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CHURCH OF ST JAMES, WHITSON STREET, BRISTOL
TREE-RING ANALYSIS OF TIMBERS OF THE NAVE AND CHANCEL ROOFS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY
Analysis undertaken on samples from the timbers of the nave and chancel roofs at this church, resulted in the dating of three site sequences. A site sequence containing seven samples from the chancel and three from the nave was found to span the period AD 1209–1396. A second contains four samples from the nave and spans the period AD 1331–1406. The final dated site sequence contains three samples from the chancel and spans the period AD 1421–71. Interpretation of the sapwood on these dated samples suggests felling of the timbers used in the initial construction of the chancel roof occurred over a period of several years in the second quarter of the fourteenth century. The inserted false 'purlins', which strengthen the chancel roof, were felled in AD 1487–1502. The nave roof is thought likely to have been constructed shortly after the felling of the timbers in AD 1411–36.
Two further site sequences are undated.

CONTRIBUTORS
Alison Arnold and Robert Howard

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The Laboratory would like to thank Kevin Lloyd of C S Williams, the building contractors, for kindly facilitating access and for all his assistance during sampling. John Thorp of Keystone was on site to offer advice, provided the drawings used to locate the samples, and allowed us to see his draft document discussing the roofs. Thanks are also given to the Scientific Dating Team at English Heritage and Cathy Tyers of the Sheffield University Dendrochronology Laboratory for their advice and assistance throughout the production of this report.

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INTRODUCTION

The grade I listed Church of St James (ST 5889 7347; Figs 1–3) represents the remains of a former priory founded in AD 1129 as a Benedictine cell. In plan the church consists of an aisled nave and chancel; the south aisle was widened and rebuilt in AD 1698, and the north aisle rebuilt in AD 1864. At the south-east corner is a four-stage, unbuttressed tower dating to about AD 1374.

Chancel

The wagon roof over this part of the church is of common rafter type, with curving arch braces providing a barrel vault (Fig 4). Documentary sources suggest that this roof is dated to the fourteenth century after the failure of the original twelfth-century one. This type of roof is susceptible to racking and at some later date false 'purlins' (or chocks) were inserted between the trusses to strengthen the roof longitudinally (Fig 5).

Nave

The five bay nave is thought to date to the late-twelfth century although the roof is obviously a later replacement. Stylistically later than the roof over the chancel, the nave wagon roof is of a type common in the fifteenth century and continuing in popularity until the early-seventeenth century. It consists of main trusses, intermediate trusses, and common rafter trusses, all with arch braces. There are side purlins and a moulded crown purlin (Fig 6).

SAMPLING

Sampling of the nave and chancel roof timbers was requested by Rob Harding, English Heritage South-West region as part of the building recording being undertaken in conjunction with a major repair programme in receipt of grant aid. It was hoped that successful tree-ring dating of the primary timbers would provide clear evidence for the construction dates of the nave and chancel roofs. In addition it was hoped that the dating of the inserted false 'purlins' of the chancel roof would allow a greater understanding of the development of this roof.

A total of 43 timbers was sampled. Each sample was given the code JMS-P (for St James' Church) and numbered 01–43. Twenty of these samples are taken from timbers of the nave roof (JMS-P01–13 and JMS-P27–33) and 23 from the chancel roof (JMS-P14–26 and JMS-P34–43). The suitability of some of the timbers sampled, such as those of the collar purlins (JMS-P13 and JMS-P26) and the false 'purlins' (JMS-P34–43) could be seen to be marginal but were considered of such importance that sampling was deemed appropriate. Trusses and frames have been numbered from east to west. The location of all samples was noted at the time of sampling and has been marked on figures 7–28. The only exception to this is sample JMS-P33 which was taken from an ex-situ wallplate. Further details relating to these samples can be found in Table 1.

ANALYSIS AND RESULTS

At this stage 12 of the samples (five from the nave roof and seven from the chancel roof) were seen to have too few rings to make secure dating a possibility and were discarded prior to measurement. The remaining 31 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 21 samples grouping to form five site sequences.

Firstly, ten samples (three from the nave and seven from the chancel) grouped to form JMSPSQ01, a site sequence of 188 rings (Fig 29). This sequence was found to match the reference chronologies at a first-ring date of AD 1209 and a last-measured ring date of AD 1396. The evidence for this dating is given by the t-values in Table 2.

Four further nave samples grouped and were combined at the relevant offset positions to form JMSPSQ02, a site sequence of 76 rings (Fig 30). This site sequence was compared against a series of relevant reference chronologies where it was found to span the period AD 1331–1406. The evidence for this dating is given by the t-values in Table 3.

Three samples taken from the inserted false ‘purlins’ of the chancel roof matched each other and were combined to form JMSPSQ03, a site sequence of 51 rings (Fig 31). This site sequence was found to match securely and consistently against the reference chronologies at a first-ring date of AD 1421 and a last-measured ring date of AD 1471. The evidence for this dating is given by the t-values in Table 4.

Two further site sequences, each containing two samples from the nave roof, were also constructed (Figs 32 and 33). Attempts to date these and the remaining ungrouped samples were unsuccessful and all remain undated.

INTERPRETATION

Chancel roof

Ten of the chancel roof samples have been successfully dated (Fig 34), seven within JMSPSQ01 and three in JMSPSQ03. All ten samples have the heartwood/sapwood boundary ring. Seven of these, representing collars, struts, rafters and an archbrace, have heartwood/sapwood boundary ring dates in the early decades of the fourteenth century, the average of which is AD 1312. This allows an estimated felling date range to be calculated for the seven timbers represented of AD 1327–52. The variation between the earliest and latest heartwood/sapwood boundary ring of these seven samples is 24 years which suggests the possibility that these timbers may have been felled over a period of several years in the second quarter of the fourteenth century.

The other three dated chancel samples are all taken from false 'purlins', not thought to be part of the primary roof structure. These three samples all have similar heartwood/sapwood boundary ring dates, suggestive of a single felling. The average of these is AD 1462, allowing an estimated felling date to be calculated for the three timbers represented to within the range AD 1487—1502.

Nave roof

All of the seven dated samples from the nave, included in site sequences JMSPSQ01 and JMSPSQ02, represent wallplates. Four of these have the heartwood/sapwood boundary ring (Fig 34), which is, in all cases, broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1396, allowing an estimated felling date to be calculated for the four timbers represented to within the range AD 1411–36. The remaining three dated nave samples do not have the heartwood/sapwood boundary so an estimated felling date cannot be calculated for them; however, their last-measured ring dates make it possible that these were also felled in AD 1411–36.

The two undated site sequences, JMSPSQ04 and JMSPSQ05, represent a pair of collars and a pair of archbraces respectively. The samples in each site sequence are clearly broadly coeval.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees in this region have between 15 and 40 sapwood rings.

DISCUSSION

Prior to tree-ring analysis being undertaken the nave roof had been identified as being of a type common from the fifteenth to early-seventeenth centuries, with the chancel being stylistically earlier and potentially fourteen century. It is now known that the chancel roof is constructed from timber felled in AD 1327–52 with felling possibly occurring over a period of several years. Construction in the second quarter of the fourteenth century makes this roof the earliest dated wagon roof in the south-west (Thorp *pers comm*). Subsequently it must have become clear that additional longitudinal strengthening was required to maintain the integrity of this roof and the false 'purlins' were inserted. This is now thought to have occurred soon after the felling of these timbers in AD 1487–1502.

The nave roof had already been identified on stylistic grounds to be later than that of the chancel and this appears to have been confirmed by the dendrochronology. Several of the wallplates of this roof have now been dated to a felling of AD 1411–36. It is unfortunate that, despite several archbraces and collars being sampled from this roof, none of these elements could be dated, making it a possibility that the rest of the roof structure is of a different date. However, structural analysis of the roof has not identified any evidence to suggest that the roof is not integral to the wallplates; the AD fifteenth-century date is as expected from a wagon roof of this type and is consistent with other dated examples (Thorp *pers comm*).

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TABLES

Table 1: Details of tree-ring samples from the nave and chancel roofs of the Church of St James, Bristol

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Nave						
JMS-P01	South archbrace, CR27	86	13	----	----	----
JMS-P02	South archbrace, CR23	76	h/s	----	----	----
JMS-P03	North archbrace, CR22	NM	--	----	----	----
JMS-P04	South archbrace, CR18	NM	--	----	----	----
JMS-P05	Collar, CR16	55	h/s	----	----	----
JMS-P06	Collar, CR13	57	--	----	----	----
JMS-P07	Collar, CR10	73	h/s	----	----	----
JMS-P08	South archbrace, CR8	49	h/s	----	----	----
JMS-P09	Collar, CR8	51	01	----	----	----
JMS-P10	North archbrace, CR6	NM	--	----	----	----
JMS-P11	Collar, CR6	85	h/s	----	----	----
JMS-P12	Collar, CR5	NM	--	----	----	----
JMS-P13	Collar purlin, CR12–CR13	NM	--	----	----	----
JMS-P27	South wallplate, IT1–CR4	110	--	1255	----	1364
JMS-P28	South wallplate, CR4–CR14	117	--	1270	----	1386
JMS-P29	South wallplate, CR14–ET	123	h/s	1274	1396	1396
JMS-P30	North wallplate, IT1–MT1	68	11	1339	1395	1406
JMS-P31	North wallplate, CR11–CR14	68	h/s	1331	1398	1398
JMS-P32	North wallplate, IT3–CR15	56	--	1335	----	1390
JMS-P33	Ex-situ wallplate, north side	67	02	1331	1395	1397
Chancel						
JMS-P14	Collar, T15	75	h/s	1252	1326	1326
JMS-P15	North strut, T13	84	h/s	1221	1304	1304
JMS-P16	North rafter, T12	77	h/s	1235	1311	1311
JMS-P17	North archbrace, T10	105	03	----	----	----
JMS-P18	South strut, T10	69	h/s	1235	1303	1303

Table 1: Details of tree-ring samples from the nave and chancel roofs of the Church of St James, Bristol

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
JMS-P19	South rafter, T9	64	h/s	----	----	----
JMS-P20	South archbrace, T7	94	h/s	1209	1302	1302
JMS-P21	Collar, T7	93	h/s	1221	1313	1313
JMS-P22	Collar, T6	76	h/s	----	----	----
JMS-P23	South rafter, T4	77	h/s	1250	1326	1326
JMS-P24	North strut, T3	91	h/s	----	----	----
JMS-P25	South archbrace, T2	81	16	----	----	----
JMS-P26	Collar purlin, west end	NM	--	----	----	----
JMS-P34	South purlin, T 9–T10	46	01	1421	1465	1466
JMS-P35	South purlin, T3–T4	41	10	1431	1461	1471
JMS-P36	South purlin, T12–T13	47	h/s	----	----	----
JMS-P37	North purlin, T7–T8	51	11	1421	1460	1471
JMS-P38	North purlin, T12–T13	NM	--	----	----	----
JMS-P39	North purlin, T11–T12	NM	--	----	----	----
JMS-P40	North purlin, T6–T7	NM	--	----	----	----
JMS-P41	North purlin, T3–T4	NM	--	----	----	----
JMS-P42	South purlin, T7–T8	NM	--	----	----	----
JMS-P43	South purlin, T5–T6	NM	--	----	----	----

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

Table 2: Results of cross-matching of site sequence JMSPSQ01 and relevant reference chronologies when the first ring date is AD 1209 and the last measured ring date is AD 1396

Reference chronology	t-value	Span of chronology	Reference
Upwich, Droitwich, Worcestershire	8.1	AD 946–1415	Groves and Hillam 1997
Wigmore Abbey, Herefordshire	8.1	AD 1055–1729	Tyers 2002
Twyning Church bellframe, Gloucestershire	7.8	AD 1251–1452	Tyers 1996
St Cuthberts, Wick, Worcestershire	7.7	AD 1255–1496	Bridge 1981
Upper Limebrook, Wigmore, Herefordshire	7.5	AD 1220–1447	Tyers 2004
New Inn House, Kingswood, Gloucestershire	7.3	AD 1191–1519	Arnold *et al* 2004
Stoneleigh Abbey, Warwickshire	6.9	AD 1124–1346	Howard *et al* 2000

Table 3: Results of cross-matching of site sequence JMSPSQ02 and relevant reference chronologies when the first ring date is AD 1331 and the last measured ring date is AD 1406

Reference chronology	t-value	Span of chronology	Reference
Mercer's Hall, Gloucester	7.8	AD 1289–1541	Howard *et al* 1996
66/68 Westgate Street, Gloucester	7.1	AD 1209–1518	Tyers and Wilson 2000
Sinai Farm, Burton-on-Trent, Staffordshire	6.6	AD 1336–1499	Arnold *et al* 2008
Manor Farm Barn, Halesowen Abbey, West Midlands	6.3	AD 1310–1535	Arnold and Howard 2008
Wardon Church (roof), Worcestershire	6.0	AD 1348–1424	Tyers 1998
All Hallow's Church, Kirkburton, West Yorkshire	5.9	AD 1306–1633	Arnold and Howard 2007
Abbey Gatehouse, Bristol Cathedral, Bristol	5.7	AD 1306–1494	Arnold *et al* 2003

Table 4: Results of cross-matching of site sequence JMSPSQ03 and relevant reference chronologies when the first ring date is AD 1421 and the last measured ring date is AD 1471

Reference chronology	t-value	Span of chronology	Reference
Warndon Church (tower), Worcestershire	7.4	AD 1391–1498	Tyers 1998
Townsend Farmhouse, Stockland, Devon	6.8	AD 1422–1484	Tyers and Groves 2003
66 Church Street, Tewkesbury, Gloucestershire	6.5	AD 1371–1474	Nayling 2005
Whites Farm, South Leverton, Nottinghamshire	6.5	AD 1359–1503	Morgan 1982
St Briavels Castle, Gloucestershire	6.5	AD 1362–1592	Howard *et al* 2001
Lower House Farm, Tupsley, Herefordshire	6.4	AD 1425–1613	Tyers 1997
Welsh Borders	6.3	AD 1341–1636	Siebenlist-Kerner 1978

FIGURES

Figure 1: *Map to show the general location of Bristol (based on the Ordnance Survey Map, with the Permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)*

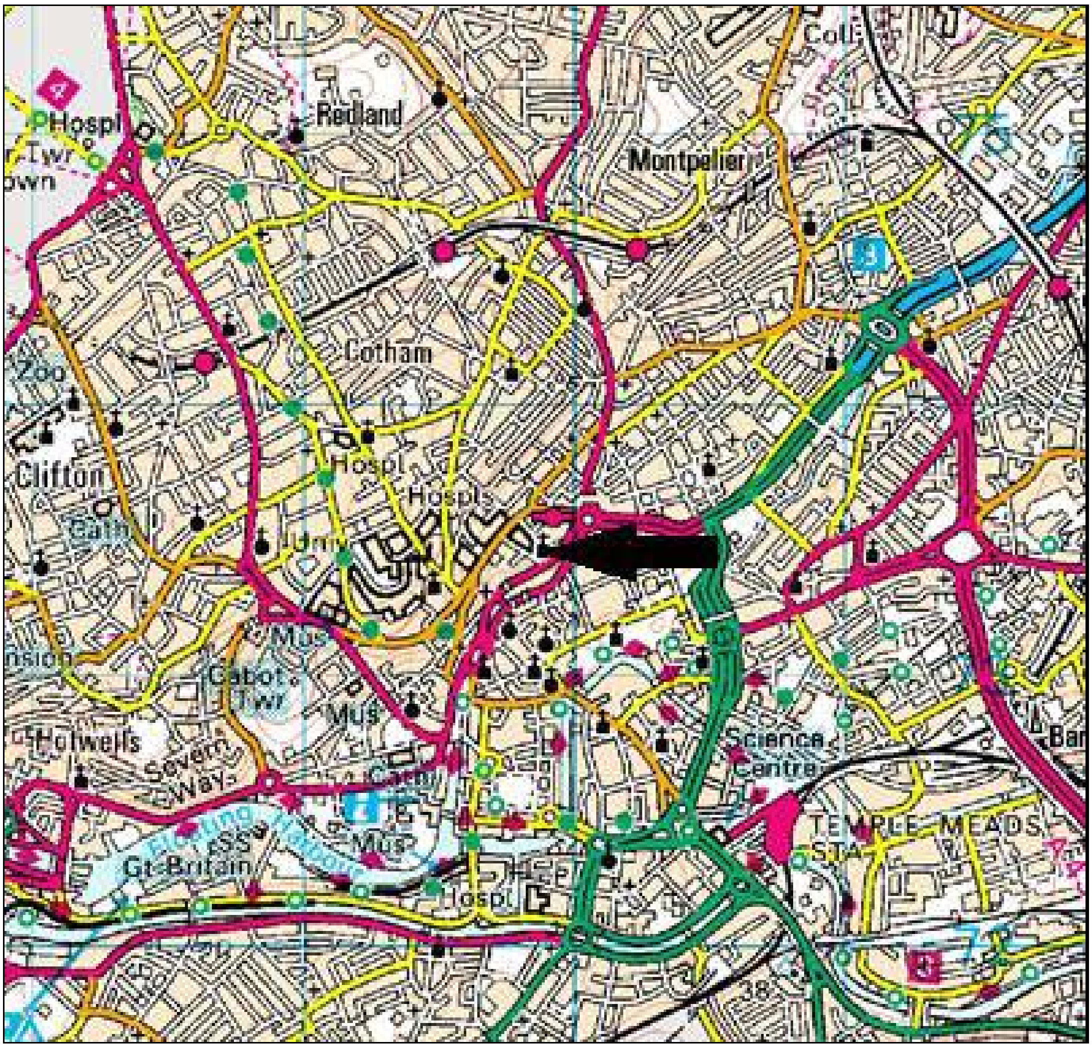


Figure 2: Map to show the general location of the Church of St James, arrowed (based on the Ordnance Survey Map, with the Permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)

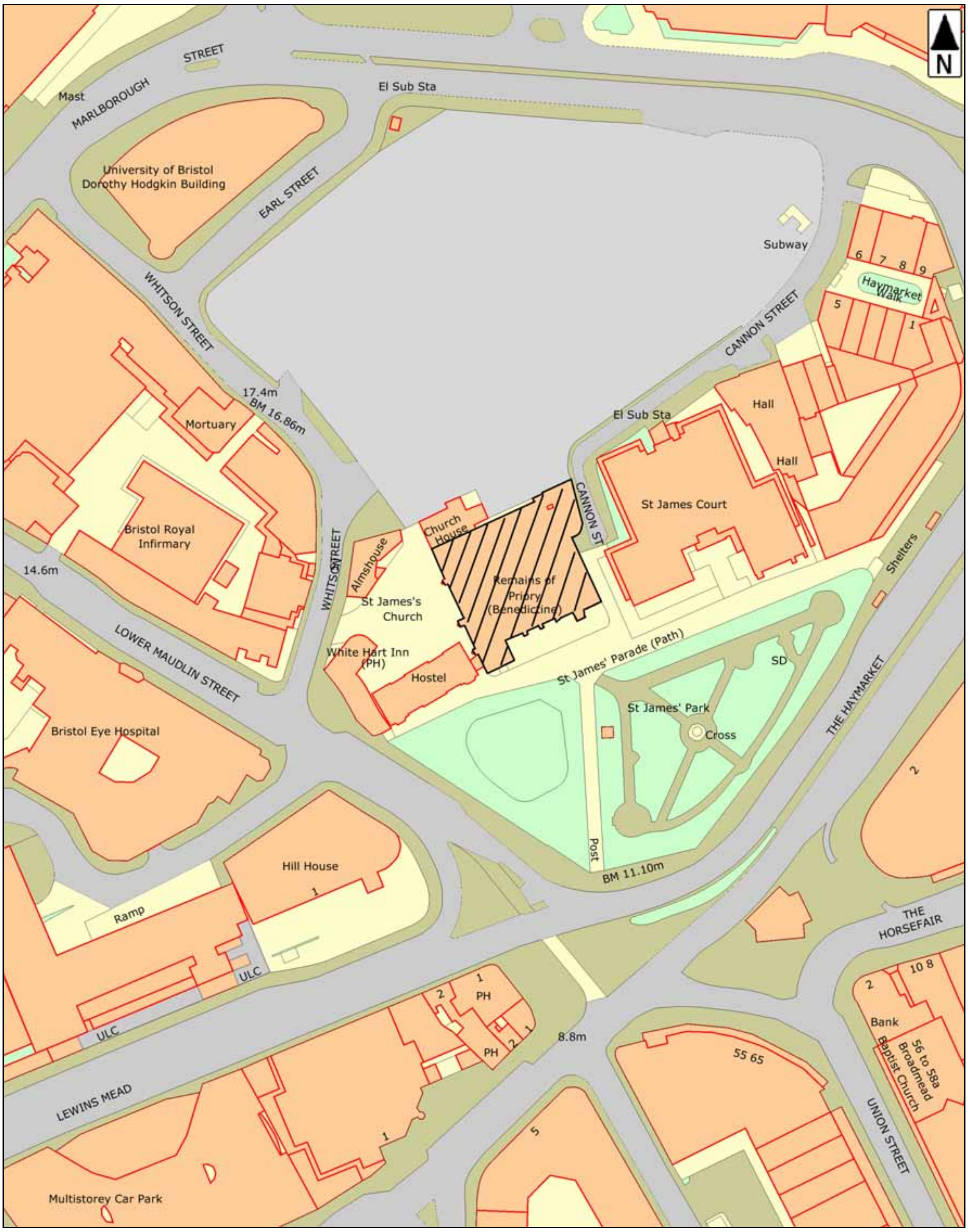


Figure 3: Map to show the location of the Church of St James, hashed (based on the Ordnance Survey Map, with the Permission of The Controller of Her Majesty's Stationery Office, ©Crown Copyright)

Figure 4: Chancel roof

Figure 5: The false 'purlins' of the chancel roof

Figure 6: Nave roof (Keystone Historic Buildings Consultants)

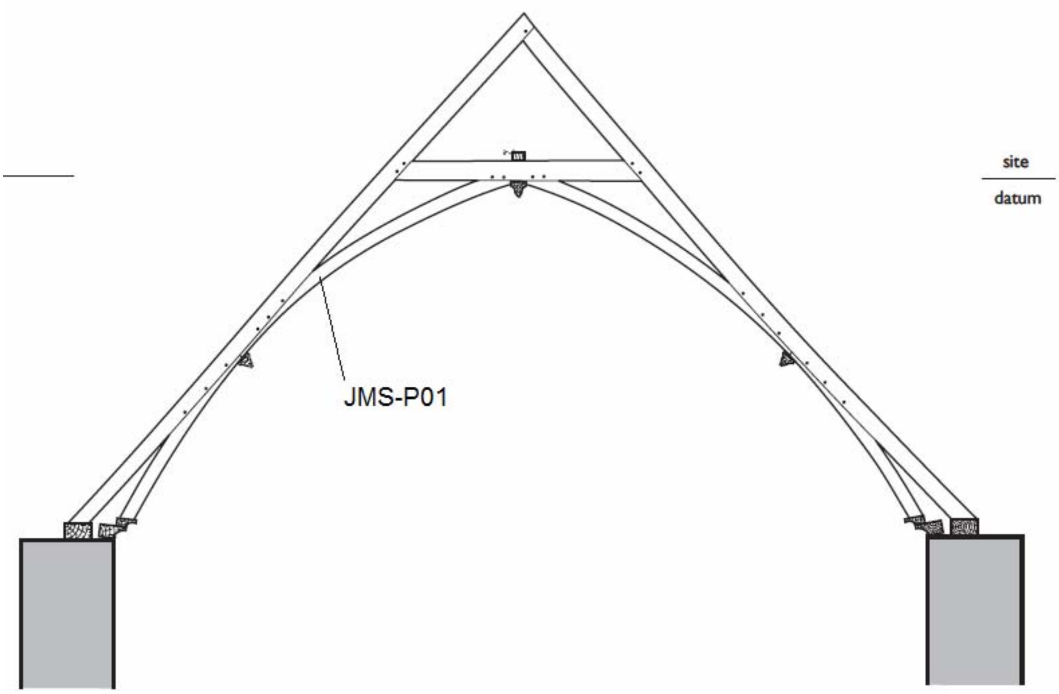


Figure 7: Nave; common rafter frame CR27, showing the location of sample JMS-P01 (John Thorp)

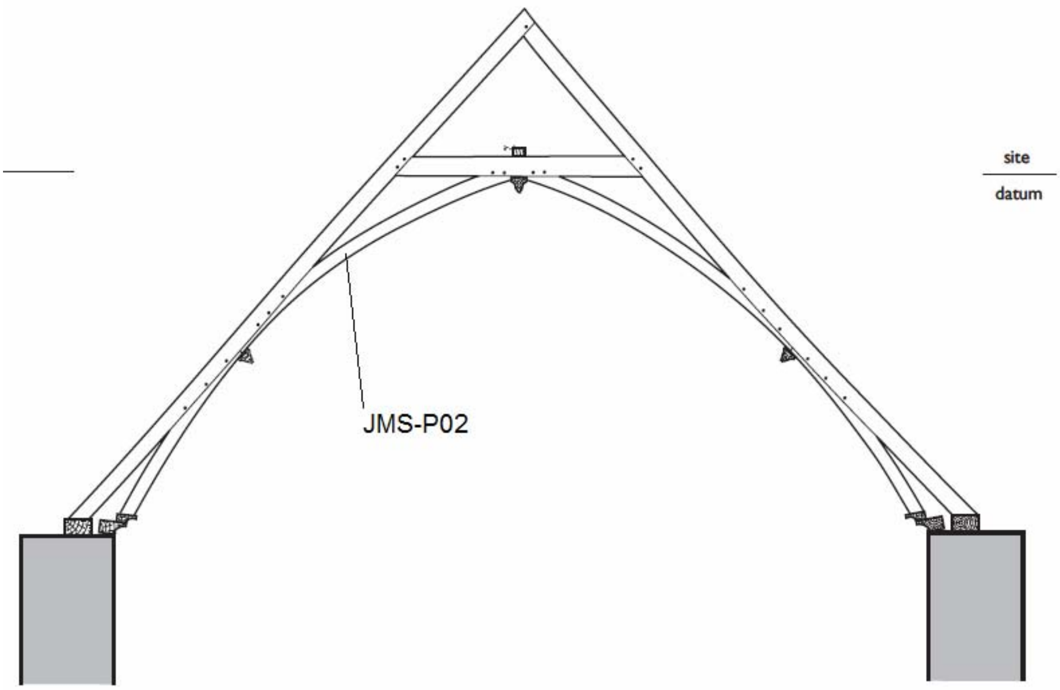


Figure 8: Nave; common rafter frame CR23, showing the location of sample JMS-P02 (John Thorp)

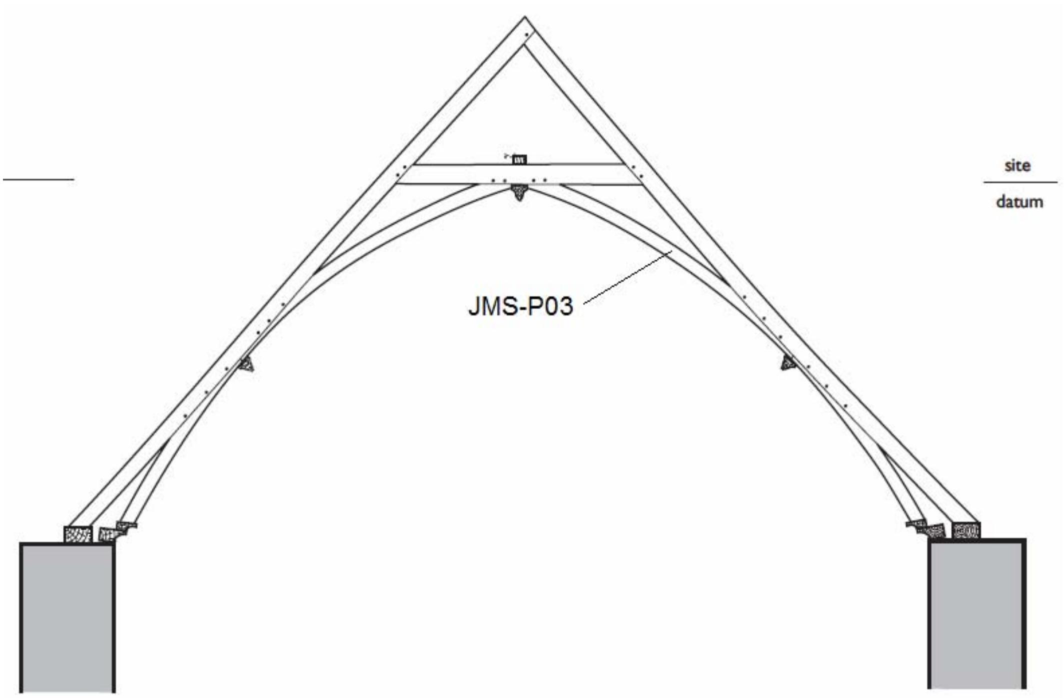


Figure 9: Nave; common rafter frame CR22, showing the location of sample JMS-P03 (John Thorp)

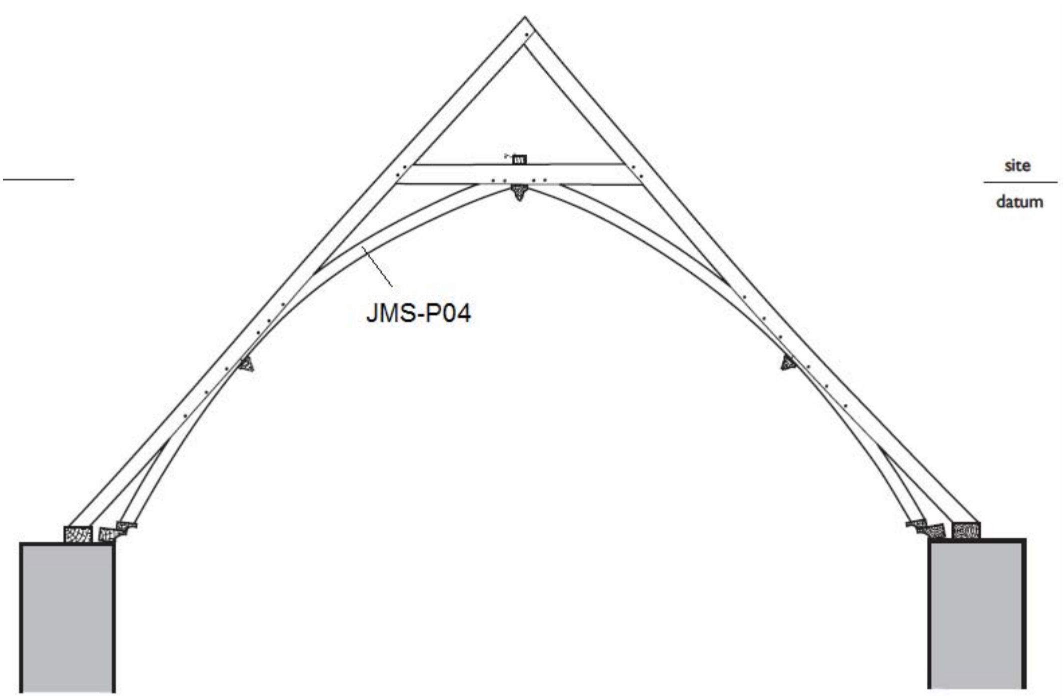


Figure 10: Nave; common rafter frame CR18, showing the location of sample JMS-P04 (John Thorp)

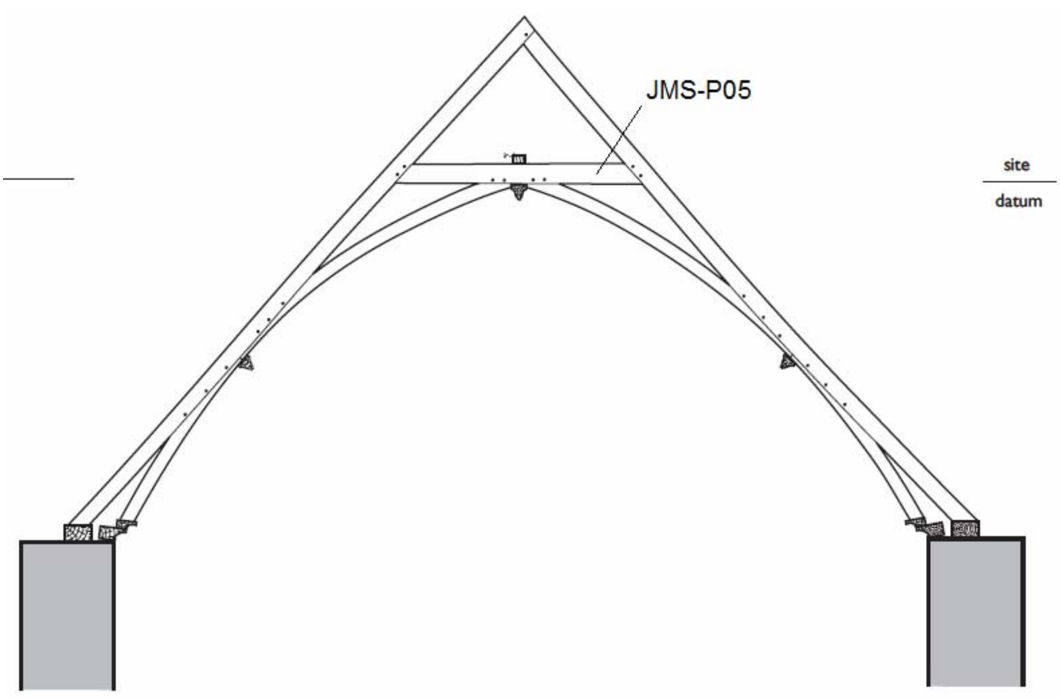


Figure 11: Nave; common rafter frame CR16, showing the location of sample JMS-P05 (John Thorp)

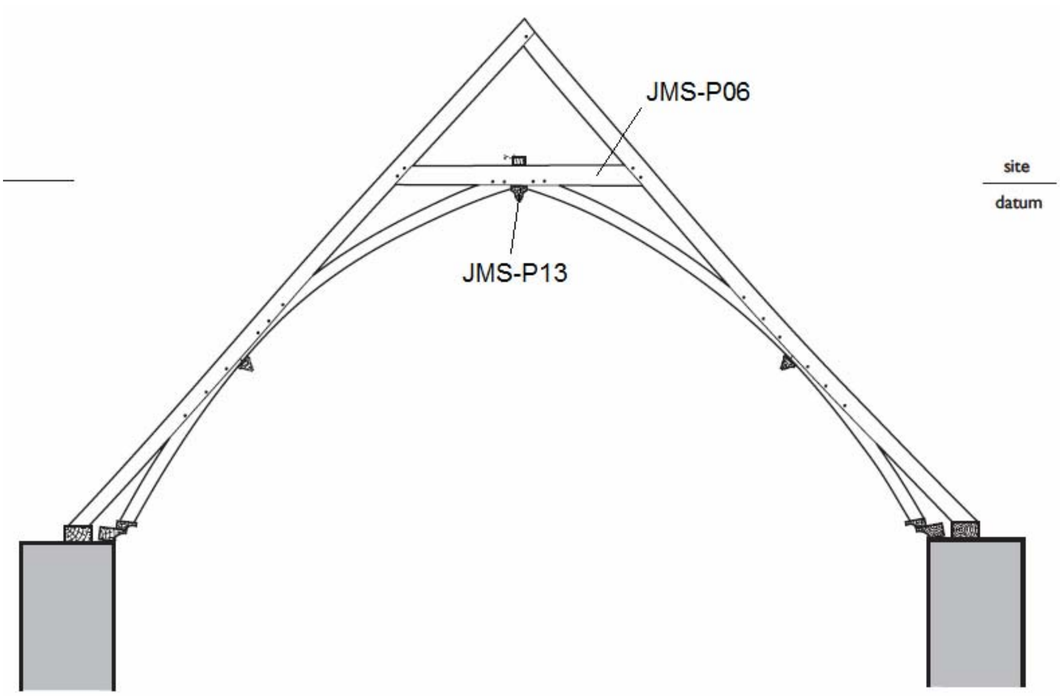


Figure 12: Nave; common rafter frame CR13, showing the location of samples JMS-P06 and JMS-P13 (John Thorp)

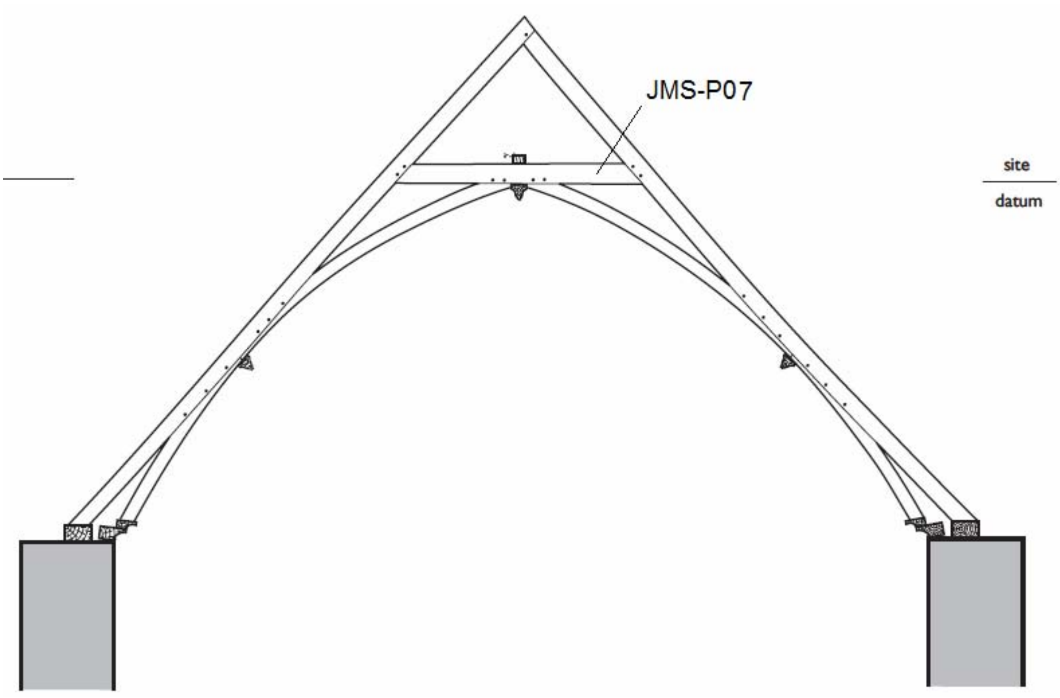


Figure 13: Nave; common rafter frame CR10, showing the location of sample JMS-P07 (John Thorp)

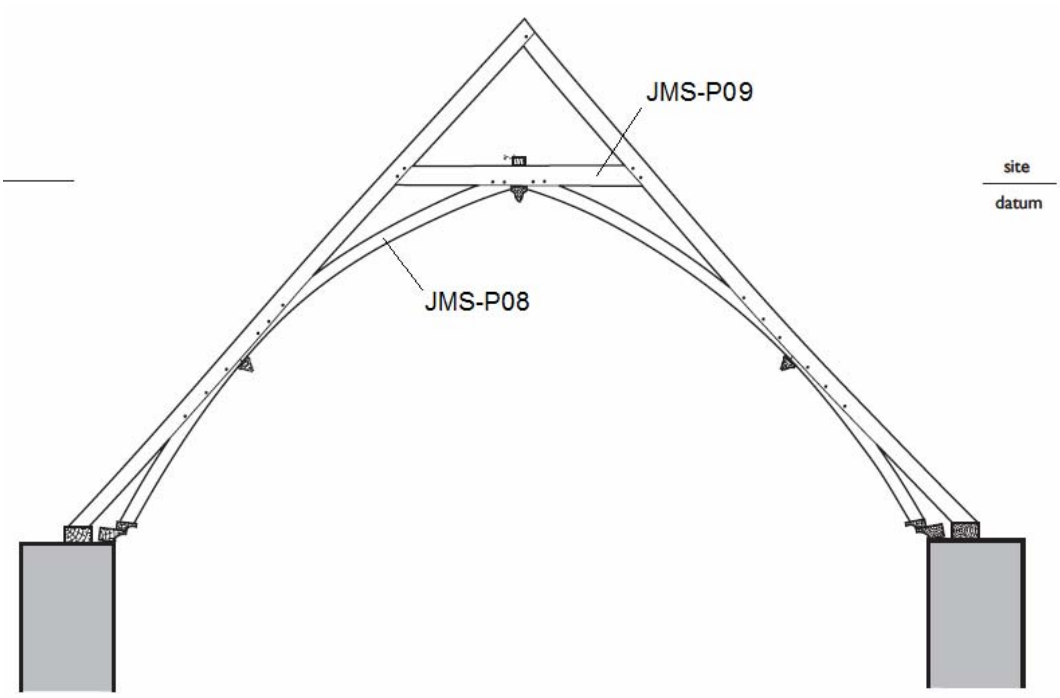


Figure 14: Nave; common rafter frame CR8, showing the location of samples JMS-P08 and JMS-P09 (John Thorp)

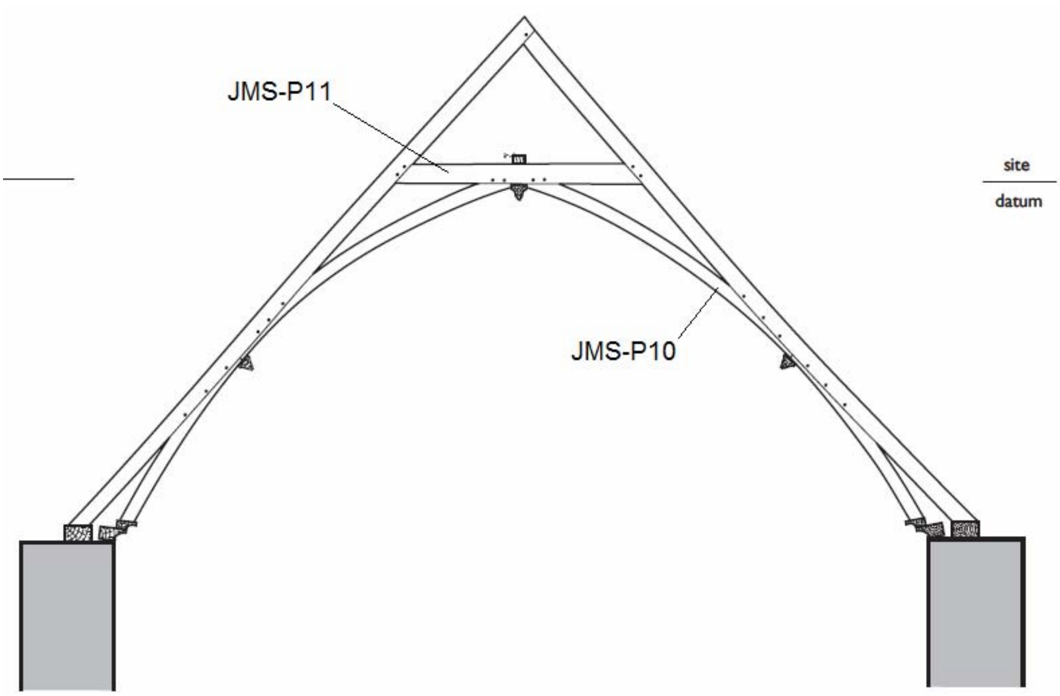


Figure15: Nave; common rafter frame CR6, showing the location of samples JMS-P10 and JMS-P11 (John Thorp)

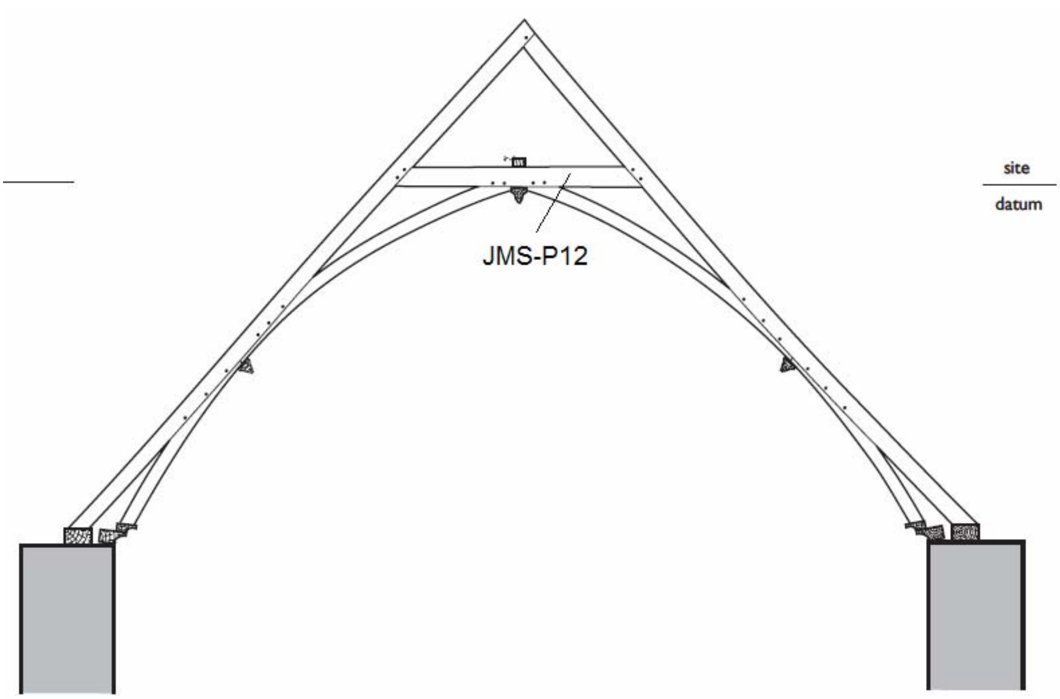


Figure 16: Nave; common rafter frame CR5, showing the location of sample JMS-P12 (John Thorp)

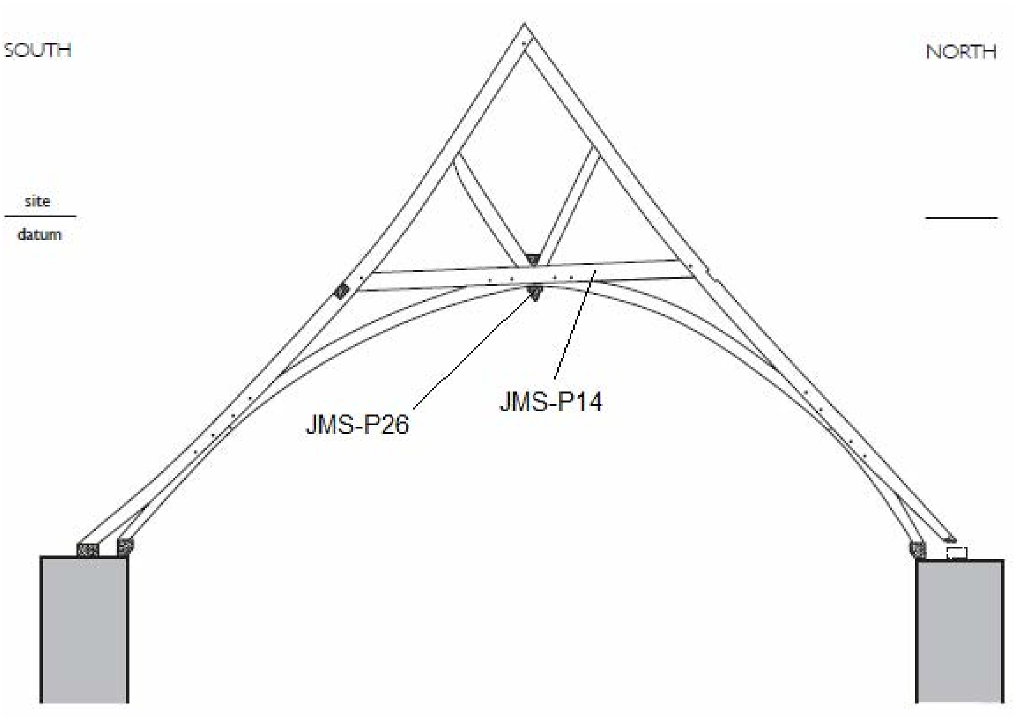


Figure 17: Chancel; frame T15, showing the location of sample JMS-P14 and JMS-P26 (John Thorp)

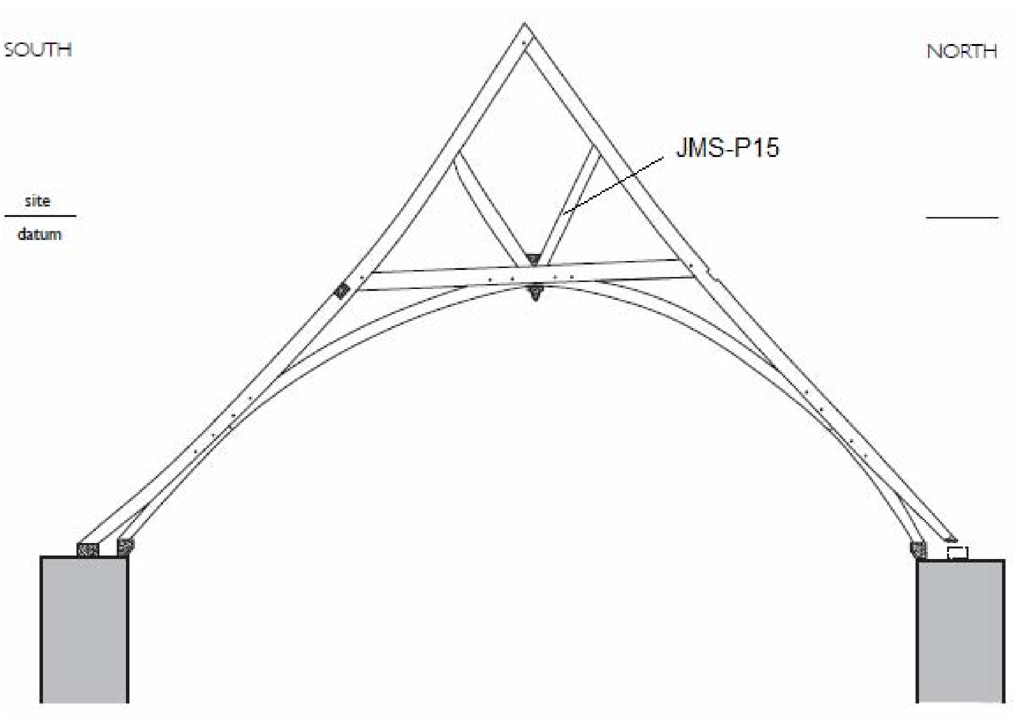


Figure 18: Chancel; frame T13, showing the location of sample JMS-P15 (John Thorp)

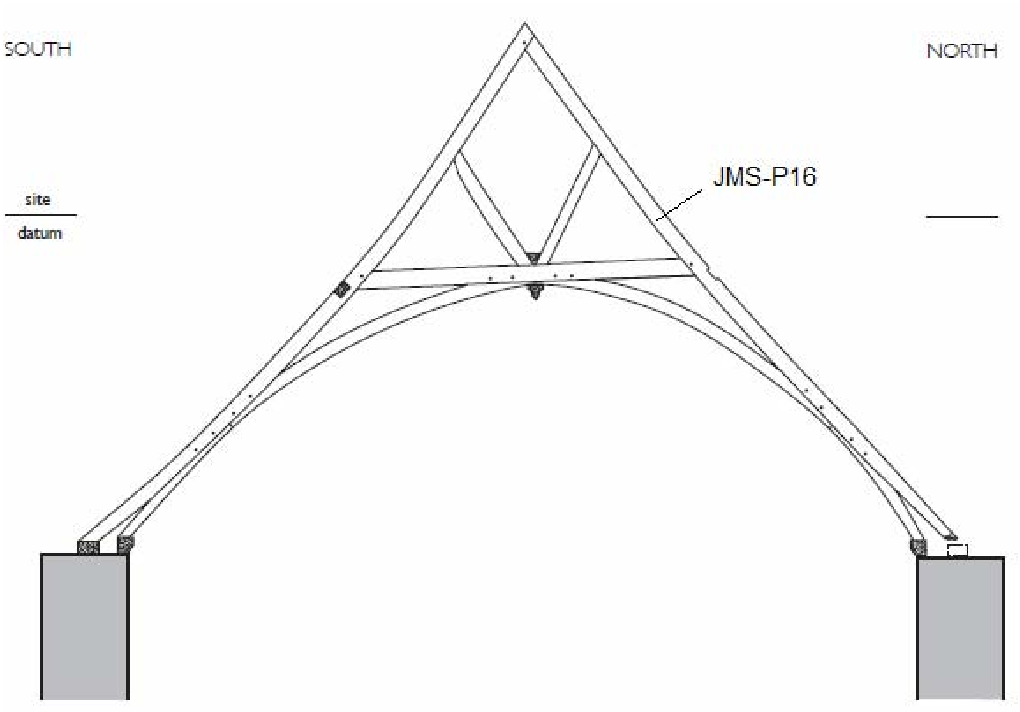


Figure 19: Chancel; frame T12, showing the location of sample JMS-P16 (John Thorp)

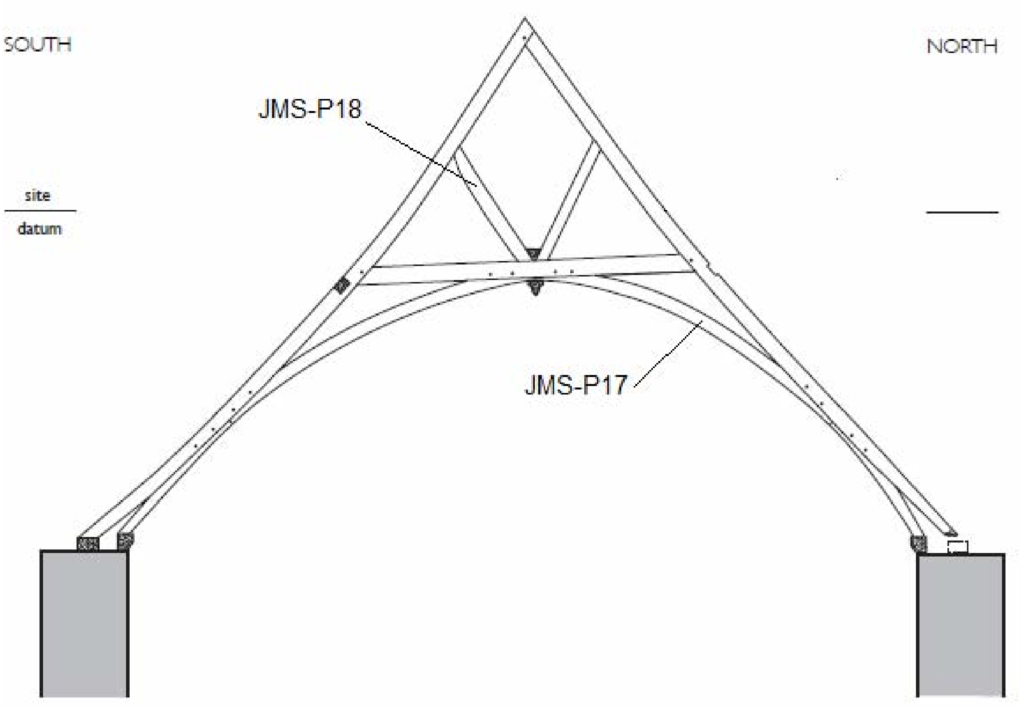


Figure 20: Chancel; frame T10, showing the location of samples JMS-P17 and JMS-P18 (John Thorp)

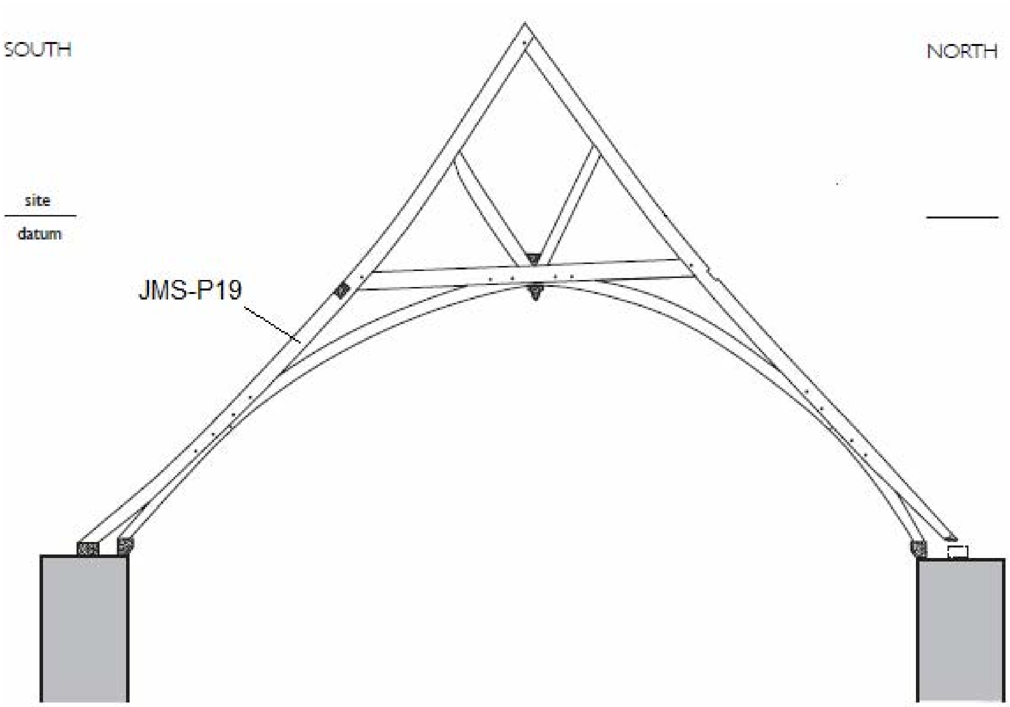


Figure 21: Chancel; frame T9, showing the location of samples JMS-P19 (John Thorp)

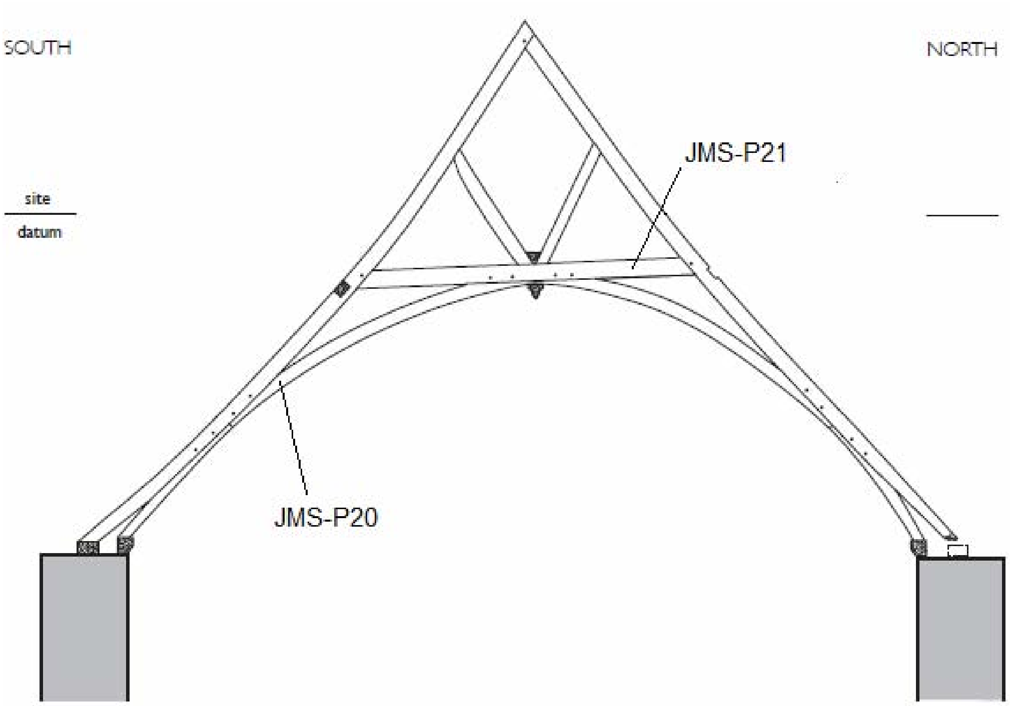


Figure 22: Chancel; frame T7, showing the location of samples JMS-P20 and JMS-P21 (John Thorp)

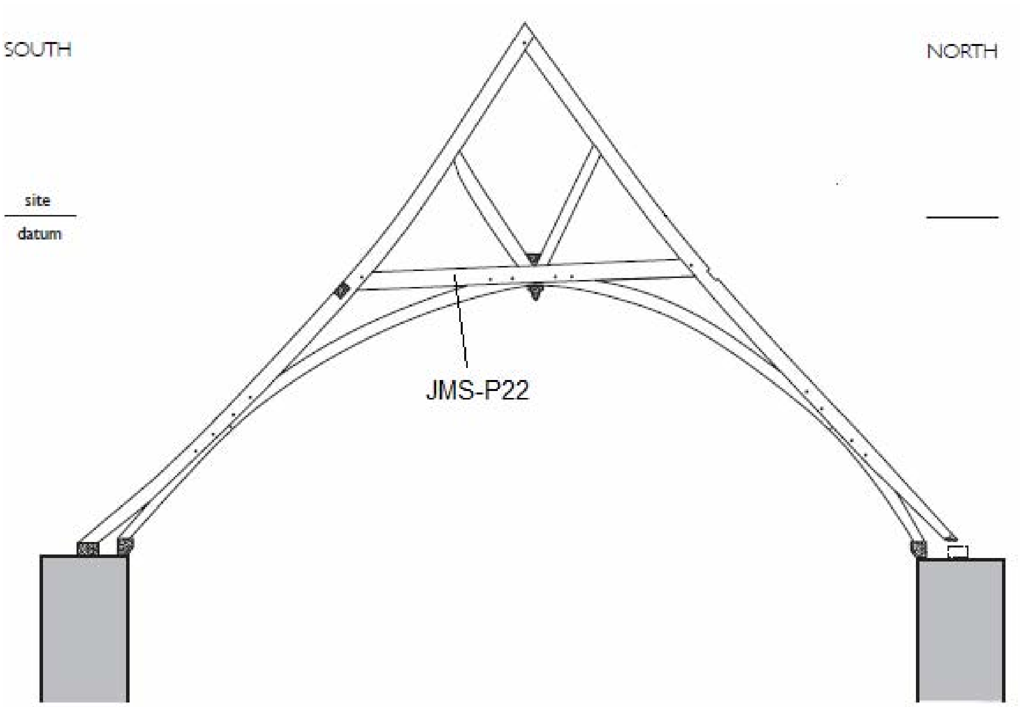


Figure 23: Chancel; frame T6, showing the location of sample JMS-P22 (John Thorp)

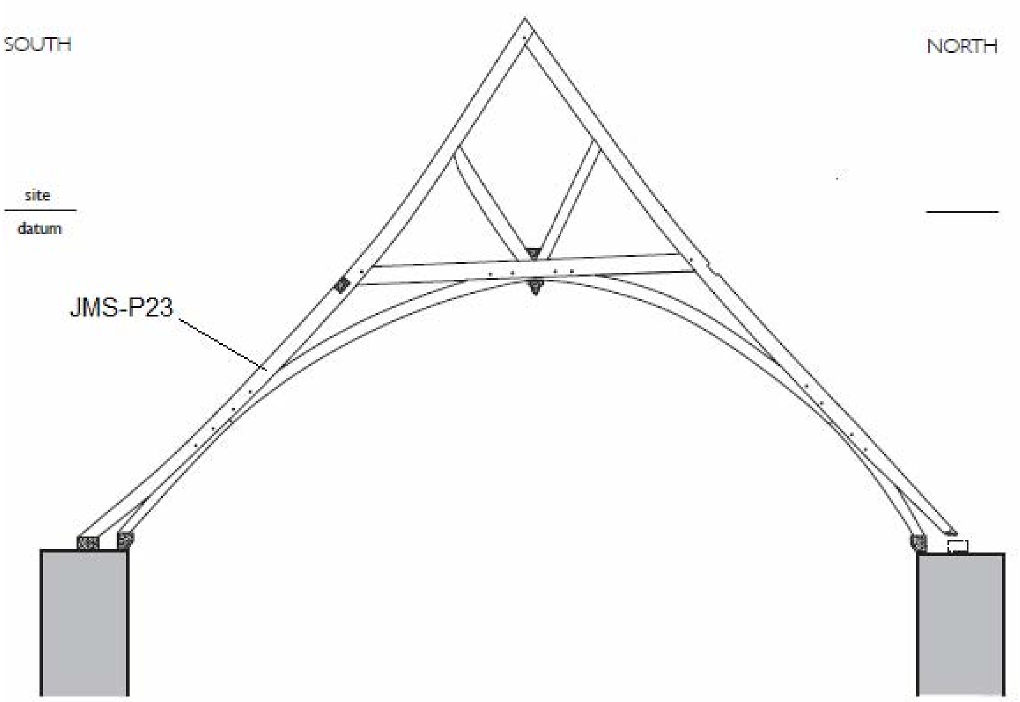


Figure 24: Chancel; frame T4, showing the location of sample JMS-P23 (John Thorp)

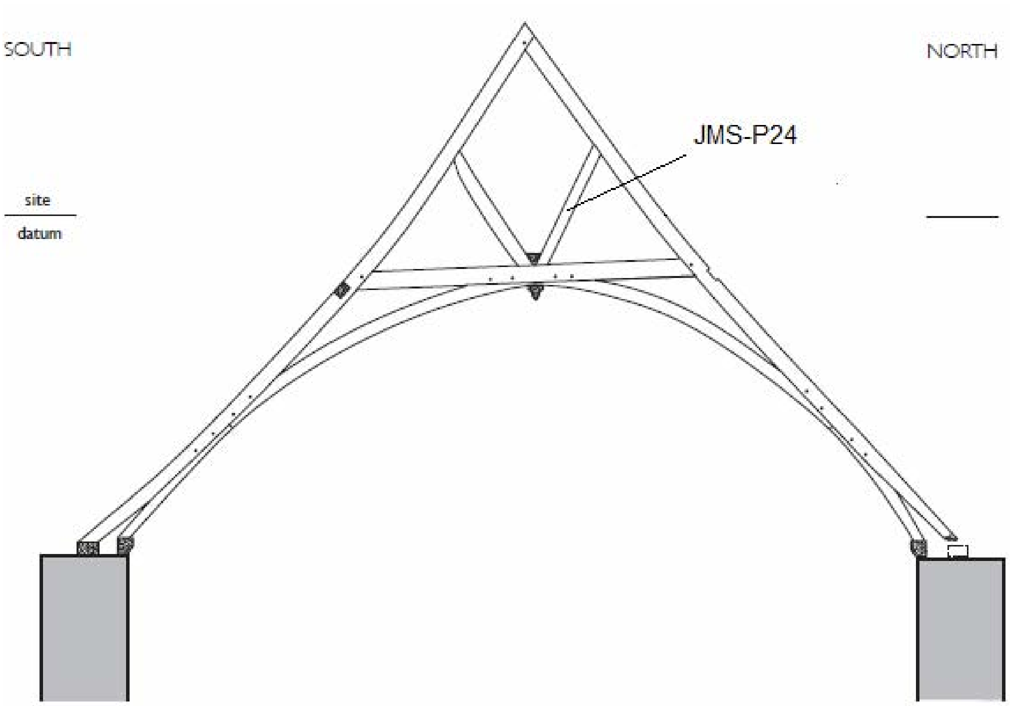


Figure 25: Chancel; frame T3, showing the location of sample JMS-P24 (John Thorp)

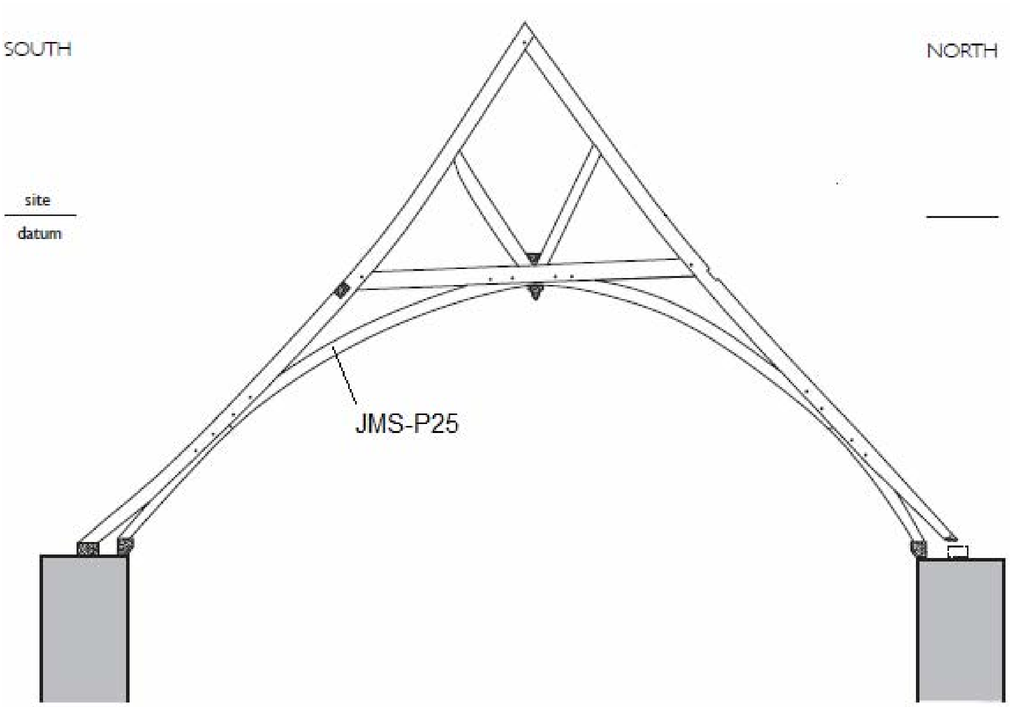


Figure 26: Chancel; frame T2, showing the location of sample JMS-P25 (John Thorp)

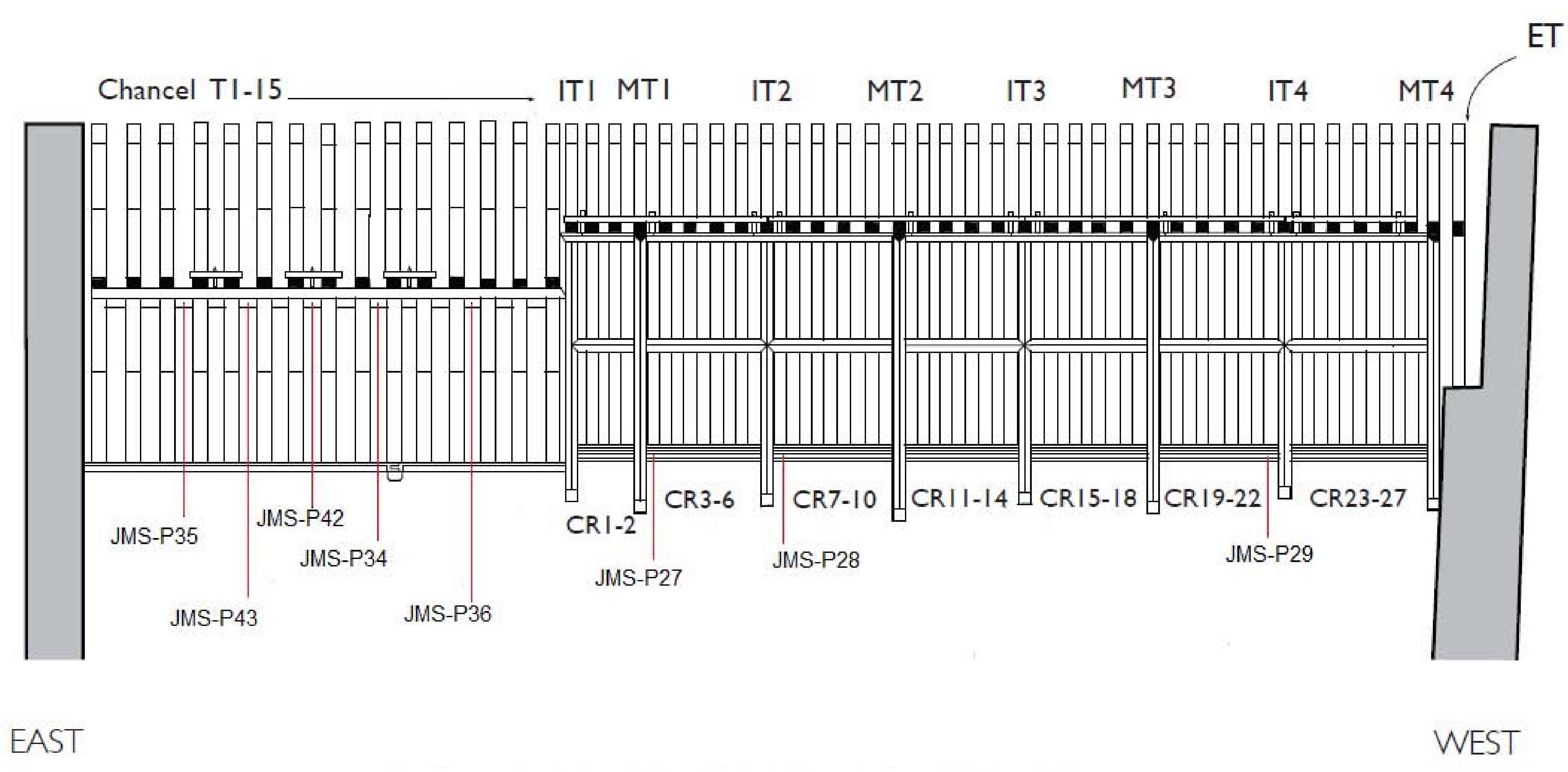


Figure 27: South section, showing the location of samples JMS-P27–9, JMS-P34–6, JMS-P42, and JMS-P43 (John Thorp)

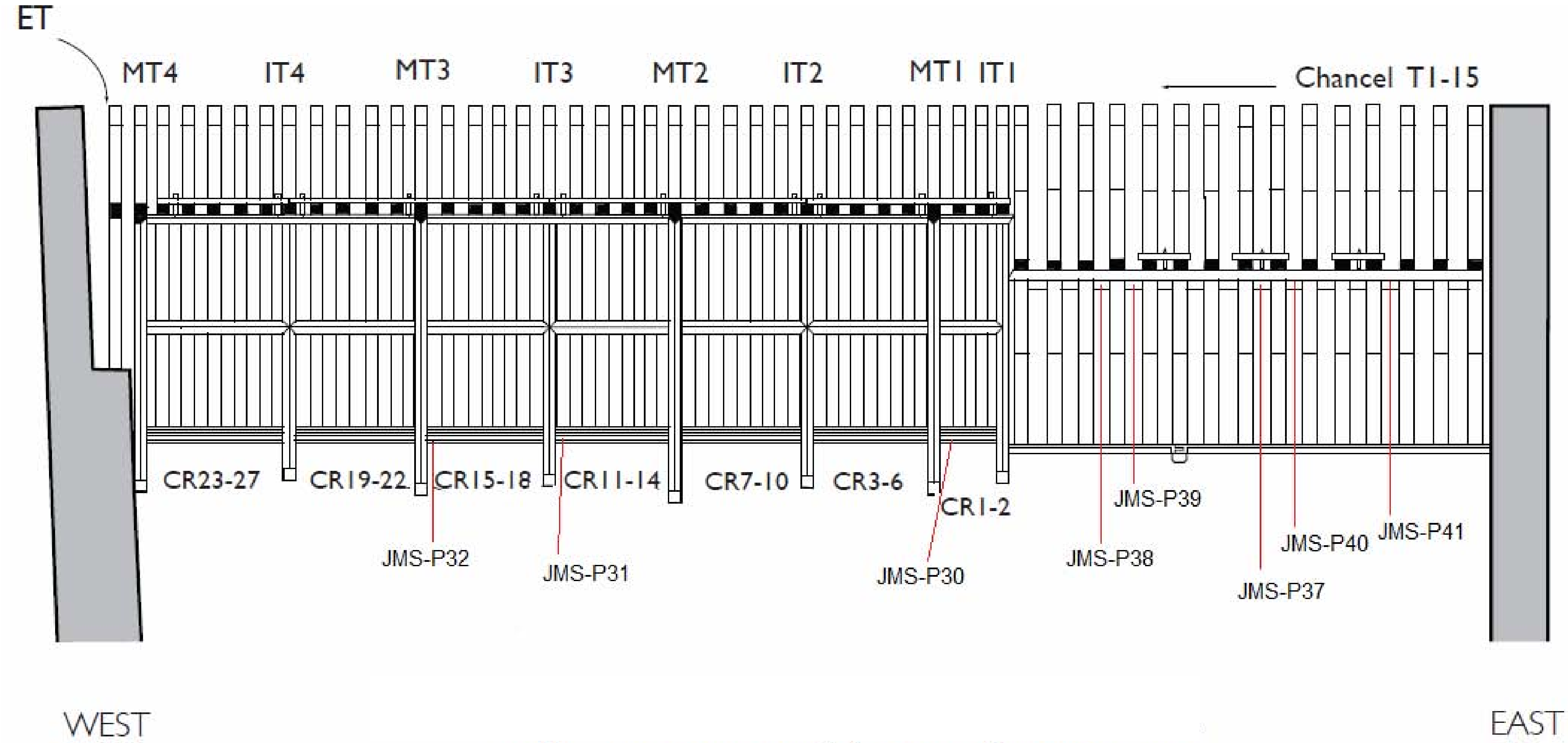


Figure 28: North section, showing the location of samples JMS-P30–32 and JMS-P37–41 (John Thorp)

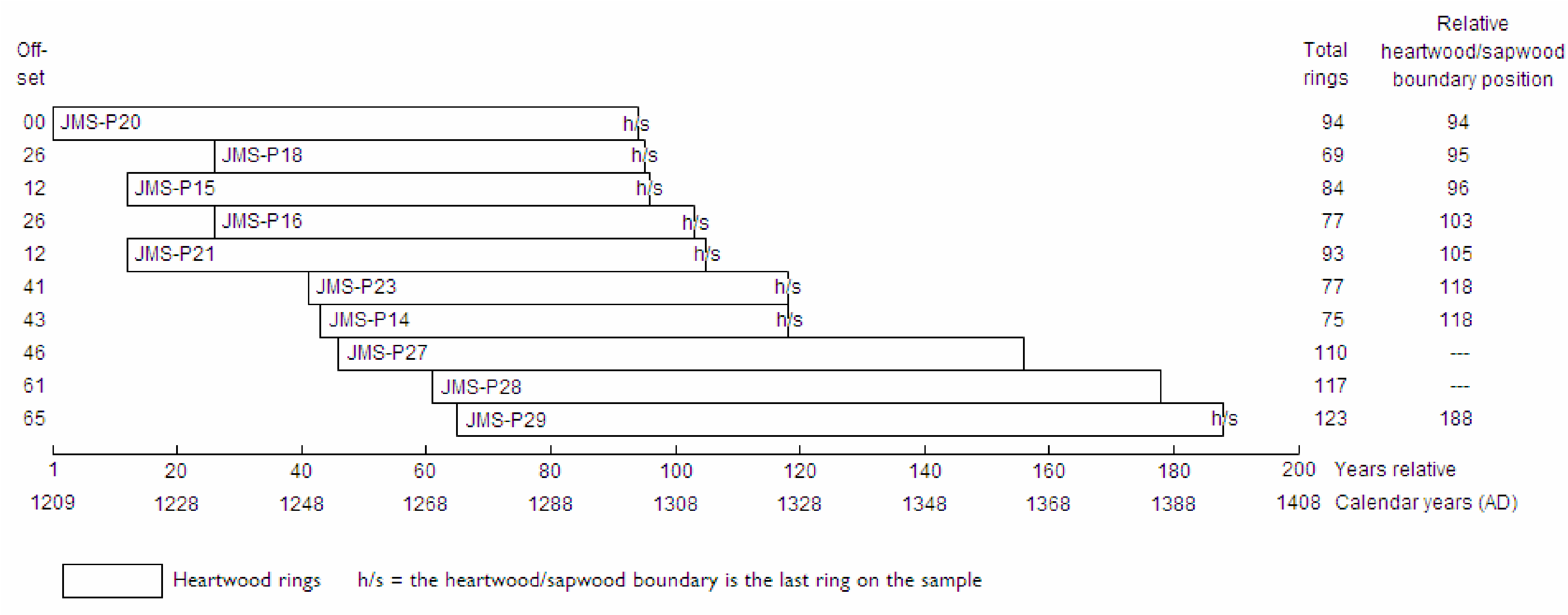


Figure 29: Bar diagram of samples in site sequence JMSPSQ01

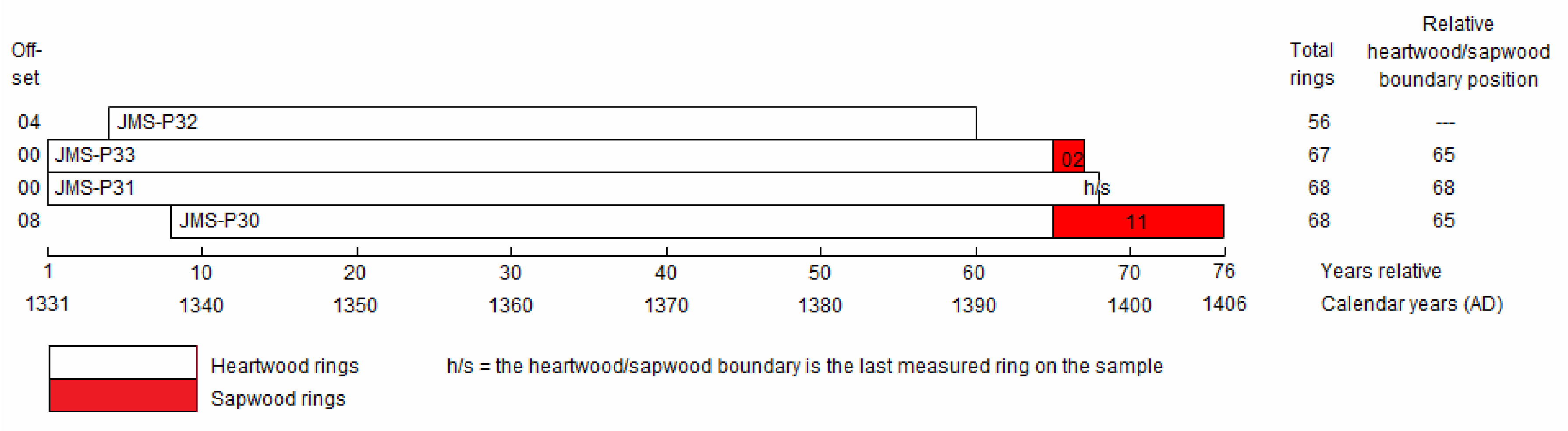


Figure 30: Bar diagram of samples in site sequence JMSPSQ02

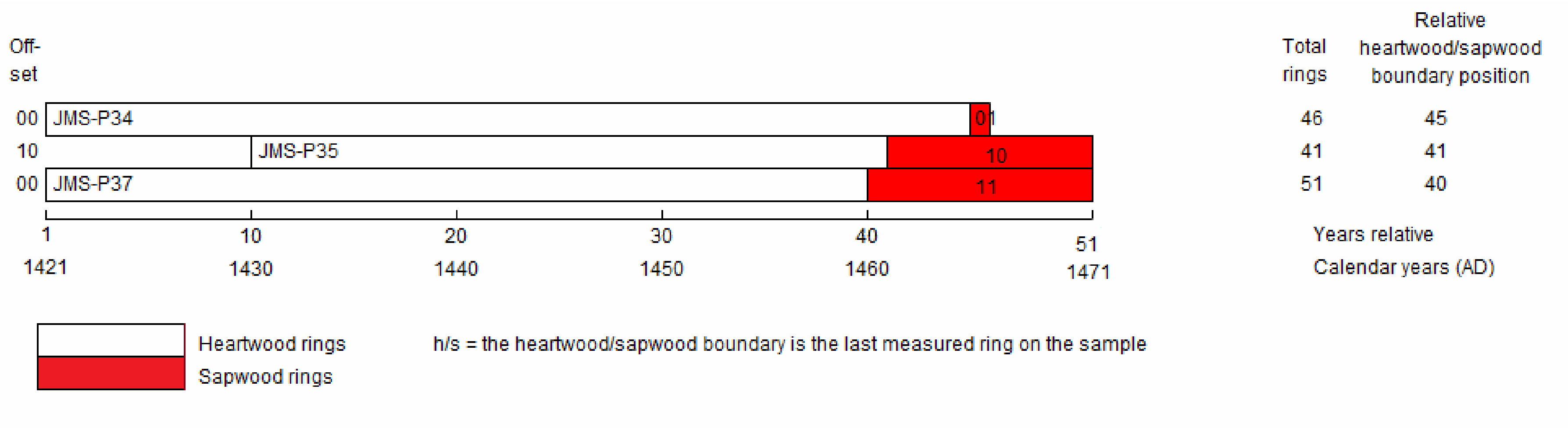


Figure 31: Bar diagram of samples in site sequence JMSPSQ03

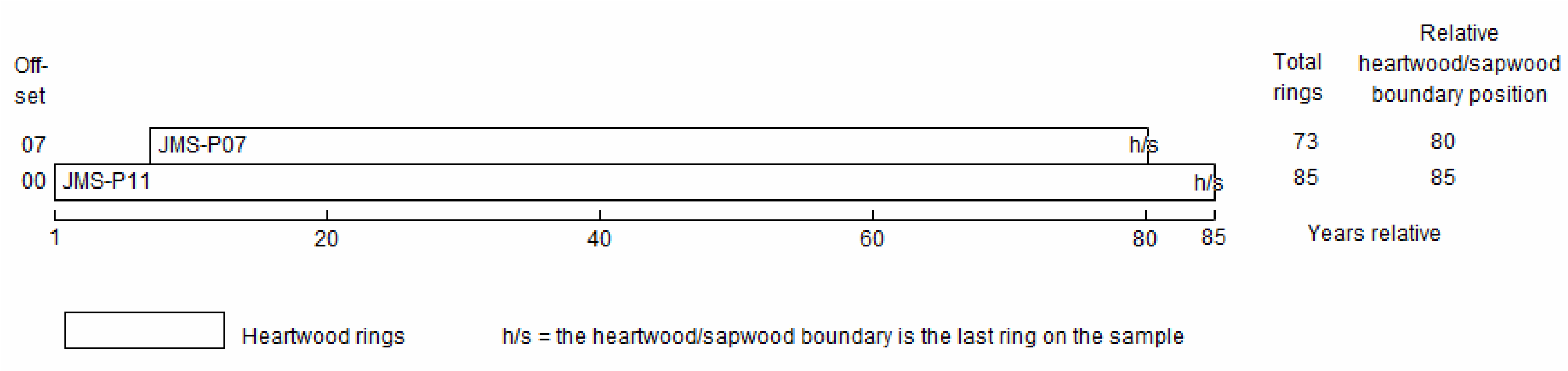


Figure 32: Bar diagram of samples in undated site sequence JMSPSQ04

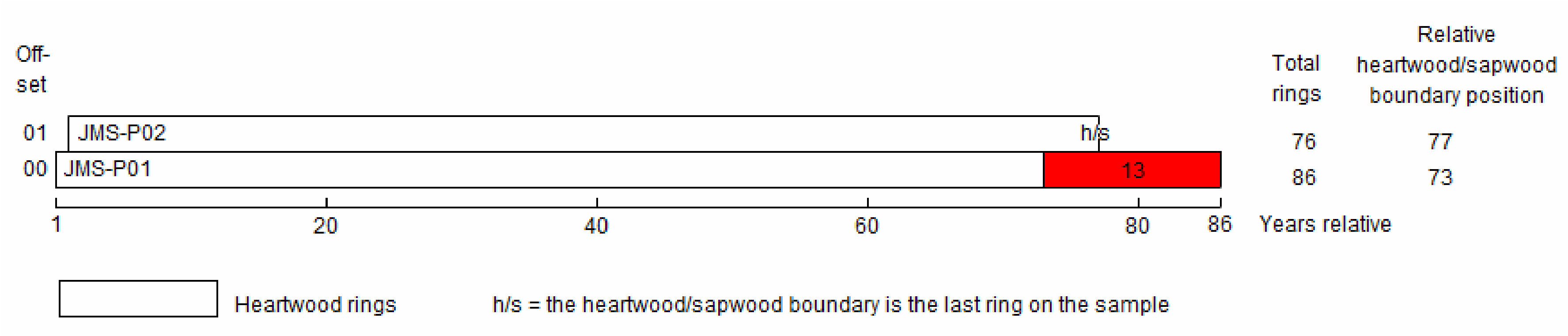


Figure 33: Bar diagram of samples in undated site sequence JMSPSQ05

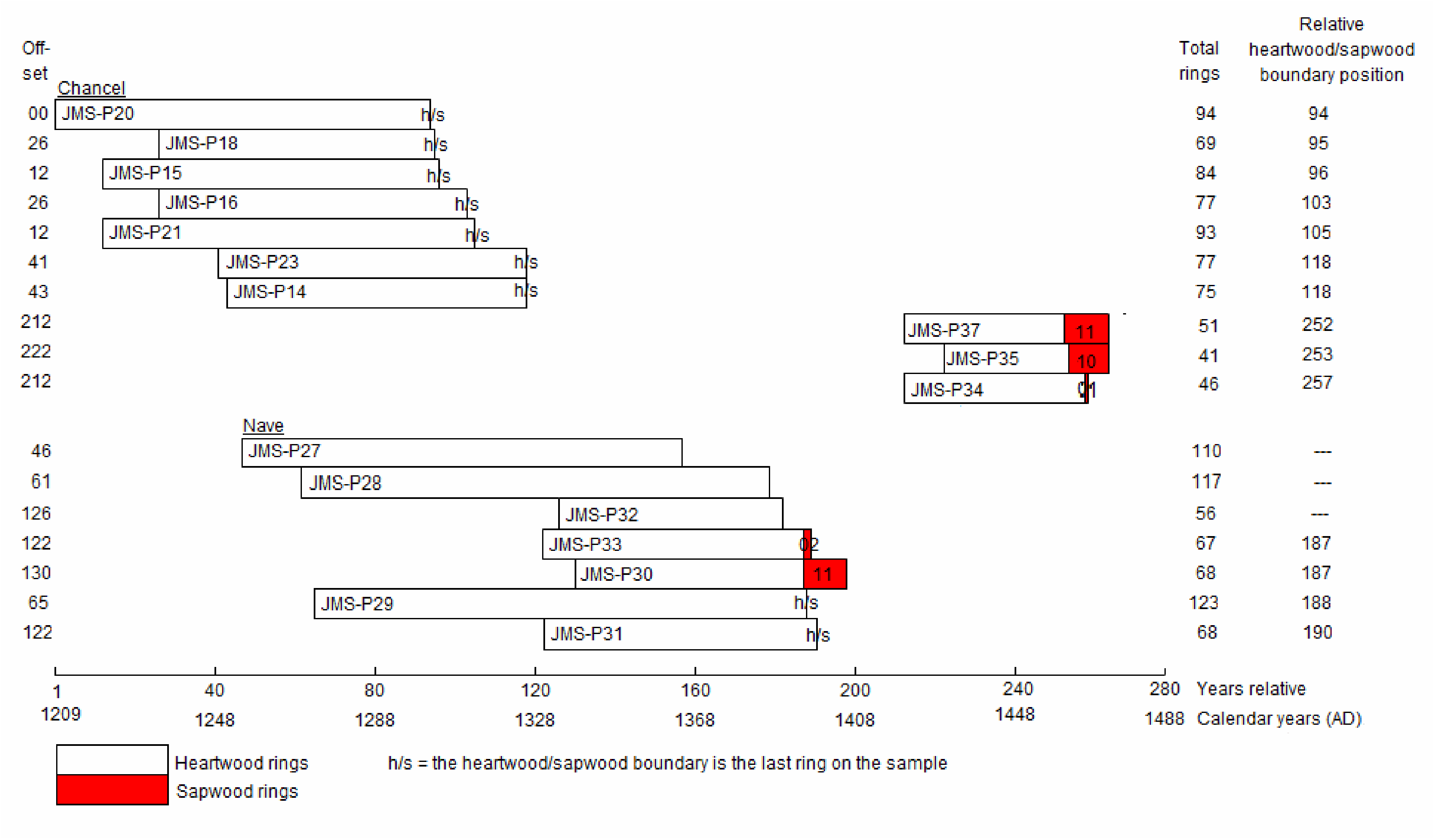


Figure 34: Bar diagram of dated samples, sorted by area and heartwood/sapwood boundary

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

JMS-P01A 86
252 186 237 265 131 168 120 116 145 154 210 185 161 184 136 157 127 122 129 119
121 157 148 100 135 153 165 164 137 129 122 174 163 143 165 154 141 142 140 163
177 196 186 179 147 142 202 225 195 294 168 176 208 133 196 151 155 180 191 151
123 168 225 170 217 191 245 145 203 157 148 243 235 190 210 160 168 220 180 181
263 127 137 176 120 140
JMS-P01B 86
236 192 220 268 131 171 122 123 148 156 208 216 157 183 142 151 126 125 123 128
113 158 126 112 133 166 199 149 136 112 115 176 164 147 158 156 138 143 137 173
194 202 190 182 160 132 211 222 196 294 166 187 201 132 197 157 153 177 184 151
116 169 225 173 217 194 251 144 205 148 149 247 237 189 209 165 167 214 181 172
271 131 140 179 118 131
JMS-P02A 76
184 224 304 145 237 152 140 161 159 206 169 200 223 224 224 150 174 176 211 131
151 131 121 159 150 151 146 172 170 161 187 178 189 226 195 172 166 250 218 213
188 213 208 191 239 304 418 267 481 222 249 255 199 257 291 340 332 321 323 318
296 313 237 320 279 294 184 200 141 171 239 275 238 277 214 243
JMS-P02B 76
179 233 310 131 240 143 141 167 173 193 165 204 236 225 218 167 182 176 197 134
139 142 113 155 163 151 144 176 168 166 194 179 188 214 201 180 132 232 223 211
185 205 212 194 241 308 414 265 472 235 263 229 211 244 307 288 320 317 322 298
292 316 221 300 295 252 181 207 132 166 262 263 251 260 196 250
JMS-P05A 55
599 485 460 522 442 428 414 332 348 363 344 393 404 410 442 380 419 364 390 385
402 409 472 392 526 338 303 483 408 286 227 230 211 281 237 263 408 415 228 447
415 366 229 232 249 203 320 327 254 183 193 257 214 214 293
JMS-P05B 55
593 472 465 520 448 434 420 346 342 367 333 386 407 397 440 371 415 372 380 373
411 413 478 373 530 339 311 480 396 279 210 238 206 279 247 279 399 433 227 436
422 361 237 264 227 204 316 329 241 171 199 247 236 190 307
JMS-P06A 57
292 276 387 553 561 589 471 606 698 653 676 590 607 404 528 732 751 606 647 715
619 690 688 615 689 507 397 597 143 134 291 415 317 395 399 394 356 326 420 466
425 419 454 388 462 389 460 440 401 303 366 277 219 277 331 344 246
JMS-P06B 57
313 280 377 540 563 609 475 613 671 655 675 586 633 387 524 722 752 618 662 716
626 667 698 619 691 513 394 586 145 131 295 418 319 399 391 395 355 328 416 460
431 420 450 384 461 392 456 450 397 309 364 282 215 277 333 348 258
JMS-P07A 73
162 128 131 173 208 95 103 165 124 265 228 246 294 262 289 299 404 461 430 312
367 191 375 281 413 486 264 224 212 414 181 304 210 276 160 274 265 241 237 207
261 293 199 282 160 225 236 206 193 220 293 268 282 93 111 166 176 205 174 234
151 179 222 78 115 124 145 239 158 157 255 79 114
JMS-P07B 73
174 127 110 160 189 84 93 174 130 270 244 240 311 239 277 301 401 462 439 317
375 192 387 279 418 509 248 225 212 419 177 301 214 294 164 270 271 245 231 208
262 293 211 287 150 235 230 222 196 229 296 265 283 84 116 169 173 199 179 233
148 179 226 76 121 119 146 239 164 151 259 83 133

JMS-P08A 49
579 576 567 256 554 314 403 305 250 230 247 249 174 263 306 210 190 217 375 409
330 207 222 245 186 176 266 303 379 258 225 206 253 195 222 193 150 184 189 144
99 121 116 136 118 107 102 109 163
JMS-P08B 49
602 569 600 234 523 327 402 271 249 238 242 245 192 256 318 196 190 218 340 407
342 206 221 235 183 189 267 307 379 264 221 198 256 203 234 187 154 197 177 156
93 120 114 146 110 117 104 96 175
JMS-P09A 51
338 308 433 340 383 402 370 402 462 370 409 334 339 333 339 300 367 410 480 363
418 306 364 389 301 370 459 480 452 356 319 325 343 283 313 309 279 329 310 323
312 261 263 251 268 239 201 258 244 218 277
JMS-P09B 51
322 323 432 338 385 409 372 411 469 392 414 328 338 331 337 316 363 420 480 356
409 309 351 391 296 368 455 482 447 358 317 321 348 287 290 327 284 331 331 316
317 259 251 244 250 237 211 258 235 230 275
JMS-P11A 85
226 250 295 365 236 216 149 106 99 105 142 185 127 144 205 161 254 246 214 193
223 259 239 247 304 280 228 275 148 272 208 272 263 208 209 191 270 210 268 181
254 178 254 233 266 277 252 252 322 210 194 175 167 210 229 151 252 227 311 246
214 169 177 157 233 140 180 181 195 175 90 97 263 181 191 177 199 160 112 173
153 80 150 141 189
JMS-P11B 85
241 239 321 353 230 229 158 99 112 100 143 189 135 128 202 188 243 246 213 197
214 259 230 258 278 259 212 232 163 274 206 275 256 213 215 185 271 214 265 181
256 169 258 241 259 281 255 245 328 208 220 179 173 219 215 155 250 235 308 251
214 165 180 153 234 140 183 179 195 176 98 92 269 182 191 169 175 146 94 166
169 78 162 142 168
JMS-P14A 75
200 245 266 304 242 207 221 582 396 290 208 140 203 208 177 159 216 190 109 102
98 115 88 72 81 115 108 85 91 93 94 96 95 96 155 103 128 122 73 54
75 87 79 89 68 64 87 66 99 121 114 77 46 85 102 96 129 88 112 113
163 259 224 425 340 286 233 202 203 172 224 207 172 156 214
JMS-P14B 75
179 280 249 311 254 210 194 641 340 282 207 144 199 213 178 167 210 188 109 93
106 107 99 61 88 115 113 76 93 88 96 99 90 98 153 99 128 125 71 52
82 77 88 83 76 62 87 71 103 125 119 67 54 84 101 91 146 78 117 123
151 258 244 392 339 273 258 210 207 183 232 197 167 157 198
JMS-P15A 84
136 118 135 144 196 209 192 217 202 227 209 132 115 175 173 90 146 106 144 148
150 148 195 191 184 145 166 94 97 124 146 169 208 257 271 222 192 131 175 147
183 248 196 207 195 184 173 226 172 118 115 208 236 226 181 196 168 113 133 172
209 215 263 229 212 232 185 177 208 185 203 213 236 165 174 182 165 156 120 182
192 162 138 158
JMS-P15B 84
124 135 142 136 191 230 219 190 207 230 198 138 122 166 188 110 150 95 146 143
159 150 173 195 182 150 164 88 98 126 152 171 207 255 274 227 188 127 193 145
182 254 193 212 191 188 182 224 169 109 122 204 236 215 180 207 174 113 138 166
205 210 259 243 209 226 184 180 209 184 209 206 227 162 182 185 164 163 127 177
190 163 136 142
JMS-P16A 77
304 130 276 283 378 521 286 321 291 237 188 276 325 292 297 228 338 303 247 166
309 318 318 261 269 254 228 277 148 256 233 249 286 357 137 61 63 68 111 136

101 107 112 104 79 88 76 95 126 114 131 158 100 94 89 73 62 78 122 66
75 91 98 109 91 86 106 58 41 66 80 127 76 80 80 115 108
JMS-P16B 77
310 130 280 286 376 487 279 328 292 188 187 284 323 297 302 229 332 309 259 179
306 311 317 269 274 249 231 273 148 271 252 253 298 364 131 72 68 76 130 137
100 101 99 116 72 94 70 96 119 114 134 153 94 100 78 82 60 76 104 91
74 92 99 106 87 88 92 70 44 58 89 118 85 92 95 121 100
JMS-P17A 105
324 297 270 207 258 258 229 222 251 312 223 282 310 271 219 248 193 209 201 189
213 288 125 105 68 59 49 60 87 104 103 103 63 62 78 92 167 164 238 165
223 281 208 220 217 189 69 76 77 87 108 117 95 113 129 178 222 206 211 254
306 106 105 102 104 120 88 116 95 132 89 97 136 93 82 69 92 51 61 67
93 84 77 87 66 79 59 49 81 67 105 93 102 83 78 41 74 90 68 80
77 87 49 49 68
JMS-P17B 105
325 299 272 210 261 243 231 220 267 316 240 276 309 283 223 236 189 210 204 184
207 292 119 107 68 72 43 61 81 102 110 82 67 62 84 86 161 163 224 179
235 267 215 217 205 181 76 60 82 83 104 117 104 109 130 168 209 208 194 252
294 125 97 90 128 108 97 108 102 136 85 100 136 90 87 68 94 53 48 86
84 91 73 90 61 88 59 44 86 72 102 95 100 82 79 52 63 98 62 81
75 93 54 39 77
JMS-P18A 69
176 126 162 98 142 169 207 213 202 237 250 176 145 113 117 134 164 213 342 361
476 324 264 153 156 156 161 272 239 242 176 172 162 286 203 142 135 168 222 212
184 182 169 119 130 141 165 157 192 201 212 220 156 146 181 167 214 193 186 145
128 132 184 182 97 129 157 141 124
JMS-P18B 69
163 125 166 99 140 174 210 207 210 222 259 173 137 114 118 136 166 216 339 361
465 321 276 154 162 145 159 272 241 256 172 173 179 265 204 143 132 173 219 218
180 186 171 109 140 146 163 164 177 199 207 217 155 149 191 160 199 202 185 148
129 137 183 182 97 125 162 141 119
JMS-P19A 64
433 286 278 219 202 205 174 182 160 206 177 182 194 122 93 72 99 137 210 169
175 201 166 217 195 212 259 289 232 240 226 200 212 143 178 164 162 142 126 113
69 119 94 86 109 128 143 133 127 80 77 99 85 83 71 90 115 110 97 93
106 86 93 192
JMS-P19B 64
428 279 270 223 200 204 180 176 164 206 177 186 199 133 87 63 105 123 225 166
177 203 171 219 195 214 263 295 235 240 224 204 212 144 179 165 155 152 133 110
75 116 94 96 112 136 150 135 126 86 77 97 94 86 68 86 118 113 94 95
106 81 90 200
JMS-P20A 94
573 522 582 570 518 480 484 485 453 387 362 294 345 368 397 457 429 437 353 397
312 195 83 86 95 105 155 65 157 115 150 112 68 63 60 70 66 97 121 126
169 209 317 150 186 174 245 221 194 183 172 235 166 78 87 116 126 225 123 170
94 43 62 109 230 177 178 151 174 153 114 136 175 181 257 134 126 176 110 124
162 103 68 52 36 95 102 121 129 131 96 145 195 140
JMS-P20B 94
586 528 570 580 524 464 495 477 450 408 362 321 320 365 397 446 438 430 354 411
307 184 93 73 110 97 147 84 152 116 140 109 69 80 69 70 78 101 121 135
176 217 296 153 182 177 274 205 196 189 168 227 168 89 71 122 133 219 138 180
77 53 72 99 241 177 172 151 179 149 102 152 183 174 255 138 132 170 107 117
158 111 60 51 46 89 101 118 125 137 90 148 215 128

JMS-P21A 93
468 515 448 335 428 442 313 469 431 329 159 152 88 179 205 122 202 123 128 149
109 76 124 105 79 137 155 126 137 112 115 117 136 159 172 159 144 118 165 145
119 117 117 123 114 106 97 174 169 69 90 134 158 164 100 114 119 90 95 156
117 101 127 138 250 260 152 145 219 139 134 193 324 278 343 318 357 269 195 210
244 179 107 145 156 161 115 118 145 150 172 214 222
JMS-P21B 93
473 509 431 325 433 437 327 470 418 324 177 153 83 175 201 131 203 121 124 157
106 70 114 106 91 136 160 118 139 110 112 128 132 157 172 152 146 120 165 144
120 107 115 125 118 102 94 171 175 73 88 133 168 141 94 117 119 94 110 153
108 106 125 132 234 260 155 147 205 125 145 194 316 264 333 308 355 268 188 210
236 168 112 148 162 156 108 115 148 160 167 206 227
JMS-P22A 76
325 296 292 293 237 283 321 211 278 286 340 267 260 253 278 222 243 279 180 196
218 240 154 165 281 312 369 218 263 251 212 271 157 198 269 250 233 248 189 278
264 229 168 187 269 238 208 200 233 199 186 214 167 178 189 254 213 175 144 198
160 163 188 268 162 125 179 138 161 214 261 237 190 164 171 154
JMS-P22B 76
315 300 284 298 228 287 328 210 296 280 346 247 241 257 280 217 250 275 177 208
219 239 155 174 272 316 389 218 254 254 213 269 160 199 271 244 228 246 189 274
263 236 168 184 269 245 176 238 215 204 188 215 161 167 179 261 216 174 141 212
149 160 209 259 175 125 185 140 161 211 262 235 193 174 165 182
JMS-P23A 77
223 162 196 205 200 241 250 282 230 303 288 218 224 175 253 181 208 134 229 185
61 106 121 138 137 133 164 137 102 156 144 156 142 212 182 210 221 166 168 221
163 222 173 182 195 200 201 130 122 117 137 150 131 87 114 109 117 133 122 105
133 130 135 117 108 130 111 125 90 149 120 132 119 117 82 118 122
JMS-P23B 77
218 172 193 208 200 243 254 280 235 294 300 204 216 161 248 180 211 165 205 174
72 88 113 151 158 124 151 146 103 154 136 154 149 211 179 207 224 166 170 216
159 219 174 181 195 216 199 130 126 115 135 152 130 85 114 115 119 132 123 109
127 132 135 120 109 143 96 131 96 145 121 127 125 104 102 97 132
JMS-P24A 91
291 234 267 177 154 195 190 117 76 101 121 142 123 169 95 150 86 101 95 162
123 120 131 139 109 117 95 102 75 92 62 86 114 111 118 128 90 106 116 140
151 164 153 158 139 121 104 94 109 138 175 142 141 151 118 85 124 159 152 160
167 139 143 130 110 112 114 105 169 218 149 138 159 180 119 93 93 127 174 149
139 112 115 115 118 111 99 80 93 94 95
JMS-P24B 91
317 237 258 163 150 188 164 114 78 99 125 144 114 190 100 145 89 100 102 165
131 122 148 113 94 126 90 98 71 98 67 102 108 113 128 132 90 103 120 133
143 171 155 159 137 125 99 96 107 145 187 142 137 148 105 75 126 158 146 163
162 132 148 140 105 113 121 118 178 218 152 136 153 181 141 81 90 121 180 135
123 108 112 114 123 119 94 81 91 100 87
JMS-P25A 81
473 439 253 340 282 197 206 278 309 490 347 421 266 248 288 192 142 260 208 244
209 201 330 192 115 121 141 80 101 133 141 134 139 117 136 122 108 71 112 134
75 82 59 91 125 75 95 55 48 54 81 95 83 108 114 70 133 72 93 78
89 81 97 80 136 108 86 131 145 107 131 103 88 127 158 116 130 127 136 133
152
JMS-P25B 81
499 328 305 295 311 227 173 334 315 508 363 462 267 267 300 203 142 258 226 243
194 205 320 190 102 119 142 83 100 137 140 133 140 119 150 124 110 69 112 136

84 79 55 101 121 79 84 68 40 54 85 85 97 96 118 74 127 77 90 84
81 82 92 96 120 100 88 127 152 110 128 101 109 131 193 120 118 129 141 151
155
JMS-P27A 110
475 461 374 284 339 374 381 348 334 157 155 179 171 257 181 130 161 183 209 180
109 128 136 96 124 190 200 182 221 183 226 245 129 166 190 312 264 260 251 222
172 166 142 115 97 142 202 196 99 109 157 166 149 155 139 208 103 88 59 99
156 184 141 110 157 118 142 141 170 119 83 108 149 130 131 102 95 67 114 135
181 118 100 90 163 177 155 102 63 51 104 128 139 160 161 106 106 105 167 157
68 82 124 108 94 80 92 173 203 154
JMS-P27B 110
455 444 365 291 335 367 402 347 319 160 144 164 172 252 180 130 161 180 210 182
98 132 146 96 132 200 204 171 219 185 223 247 130 163 192 308 262 263 254 214
174 164 146 115 94 147 196 196 100 108 158 168 148 157 133 212 103 83 62 93
164 180 143 109 152 122 136 140 169 126 91 105 147 130 131 107 90 68 114 136
179 123 100 91 165 175 154 98 64 57 96 125 144 162 170 108 102 104 167 159
73 84 117 112 99 80 90 170 211 161
JMS-P28A 117
282 263 376 430 299 161 192 228 148 187 275 253 256 240 240 201 276 143 192 257
287 194 269 226 192 156 155 152 113 98 116 110 122 69 80 116 123 97 116 109
101 92 49 42 67 83 99 91 92 99 76 95 111 116 102 81 79 96 83 106
79 53 46 84 104 133 83 76 84 158 131 110 91 69 73 96 112 104 98 121
80 64 89 121 132 67 68 116 91 65 66 61 105 148 101 74 96 81 65 115
100 81 80 96 115 120 92 63 85 122 132 119 87 100 86 134 138
JMS-P28B 117
316 315 373 467 299 157 208 236 142 193 298 251 263 245 259 197 261 145 183 264
282 199 262 219 200 160 150 159 113 94 123 107 119 73 70 132 126 103 103 101
116 85 54 47 50 94 105 94 82 96 66 88 116 115 103 72 96 86 92 104
82 49 43 85 107 134 86 74 82 153 121 115 73 71 67 106 91 106 96 123
79 79 85 125 122 67 69 107 99 58 73 68 104 158 98 82 83 78 71 102
105 80 92 98 120 129 87 70 73 135 148 110 94 89 92 128 135
JMS-P29A 123
162 107 183 170 109 118 173 208 246 268 295 253 322 144 188 193 252 187 289 319
317 249 269 269 138 127 141 134 176 101 88 133 128 113 145 137 141 145 94 128
108 228 170 195 123 219 155 149 165 194 184 106 116 159 157 163 142 95 111 108
129 188 115 75 78 156 117 108 78 82 72 134 116 111 113 114 82 94 94 145
164 65 56 114 64 66 72 62 83 107 113 72 75 70 65 117 132 103 117 122
112 133 107 86 96 126 113 96 94 75 88 79 87 70 104 71 61 76 72 92
71 84 101
JMS-P29B 123
224 134 164 159 110 116 174 209 255 259 294 251 317 147 185 192 256 187 285 296
321 245 259 267 140 129 140 141 167 101 91 128 126 118 148 125 141 153 87 127
109 217 188 182 119 213 164 152 159 201 183 104 115 157 158 160 140 83 87 108
125 192 111 76 82 163 114 94 82 78 73 135 128 106 116 125 72 96 96 144
160 64 63 109 68 70 69 64 78 111 110 78 76 70 67 113 133 107 109 124
111 132 108 88 96 120 122 88 86 87 83 74 84 67 102 72 69 79 76 82
75 91 96
JMS-P30A 68
70 89 176 143 143 193 197 210 234 334 350 321 348 272 318 301 360 344 326 288
363 233 248 413 277 342 283 298 272 177 233 202 193 265 254 291 204 176 190 111
127 94 91 101 81 103 84 108 106 116 117 115 105 88 101 104 114 89 98 108
107 115 114 87 100 95 102 100

JMS-P30B 68
72 100 183 146 139 202 174 199 229 345 352 321 354 267 323 302 357 341 332 285
362 228 244 420 273 341 290 295 266 181 241 196 197 255 257 284 206 181 184 114
129 101 91 95 85 107 80 113 118 132 121 114 106 83 102 108 106 92 89 106
102 116 120 81 109 93 99 108
JMS-P31A 68
142 233 254 192 370 350 576 457 350 259 305 259 330 322 260 246 245 292 310 235
238 171 228 177 223 186 235 211 287 187 189 392 249 257 224 240 215 160 235 199
181 212 201 330 199 205 183 135 178 175 131 168 109 190 123 162 157 163 191 137
171 120 154 97 98 96 115 153
JMS-P31B 68
144 227 258 207 360 349 580 454 351 252 308 269 337 331 257 244 248 288 314 232
242 174 223 173 233 192 238 217 295 185 189 397 249 253 218 243 215 160 234 200
178 208 207 330 202 212 176 136 176 178 124 164 115 189 131 161 154 162 189 133
177 123 150 98 96 107 115 154
JMS-P32A 56
241 317 315 255 232 226 302 294 222 199 214 167 179 247 312 210 249 185 225 204
188 202 202 203 193 134 151 235 225 204 210 232 239 173 198 219 182 207 182 208
213 185 200 266 292 238 236 241 189 256 169 213 198 145 235 164
JMS-P32B 56
245 314 311 253 237 233 301 295 207 200 202 185 187 223 315 238 237 185 218 214
188 193 205 203 198 135 136 230 224 200 205 220 250 179 200 208 199 195 175 203
207 189 198 267 291 232 238 241 194 258 161 216 189 158 238 159
JMS-P33A 67
155 397 362 179 320 269 325 351 272 169 241 259 424 473 452 432 421 595 672 444
552 307 457 342 314 313 314 393 340 210 222 299 248 223 203 202 192 140 220 177
192 271 247 326 231 193 218 162 202 162 131 146 124 196 164 197 180 178 178 158
172 147 164 148 154 141 132
JMS-P33B 67
159 411 364 164 333 262 343 342 292 174 234 313 437 462 458 406 393 540 740 475
564 336 469 364 313 301 315 357 343 208 220 299 240 223 208 207 194 145 216 179
188 278 238 335 221 201 212 163 216 151 130 148 134 195 160 201 178 177 183 156
171 139 168 147 152 147 129
JMS-P34A 46
166 175 77 74 85 111 74 134 137 139 154 218 184 208 249 258 177 150 149 198
224 168 216 207 180 140 171 205 217 172 236 145 173 196 172 190 141 118 139 192
162 185 169 87 166 117
JMS-P34B 46
146 180 72 76 85 120 72 144 144 131 157 228 181 205 251 266 181 156 151 193
222 168 209 221 181 133 175 198 217 158 215 145 168 204 167 186 147 114 132 194
163 181 170 92 166 128
JMS-P35A 41
254 311 258 261 269 248 196 184 149 149 192 168 260 329 308 171 215 246 321 243
353 310 239 368 272 276 226 223 190 219 188 179 187 114 181 185 184 184 170 160
154
JMS-P35B 41
264 291 231 266 268 243 197 177 152 143 197 166 291 326 302 206 212 241 322 251
356 298 254 348 260 275 219 225 193 222 185 181 187 113 182 186 183 184 168 160
153
JMS-P36A 47
458 559 531 506 537 791 435 634 446 384 298 258 196 206 254 363 355 396 326 245
219 345 260 368 377 277 256 300 45 39 73 85 134 164 114 63 151 73 72 38
75 84 80 60 71 50 37

JMS-P36B 47
573 560 687 588 574 767 448 640 445 383 297 258 197 224 253 365 349 385 339 246
228 345 260 373 381 287 265 281 43 38 71 80 139 164 111 66 149 78 81 43
61 80 85 54 67 45 45
JMS-P37A 51
284 240 205 159 144 110 146 119 106 118 113 211 135 195 213 208 139 126 96 78
125 98 112 172 172 111 121 121 203 193 199 152 183 202 153 214 155 178 144 185
147 156 160 83 156 146 154 151 194 155 132
JMS-P37B 51
277 229 260 218 139 113 157 127 99 115 112 214 134 192 194 201 122 127 90 87
122 99 131 180 170 109 118 127 200 197 203 150 181 208 151 213 159 159 138 186
147 153 163 93 149 146 157 155 196 154 128

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

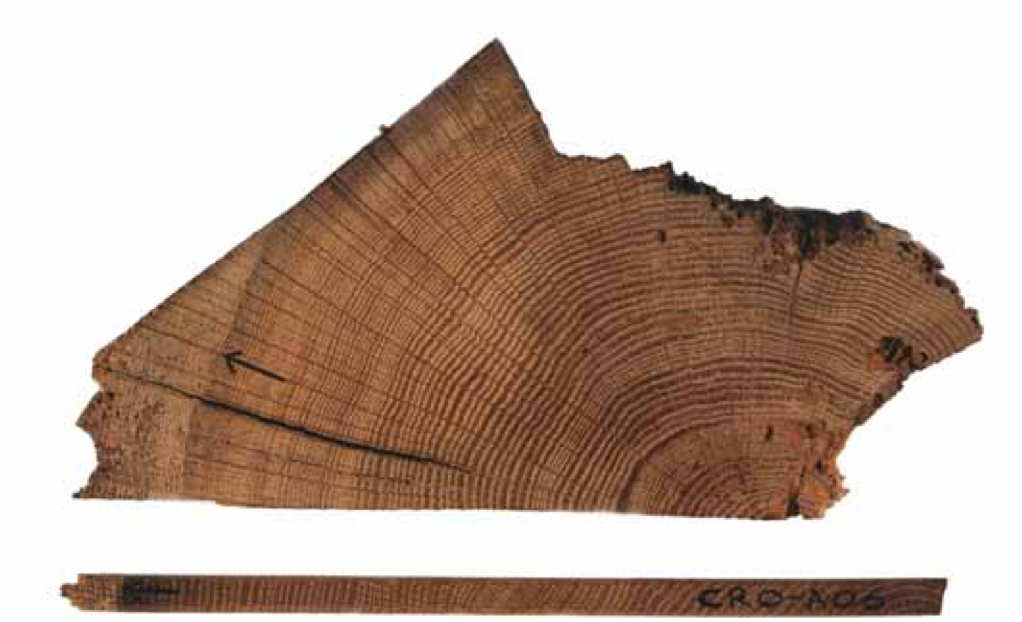


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

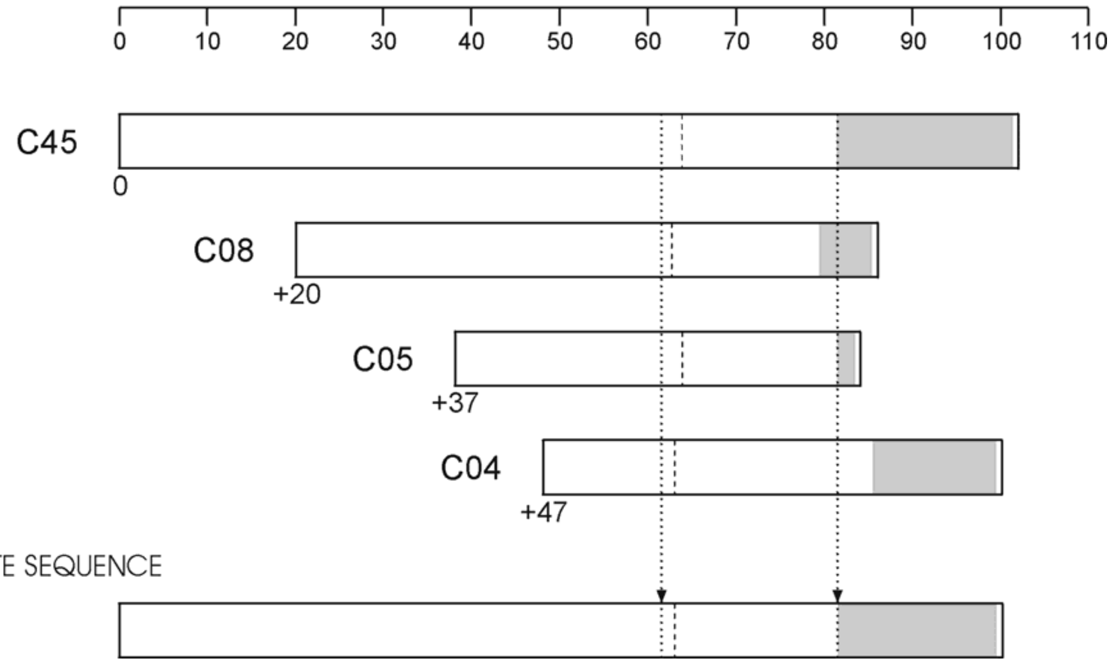


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

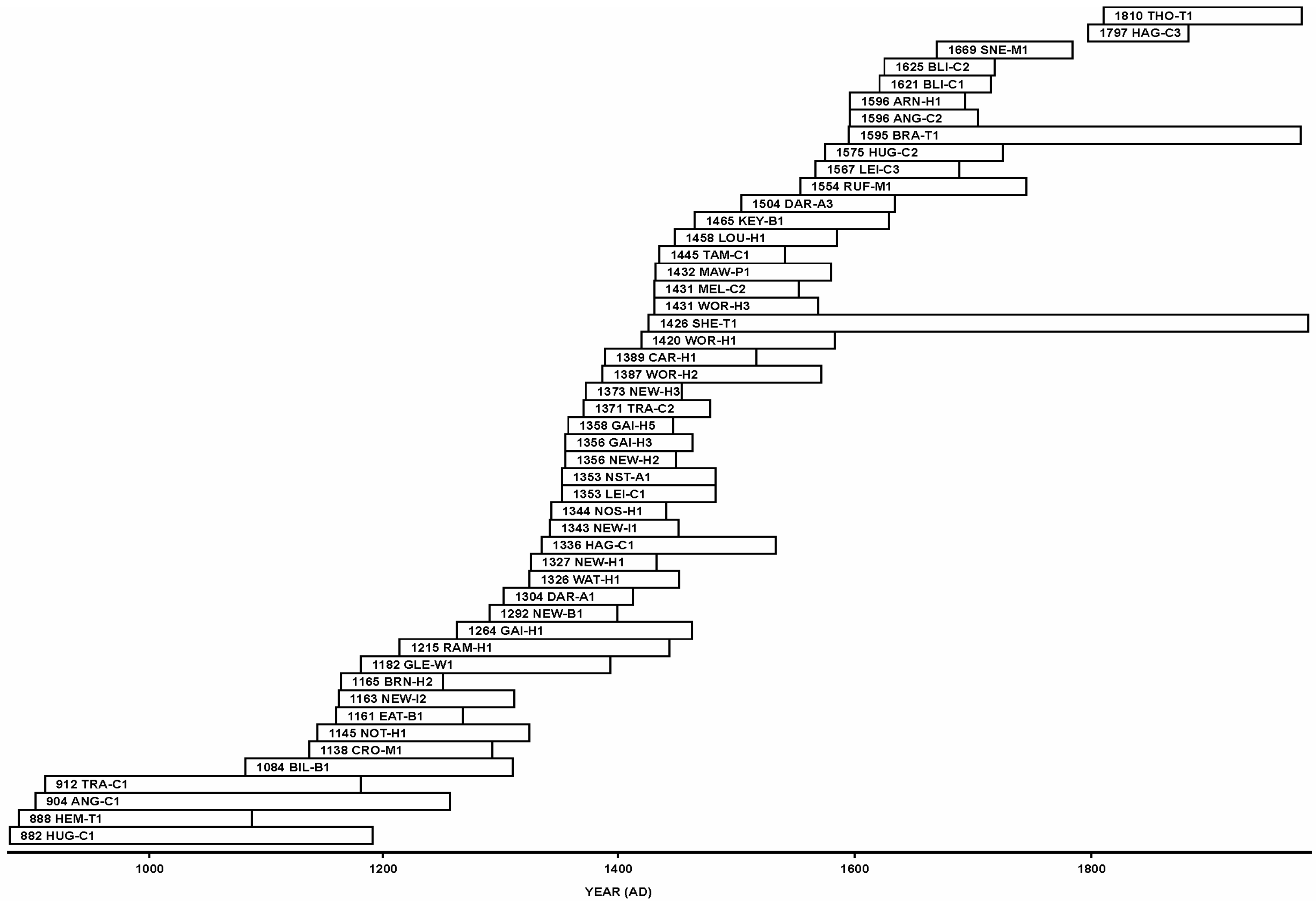
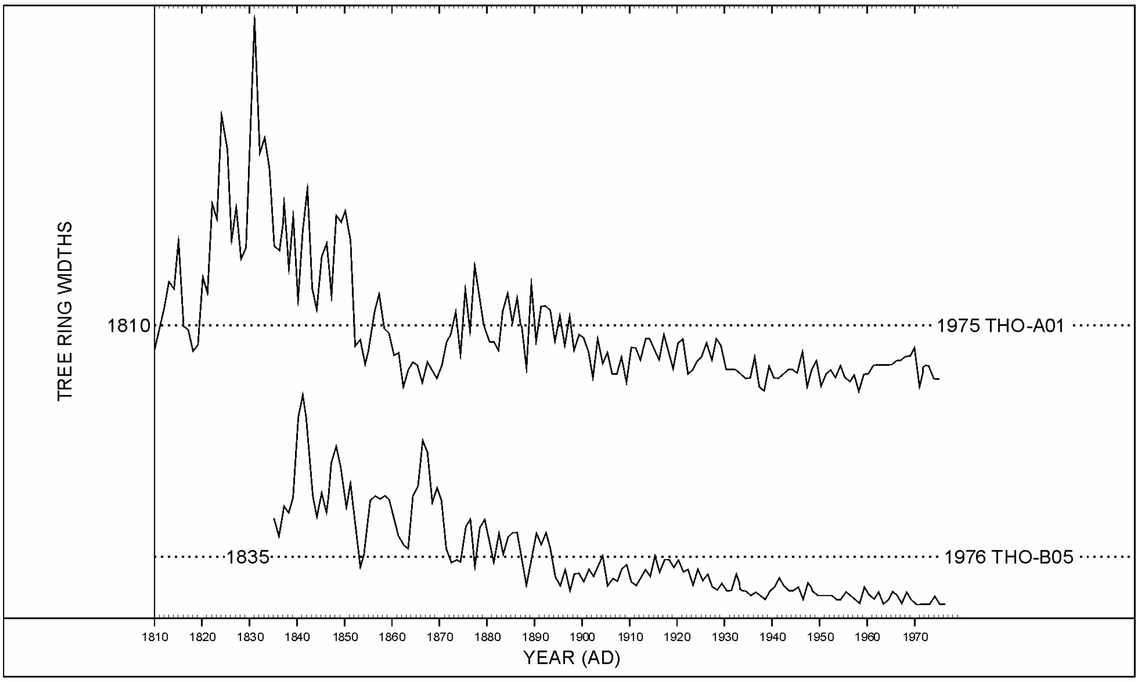


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

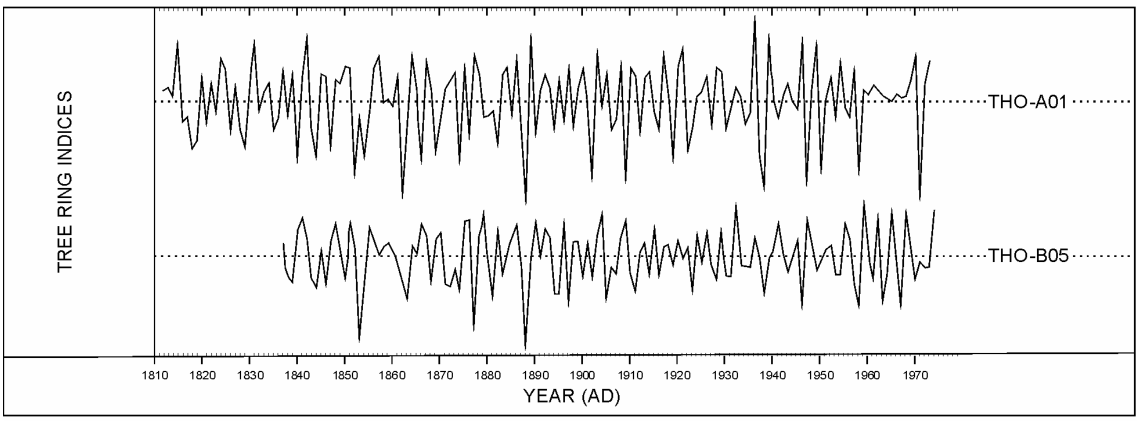


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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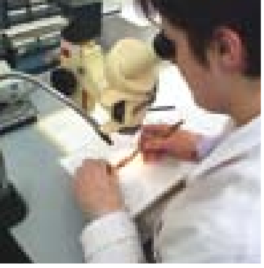
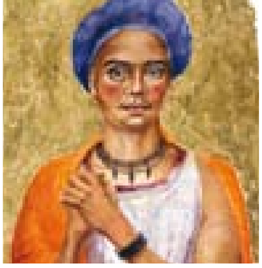



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