107
102 90 133 161 132 94 137 126 112 91 133 70 90 90 98 123 107 85 115 141
150 123 118 85 114 103 122
TRC-E07A 81
115 100 170 216 219 189 156 176 200 195 193 121 106 133 142 133 97 144 143 127
153 168 166 169 173 165 106 166 174 160 137 121 173 99 156 143 89 132 164 130
166 114 95 79 113 91 77 74 99 116 98 68 96 99 172 145 128 205 253 151
194 262 254 229 156 197 211 143 196 147 170 148 218 250 156 154 153 135 173 172
204
TRC-E07B 81
161 99 181 191 170 169 177 200 195 191 199 104 111 140 142 131 98 152 136 126
142 169 161 163 154 162 122 165 148 169 141 109 165 123 181 130 86 118 159 137
169 126 96 86 108 99 76 70 107 103 116 59 87 104 157 150 116 225 251 150
193 244 280 230 158 221 201 150 196 136 162 158 193 225 167 144 147 149 168 162
210
TRC-E08A 83
169 180 223 210 198 206 243 240 198 249 185 253 215 165 233 211 276 299 202 255
260 226 308 275 302 219 103 209 121 133 120 146 168 130 160 194 329 304 216 175
236 237 181 210 246 181 208 202 218 214 274 247 174 245 163 176 107 99 114 144
199 161 174 191 166 113 88 102 76 86 91 91 132 73 42 78 104 99 82 73
57 61 60
TRC-E08B 83
208 169 206 207 193 201 227 241 203 260 176 253 204 145 241 211 314 293 221 243
255 225 328 261 293 214 103 197 149 142 134 160 172 131 144 178 346 317 205 177
241 219 172 193 233 204 209 193 234 208 265 231 190 244 154 185 106 93 115 141
184 156 175 192 165 118 87 103 77 82 97 80 130 77 46 76 103 98 84 69
74 63 47
TRC-E09A 119
348 263 305 247 416 339 283 283 265 234 313 299 244 176 155 177 219 191 166 158
181 162 164 207 135 166 177 153 140 144 143 130 182 183 205 199 172 192 133 137
205 139 197 202 117 176 124 115 193 134 148 121 152 144 118 123 168 189 228 122
128 161 181 222 166 299 162 98 144 196 263 216 139 201 195 139 198 123 91 121
206 305 223 134 162 151 145 153 201 170 127 102 88 192 112 238 196 181 164 244
199 155 142 250 136 151 138 193 178 120 123 217 153 241 162 201 216 236 190
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336 264 318 236 399 352 267 284 269 244 289 288 233 171 162 183 195 185 175 149
191 162 164 203 143 168 167 165 150 134 141 144 151 181 212 205 180 196 141 120
197 137 199 200 140 158 127 123 210 132 147 122 154 150 123 126 174 189 263 135
125 167 183 214 154 297 155 103 151 200 260 208 126 220 182 145 192 120 114 120
181 312 238 129 145 146 160 164 196 171 120 96 94 200 119 207 202 167 168 248
207 141 163 269 124 142 136 193 185 120 136 230 150 240 145 212 217 221 192
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81 234 214 258 198 229 199 218 183 243 236 221 278 188 205 238 255 249 311 337
289 367 258 215 327 161 216 161 201 238 227 238 236 244 264 191 183 154 211 146
122 123 153 115 197 214 221 196 263 203 179 213 285 292 324 213 230 298 309 251
242 295 242 179 192 272 262 190 173 229 237 239 247 164 136 185 199 281 188 268

212 235 179 171 201 244 240 252 240 290
TRC-E10B 90
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274 373 270 220 319 161 223 142 208 267 206 220 242 245 265 189 177 161 205 154
110 126 158 129 188 212 224 196 252 214 175 208 292 282 325 228 219 289 321 252
226 293 229 189 191 272 250 205 178 236 233 235 253 176 147 181 201 284 187 259
208 269 163 166 192 241 258 228 264 332
TRC-E11A 56
192 278 208 199 227 483 567 472 343 297 242 226 409 331 259 370 349 253 177 200
275 378 325 272 210 181 166 201 141 150 110 116 334 556 399 413 323 125 112 211
284 380 241 223 207 131 79 142 93 139 119 109 94 161 158 200
TRC-E11B 56
201 290 249 234 210 457 567 461 358 275 245 259 440 358 259 387 342 303 173 208
288 354 344 293 203 194 169 191 137 132 99 117 342 558 421 475 363 134 132 251
285 465 235 198 211 135 97 153 124 164 134 109 87 154 157 262
TRC-E12A 152
116 197 208 202 141 140 159 65 104 138 190 177 150 98 81 98 84 71 153 162
133 143 129 129 134 85 121 151 179 147 219 125 83 117 145 128 142 158 158 112
147 81 77 134 66 96 55 84 68 78 129 118 83 68 79 76 56 43 29 41
45 41 54 54 38 47 52 52 54 73 60 45 63 32 36 23 27 24 33 42
47 58 49 35 65 36 68 81 92 86 89 74 83 93 84 87 101 81 70 71
63 66 69 28 42 40 52 52 46 92 93 50 58 46 75 79 66 62 49 44
52 52 48 35 47 65 42 72 66 61 55 35 69 71 64 74 45 85 73 58
84 103 161 165 153 135 156 137 124 146 96 97
TRC-E12B 152
209 236 235 188 145 139 161 62 93 146 225 173 169 107 74 113 77 61 145 171
125 150 144 153 134 87 126 157 192 148 184 100 84 113 130 137 131 158 161 108
127 82 68 117 100 102 59 92 65 94 116 113 87 69 78 76 58 53 35 31
56 46 45 48 46 44 48 63 54 63 66 45 59 37 33 23 25 31 35 38
46 58 44 40 56 49 65 73 91 77 94 73 84 91 87 86 96 85 67 72
60 69 74 32 35 43 53 51 51 83 102 64 54 51 82 80 52 65 45 47
48 50 48 36 50 66 42 72 64 61 48 45 60 75 75 76 47 86 72 58
96 100 158 164 149 140 158 134 127 149 89 122
TRC-E13A 69
133 187 193 246 167 122 122 80 141 141 136 222 231 165 278 237 212 226 268 177
196 206 236 281 321 179 105 168 174 149 132 243 208 101 118 162 182 186 120 164
128 153 208 135 80 134 185 235 194 176 215 190 127 119 130 163 176 142 149 207
152 145 102 121 208 212 252 188 190
TRC-E13B 69
115 187 207 247 182 107 140 100 146 137 110 204 246 171 291 184 190 216 271 190
189 207 263 317 305 196 101 187 157 132 149 254 221 90 135 161 198 179 131 158
111 153 220 136 86 130 170 245 183 184 215 186 133 130 141 144 196 155 142 196
164 152 89 127 207 243 251 185 190
TRC-E14A 88
277 242 231 275 358 392 395 364 362 374 369 356 349 350 351 341 336 329 237 260
166 184 284 258 215 228 171 131 84 70 124 177 199 199 172 212 203 228 214 248
264 230 210 241 219 198 202 184 128 248 167 196 168 166 164 134 141 151 130 172
184 121 150 128 212 217 156 189 168 152 111 135 180 182 202 205 182 202 166 154
178 182 170 161 137 169 218 172
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304 248 225 277 351 377 388 361 371 429 342 347 329 361 349 354 342 310 250 260
162 178 262 268 217 209 179 133 76 73 143 180 187 198 165 215 200 222 191 268
251 223 209 254 212 204 213 161 142 194 155 209 175 174 143 137 150 151 128 177

178 129 165 128 182 195 163 187 165 141 124 132 186 189 192 210 174 198 184 149
183 161 164 175 148 171 208 206
TRC-E16A 110
168 248 144 131 144 95 47 79 107 103 207 119 131 75 54 44 132 145 131 127
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53 97 117 128 77 53 67 72 70 81 94 95 79 81 148 172 177 103 147 130
140 178 120 57 133 130 257 164 220 188 82 43 63 69 137 171 157 129 158 68
44 74 167 165 157 140 162 159 161 145 96 110 123 78 97 148 149 137 154 117
69 48 51 52 90 124 121 131 117 141
TRC-E16B 110
180 241 145 118 148 121 74 94 136 141 204 106 135 66 48 51 113 153 128 126
149 113 95 51 59 66 71 94 126 69 77 98 112 130 83 86 113 137 70 55
58 95 117 131 74 54 57 78 78 84 84 104 70 82 155 156 173 102 140 123
137 168 111 67 133 134 253 159 208 185 77 42 51 68 123 156 145 138 157 60
44 65 169 158 156 144 158 156 164 134 81 96 124 77 74 154 157 136 153 150
66 51 52 59 73 135 119 135 124 146
TRC-E17A 71
178 187 244 250 221 257 213 185 238 231 216 291 325 292 320 231 243 266 285 195
209 194 142 153 233 314 377 275 216 258 276 189 287 264 175 128 131 202 184 202
154 239 263 177 244 172 148 134 181 165 133 176 179 148 118 132 142 118 100 101
106 101 59 83 44 61 74 124 121 138 120
TRC-E17B 71
172 151 256 243 224 245 225 184 231 238 223 282 336 298 328 220 247 262 285 207
208 174 148 153 234 312 377 272 221 253 273 185 285 266 180 135 119 216 172 205
153 230 259 184 244 171 147 143 175 171 127 177 192 157 128 131 146 113 99 99
102 109 55 71 59 58 65 122 128 132 109
TRC-E18A 72
186 148 156 184 119 121 125 100 118 84 92 101 67 64 77 131 109 65 62 51
97 123 106 176 169 170 198 142 117 121 115 168 111 101 92 93 115 82 120 119
92 113 119 162 196 191 201 220 340 204 137 70 73 51 48 58 66 52 59 62
69 123 151 210 284 228 146 103 123 172 135 70
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183 140 158 159 136 109 118 104 111 71 82 108 69 68 79 138 124 56 57 57
85 130 99 167 171 177 213 103 121 125 135 171 107 126 97 88 106 92 106 120
96 109 120 170 184 194 199 239 333 201 140 72 74 48 50 55 71 49 63 59
68 119 155 219 281 226 146 97 138 165 127
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65 72 67 139 159 155 185 180 175 70 105 92 145 143 148 169 141 116 165 138
135 133 160 123 108 85 98 96 105 84 58 95 130 114 138 140 90 54 61 96
143 100 76 78 98 80 104 81 38 55 48 86 56 88 101 56 57 61 67 78
104 80 94 123 78 55 62 104 111 128 142 114 194 189 126 79 75 59 53 74
57 67
TRC-E19B 102
143 178 103 100 107 109 114 90 78 78 102 41 59 71 115 162 170 117 194 100
64 70 72 121 144 163 173 179 168 77 93 93 145 151 169 156 128 119 158 141
145 129 167 137 96 84 89 95 104 72 72 98 125 128 133 149 80 53 67 93
132 93 76 81 93 82 109 72 42 53 34 90 61 89 98 62 52 65 54 94
102 74 99 120 66 57 56 105 107 136 147 99 196 183 128 72 87 57 51 70
66 95
TRC-E21A 76
156 128 177 120 144 133 92 138 167 113 161 134 158 124 212 148 108 89 145 123
171 110 84 162 168 169 206 226 138 103 98 194 257 284 232 239 236 215 299 169

137 95 109 142 137 181 171 119 131 103 157 150 145 148 155 165 82 89 78 135
150 222 187 139 209 224 156 99 64 52 53 65 71 78 108 139
TRC-E21B 76
230 134 189 109 167 125 101 126 174 114 163 141 156 121 199 157 110 97 132 125
179 99 88 168 161 170 216 228 136 101 101 203 263 281 245 229 237 228 288 180
136 104 107 144 127 175 170 131 127 113 156 136 143 140 156 161 89 95 73 126
155 231 194 134 200 228 171 101 59 51 56 71 67 86 103 154
TRC-E22A 88
198 327 451 236 200 117 159 173 126 148 140 174 165 206 161 104 112 121 154 135
111 136 179 165 165 157 116 133 122 117 111 113 117 114 121 113 131 143 129 179
111 117 165 115 168 175 91 136 124 114 170 105 108 90 119 117 81 116 160 166
199 84 109 123 144 149 117 239 151 85 103 139 192 147 84 127 115 122 198 122
107 85 134 165 258 165 133 190
TRC-E22B 87
208 337 442 234 202 111 168 174 126 147 144 167 191 195 178 115 105 123 161 148
115 141 186 171 185 156 114 134 119 112 129 108 106 113 122 120 118 150 134 172
122 120 188 113 172 157 104 119 128 115 172 112 105 98 120 120 87 123 178 168
204 87 100 129 144 161 108 224 160 78 103 122 203 140 86 127 103 116 174 109
69 132 174 245 179 155 193
TRC-E23A 91
166 146 243 195 196 229 233 230 174 176 130 193 227 229 227 126 184 135 140 129
168 167 141 123 137 137 112 196 198 146 142 104 126 122 129 148 117 162 106 99
104 107 146 103 102 101 82 82 82 105 98 64 80 69 94 71 58 70 86 71
95 60 52 70 66 95 76 79 89 75 68 46 59 60 43 44 46 62 67 95
69 55 84 64 59 65 72 106 69 64 84
TRC-E23B 91
138 144 248 193 200 229 222 202 179 173 133 196 227 224 213 125 194 127 142 133
165 161 146 113 139 136 111 194 200 140 139 110 123 117 129 145 114 159 111 104
109 107 136 106 91 110 78 81 82 108 95 69 73 67 96 66 55 72 83 81
85 62 50 67 75 92 66 84 86 75 70 49 50 58 43 52 43 61 65 106
66 68 82 67 61 56 72 97 68 69 86
TRC-E24A 96
96 98 67 76 97 142 173 161 61 44 59 69 51 76 67 98 60 109 54 43
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191 34 37 40 33 27 47 67 89 97 71 74 79 91 102 123 97 126 118 143
148 149 137 128 180 214 223 213 167 150 152 206 204 233 209 183 153 98 104 163
155 155 153 144 151 117 126 134 158 166 146 135 129 176 111 113
TRC-E24B 96
93 87 84 65 97 139 177 169 61 43 50 67 58 60 71 103 80 101 48 35
44 59 72 92 116 126 200 191 159 161 196 161 80 69 58 54 65 89 117 176
192 40 39 41 35 34 44 63 97 94 60 71 88 91 101 121 106 119 109 139
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160 156 142 155 160 105 145 131 161 173 154 129 139 171 110 146
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145 118 128 263 207 159 171 110 242 222 263 203 198 198 157 215 217 164 218 130
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103 138 105 68 107 98 70 80 113 142 115 110 79 138 62 125 128 204 129 166
161 147 94 115 85 122 113 105 95 112 110 189 103 134 116 98 103
TRC-E25B 77
157 133 141 259 209 134 165 120 240 220 231 200 213 183 146 220 230 150 218 141
138 117 87 103 98 95 66 52 90 90 114 119 80 114 99 74 107 71 85 92
99 156 81 72 109 105 79 67 122 140 116 116 78 137 75 120 131 197 141 164
168 138 98 117 84 121 116 101 100 115 114 182 111 128 113 111 107

TRC-E26A 83
176 245 345 367 325 453 340 307 274 238 283 199 124 111 90 106 202 211 183 158
126 188 165 167 117 113 111 165 139 188 161 153 145 151 141 149 199 98 196 260
242 246 152 182 126 133 122 150 188 167 120 128 123 146 253 188 192 202 143 206
153 153 150 131 159 109 102 123 115 142 103 105 118 121 97 99 125 120 88 98
124 114 126
TRC-E26B 83
170 279 361 380 343 445 372 285 257 244 300 185 136 95 95 110 193 225 166 170
147 169 144 172 138 116 104 168 146 171 163 152 142 140 146 153 196 97 193 249
226 242 154 157 157 126 121 161 179 166 126 129 122 143 253 222 194 213 147 216
149 161 145 119 163 98 113 123 122 148 117 107 117 106 96 82 133 121 79 98
120 115 125
TRC-E27A 80
250 169 249 234 435 467 389 356 205 158 129 123 148 150 166 230 172 73 89 72
102 107 113 107 151 143 170 59 76 65 62 76 70 78 114 142 152 161 136 165
219 78 60 46 58 87 97 129 153 164 53 54 63 78 56 107 153 187 174 164
182 193 144 190 251 268 255 191 212 180 158 169 150 200 178 246 176 183 184 238
TRC-E27B 80
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186 177 148 199 268 200 247 184 195 184 154 161 158 185 202 242 167 159 221 249
TRC-E28A 94
166 154 134 159 133 144 174 149 179 149 140 118 104 112 107 154 139 130 148 154
203 209 169 123 184 110 157 128 145 135 120 107 114 121 131 162 154 73 94 78
90 88 95 147 111 73 92 100 113 89 64 90 121 102 104 85 59 92 99 118
64 90 110 112 74 59 107 104 122 102 40 34 20 21 38 58 65 51 70 76
115 120 78 78 100 76 70 88 137 95 96 199 142 140
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188 195 169 133 197 120 148 142 144 126 121 116 107 121 136 172 148 63 94 79
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71 77 111 109 73 60 101 118 137 118 34 35 21 27 40 62 61 51 62 81
120 118 72 82 94 80 61 96 134 99 88 207 139 128
TRC-E30A 85
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142 131 151 135 110 225 167 161 185 145 210 152 193 180 155 174 117 162 175 130
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85 72 85 120 87 102 106 94 84 77 98 85 79 86 77 85 75 62 89 95
95 96 81 61 64
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205 174 118 132 140 159 146 232 114 198 246 199 161 131 134 112 117 128 150 158
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168 133 120 171 115 112 118 145 122 139 107 137 133 87 93 104 125 94 129 102
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95 92 79 73 69
TRC-E31A 109
342 366 300 183 162 142 112 103 146 178 162 58 69 75 78 62 85 96 112 91
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67 81 128 128 50 27 31 36 35 54 107 135 114 126 116 154 134 172 139 112
166 111 161 173 114 136 153 184 189 227 173 153 147 131 229 209 198 200 164 152
96 108 159 164 148 143 180 126 98 120 131 146 139 177 151 167 207 133 133 110
77 70 92 88 102 114 157 168 154

TRC-E31B 109
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157 118 159 179 106 136 153 189 182 227 179 142 152 135 228 213 200 201 170 147
106 110 160 166 145 147 171 136 94 114 138 142 136 176 146 173 202 131 138 111
70 80 91 94 99 120 152 172 158
TRC-E32A 89
433 368 449 373 296 276 189 356 222 293 309 331 216 296 303 215 314 159 133 95
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159 154 159 164 122 122 85 119 82 75 75 93 99 74 68 94 85 69 64 68
88 97 112 118 161 79 61 59 123
TRC-E32B 89
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157 186 268 267 196 186 230 218 452 302 161 198 178 194 228 162 209 254 180 218
177 111 112 152 148 83 75 108 121 198 167 98 93 101 93 69 107 119 69 97
164 165 159 171 117 128 87 134 82 72 80 107 98 75 57 98 94 74 60 72
88 93 102 128 168 70 61 61 112
TRC-E33A 68
153 148 188 190 222 348 186 207 274 195 283 227 227 144 167 186 104 151 191 184
267 146 155 171 134 125 122 117 120 86 94 131 132 118 101 121 108 90 136 77
94 97 98 147 120 80 99 91 82 85 105 130 93 89 75 101 64 60 94 90
109 127 83 84 108 106 63 110
TRC-E33B 68
162 161 176 192 230 351 168 207 282 196 272 224 217 146 171 185 111 141 195 186
269 142 144 177 129 128 119 116 119 106 89 127 133 114 90 125 99 84 144 71
102 101 90 146 114 89 97 89 63 79 115 119 92 93 85 103 52 64 90 97
94 129 83 99 104 133 62 94
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159 155 114 116 176 140 200 138 139 118 103 97 116 150 115 87 126 113 107 147
112 98 131 85 109 122 108 107 79 82 56 69 76 70 100 78 92 103 84 93
89 140 80 126 99 120 122 102 72 111 135 95 120 84 62 100 116 101 94 109
145 121 100 76 109 108 99 85 78 82 85 61 88 104 105 87 91 81 90 96
TRC-E34B 101
151 252 189 150 140 156 183 188 178 250 173 147 214 132 241 178 177 166 227 223
162 147 123 111 173 144 202 147 128 117 106 90 109 161 114 90 126 116 106 141
112 109 127 101 106 137 101 103 87 76 58 68 78 74 92 85 90 98 87 91
99 127 77 132 87 127 112 103 76 99 155 94 113 84 72 85 118 109 96 113
129 115 99 73 115 103 98 97 84 81 77 62 102 106 102 91 95 85 91 99
84
TRC-E35A 80
327 297 280 242 233 280 248 181 421 271 208 321 204 191 275 308 184 184 160 117
130 141 168 217 129 139 207 164 119 139 164 96 134 104 122 151 130 88 138 167
124 143 104 116 146 124 140 119 104 114 117 104 64 74 89 88 96 83 83 74
83 79 111 113 96 102 109 117 138 109 61 81 82 74 60 79 108 93 111 103
TRC-E35B 80
309 289 295 265 205 278 243 210 383 288 162 297 202 192 276 313 201 191 171 110
135 136 176 211 134 139 207 161 126 137 148 96 135 103 129 151 119 93 148 155
120 141 107 123 138 123 141 117 113 101 108 108 65 77 87 86 97 86 86 72
75 95 104 118 94 103 107 113 141 112 59 79 80 61 73 84 120 89 113 107

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

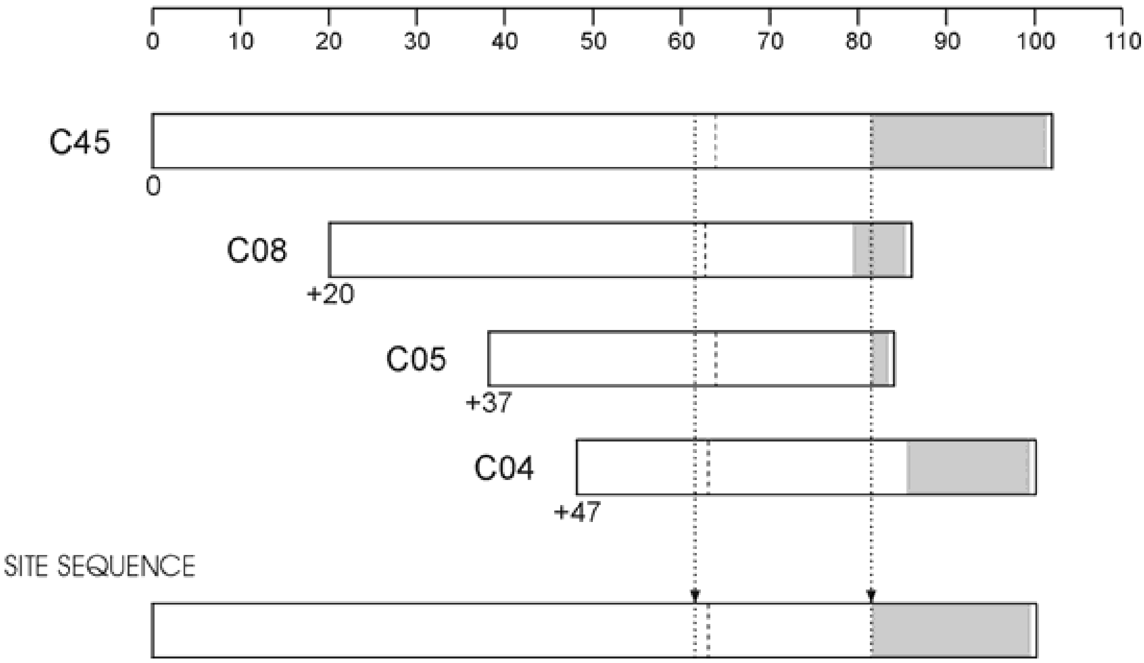


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

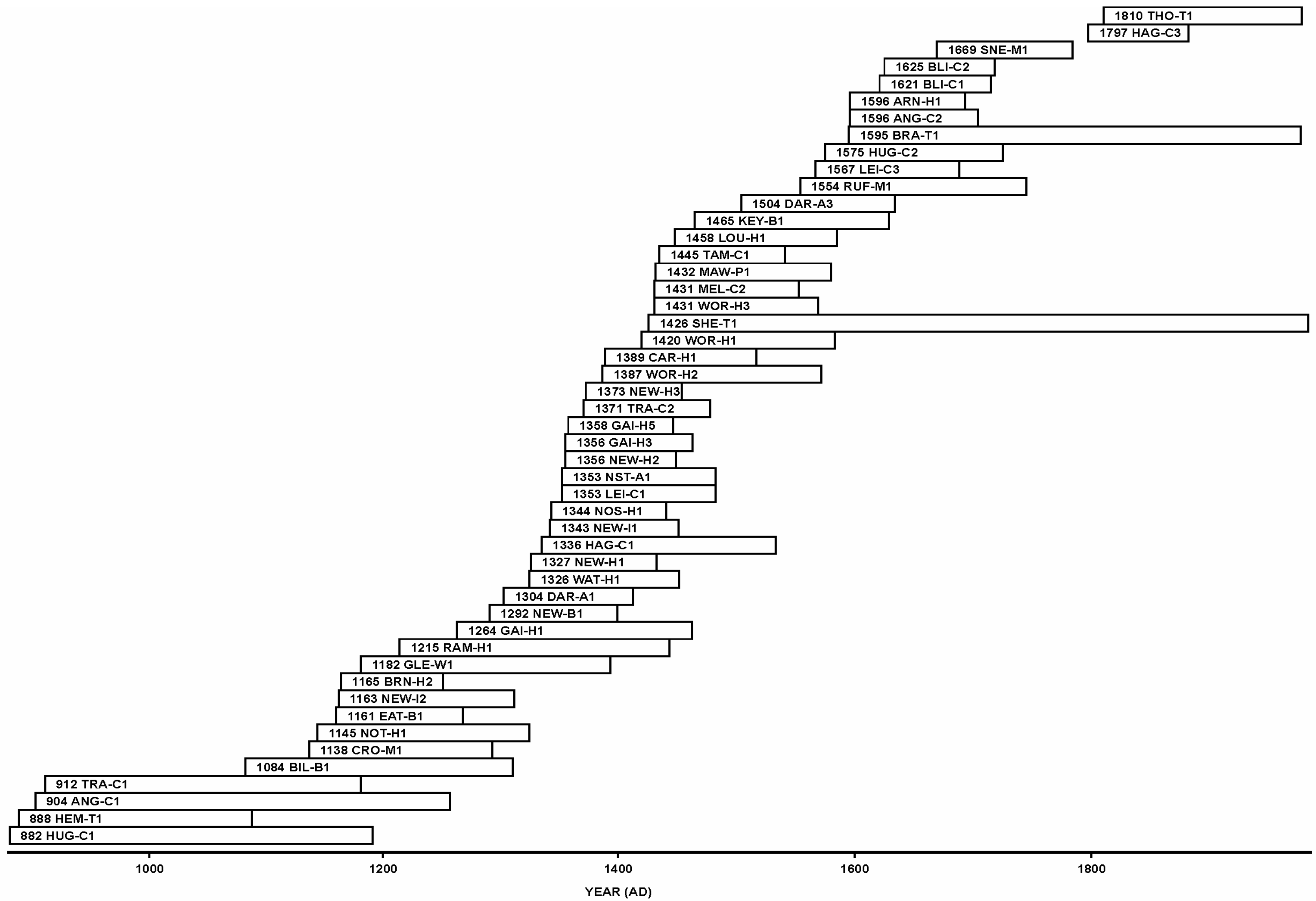
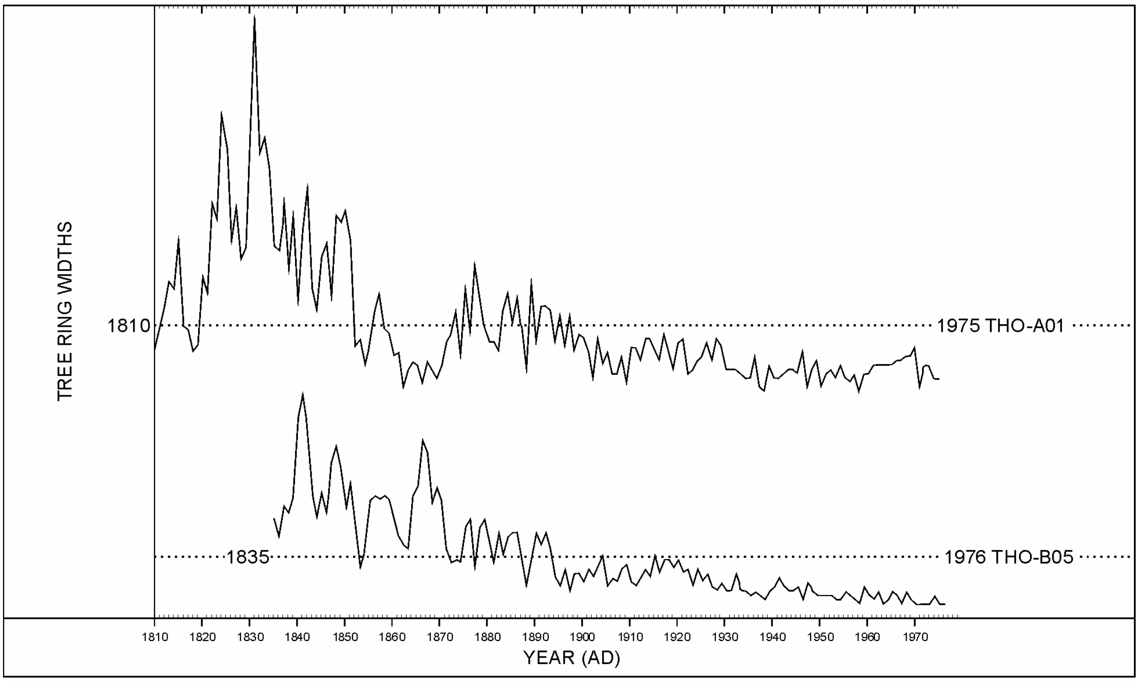


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

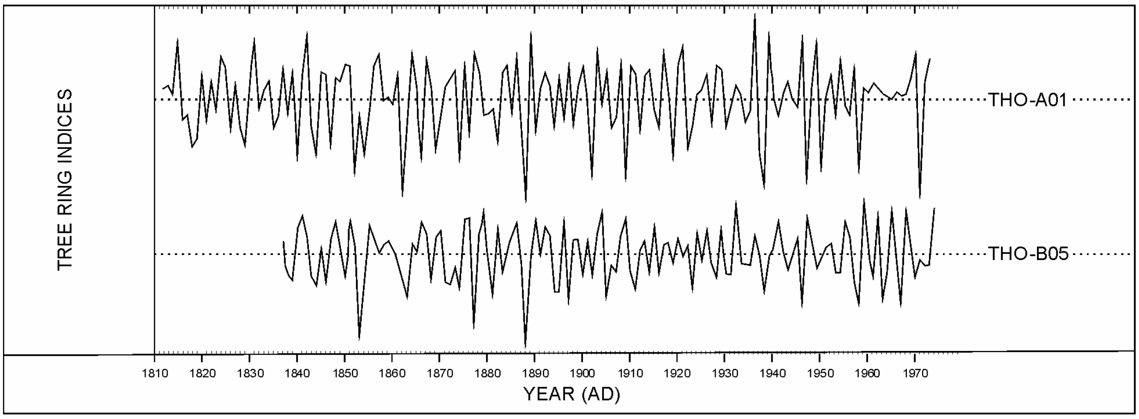


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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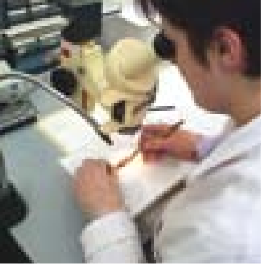
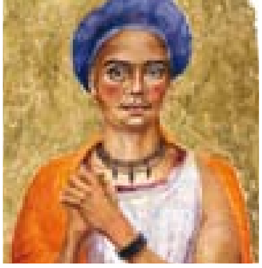



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