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# CHURCH OF ST NICHOLAS, CHURCH ROAD, POTTER HEIGHAM, NORFOLK
# TREE-RING ANALYSIS OF TIMBERS

## SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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# TREE-RING ANALYSIS OF TIMBERS

Alison Arnold and Robert Howard

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## SUMMARY
Fourteen samples taken from the timbers of the nave roof were analysed along with the re-analysis of 12 samples previously taken from the north aisle roof. This resulted in the construction of five site sequences, of which four were dated. Thus, eight of the north aisle samples have been dated, with interpretation of the sapwood suggesting felling of these timbers in AD 1533–58, and eleven nave samples have been dated indicating that these timbers were felled in AD 1485–1509.

## CONTRIBUTORS
Alison Arnold and Robert Howard

## ACKNOWLEDGEMENTS
The Laboratory would like to thank Richard Bannister, lead contractor on site, for facilitating access and for all his assistance during sampling. Thanks are also given to Cathy Tyers and Shahina Farid of the English Heritage Scientific Dating Team for their advice and assistance throughout the production of this report. Figures were provided by Nicholas Warns Architect Limited.

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## DATE OF INVESTIGATION
2012/13

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# INTRODUCTION

The Grade I listed parish church of St Nicholas, located in Potter Heigham, Norfolk (Figs 1–3), is believed to have its origins in the twelfth century. Remnants of this early church are thought to be the west tower and chancel, although both were re-modelled in the fifteenth century. The nave and aisles are believed to date to the thirteenth century but bequests dating from AD 1479 to AD 1535 had suggested modifications to these areas, including re-roofing, in *c* AD 1500. Previous dendrochronological analysis of the timbers of the north aisle had demonstrated the use of timber felled in AD 1533–58, slightly later than expected (Arnold and Howard 2007).

## North aisle

The roof over the north (and south) aisle consists of nine principal-rafter trusses, with alternating trusses having arch braces, springing from posts. The principal rafters have roll moulding decoration, as do the braces, wall posts, and plates. There is a single tier of purlins running between the trusses (Fig 4).

## Nave

The roof over the nave is of hammer-beam type with wooden wall posts rising from stone corbels. The hammer beams and principal rafters are supported by arch braces. All timbers are moulded and decorated and the spandrels between the braces filled with tracery. There are two tiers of butt purlins and a ridge piece with bosses (Fig 5).

# SAMPLING

Following on from the grant-aided repair work undertaken on the north-aisle roof in 2006, further grant-aid was forthcoming for repairs to the nave roof. Ian Harper (English Heritage, Heritage at Risk Architect/Surveyor) requested dendrochronological sampling to be undertaken to ascertain whether the nave roof is of a similar date to the north aisle roof and also determine whether the provision of additional data from the site allowed any of the undated samples from the north aisle to be dated.

A total of 17 timbers from the nave roof was sampled by coring. Each sample was given the code PTH-A and numbered 13–29, following on from the north aisle samples (PTH-A01–12). The location of samples from both the north aisle and nave roofs was noted at the time of sampling and has been marked on Figures 6–18. Further details relating to the samples can be found in Table 1.

## ANALYSIS AND RESULTS

Three of the nave-roof samples had too few rings for secure dating and so were discarded prior to measurement. The remaining 14 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements from these, and the north aisle roof sample, are given at the end of the report. These newly measured samples and those taken from the north aisle were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 21 samples matching to form five groups.

Firstly, three of the north-aisle samples, all from braces, matched each other and were combined at the relevant offset positions to form PTHASQ01, a site sequence of 124 rings (Fig 19). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to span the period AD 1356–1479. The evidence for this dating is given by the *t*-values in Table 2.

Three other north-aisle samples, from an aisle plate and two common rafters, grouped to form PTHASQ02, a site sequence of 65 rings (Fig 20). This was dated to spanning the period AD 1456–1520 (Table 3).

Two north-aisle samples, representing an aisle plate and a wall post, matched each other and were combined to form PTHASQ03, a site sequence of 92 rings (Fig 21). This was found to match consistently and securely at a first-ring date of AD 1425 and a last-measured ring date of AD 1516 (Table 4).

A fourth site sequence of 66 rings, PTHASQ04 (Fig 22), contains two samples representing a principal rafter and a common rafter, but attempts to date this site sequence were unsuccessful and it remains undated.

Finally, 11 of the samples from the nave matched each other and were combined at the relevant offset positions to form PTHASQ05, a site sequence of 132 rings (Fig 23). This site sequence was compared against the reference chronologies where it was found to match securely and consistently at a first-ring date of AD 1353 and a last-measured ring date of AD 1484. The evidence for this dating is given by the *t*-values in Table 5.

The remaining five ungrouped samples were then compared individually against the reference chronologies but no secure matches were found and all remain undated.

## INTERPRETATION

Felling date ranges have been calculated using the estimate that mature oak trees in this region have 15–40 sapwood rings.

### North aisle

Tree-ring dating has resulted in the successful dating of eight of the north-aisle samples, four of which have similar heartwood/sapwood boundary ring dates (Fig 24). The average of these is AD 1518, allowing an estimated felling date to be calculated for the four timbers represented to within the range AD 1533–58. Four of the dated samples do not have the heartwood/sapwood boundary, however it is thought likely that these were also felled in AD 1533–58. This is despite the fact that three of them, PTH-A03, PTH-A04, and PTH-A08, all taken from curved braces, have first and last-measured ring dates somewhat earlier than those of the other five dated samples (Table 1; Fig 24). This may be due to the way in which these three braces were cut from the original timber, with all three probably being cut from near the middle of the same tree (*t*-values as high as 12.0 and 10.6 being found between these samples), whilst the other beams have been cut from the outer portions of their respective trees.

### Nave

Eleven of these samples have been dated, nine of which have the heartwood/sapwood boundary ring. Although there is some variation in these heartwood/sapwood boundary ring dates (from AD 1459 to AD 1481) these are broadly contemporary and likely to indicate a single-felling programme. The average heartwood/sapwood boundary ring date is AD 1469, allowing an estimated felling date to be calculated for the timbers represented within the range AD 1485–1509, taking into account the date of the outermost measured ring of sample PTH-A26. The other two nave samples without the heartwood/sapwood boundary ring have last-measured heartwood dates in the first half of the fifteenth century making it possible they were also felled in AD 1485–1509 which, from the overall level of cross-matching within this group of timbers, seems likely.

## DISCUSSION

Prior to tree-ring dating being undertaken, the documentary evidence relating to a series of bequests received between AD 1479 and AD 1535 had been taken to relate to works including re-roofing of the nave and the aisles.

The timbers of the nave are now known to have been felled in AD 1485–1509, with construction likely to have occurred soon after, and thus the re-roofing of the nave does appear to relate to the bequests made. The timbers from the north aisle roof, however, were felled, and utilised sometime later, in AD 1533–58, perhaps having to await sufficient funding to become available.

It had been hoped that analysing samples from the two areas would aid the dating of the four undated north-aisle samples and that there might be some matching between timbers used in the two areas. However, this has not occurred, with timbers from each area only matching with others of the same area, despite there being some overlap in date. It may be that a different source for the timber was used for the nave and the north aisle, which might account for the lack of matching. However, this is not obvious when looking at which reference chronologies match each site sequence most highly, with all seemingly to be relatively close (Tables 2–5).

The intra-site matching of samples from the nave is very good, pointing to all timber utilised being taken from a single source whereas the samples taken from the north aisle have grouped into four distinct site sequences suggesting a somewhat more disparate source of timber being used. However, it should be noted that the overlap in date between site sequence PTHASQ01, thought to represent timbers cut from the middle of a tree, and site sequence PTHASQ02 is only 20 years which would not be long enough to cross-match. There is some evidence for a tree being utilised to produce more than one timber within the north-aisle roof. The three braces represented by samples PTH-A03, PTH-A04, and PTH-A08 mentioned above and also samples PTH-A06 and PTH-A07, both taken from aisle plates, match each other at the extremely high value of $t$=17.

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# TABLES

*Table 1: Details of samples from the Church of St Nicholas, Potter Heigham, Norfolk*

| Sample number | Sample location | Total rings* | Sapwood rings** | First measured ring date (AD) | Last heartwood ring date (AD) | Last measured ring date (AD) |
|---|---|---|---|---|---|---|
| North aisle roof | | | | | | |
| PTH-A01 | North aisle plate bay A | 64 | h/s | 1456 | 1519 | 1519 |
| PTH-A02 | Common rafter 5, bay A | 54 | h/s | 1467 | 1520 | 1520 |
| PTH-A03 | South brace, truss 3 | 120 | -- | 1360 | ------ | 1479 |
| PTH-A04 | South brace, truss 5 | 119 | -- | 1356 | ------ | 1474 |
| PTH-A05 | Common rafter 4, bay D | 56 | -- | 1459 | ------ | 1514 |
| PTH-A06 | North aisle plate, bay F | 90 | h/s | 1426 | 1515 | 1515 |
| PTH-A07 | North wall post, truss 7 | 92 | h/s | 1425 | 1516 | 1516 |
| PTH-A08 | North brace, truss 7 | 92 | -- | 1372 | ------ | 1463 |
| PTH-A09 | South brace, truss 7 | 55 | -- | ------ | ------ | ------ |
| PTH-A10 | North aisle plate, bay G | 56 | -- | ------ | ------ | ------ |
| PTH-A11 | Principal rafter, truss 8 | 62 | h/s | ------ | ------ | ------ |
| PTH-A12 | Common rafter 3, bay H | 63 | -- | ------ | ------ | ------ |
| Nave roof | | | | | | |
| PTH-A13 | North lower archbrace, truss A | NM | -- | ---- | ---- | ---- |
| PTH-A14 | North principal rafter, truss AB | NM | -- | ---- | ---- | ---- |
| PTH-A15 | North hammerbeam, truss AB | 73 | -- | 1362 | ---- | 1434 |
| PTH-A16 | North common rafter 3, bay B | 78 | h/s | 1400 | 1477 | 1477 |
| PTH-A17 | South principal rafter, truss BC | 86 | h/s | 1389 | 1474 | 1474 |
| PTH-A18 | North principal rafter, truss BC | 102 | h/s | 1360 | 1461 | 1461 |
| PTH-A19 | South lower archbrace, truss BC | 98 | h/s | 1374 | 1471 | 1471 |
| PTH-A20 | North lower archbrace, truss CD | 79 | h/s | 1403 | 1481 | 1481 |
| PTH-A21 | Ridge, bay D | 72 | h/s | 1402 | 1473 | 1473 |
| PTH-A22 | North lower archbrace, truss DE | 61 | -- | ---- | ---- | ---- |
| PTH-A23 | South principal rafter, truss DE | 107 | h/s | 1364 | 1470 | 1470 |
| PTH-A24 | South upper purlin, bay E | NM | -- | ---- | ---- | ---- |

*Table 1: (cont)*

| | | | | | | |
|---|---|---|---|---|---|---|
| PTH-A25 | Ridge, bay E | 107 | h/s | 1353 | 1459 | 1459 |
| PTH-A26 | South hammerbeam, truss EF | 121 | 25 | 1364 | 1459 | 1484 |
| PTH-A27 | North hammerbeam, truss EF | 84 | h/s | ---- | ---- | ---- |
| PTH-A28 | South lower archbrace, truss FG | 66 | -- | 1368 | ---- | 1433 |
| PTH-A29 | South hammerbeam, truss FG | 59 | h/s | ---- | ---- | ---- |

*NM = not measured
**h/s = heartwood/sapwood boundary is the last-measured ring

*Table 2: Results of the cross-matching of site sequence PTHASQ01 and relevant reference chronologies when the first-ring date is AD 1356 and the last-measured ring date is AD 1479*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| East Anglia | 7.7 | AD 406–2001 | Tyers *pers comm* 2004 |
| Church House, Edenbridge, Kent | 6.6 | AD 1377–1538 | Howard *et al* 2000a |
| Lawns Farm, Great  Leighs, Essex | 6.3 | AD 1377–1536 | Miles *et al* 2004 |
| Chicksands Priory, Bedfordshire | 6.1 | AD 1175–1541 | Howard *et al* 1998 |
| Sutton House, Hackney, London | 5.6 | AD 1319–1534 | Tyers 1991 |
| Thaxted Church, Essex | 5.2 | AD1345–1526 | Tyers 1990 |
| Ashpools, Chapel Lane, Northall, Buckinghamshire | 5.1 | AD 1260–1466 | Howard *et al* 1990 unpubl |

*Table 3: Results of the cross-matching of site sequence PTHASQ02 and relevant reference chronologies when the first-ring date is AD 1456 and the last-measured ring date is AD 1520*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| East Anglia | 5.8 | AD 406–2001 | Tyers *pers comm* 2004 |
| Post Mill, Drinkstone, Suffolk | 8.4 | AD 1464–1586 | Bridge 2001a |
| Chiddingly Place, East Sussex | 6.1 | AD 1324–1576 | Arnold and Litton 2003 |
| Otley Hall, Suffolk | 6.0 | AD 1380–1555 | Tyers 2000 |
| Lacock Abbey, Wiltshire | 5.6 | AD 1395–1546 | Esling *et al* 1990 |
| Priory Barn, Little Wymondley, Hertfordshire | 5.3 | AD 1450–1540 | Bridge 2001b |
| Fiddleford Manor, Sturminster Newton, Dorset | 5.3 | AD 1433–1553 | Bridge 2003 |

*Table 4: Results of the cross-matching of site sequence PTHASQ03 and relevant reference chronologies when the first-ring date is AD 1425 and the last-measured ring date is AD 1516*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| East Anglia | 5.9 | AD 406–2001 | Tyers *pers comm* 2004 |
| Abbas Hall, Great Cornard, Suffolk | 6.6 | AD 1421–1548 | Bridge 2000 |
| Thames foreshore, Richmond, London | 5.3 | AD 1358–1584 | Hillam 1997 |
| St Mary's Church, Strethall, Essex | 5.1 | AD 1347–1511 | Bridge 2004 |
| All Saints Church, Little Totham, Essex | 5.0 | AD 1380–1517 | Tyers 1996 |
| Manningtree, Essex | 5.0 | AD 1384–1534 | Loader *pers comm* 1996 |
| White Colne, Essex | 5.0 | AD 1439–1516 | Tyers *pers comm* 2002 |

*Table 5: Results of the cross-matching of site sequence PTHASQ05 and relevant reference chronologies when the first-ring date is AD 1353 and the last-measured ring date is AD 1484*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| East Anglia | 5.3 | AD 406–2001 | Tyers *pers comm* 2004 |
| Marriots warehouse, Kings Lynn, Norfolk | 7.8 | AD 1310–1583 | Tyers 1999 |
| Ayscoffee Hall, Spalding, Lincolnshire | 6.7 | AD 1343–1452 | Howard 2004 unpubl |
| Abbey Farm Barns, Thetford, Norfolk | 6.4 | AD 1332–1536 | Howard *et al* 2000b |
| Gainsborough Old Hall, Lincolnshire | 5.8 | AD 1264–1462 | Howard *et al* 1988 |
| Bellframe, Cranfield, Bedfordshire | 5.5 | AD 1342–1469 | Bridge 1998 |
| 9–11 East Street, Crowland, Lincolnshire | 5.5 | AD 1345–1444 | Arnold *et al* 2008 |

## FIGURES


*Figure 1: Map to show the location of Potter Heigham, circled.* 

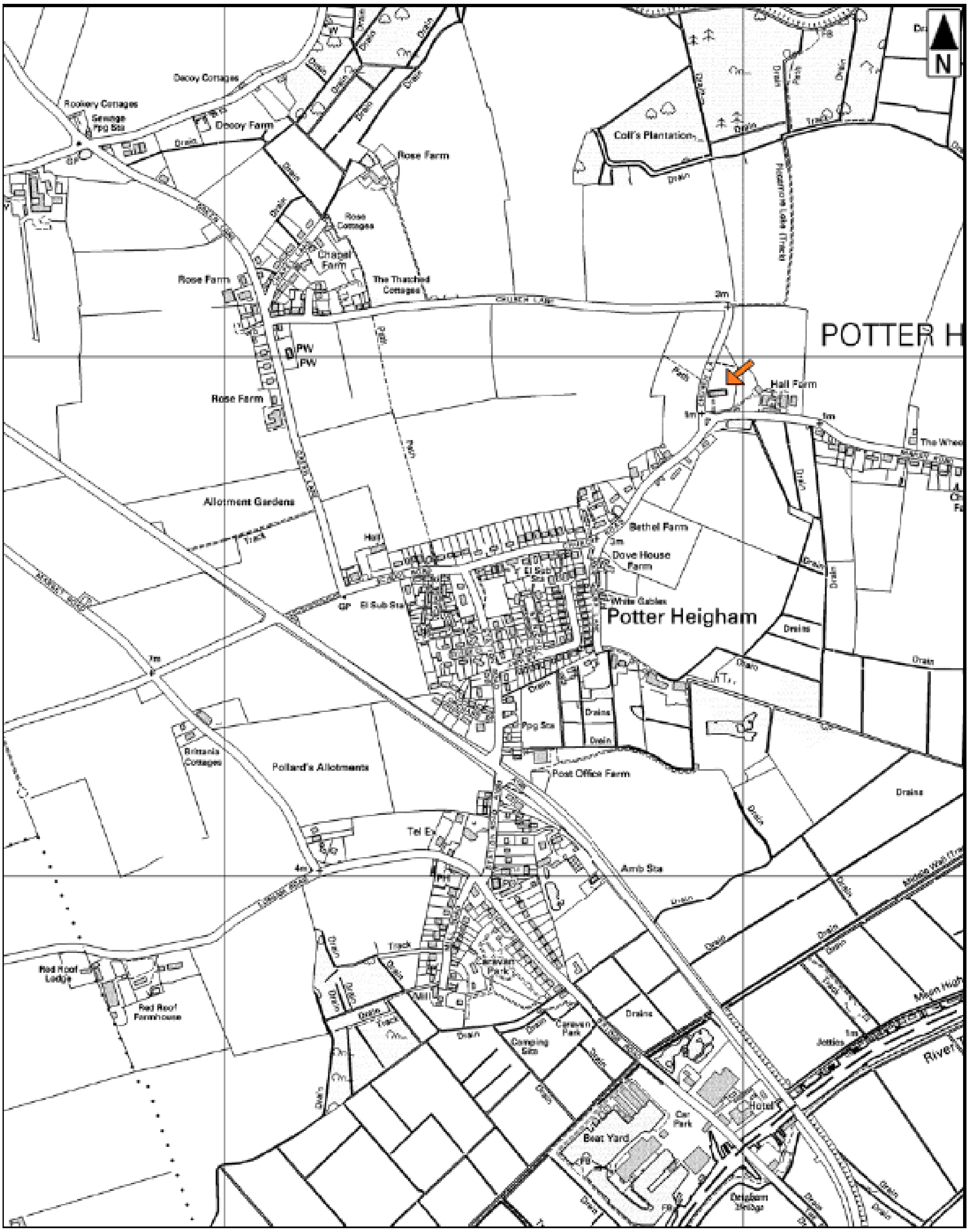


*Figure 2: Map to show the general location of St Nicholas Church, arrowed.* 

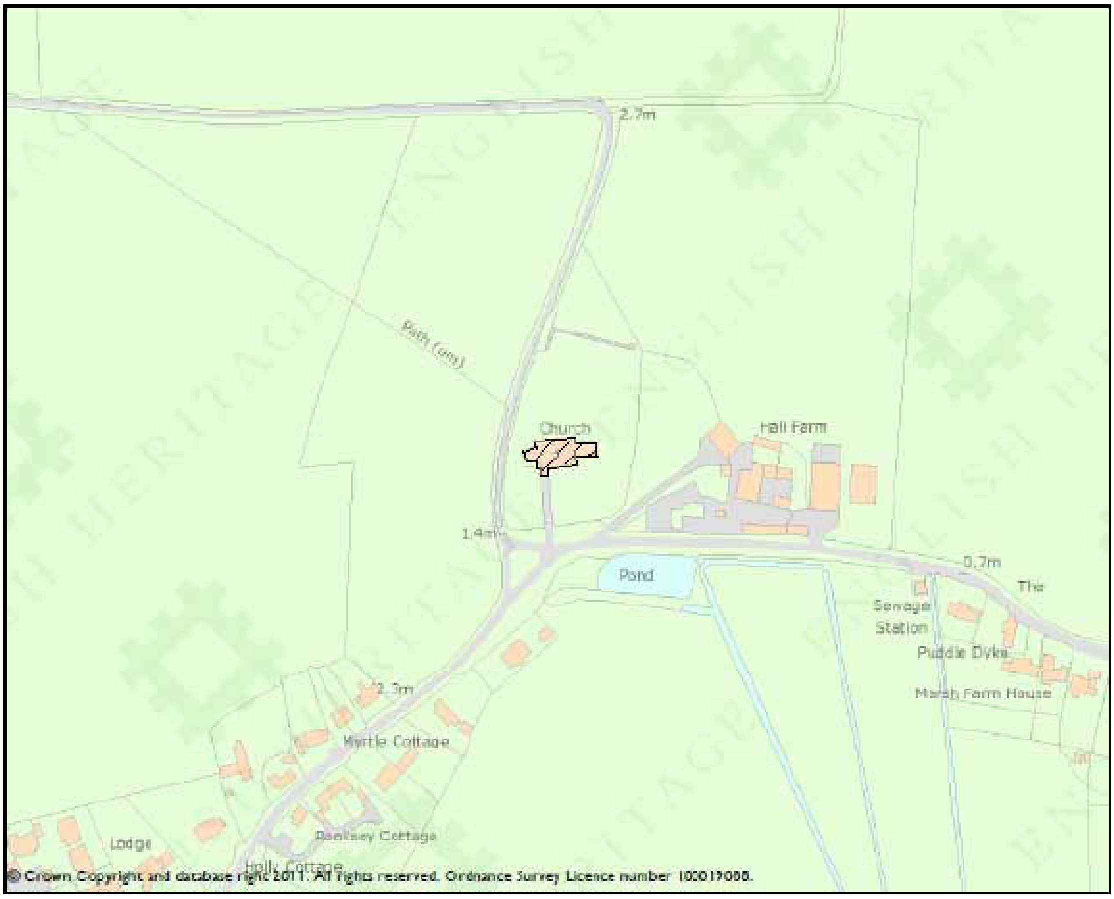


*Figure 3: Map to show the location of the Church of St Nicholas, hashed. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900.*

*Figure 4: North aisle roof, photograph taken looking east (Robert Howard)*

*Figure 5: Nave roof, photograph taken looking west (Robert Howard)*

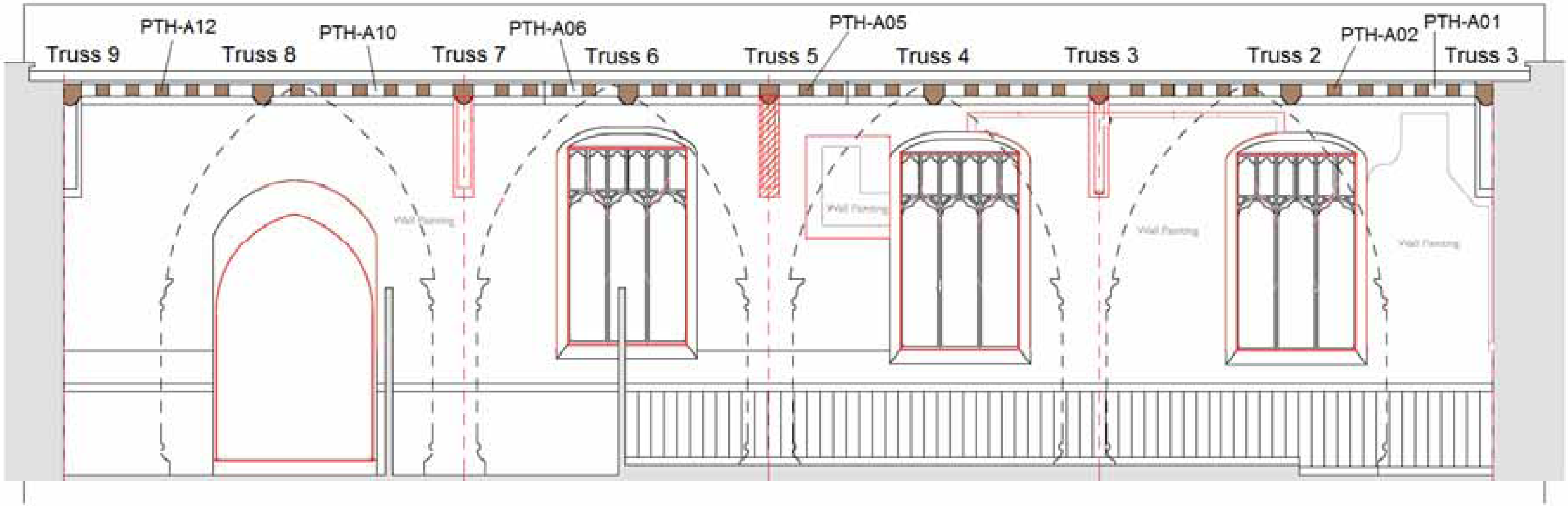


*Figure 6: North aisle, section (internal elevation looking north), showing the location of samples PTH-A01–02, PTH-A05–06, PTH-A10 and PTH-A12 (Nicholas Warns Architects Limited)*

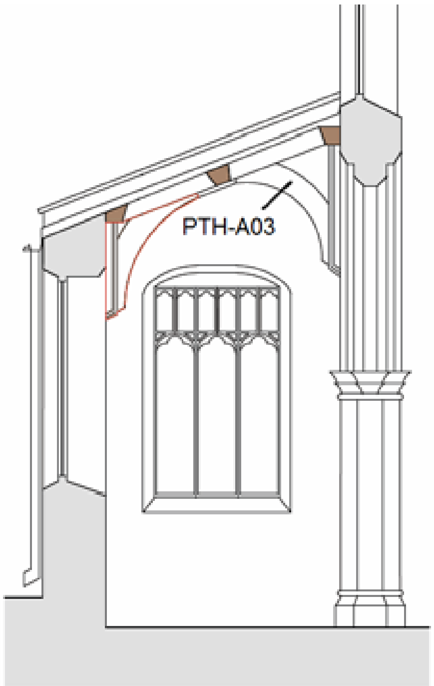


*Figure 7: North aisle, truss 3, showing the location of sample PTH-A03 (Nicholas Warns Architects Limited)*

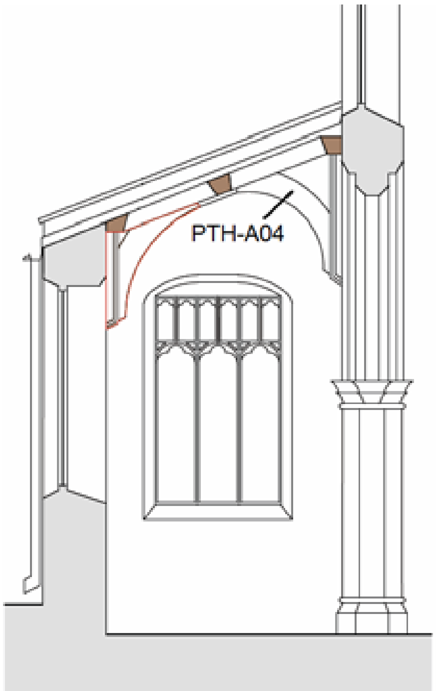


*Figure 8: North aisle, truss 5, showing the location of sample PTH-A04 (Nicholas Warns Architects Limited)*

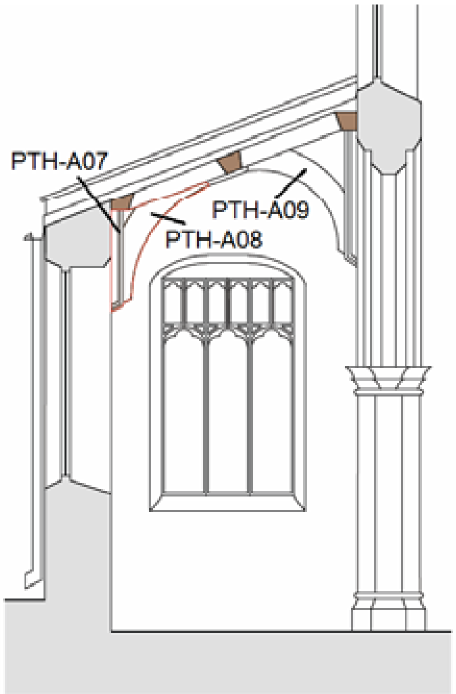


*Figure 9: North aisle, truss 7, showing the location of samples PTH-A07–09 (Nicholas Warns Architects Limited)*

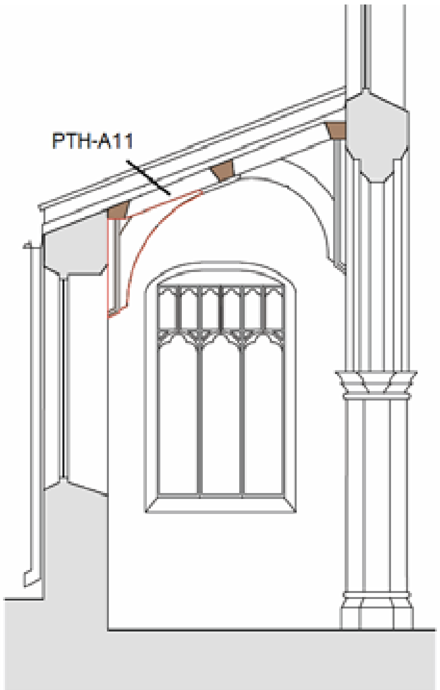


*Figure 10: North aisle, truss 8, showing the location of sample PTH-A11 (Nicholas Warns Architects Limited)*

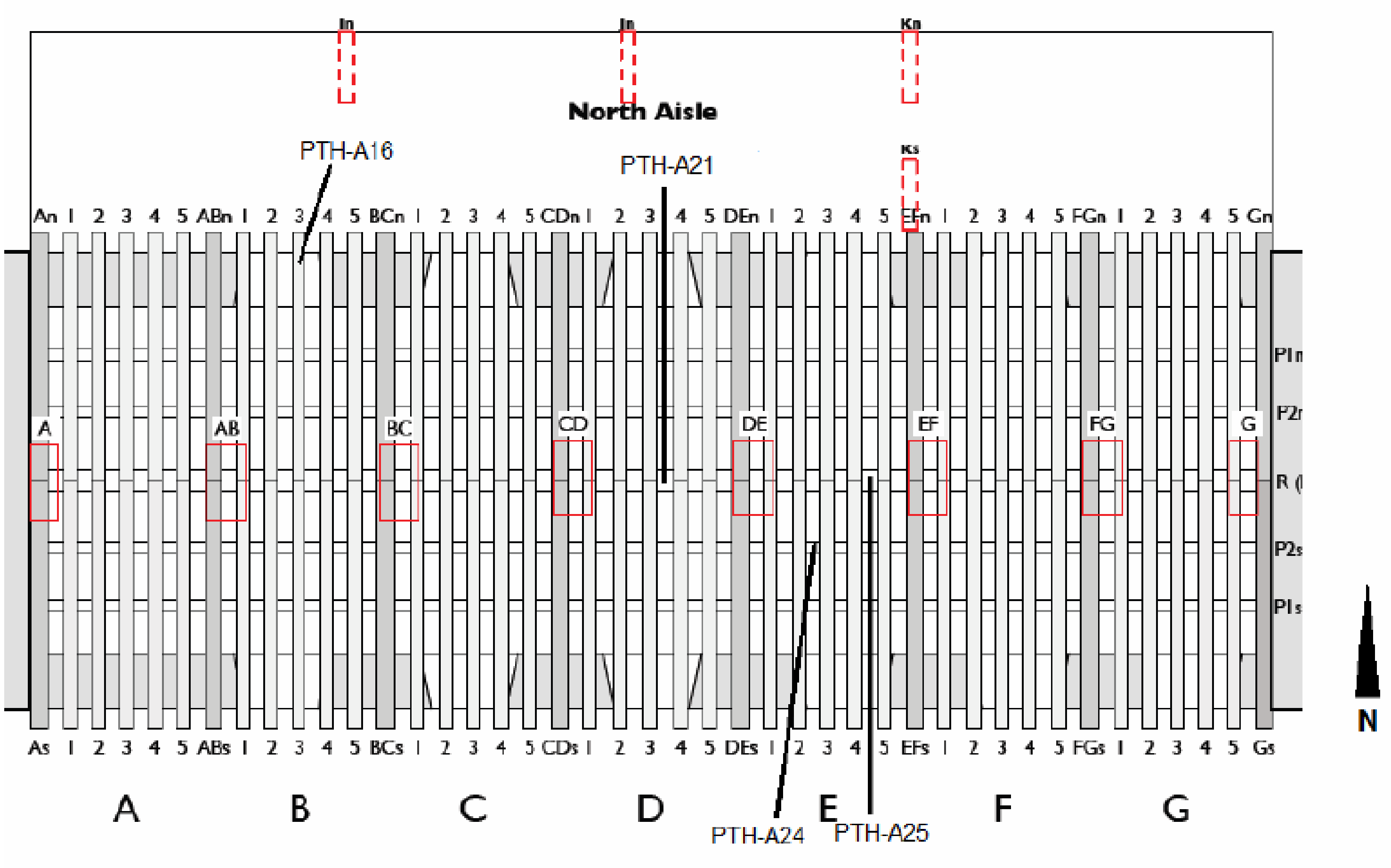


*Figure 11: Nave, plan, showing the location of samples PTH-A16, PTH-A21, and PTH-A24–5 (Nicholas Warns Architects Limited)*

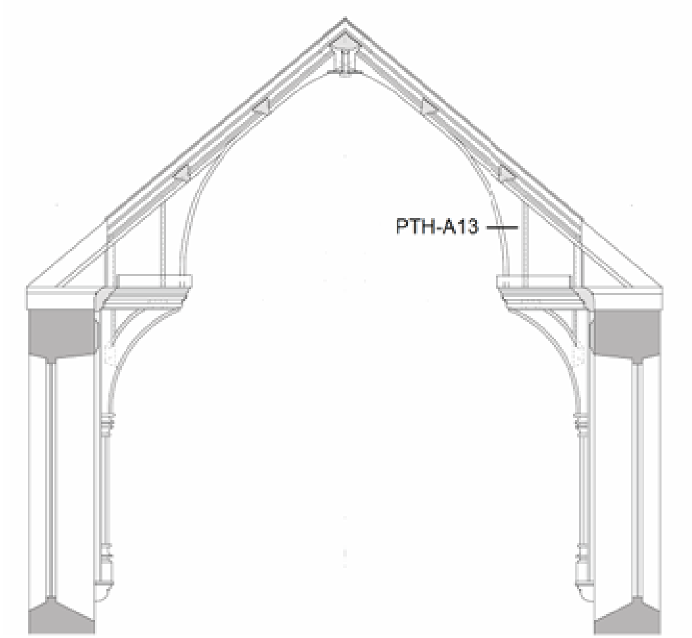


*Figure 12: Nave, truss A, showing the location of sample PTH-A13 (Nicholas Warns Architects Limited)*

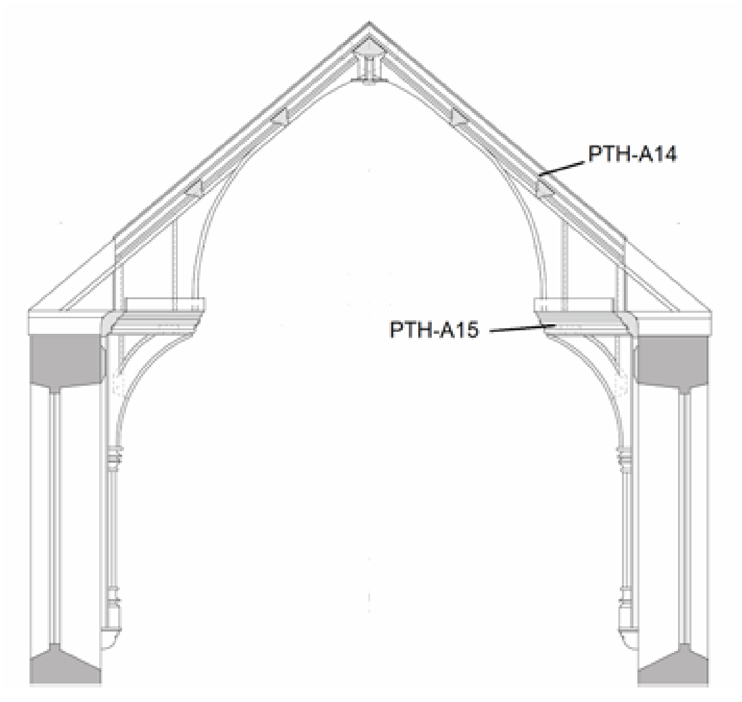


*Figure 13: Nave roof, truss AB, showing the location of samples PTH-A14 and PTH-A15 (Nicholas Warns Architects Limited)*

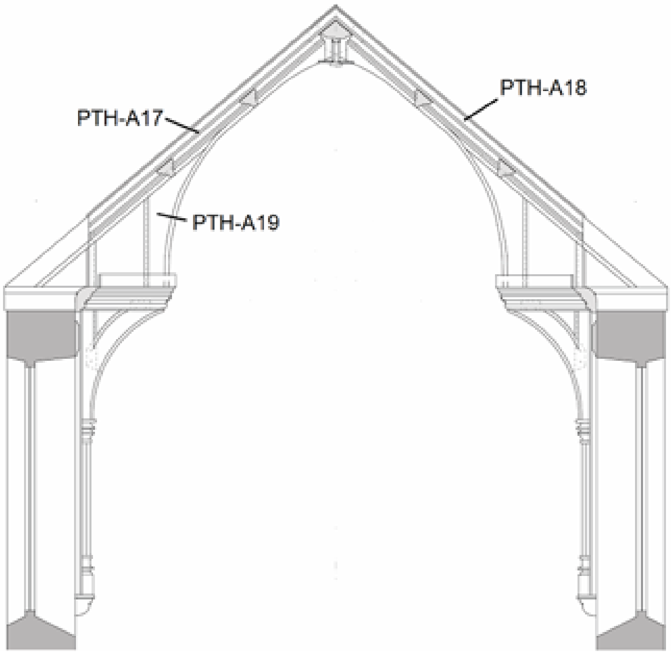


*Figure 14: Nave roof, truss BC, showing the location of samples PTH-A17–19 (Nicholas Warns Architects Limited)*

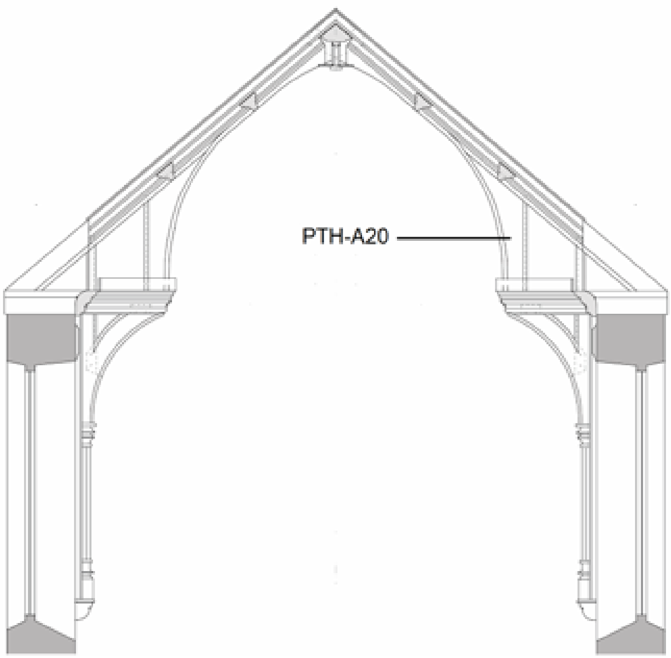


*Figure 15: Nave roof, truss CD, showing the location of sample PTH-A20 (Nicholas Warns Architects Limited)*

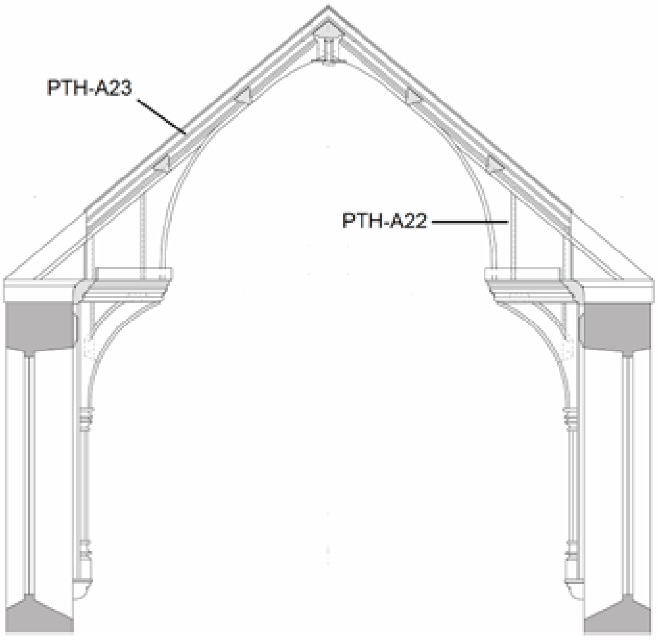


*Figure 16: Nave roof, truss DE, showing the location of samples PTH-A22 and PTH-A23 (Nicholas Warns Architects Limited)*

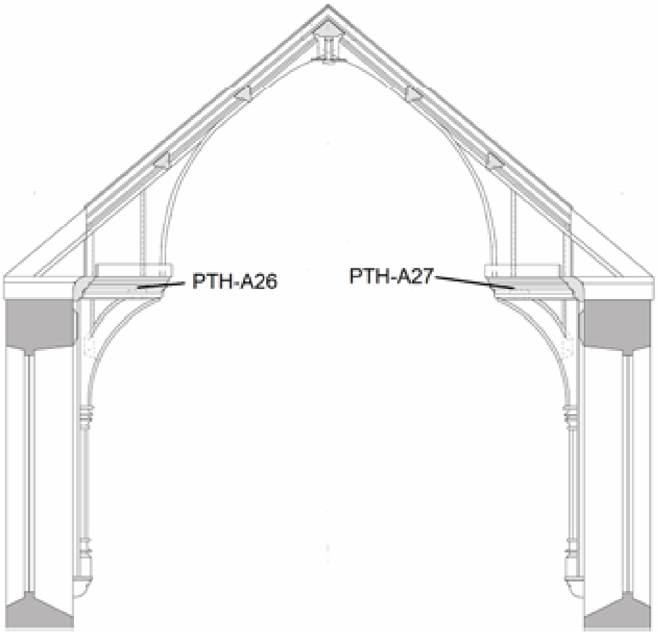


*Figure 17: Nave roof, truss EF, showing the location of samples PTH-A26 and PTH-A27 (Nicholas Warns Architects Limited)*

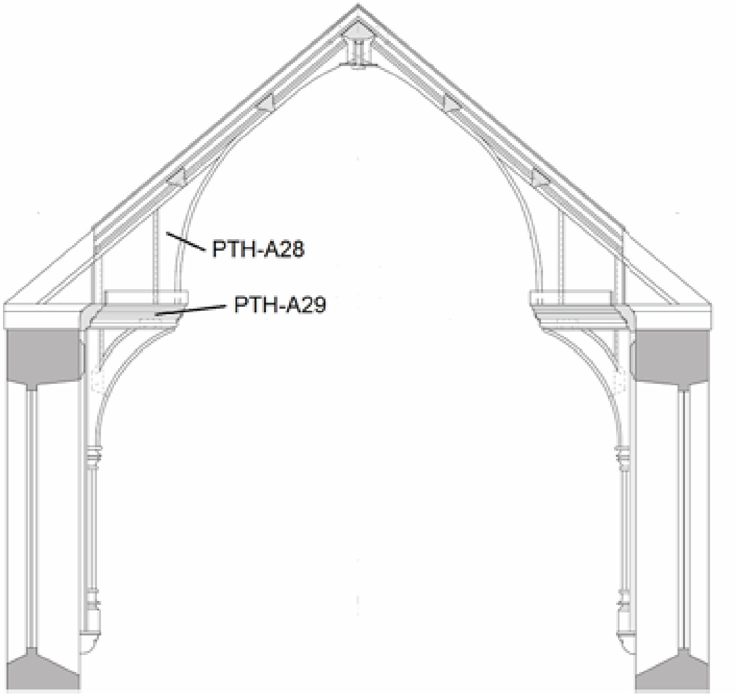


*Figure 18: Nave, truss FG, showing the location of samples PTH-A28 and PTH-A29 (Nicholas Warns Architects Limited)*

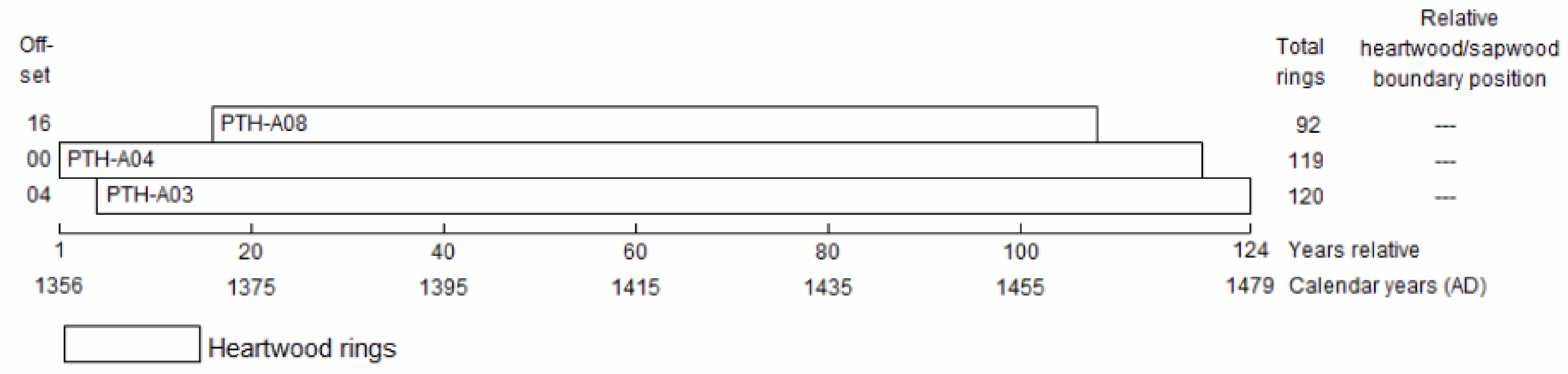


*Figure 19: Bar diagram of samples in site sequence PTHASQ01*

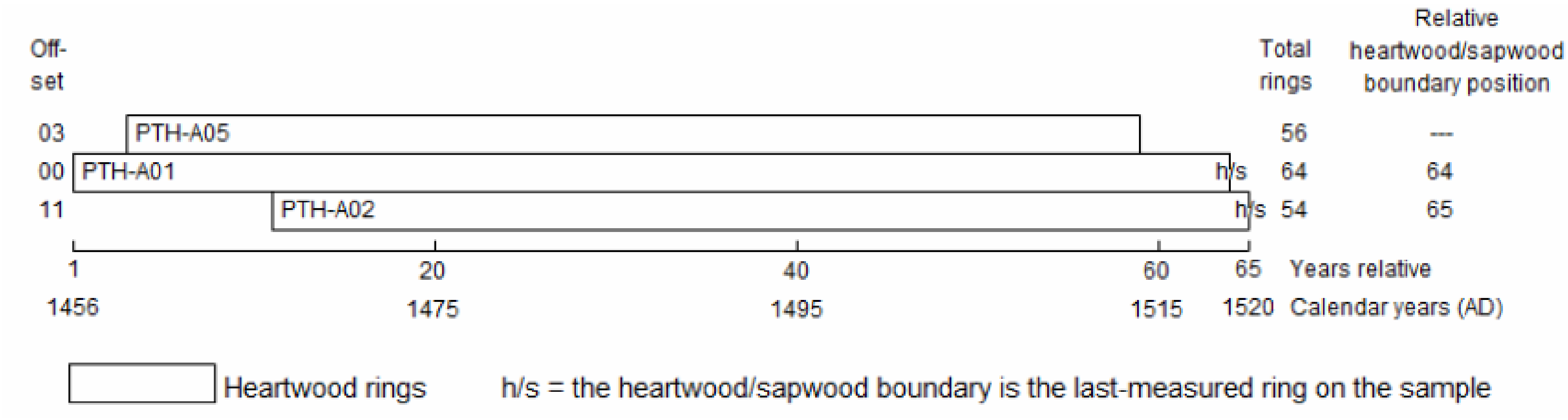


*Figure 20: Bar diagram of samples in undated site sequence PTHASQ02*

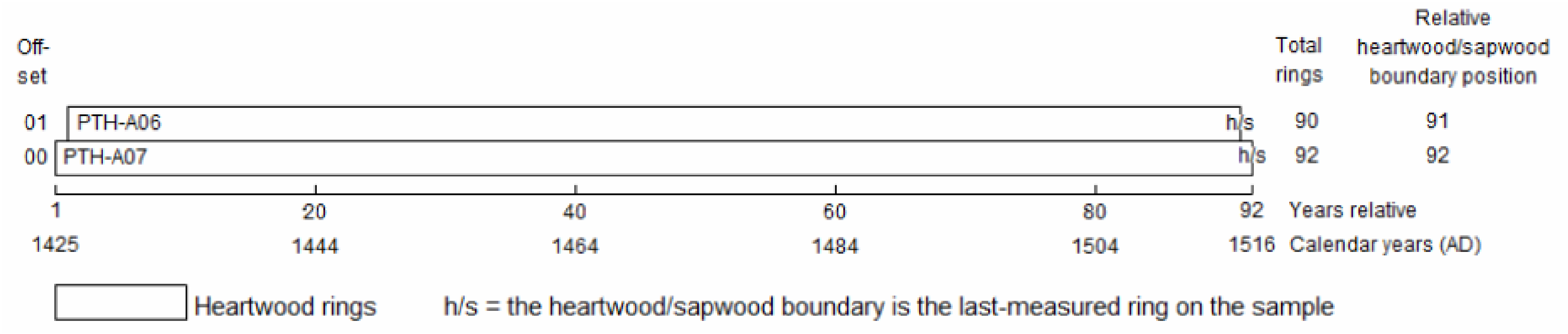


*Figure 21: Bar diagram of samples in undated site sequence PTHASQ03*

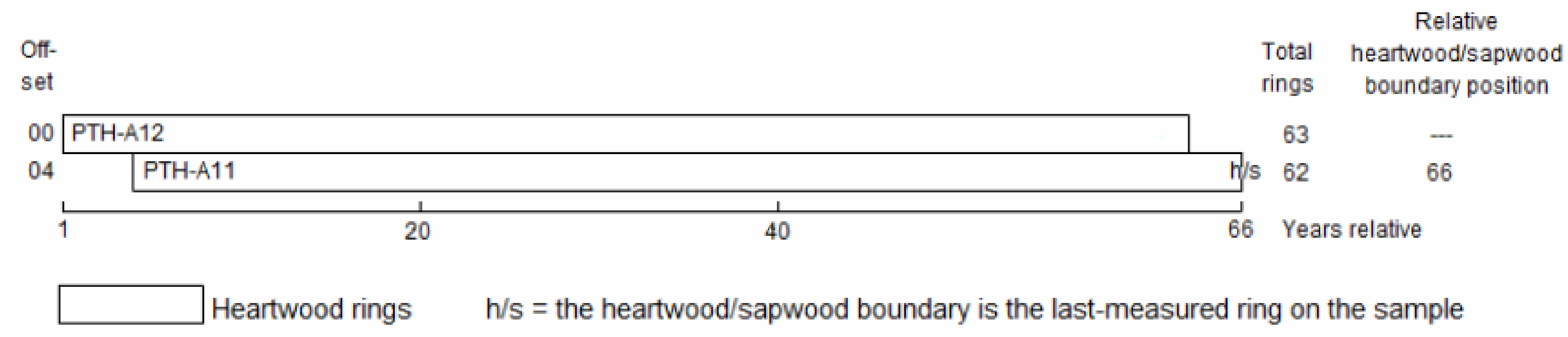


*Figure 22: Bar diagram of samples in undated site sequence PTHASQ04*

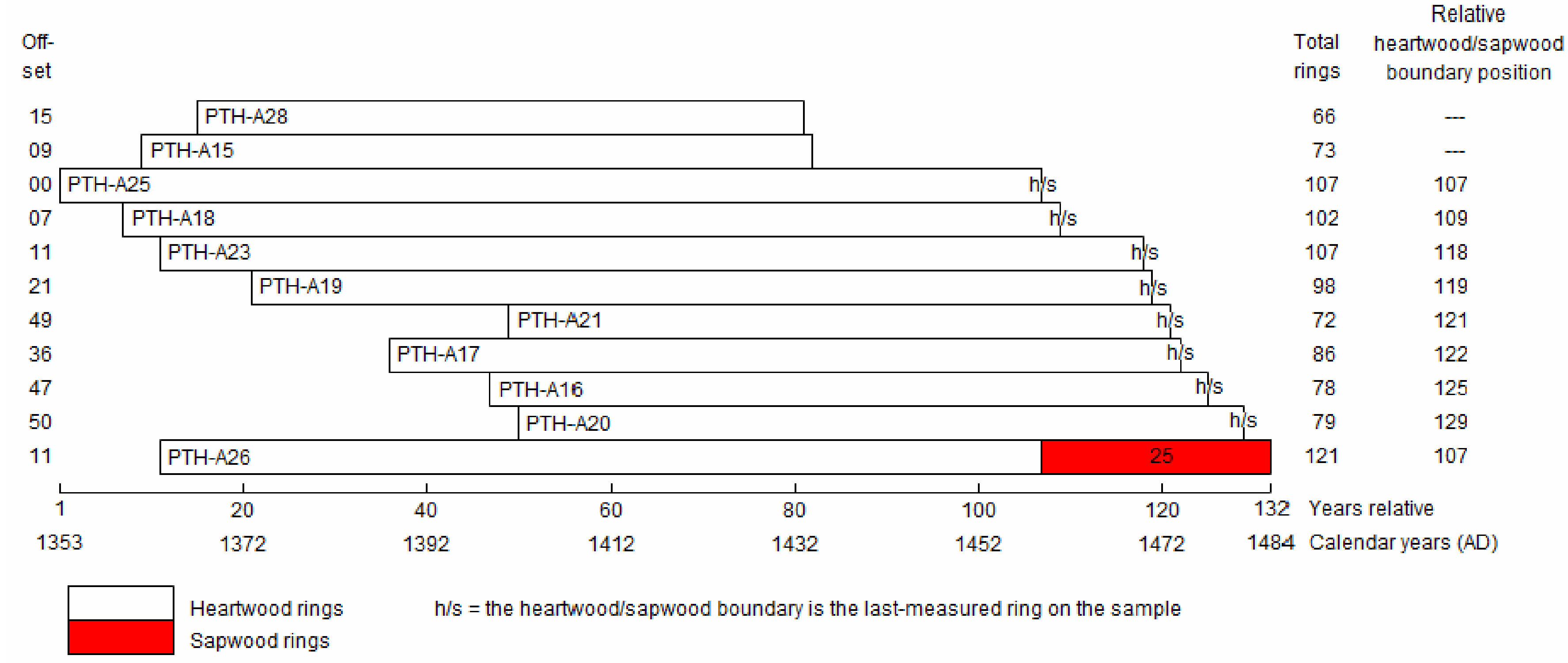


*Figure 23: Bar diagram of samples in site sequence PTHASQ05*

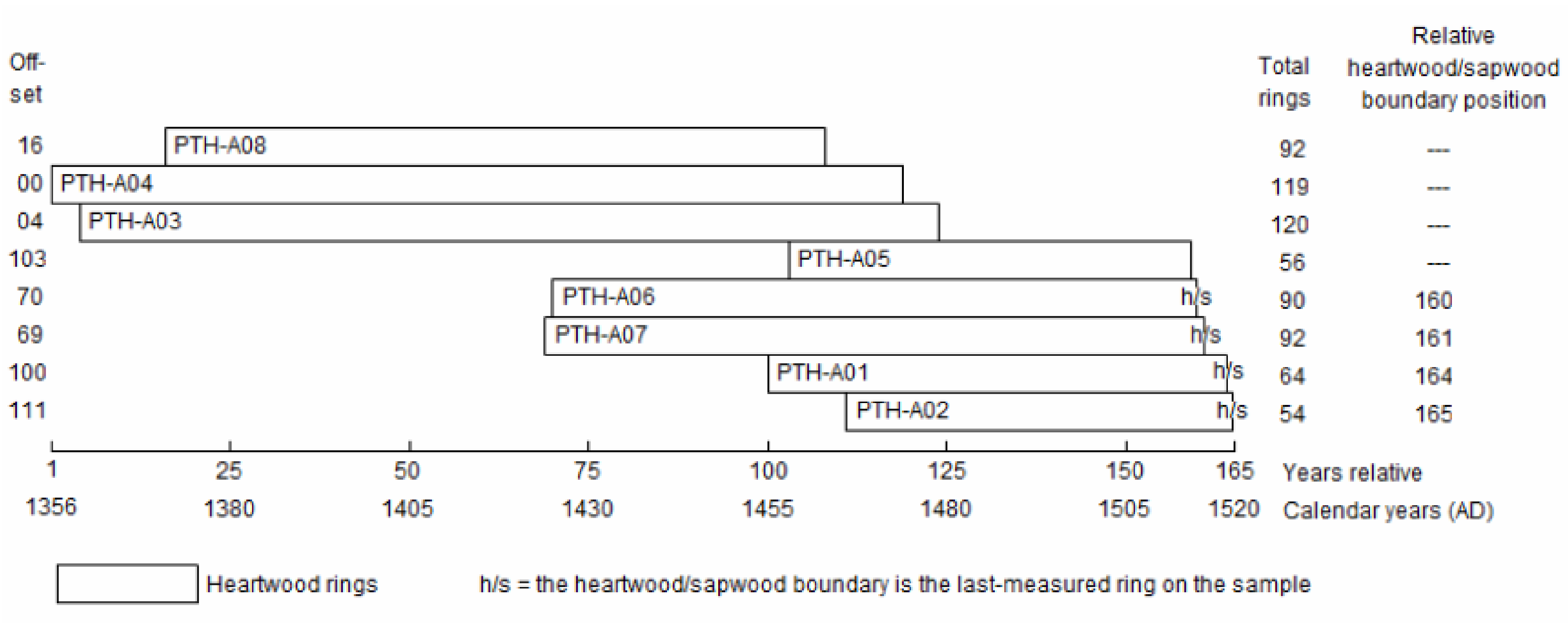


*Figure 24: Bar diagram of all dated north aisle samples*

# DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

PTH-A01A 64
196 182 199 226 174 98 246 297 263 350 436 366 267 359 418 284 384 333 322 327
210 198 215 267 244 270 286 279 221 165 279 316 241 299 248 206 242 231 287 305
362 242 160 161 170 179 303 204 173 168 161 123 234 215 300 219 276 226 172 207
235 188 263 273
PTH-A01B 64
237 196 204 223 169 105 243 294 263 352 405 365 272 352 419 303 386 320 347 332
207 221 213 267 276 260 341 259 214 183 272 325 237 296 246 200 233 248 289 318
358 227 158 151 177 188 305 212 161 167 152 118 235 197 275 230 272 237 180 186
243 191 245 311
PTH-A02A 54
213 363 272 247 279 283 317 249 389 166 150 248 314 320 281 273 244 261 178 236
120 60 70 70 66 75 153 144 305 271 167 179 171 158 139 211 108 111 107 132
97 134 137 169 146 165 131 134 143 158 159 134 199 195
PTH-A02B 54
263 359 223 234 290 253 271 267 336 190 142 244 305 322 288 306 247 247 177 236
130 70 62 82 63 61 112 123 274 208 194 169 156 148 121 175 100 110 92 137
99 129 166 165 161 153 135 147 141 157 153 128 200 199
PTH-A03A 120
296 209 363 323 230 291 150 217 265 272 371 262 338 157 244 220 244 236 294 231
217 265 254 304 136 114 203 182 193 146 118 102 112 167 191 137 249 302 307 343
421 403 306 413 468 214 165 176 159 179 235 249 321 255 159 255 357 389 265 345
330 372 393 277 344 304 295 315 322 262 310 238 342 157 173 226 274 171 215 231
199 259 278 271 212 166 152 140 138 150 162 178 145 163 222 242 194 263 105 133
115 232 250 196 225 183 260 192 257 330 230 228 437 279 369 500 333 218 222 391
PTH-A03B 120
302 209 348 370 215 268 142 222 252 270 380 264 337 156 251 217 250 231 302 226
213 266 250 307 145 118 190 188 200 171 128 92 125 174 176 163 222 301 329 349
395 395 336 400 443 221 165 158 146 204 199 241 287 297 165 267 369 310 301 347
325 370 387 279 343 315 300 308 330 260 284 242 345 156 174 222 289 172 213 248
194 246 260 269 226 174 141 145 133 138 182 171 151 169 218 203 196 265 93 145
118 226 244 210 228 196 304 194 223 358 230 233 432 280 357 488 329 187 222 353
PTH-A04A 119
142 161 131 225 226 93 170 212 133 196 167 154 177 258 239 141 233 129 264 276
263 266 322 202 285 326 359 369 184 200 294 320 286 219 266 161 136 234 231 239
421 331 390 446 454 375 346 342 381 283 211 152 143 198 198 202 215 170 135 162
202 275 206 310 321 320 311 311 295 216 217 190 239 306 336 290 404 176 135 209
171 134 169 165 189 187 199 194 209 168 201 149 126 204 224 197 167 192 258 275
309 311 144 156 201 291 308 213 215 187 302 263 427 408 304 278 429 341 380
PTH-A04B 119
117 150 130 211 230 95 169 222 129 206 154 162 192 258 218 157 229 134 269 280
258 266 332 206 263 324 370 381 166 194 296 327 274 233 265 155 156 232 241 230
431 344 397 448 431 418 325 333 385 277 223 151 149 193 191 219 194 169 138 150
212 264 220 295 318 312 282 335 292 234 221 191 232 290 329 335 357 179 144 170
168 150 180 168 170 170 180 190 190 156 195 171 133 199 181 212 161 198 217 273
333 320 142 161 187 279 326 198 211 189 276 249 425 399 309 258 436 340 377
PTH-A05A 56
244 205 258 211 348 221 248 288 322 381 493 456 330 342 312 405 436 376 263 374

407 602 408 301 234 231 161 253 314 143 234 245 98 116 130 169 206 208 169 147
178 133 205 269 189 170 169 192 194 211 238 289 264 216 228 268
PTH-A05B 56
241 316 251 255 311 239 247 289 290 435 503 490 316 358 295 419 443 380 277 384
442 605 452 291 230 211 154 249 305 165 214 237 99 126 127 186 237 219 157 140
154 153 213 229 178 181 184 180 193 242 234 302 285 223 214 258
PTH-A06A 90
168 170 175 181 128 159 150 164 118 161 118 149 130 83 134 137 220 206 113 80
135 172 60 74 54 76 69 108 101 113 139 159 99 103 100 127 140 133 110 91
163 106 162 149 156 153 99 91 96 109 82 64 100 100 129 118 108 115 113 149
143 167 128 153 170 108 116 132 179 158 238 124 80 96 117 126 153 165 151 126
115 96 131 190 177 171 155 154 134 129
PTH-A06B 90
151 115 121 121 81 103 146 154 116 169 125 155 119 84 136 156 222 213 114 70
144 180 59 81 54 70 68 105 108 111 135 162 104 96 103 128 133 132 112 102
158 105 158 155 153 152 100 93 87 105 97 64 100 100 120 119 117 130 120 136
146 157 133 157 163 108 115 126 183 153 234 129 81 94 118 123 157 164 142 124
93 89 125 198 171 169 157 174 129 126
PTH-A07A 92
94 162 146 197 166 133 150 144 149 112 185 123 163 138 106 130 150 225 202 121
77 165 150 70 67 54 84 72 104 135 119 126 167 111 101 114 163 142 128 122
99 159 122 171 170 139 152 93 95 87 119 90 83 101 101 134 129 112 113 110
130 138 152 143 174 156 112 111 123 171 139 239 119 94 94 112 124 152 153 148
121 119 73 128 216 216 172 153 239 183 148 192
PTH-A07B 92
116 193 117 182 160 132 159 133 146 126 180 119 173 135 128 135 147 225 208 116
75 161 187 70 50 79 72 85 125 127 134 130 163 112 106 95 147 135 130 131
92 160 123 168 166 144 157 90 99 85 117 97 76 100 104 138 120 116 110 118
130 142 154 134 157 173 104 114 119 177 137 237 110 100 99 111 127 141 159 144
125 113 73 138 208 200 176 161 241 191 136 188
PTH-A08A 92
212 143 231 280 363 370 407 328 468 529 526 777 216 269 316 383 353 303 316 256
251 423 396 338 520 587 669 737 829 546 548 486 633 442 311 177 119 147 111 131
161 134 88 181 320 307 350 361 399 371 335 367 354 282 366 273 284 451 305 297
313 186 157 222 131 136 220 206 251 259 298 241 201 133 185 150 92 137 170 153
129 138 178 167 299 398 102 105 114 286 448 382
PTH-A08B 92
247 126 243 273 387 364 400 329 403 541 539 754 207 268 306 370 355 313 327 256
248 445 417 306 569 600 660 748 837 544 546 481 625 451 312 182 123 147 110 121
164 127 105 170 314 303 327 362 389 372 363 360 363 278 367 265 297 446 320 274
376 183 160 210 115 150 197 204 257 240 271 249 196 139 185 139 105 141 167 165
128 133 187 166 312 433 114 94 118 287 464 388
PTH-A09A 55
159 217 190 81 87 95 135 129 124 131 119 122 89 153 136 145 179 190 219 238
362 294 253 170 261 261 316 348 266 379 224 251 379 372 292 254 286 264 240 378
526 415 382 145 305 261 358 181 157 120 106 121 166 151 200
PTH-A09B 55
182 199 198 95 95 88 132 133 122 133 115 114 103 151 138 145 171 178 216 237
350 286 240 192 259 278 297 335 270 392 244 261 369 321 318 232 322 237 287 369
501 406 377 205 318 268 339 175 156 117 104 117 163 150 210
PTH-A10A 56
110 149 187 179 139 137 181 174 200 193 170 136 130 157 89 105 134 144 120 131
95 192 135 105 126 110 137 118 75 97 236 239 202 218 251 234 272 202 120 121

92 151 139 151 135 112 130 133 150 189 226 221 172 217 178 220
PTH-A10B 56
121 159 172 183 136 141 170 174 207 210 173 134 124 157 83 115 143 136 127 118
96 163 160 96 137 111 136 117 75 111 207 242 187 212 240 226 274 206 123 110
100 163 132 146 136 115 132 129 150 184 227 220 177 214 182 218
PTH-A11A 62
432 290 420 373 386 481 354 280 397 389 214 239 320 329 262 142 268 327 297 341
514 463 360 356 383 381 349 352 430 312 322 178 148 149 110 155 134 163 159 204
206 171 219 218 154 178 297 222 154 139 151 135 112 130 133 150 189 226 246 168
139 198
PTH-A11B 62
409 284 329 397 387 456 401 261 404 400 212 252 315 329 271 129 269 333 309 352
527 443 369 381 370 374 357 352 418 349 314 178 126 139 92 174 138 168 169 181
215 177 222 214 142 192 302 218 152 136 146 141 115 132 127 153 194 227 250 180
144 194
PTH-A12A 63
336 416 281 149 316 287 359 428 481 471 508 261 418 612 266 240 274 377 235 155
149 234 208 227 412 304 223 243 200 271 299 215 331 270 237 94 68 72 64 127
106 129 104 133 127 98 117 121 103 106 181 170 138 139 137 131 93 108 132 156
161 162 222
PTH-A12B 63
344 375 286 156 339 283 370 440 474 460 506 252 417 612 274 252 260 384 261 142
133 252 201 217 406 302 224 232 218 254 301 220 325 283 239 97 64 77 64 125
97 134 107 131 136 84 119 120 105 107 197 162 140 155 120 131 102 103 117 167
157 163 209
PTH-A15A 73
260 310 265 308 133 227 430 709 572 345 295 184 190 361 507 223 172 125 260 380
461 271 193 270 361 547 586 355 312 165 109 167 193 308 402 249 205 377 534 296
199 204 201 186 223 190 178 389 184 98 48 79 85 77 72 95 156 153 126 172
234 271 266 169 206 177 262 319 122 124 165 96 131
PTH-A15B 73
258 317 277 291 127 227 386 672 562 343 294 190 194 356 450 241 185 126 282 390
449 263 207 285 361 526 542 390 307 169 102 171 193 298 392 242 198 358 513 310
204 212 207 185 222 189 184 372 183 97 47 85 83 79 68 102 149 146 121 167
238 277 268 173 203 174 249 317 130 121 169 93 135
PTH-A16A 78
496 454 356 301 148 133 112 221 228 278 138 133 113 124 105 105 119 205 246 123
131 130 172 198 294 126 212 131 186 289 172 195 195 161 298 282 147 135 182 196
217 190 167 177 160 131 243 254 209 211 99 82 113 179 207 142 171 158 127 83
65 107 70 153 187 134 176 190 107 173 207 180 163 146 125 201 215 171
PTH-A16B 78
536 466 387 325 166 131 114 233 230 296 141 133 115 129 105 111 121 212 220 128
135 129 173 195 287 138 227 123 196 286 181 192 187 162 296 284 155 133 184 200
220 185 171 171 164 134 256 266 211 214 89 76 106 173 210 122 174 157 127 81
72 104 70 156 185 130 176 195 108 173 201 195 161 149 131 199 224 155
PTH-A17A 86
250 194 124 70 124 161 272 219 130 136 212 253 204 161 173 132 113 124 139 114
189 201 124 85 101 110 123 125 184 259 235 351 212 244 320 304 197 266 200 254
299 142 135 217 193 163 162 106 146 135 123 116 205 181 197 140 112 209 201 158
166 141 88 137 193 187 225 311 161 133 89 153 159 92 88 132 115 163 109 139
223 226 230 135 191 120
PTH-A17B 86
249 192 122 72 113 166 259 219 129 129 214 266 202 165 165 135 105 124 135 112

204 198 120 82 103 112 125 125 189 259 241 349 212 246 315 306 198 246 204 249
300 147 134 219 185 168 159 110 147 136 117 117 207 176 206 132 125 199 195 161
165 130 98 126 200 174 232 318 156 134 88 151 160 97 89 135 119 158 107 141
224 231 218 140 185 118
PTH-A18A 102
88 73 83 110 110 73 76 62 101 78 102 118 101 84 99 144 145 116 99 103
173 147 124 135 110 117 111 115 135 104 84 102 67 70 83 76 113 94 96 73
86 92 99 88 73 59 51 72 83 92 87 65 64 92 63 71 69 73 81 84
54 76 86 108 117 85 56 72 73 77 60 59 61 78 84 88 56 74 74 52
106 75 96 85 96 81 103 137 129 140 100 61 126 111 125 113 135 122 87 74
74 66
PTH-A18B 102
80 70 89 111 104 79 74 65 100 77 102 115 100 86 101 149 137 112 94 104
173 140 119 138 104 109 114 117 132 103 79 111 65 79 80 77 105 109 80 71
89 96 96 90 64 54 63 64 84 87 89 64 62 94 61 79 70 75 86 82
60 74 79 109 114 91 55 68 70 86 58 61 62 72 91 85 54 73 76 56
101 75 100 83 92 84 106 134 135 134 96 72 129 108 126 115 129 125 87 75
77 60
PTH-A19A 98
236 296 234 162 132 159 213 475 535 402 123 177 180 338 356 199 230 118 169 253
226 267 260 222 238 209 220 226 285 248 327 160 264 223 231 214 234 164 158 161
124 85 135 178 197 250 243 148 220 280 286 193 195 163 205 266 172 207 158 102
122 198 146 127 139 137 172 160 156 149 121 141 208 163 161 172 147 142 159 200
205 194 221 111 99 119 176 108 95 124 166 196 152 134 180 159 178 199
PTH-A19B 98
214 312 287 176 138 174 225 496 556 409 126 181 188 337 363 206 233 116 171 272
230 279 263 221 242 213 225 235 291 241 330 167 269 218 228 219 244 172 165 170
143 93 137 170 205 256 246 158 243 273 285 185 179 157 200 268 168 206 155 105
126 190 145 128 132 139 152 169 153 135 113 136 213 173 153 167 150 142 155 204
200 197 204 112 93 119 182 107 94 125 139 178 151 138 185 150 190 208
PTH-A20A 79
198 265 144 246 241 236 241 208 159 140 142 146 82 124 145 151 179 148 178 172
249 241 129 79 142 139 180 110 99 139 129 183 184 170 157 169 111 138 140 109
123 135 133 143 166 137 165 115 119 134 169 148 168 200 129 102 98 142 86 75
83 97 123 92 96 144 108 131 131 77 102 79 113 128 102 96 59 60 97
PTH-A20B 79
206 267 165 245 237 237 242 211 135 146 140 146 85 126 149 157 178 146 184 186
246 249 117 91 139 127 184 105 118 138 128 185 183 166 148 160 119 138 128 115
131 126 139 144 167 140 161 109 116 134 170 144 167 188 123 105 95 145 96 68
87 92 124 96 96 141 104 133 124 89 104 74 101 146 104 93 65 61 80
PTH-A21A 72
108 109 123 82 141 152 79 214 183 111 101 132 106 106 190 156 136 149 88 106
317 377 340 167 152 177 269 357 191 206 216 138 227 206 180 163 131 165 199 147
206 256 137 123 140 194 151 156 140 122 141 135 168 118 187 118 95 114 94 94
100 134 129 118 115 96 134 159 133 167 120 120
PTH-A21B 72
100 113 123 76 141 159 84 210 188 110 101 132 103 108 198 155 141 148 82 113
310 381 338 167 150 170 252 357 192 198 238 135 225 206 200 153 142 174 200 123
188 277 143 119 140 189 158 150 127 110 143 131 187 137 224 125 97 106 97 96
97 143 131 126 113 95 139 157 137 167 123 116
PTH-A22A 61
62 78 70 127 160 105 73 51 69 92 156 121 130 140 93 64 80 55 133 154
202 168 156 171 83 141 146 146 144 138 102 74 95 113 153 197 115 113 81 145

141 142 159 108 93 106 97 119 80 102 73 88 84 107 108 99 104 90 89 127
108
PTH-A22B 61
68 71 81 112 161 114 63 58 65 94 153 125 137 138 92 62 77 69 132 154
192 176 161 165 88 138 141 141 140 135 102 83 87 117 154 207 120 100 84 136
144 142 165 105 87 98 98 117 72 133 79 87 81 110 102 102 105 84 97 134
104
PTH-A23A 107
291 267 256 266 278 359 321 254 307 258 289 327 252 190 128 135 257 142 273 309
239 213 242 206 187 171 148 134 93 90 150 109 130 63 52 72 125 127 114 99
63 65 69 60 71 111 89 101 64 90 112 82 79 106 98 74 110 158 143 149
193 119 121 139 246 195 107 128 167 114 135 109 108 79 52 29 38 74 87 87
71 66 105 107 165 114 116 164 230 226 251 277 309 254 230 181 163 176 111 143
109 150 128 132 165 143 134
PTH-A23B 107
278 275 253 231 277 367 380 227 302 254 283 326 254 190 126 128 257 144 265 313
236 228 229 208 183 174 146 137 87 92 150 109 129 65 58 64 126 130 112 102
69 67 68 54 66 107 87 102 70 88 116 89 71 105 97 87 110 150 143 138
203 124 116 136 234 194 113 132 171 104 134 111 113 83 50 34 32 85 78 105
67 78 106 115 158 110 112 167 235 235 236 276 310 255 227 182 170 173 116 143
112 148 129 130 163 141 138
PTH-A25A 107
152 163 136 201 147 91 67 61 62 95 147 107 63 57 37 38 162 187 144 182
112 164 179 159 120 107 98 99 133 161 146 76 117 91 114 111 102 83 75 53
76 58 85 129 90 94 91 120 114 119 113 119 73 156 91 163 157 147 124 100
147 118 136 118 177 227 198 141 127 167 252 224 130 147 77 107 134 135 114 113
94 111 103 95 96 99 123 125 133 130 132 93 83 99 85 109 117 86 79 81
97 83 83 96 104 78 70
PTH-A25B 107
131 182 136 205 146 95 66 64 58 95 141 112 67 49 39 37 162 172 131 180
106 167 182 157 119 109 99 98 138 156 148 75 114 98 116 105 100 78 74 51
69 70 78 152 93 94 90 121 116 116 112 115 69 153 90 156 164 150 124 99
145 117 133 117 185 226 193 141 126 171 246 226 117 143 82 108 133 135 115 111
94 110 95 85 98 98 118 127 127 131 140 102 85 105 88 118 124 85 80 81
95 82 83 101 100 76 77
PTH-A26A 121
336 299 207 259 222 289 205 177 184 107 103 215 162 153 107 73 130 189 169 163
150 158 185 164 156 132 158 91 113 143 212 171 200 103 107 105 128 133 95 141
99 99 88 98 97 147 112 90 80 77 76 68 76 83 122 109 82 95 108 109
139 77 67 62 94 80 65 79 90 65 69 90 67 56 63 60 66 45 74 79
59 50 51 59 64 73 57 44 42 49 46 41 51 50 48 56 41 52 44 47
41 56 53 53 55 48 42 48 51 40 44 39 47 58 54 41 33 52 49 41
61
PTH-A26B 121
341 299 208 254 233 280 208 178 182 102 113 214 166 152 104 72 135 188 176 161
145 160 183 166 151 133 160 92 109 144 209 172 197 111 112 105 125 136 93 145
96 94 89 93 107 142 107 91 79 72 80 71 78 80 122 115 78 90 105 113
134 71 64 65 89 83 65 78 77 67 69 83 59 62 56 64 65 48 63 76
58 45 51 56 74 68 55 44 41 51 45 44 62 44 61 48 44 39 43 43
47 62 50 57 52 42 52 44 45 50 42 39 48 56 53 46 33 55 45 43
64
PTH-A27A 84
398 379 148 287 405 325 221 405 400 388 440 413 288 238 233 195 203 136 125 158

131 103 61 76 80 117 147 100 150 144 124 101 138 116 100 86 114 131 75 92
81 83 74 81 85 105 132 131 96 101 78 114 95 125 172 141 128 110 144 265
214 264 305 188 124 118 136 171 200 207 205 201 163 129 99 201 242 244 287 252
428 209 226 190
PTH-A27B 84
384 384 140 296 405 325 220 405 401 388 439 395 288 266 231 193 178 143 126 144
126 105 57 75 85 112 143 122 174 140 127 111 136 107 108 87 116 138 75 87
83 92 71 80 84 102 131 138 100 96 82 117 93 119 175 134 137 102 153 263
211 259 294 200 124 120 137 178 195 207 194 211 152 139 97 197 247 251 269 257
441 211 214 165
PTH-A28A 66
85 113 108 81 66 60 96 128 142 81 74 54 96 117 132 115 84 73 111 144
125 82 89 69 58 62 120 131 133 149 92 77 143 199 144 231 169 116 178 127
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184 161 123 146 177 122
PTH-A28B 66
106 100 108 79 68 59 107 125 131 85 71 51 98 114 129 127 83 73 110 140
127 77 85 73 62 62 133 129 133 145 94 77 122 201 140 227 170 111 175 120
94 101 99 85 70 87 72 86 126 145 185 162 130 164 123 179 222 119 118 149
188 148 126 145 171 137
PTH-A29A 59
495 468 300 361 320 333 387 333 432 519 621 719 556 414 334 338 259 360 281 359
277 372 311 315 277 280 412 353 314 329 349 353 340 135 117 146 142 133 110 183
183 150 83 115 113 96 109 99 110 147 124 162 95 139 97 106 98 112 120
PTH-A29B 59
505 478 301 363 316 337 385 341 431 530 605 725 556 415 339 335 253 368 285 361
276 368 304 320 274 278 413 349 310 330 347 349 320 138 119 145 136 131 119 183
186 138 81 116 108 99 107 102 114 145 129 156 114 119 98 106 102 104 125

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

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

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

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

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

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

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

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

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

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


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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

*t*-value/offset Matrix

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

Bar Diagram

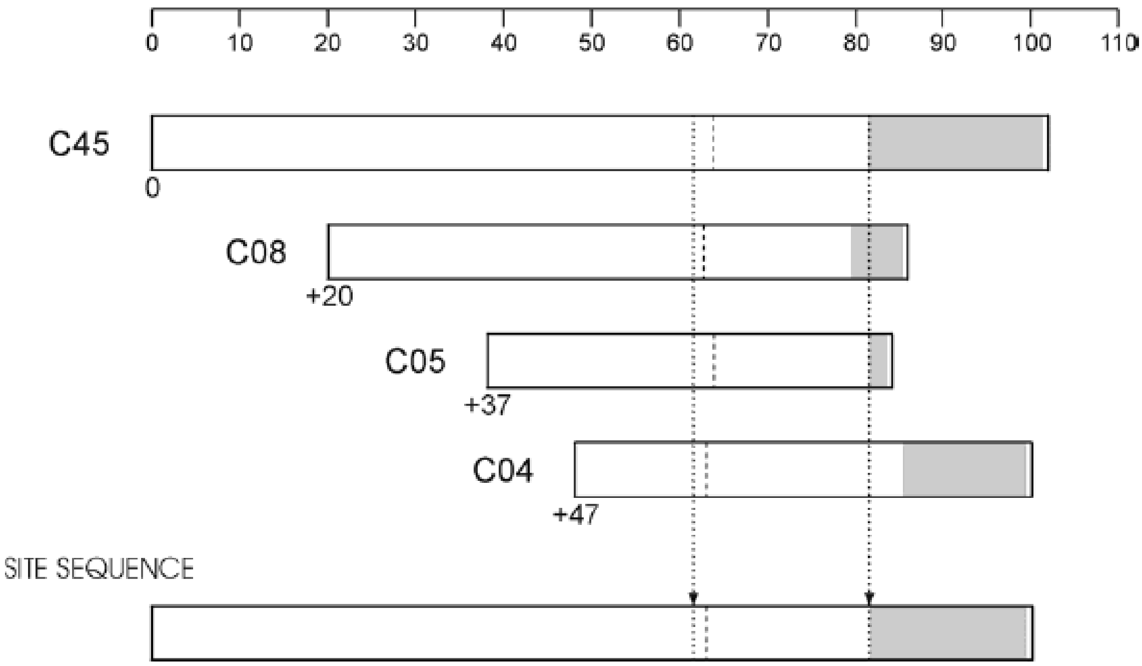



*Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

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.

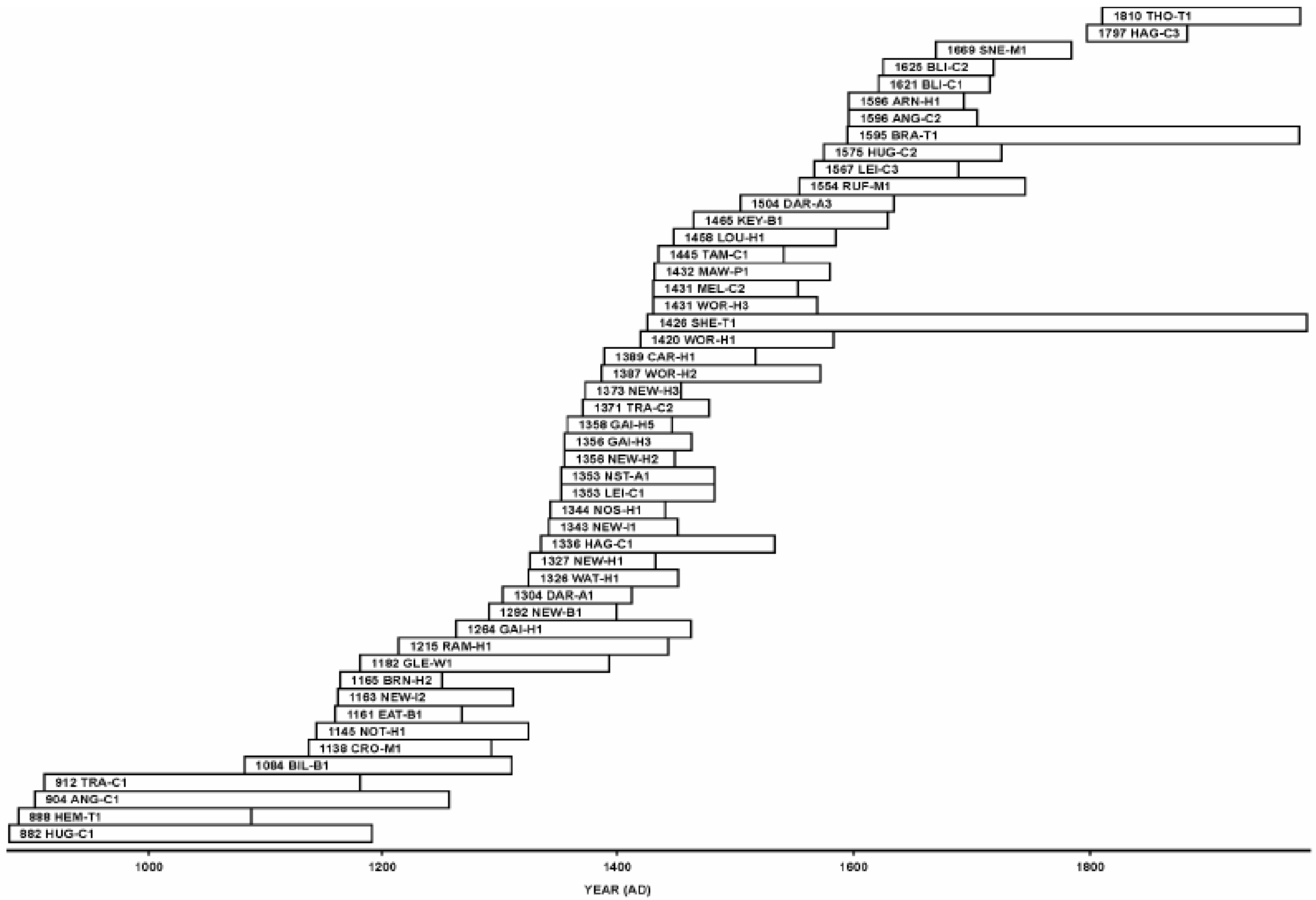
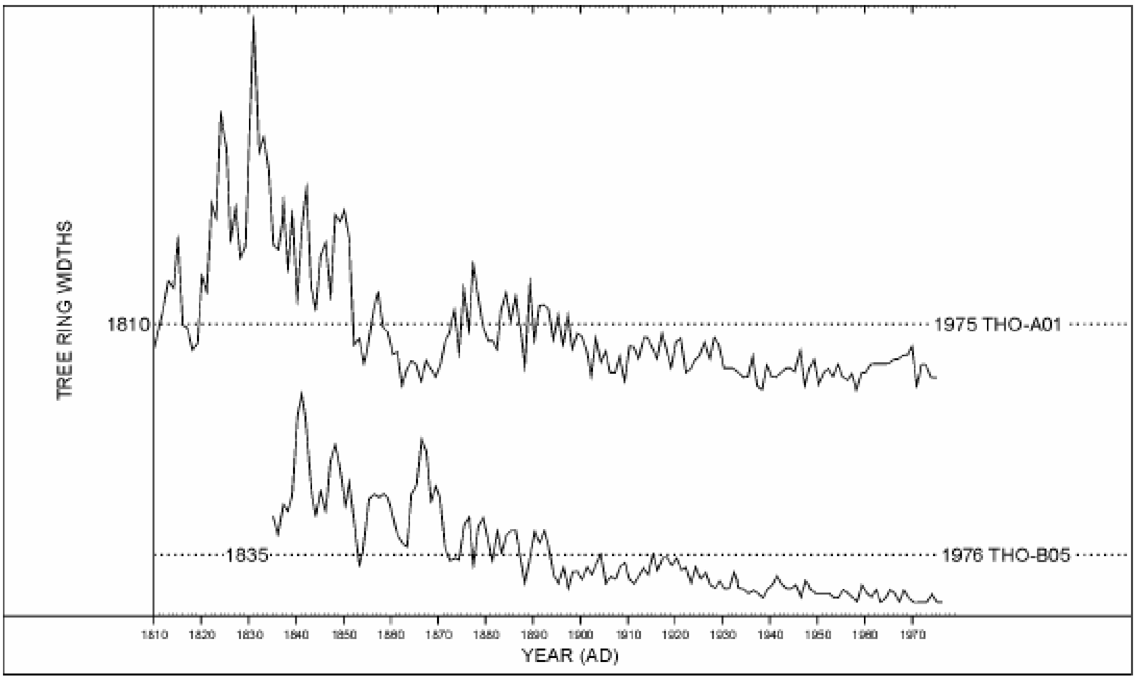



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

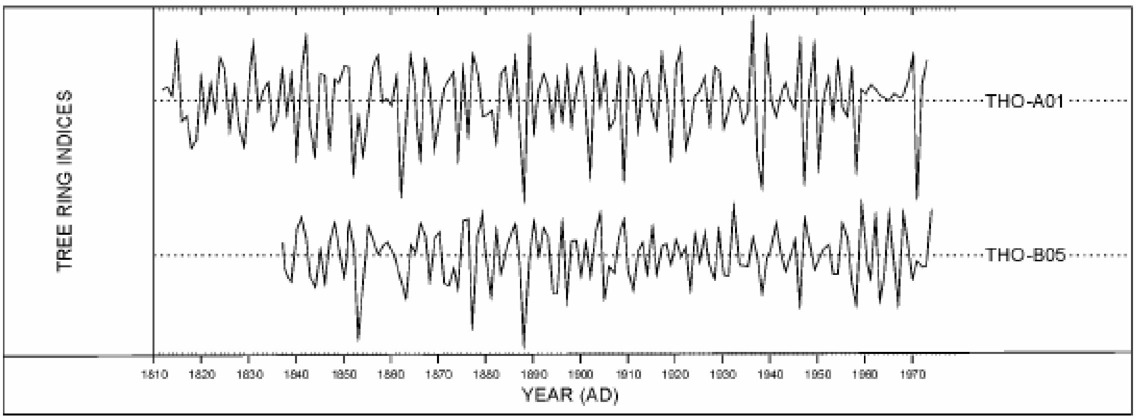



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

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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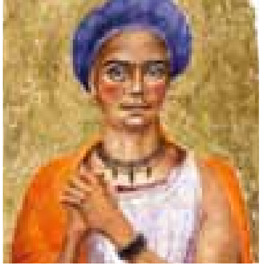


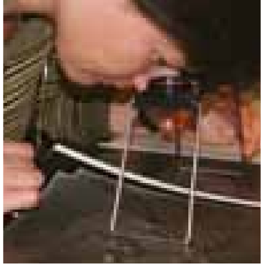


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