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GODWICK GREAT BARN, GODWICK, TITTLESHALL, NORFOLK
TREE-RING DATING OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

Research Report Series 14-2013

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Alison Arnold and Robert Howard

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SUMMARY
Samples were taken from the timbers of the roof and floor frames in this building, resulting in the construction and dating of two site sequences and the individual dating of one other sample. Site sequence GDWKSQ01 contains 21 samples and spans the period AD 1406–1597. The second site sequence, GDWKSQ01, contains five samples and spans the period AD 1624–1701. Sample GDW-K20 was found to span the period AD 1582–1683.

The analysis indicates that the extant floor-framing at the northern end of the barn is constructed with timber felled in AD 1597. The majority of the timbers in the roof were felled in AD 1588–1613, though some common rafters were felled in AD 1712–37 and a purlin was potentially felled at the same time or very slightly earlier in AD 1695–1720. These results suggest the floor-frames and primary construction of the roof are contemporary, with both likely to date to, or shortly after AD 1597, with repairs to the roof undertaken in the first decades of the eighteenth century.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
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INTRODUCTION

This grade II* listed barn, is located in the deserted medieval village of Godwick, just south of Fakenham, between the villages of Tittleshall and Whissonsett (Figs 1–3). It was associated with the now demolished Godwick Hall which was built in AD 1586. The barn is important due to both its great size and distinctive roof structure. The roof consists of 11 trusses of alternating hammer-beam and queen-strut style (Figs 4 and 5) apart from at the northern end which has as a surviving second floor and attic and evidence of partitioning within the body of the building (Fig 6). This roof is similar to that of the barn at Paston which dates to AD 1581 (Tyers 1999) and at Waxham, dated to AD 1583/4 (Moir 2004). It has been suggested that the construction of these three barns was the result of rivalry amongst the high-status families in the area at this time.

SAMPLING

Sampling was requested by Will Fletcher, English Heritage Inspector of Ancient Monuments, to provide a precise date for this barn that lies within a Scheduled Ancient Monument and to determine its chronological relationship to the barns at Paston and Waxham.

A total of 38 timbers was sampled by coring. Each sample was given the code GDW-K (for Godwick) and numbered 01–38. Twenty-seven of these were from the roof (GDW-K01–27) and 11 from the floor-frames at the northern end of the barn (GDW-K28–38). The location of samples was noted at the time of sampling and has been marked on Figures 7–18. Further details relating to the samples can be found in Table 1. The timber used within the floor frames was of mixed character, a large number being wide ringed and unsuitable for sampling which is why the number of floor samples taken is lower than would perhaps be recommended. Additionally, none of the timbers used within the partitions were thought to be suitable for tree-ring dating, as they clearly contained too few rings for secure dating and so were not sampled.

ANALYSIS AND RESULTS

Ten of the samples, five from the roof and five from the floor frames, were found to have too few rings for secure dating and so were discarded prior to analysis. The remaining 28 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 26 samples matching to form two groups.

Firstly, 21 samples matched each other and were combined at the relevant offset positions to form GDWKSQ01, a site sequence of 192 rings (Fig 19). This site sequence was compared against a series of relevant reference chronologies where it was found to match consistently and securely at a first-ring date of AD 1406 and a last-measured ring date of AD 1597. The evidence for this dating is given by the *t*-values in Table 2.

Secondly, five samples grouped and were combined to form GDWKSQ02, a site sequence of 78 rings (Fig 20). When compared against the reference chronologies it was found to span the period AD 1624–1701. The evidence for this dating is given by the *t*-values in Table 3.

Attempts were then made to date the remaining two ungrouped samples by comparing them individually against the reference chronologies resulting in sample GDW-K20 being found to span the period AD 1582–1683. The evidence for this dating is given by the *t*-values in Table 4. The remaining sample, GDW-K19, could not be matched and remains undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 27 of the samples: 21 from the roof and six from the floor-frames (Fig 21). 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.

Roof

There are at least two and potentially three separate fellings represented within the dated timbers from the roof.

Eight samples dated within site sequence GDWKSQ01 have broadly contemporary heartwood/sapwood boundary ring dates, suggestive of a single felling (Figs 19 and 21; Table 1). The average of these is AD 1573, allowing an estimated felling date range to be calculated for the eight timbers represented of AD 1588–1613. The other seven roof samples dated within this site sequence all have last-measured heartwood ring dates in the sixteenth century which, combined with the overall level of similarity found between these ring series, make it likely that they were also felled in AD 1588–1613.

The heartwood/sapwood boundary ring date of four of the samples within site sequence GDWKSQ02 are again suggestive of a single felling (Figs 20 and 21; Table 1). The average of this is AD 1697, allowing an estimated felling date range to be calculated for the four timbers represented of AD 1712–37. These four timbers are all common rafters and it seems likely that the other dated common rafter within site sequence GDWKSQ02, with a last-measured ring date of AD 1689 was also likely to have been felled in AD 1712–37.

The individually dated sample GDW-K20, taken from a purlin, has a heartwood/sapwood boundary ring date of AD 1680 (Fig 21; Table 1), allowing an estimated felling date range to be calculated for the timber represented of AD 1695–1720.

Floor frames

Six of these samples, representing two main beams from the first floor and six joists from the second floor, have been dated within site sequence GDWKSQ01. Two of these timbers, a first-floor main beam and a second-floor joist, have complete sapwood and the last-measured ring date of AD 1597, the felling date of the two timbers represented. Three of the remaining dated timbers have heartwood/sapwood boundary dates which are similar and imply that these are also likely to have been felled in AD 1597. With a last measured heartwood ring date of AD 1570 it appears likely that the last of the dated samples from the floor-frames is likely to be contemporary and hence probably felled in AD 1597.

DISCUSSION

Prior to tree-ring analysis being undertaken on the timbers of the roof and floors at this barn it was thought likely to date to sometime shortly after AD 1586, the date of construction of Godwick Hall. The similarity in design between this roof and those of the great barns at Paston and Waxham had been highlighted but it was unclear where this barn fitted chronologically.

It is now known that the majority of the dated timbers from the roof were felled in AD 1588–1613, whilst the floor frames contain timber felled in AD 1597. These results suggest that the roof and floor frames are contemporary, with the construction of both likely to have occurred in or soon after felling of the timbers in AD 1597. This thus places Godwick Great barn slightly later than the barns at Paston (AD 1581) and Waxham (AD 1583/4).

In addition a number of common rafters and a purlin clearly represent later repairs to the roof just over a century after the initial construction. The common rafters were felled in the period AD 1712–37, whilst the purlin has an estimated felling date of AD 1695–1720. Clearly it is possible that these six timbers were all part of a single felling episode in the first decades of the eighteenth century.

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TABLES

Table 1: Details of tree-ring samples from Godwick Great Barn, Tittleshall, Norfolk

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
GDW-K01	Collar, truss 1	NM	--	----	----	----
GDW-K02	East middle purlin, bay 1	NM	--	----	----	----
GDW-K03	West middle purlin, bay 1	119	--	1434	----	1552
GDW-K04	East strut, truss 2	NM	--	----	----	----
GDW-K05	West strut, truss 2	73	01	1509	1580	1581
GDW-K06	East principal rafter, truss 3	NM	--	----	----	----
GDW-K07	East corbel, truss 4	54	h/s	1517	1570	1570
GDW-K08	East principal rafter, truss 5	50	--	1518	----	1567
GDW-K09	West common rafter 2, bay 5	74	h/s	1627	1700	1700
GDW-K10	East common rafter 3, bay 5	63	h/s	1630	1692	1692
GDW-K11	East common rafter 4, bay 5	58	--	1632	----	1689
GDW-K12	West common rafter 5, bay 5	71	02	1630	1698	1700
GDW-K13	West hammer beam, truss 6	55	01	1528	1581	1582
GDW-K14	East hammer beam, truss 6	NM	--	----	----	----
GDW-K15	West corbel, truss 6	55	h/s	1514	1568	1568
GDW-K16	East common rafter 2, bay 6	78	04	1624	1697	1701
GDW-K17	East corbel, truss 7	53	h/s	1517	1569	1569
GDW-K18	East hammer beam, truss 8	79	--	1490	----	1568
GDW-K19	West hammer beam, truss 8	57	h/s	----	----	----
GDW-K20	East lower purlin, bay 8	102	03	1582	1680	1683
GDW-K21	East common rafter 2, bay 8	54	--	1500	----	1553
GDW-K22	East common rafter 4, bay 8	96	--	1429	----	1524
GDW-K23	East principal rafter, truss 9	101	--	1422	----	1522
GDW-K24	West principal rafter, truss 9	169	h/s	1406	1574	1574
GDW-K25	West corbel, truss 9	57	02	1514	1568	1570
GDW-K26	East hammer beam, truss 10	92	--	1481	----	1572

GDW-K27	West hammer beam, truss 10	82	h/s	1494	1575	1575
<u>Floor</u>						
GDW-K28	1st floor, main beam, truss 2	68	17C	1530	1580	1597
GDW-K29	1st floor, main beam, truss 3	50	h/s	1531	1580	1580
GDW-K30	2nd floor, main beam, truss 2	NM	--	----	----	----
GDW-K31	2nd floor, joist 11, bay 1	60	--	1511	----	1570
GDW-K32	2nd floor, joist 5, bay 1	NM	--	----	----	----
GDW-K33	2nd floor, joist 9, bay 1	67	17C	1531	1580	1597
GDW-K34	2nd floor, joist 13, bay 1	58	h/s	1523	1580	1580
GDW-K35	2nd floor, joist 16, bay 1	NM	--	----	----	----
GDW-K36	2nd floor, joist 19, bay 1	56	h/s	1514	1569	1569
GDW-K37	2nd floor, joist 14, bay 2	NM	--	----	----	----
GDW-K38	2nd floor, joist 15, bay 2	NM	--	----	----	----

*NM = not measured

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

C = complete sapwood retained on sample, last-measured ring is the felling date

Table 2: Results of the cross-matching of site sequence GDWKSQ01 and the reference chronologies when the first-ring date is AD 1406 and the last measured ring date is AD 1597

Reference chronology	*t*-value	Span of chronology	Reference
Newnham Hall Farm House, Newnham Murren, near Wallingford, Oxfordshire	9.7	AD 1412–1614	Arnold and Howard 2006 unpubl
Newnham Hall Farm Cottage, Newnham Murren, near Wallingford, Oxfordshire	8.4	AD 1414–1551	Arnold and Howard 2006 unpubl
Cobham Hall, Cobham, Kent	7.6	AD 1317–1663	Arnold and Howard 2003 unpubl
The White Tower, Tower of London, London	7.5	AD 1463–1612	Miles 2007
Powcher's Hall (east roof), Ely Cathedral Precinct, Ely, Cambridgeshire	7.3	AD 1457–1609	Arnold *et al* 2004
Manor House, Alford, Lincolnshire	7.1	AD 1500–1668	Arnold *et al* 2003a
Astley Castle, Warwickshire	7.0	AD 1495–1627	Howard and Litton 1997

Table 3: Results of the cross-matching of site sequence GDWKSQ02 and the reference chronologies when the first-ring date is AD 1624 and the last measured ring date is AD 1701

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	6.7	AD 882–1981	Laxton and Litton 1988
Castle House, Melbourne, Derbyshire	6.4	AD 1583–1720	Arnold and Howard 2009 unpubl
Shenton Hall Dovecote, Shenton, Leicestershire	6.2	AD 1606–1719	Arnold *et al* 2008
St Firmin Church, Thurlby, Lincolnshire	5.8	AD 1599–1792	Arnold and Howard, 2010a
All Saints' Church, North Scarle, Lincolnshire	5,8	AD 1602–1716	Arnold and Howard 2010b
6/12 Chain Lane, Newark, Nottinghamshire	5.6	AD 1608–1684	Arnold *et al* 2002
Sinai Park, Burton on Trent, Staffordshire	5.6	AD 1227–1750	Tyers 1997

Table 4: Results of the cross-matching of sample GDW-K20 and the reference chronologies when the first-ring date is AD 1582 and the last measured ring date is AD 1683

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	6.3	AD 882–1981	Laxton and Litton 1988
Blidworth, Nottinghamshire	5.9	AD 1621–1713	Laxton *et al* 1982
Bolsover Castle (Riding School), Bolsover, Derbyshire	5.2	AD 1494–1744	Howard *et al* 2005
Fellows Quad, Mertons College, Oxfordshire	5.2	AD 1442–1608	Miles and Worthington 2006
Hulme Hall, Allostock, Near Northwich,	5.1	AD 1574–1689	Arnold *et al* 2003b
Hempshill Hall, Nottinghamshire	5.1	AD 1566–1702	Arnold and Howard 2007
Stokesay Castle, Shropshire	4.9	AD 1463–1662	Miles and Worthington 1997

FIGURES

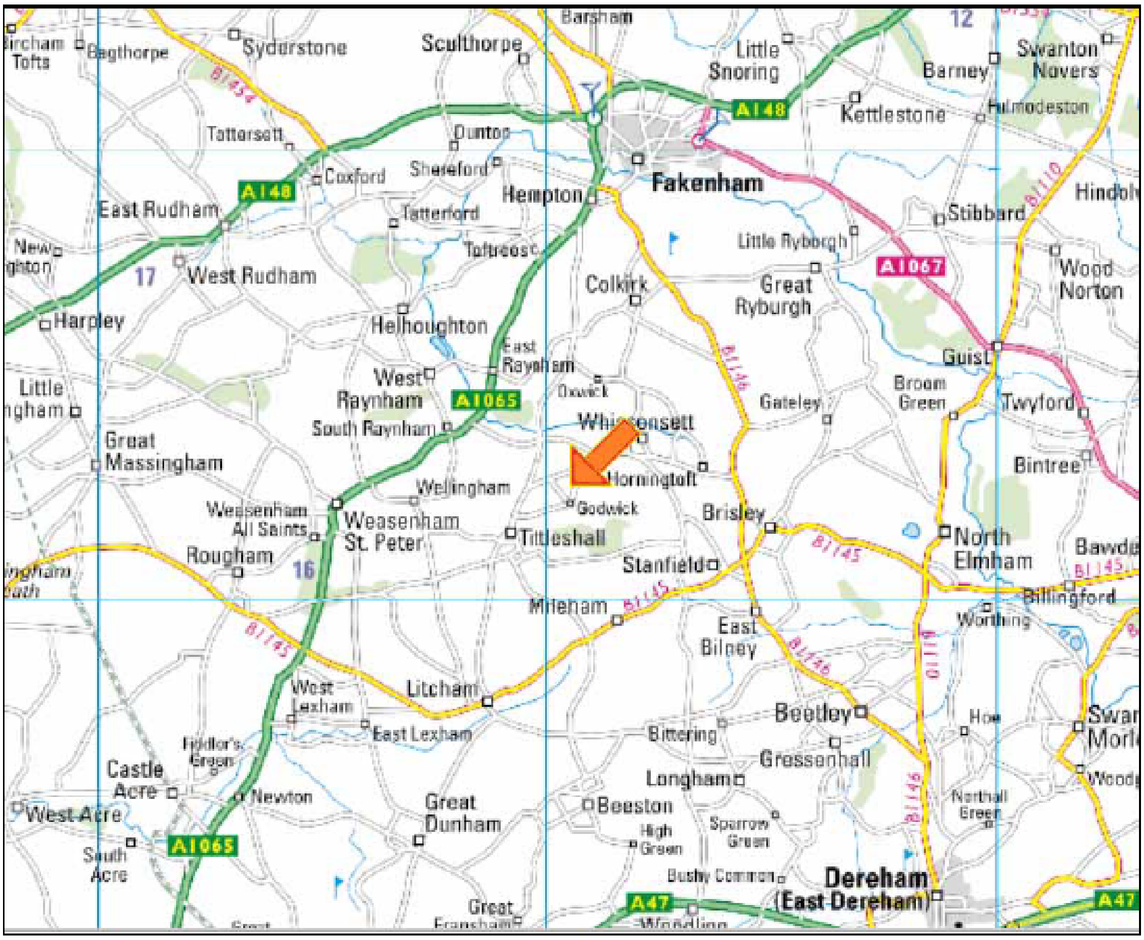

Figure 1: Map to show the general location of Godwick Great Barn, arrowed. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location of Godwick Great Barn, hatched. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Godwick Great Barn roof (photograph taken from the south-west) Photograph Robert Howard

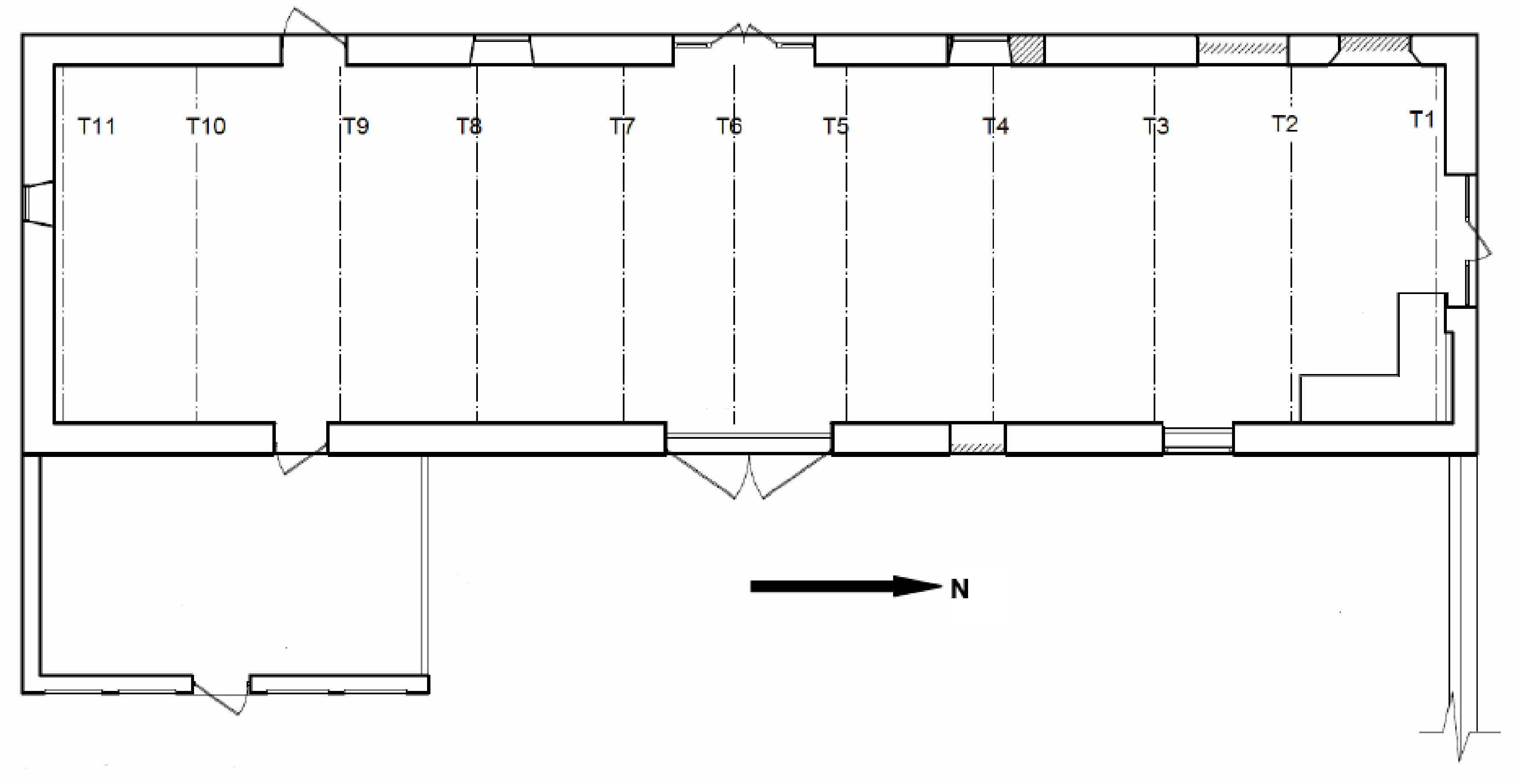

Figure 4: Ground-floor plan; showing truss locations (Wood and Stephen Design Management)

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Figure 5: Godwick Great Barn partitioning at truss 5 in the foreground (photograph taken from the south-west) Photograph Robert Howard

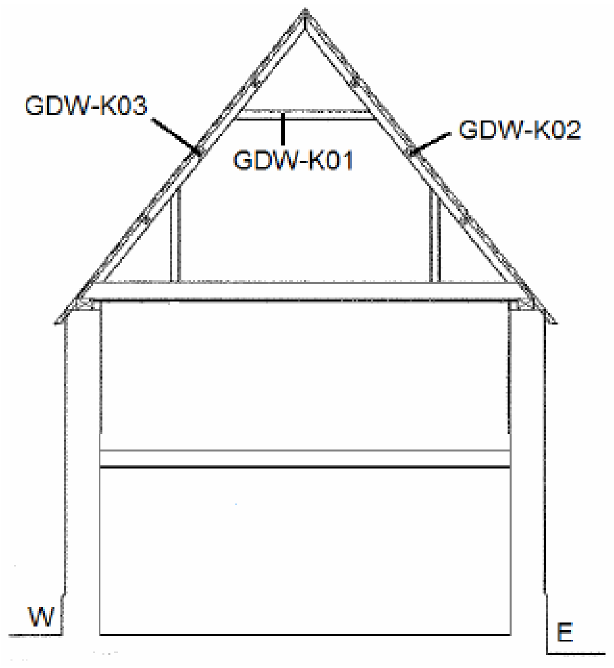


Figure 6: Truss 1, showing the location of samples GDW-K01–3 (Wood and Stephen Design Management)

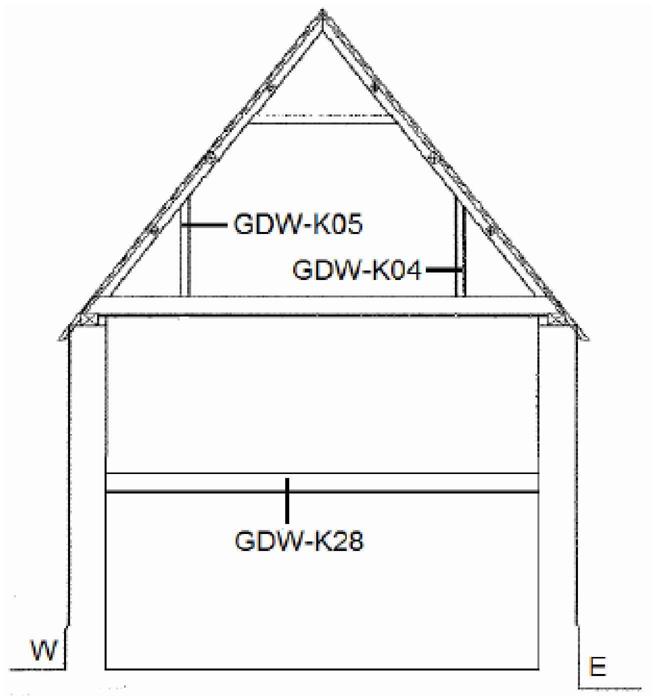


Figure 7: Truss 2, showing the location of samples GDW-K04, GDW-K05, and GDW-K28 (Wood and Stephen Design Management)

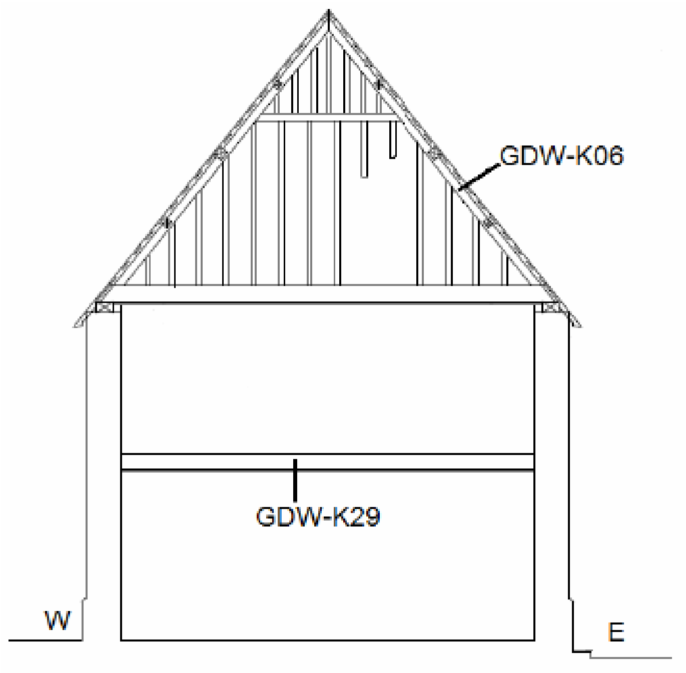


Figure 8: Truss 3, showing the location of samples GDW-K06 and GDW-K29 (Wood and Stephen Design Management)

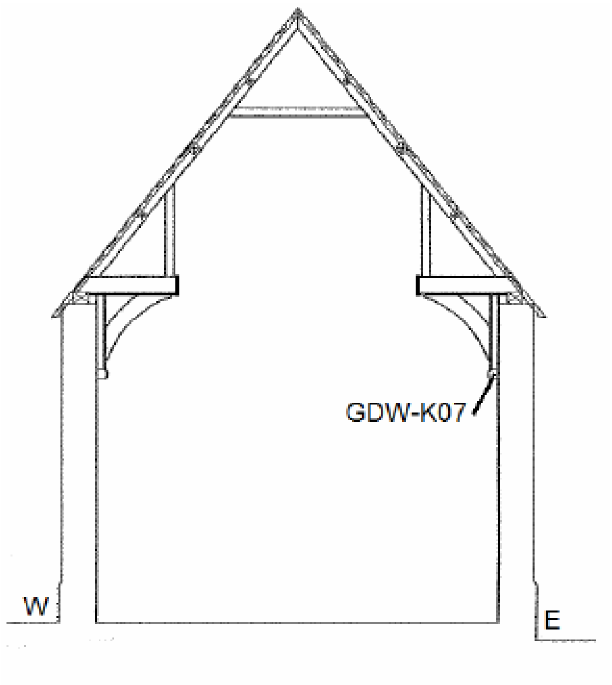


Figure 9: Truss 4, showing the location of sample GDW-K07 (Wood and Stephen Design Management)

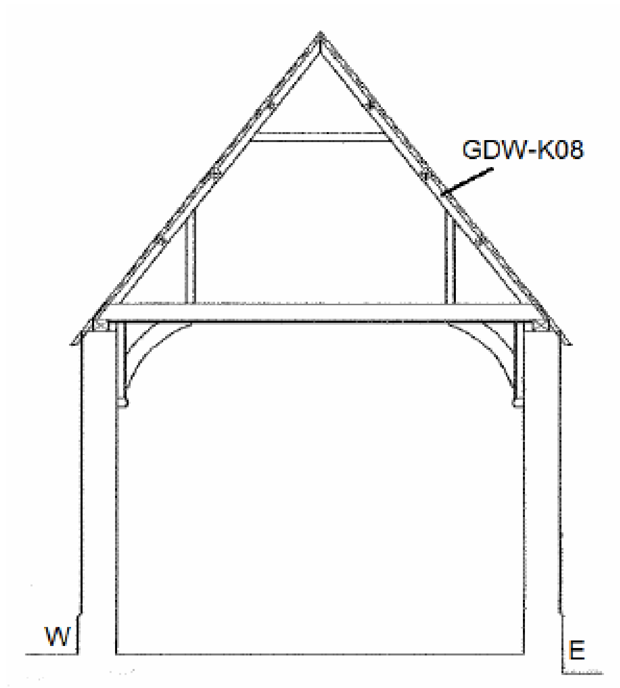


Figure 10: Truss 5, showing the location of sample GDW-K08 (Wood and Stephen Design Management)

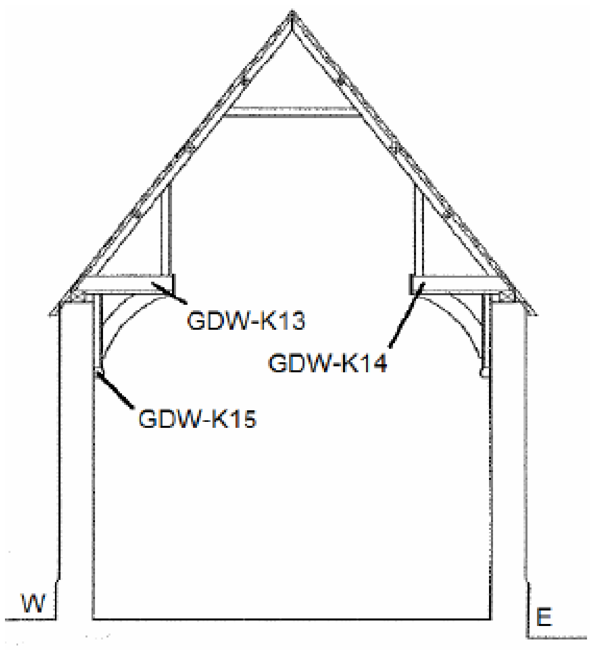


Figure 11: Truss 6, showing the location of samples GDW-K13–15 (Wood and Stephen Design Management)

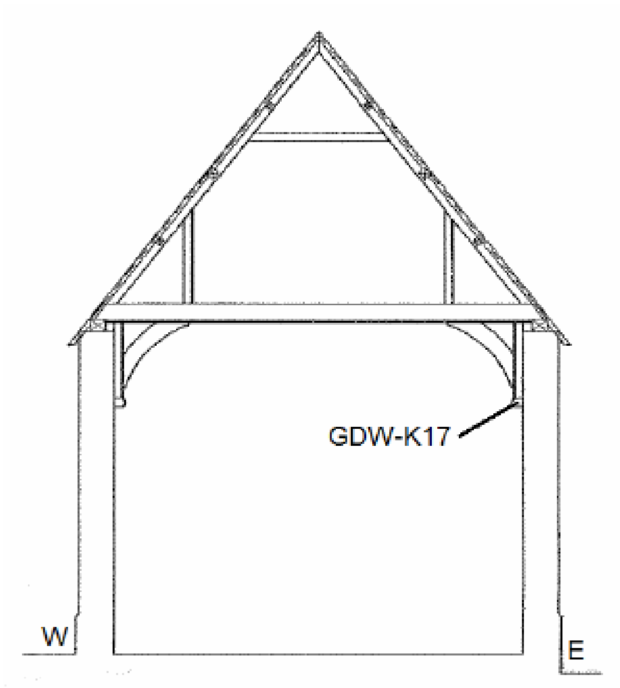


Figure 12: Truss 7, showing the location of sample GDW-K17 (Wood and Stephen Design Management)

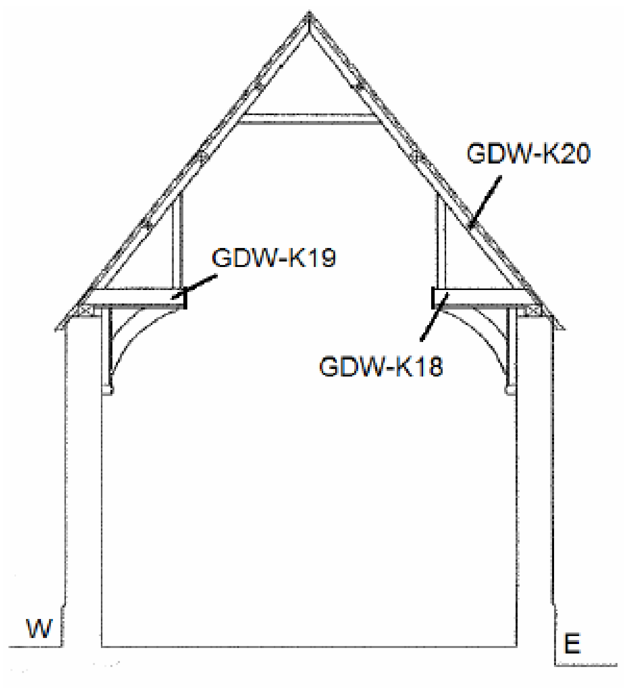


Figure 13: Truss 8, showing the location of samples GDW-K18-20 (Wood and Stephen Design Management)

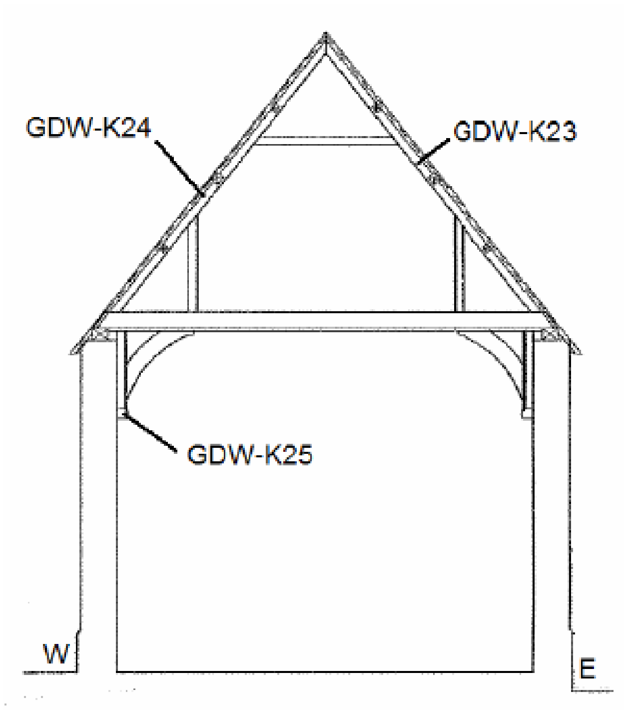


Figure 14: Truss 9, showing the location of samples GDW-K23-5 (Wood and Stephen Design Management)

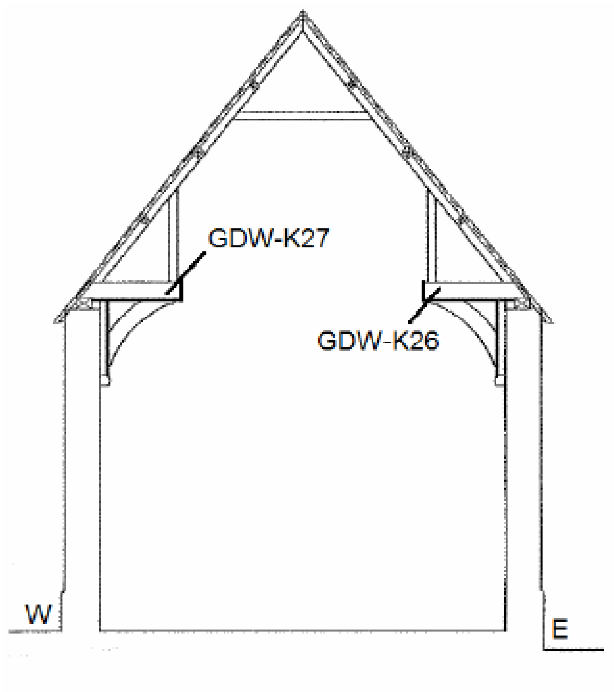


Figure 15: Truss 10, showing the location of samples GDW-K26 and GDW-K27 (Wood and Stephen Design Management)

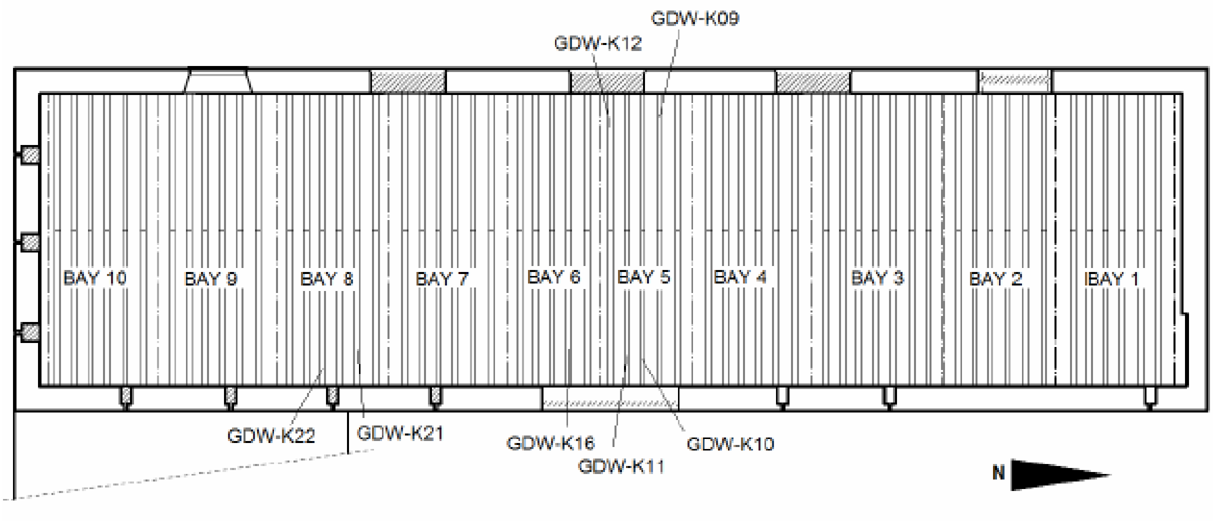


Figure 16: Plan of rafters, showing the location of samples GDW-K09-12, GDW-K16, and GDW-K21-2 (after Wood and Stephen Design Management)

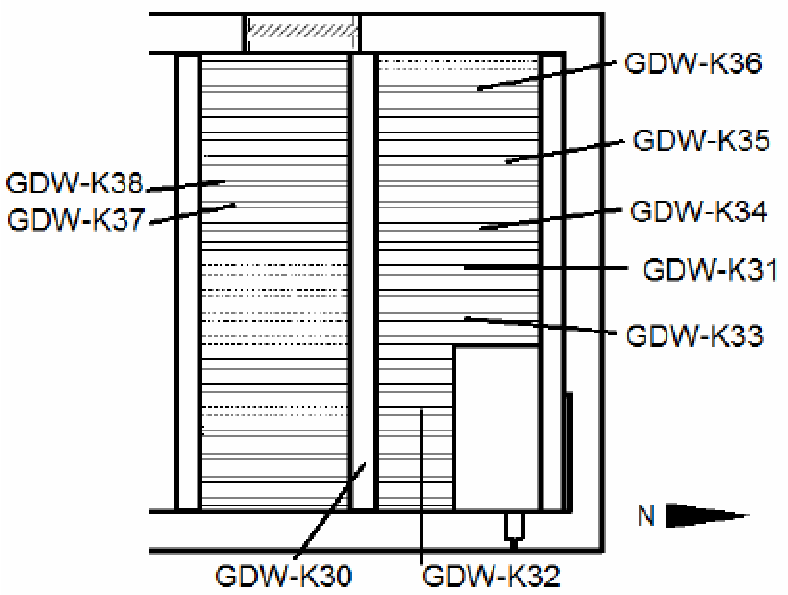


Figure 17: Second-floor plan, showing the location of samples GDW-K30-38 (after Wood and Stephen Design Management)

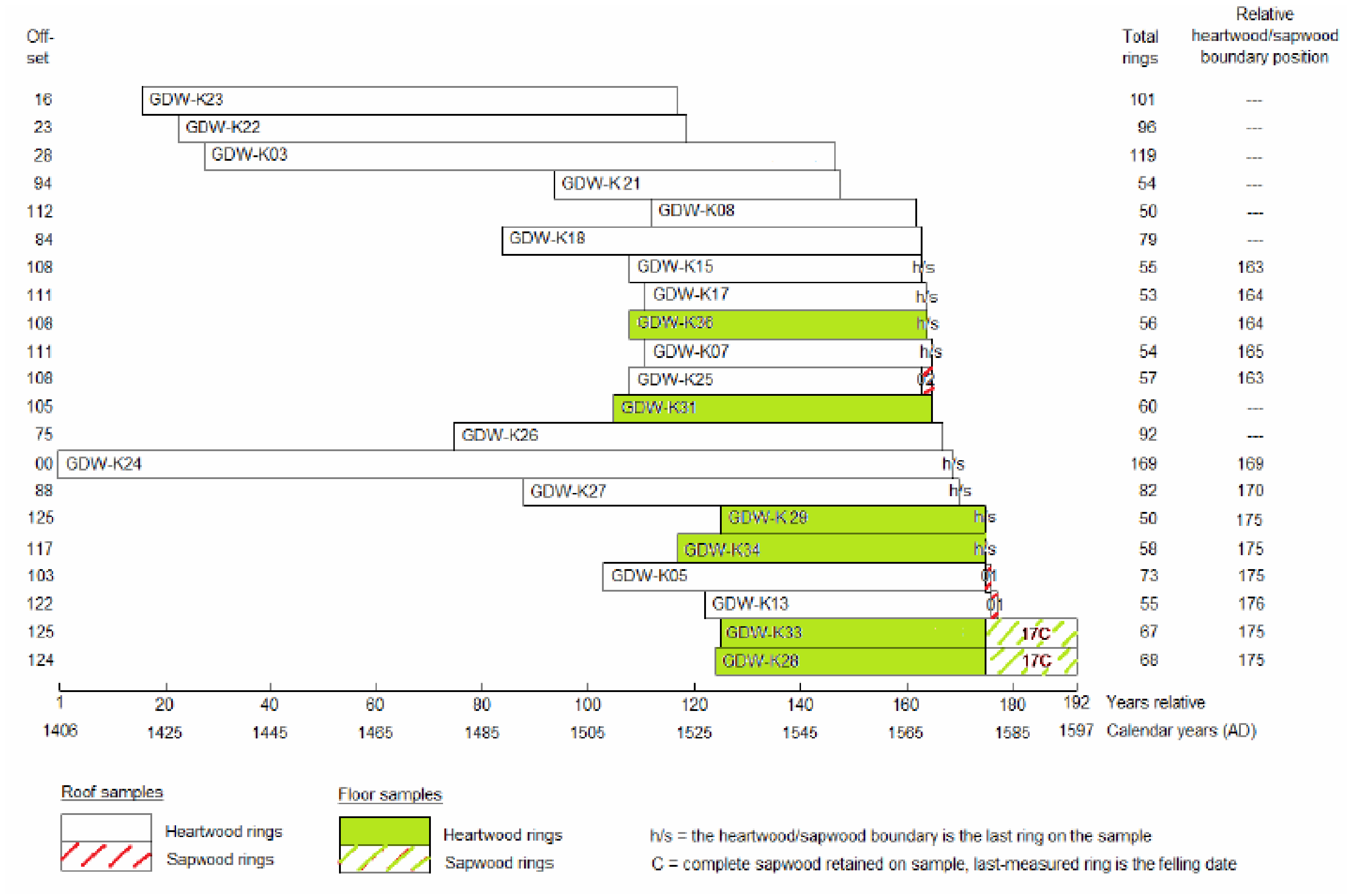


Figure 18: Bar diagram of samples in site sequence GDWKSQ01

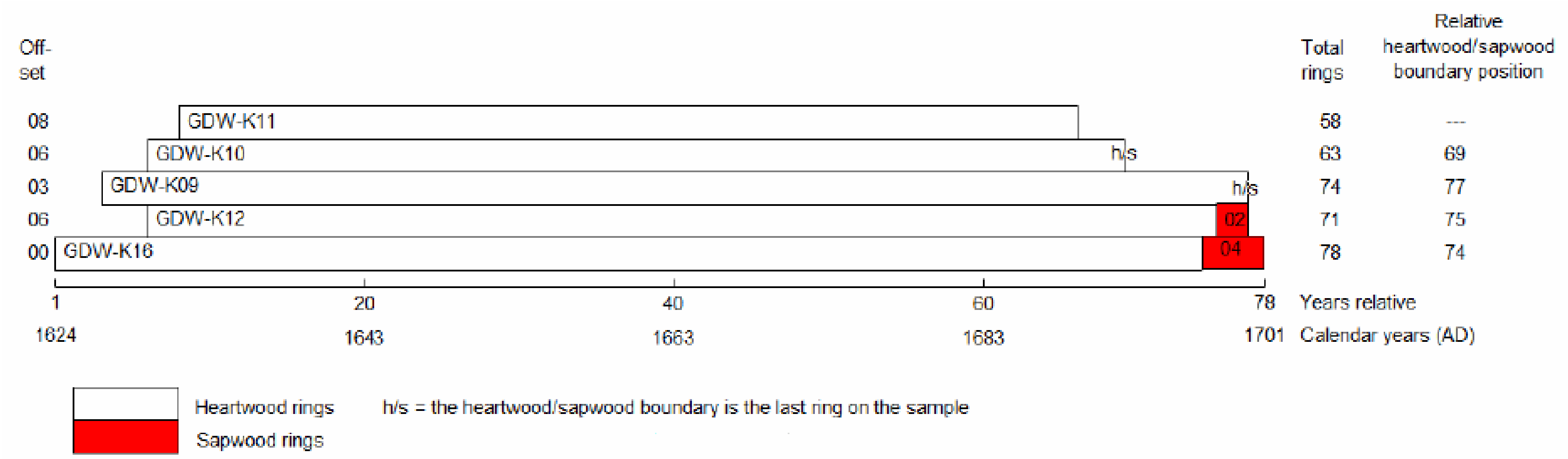


Figure 19: Bar diagram of samples in site sequence GDWKSQ02

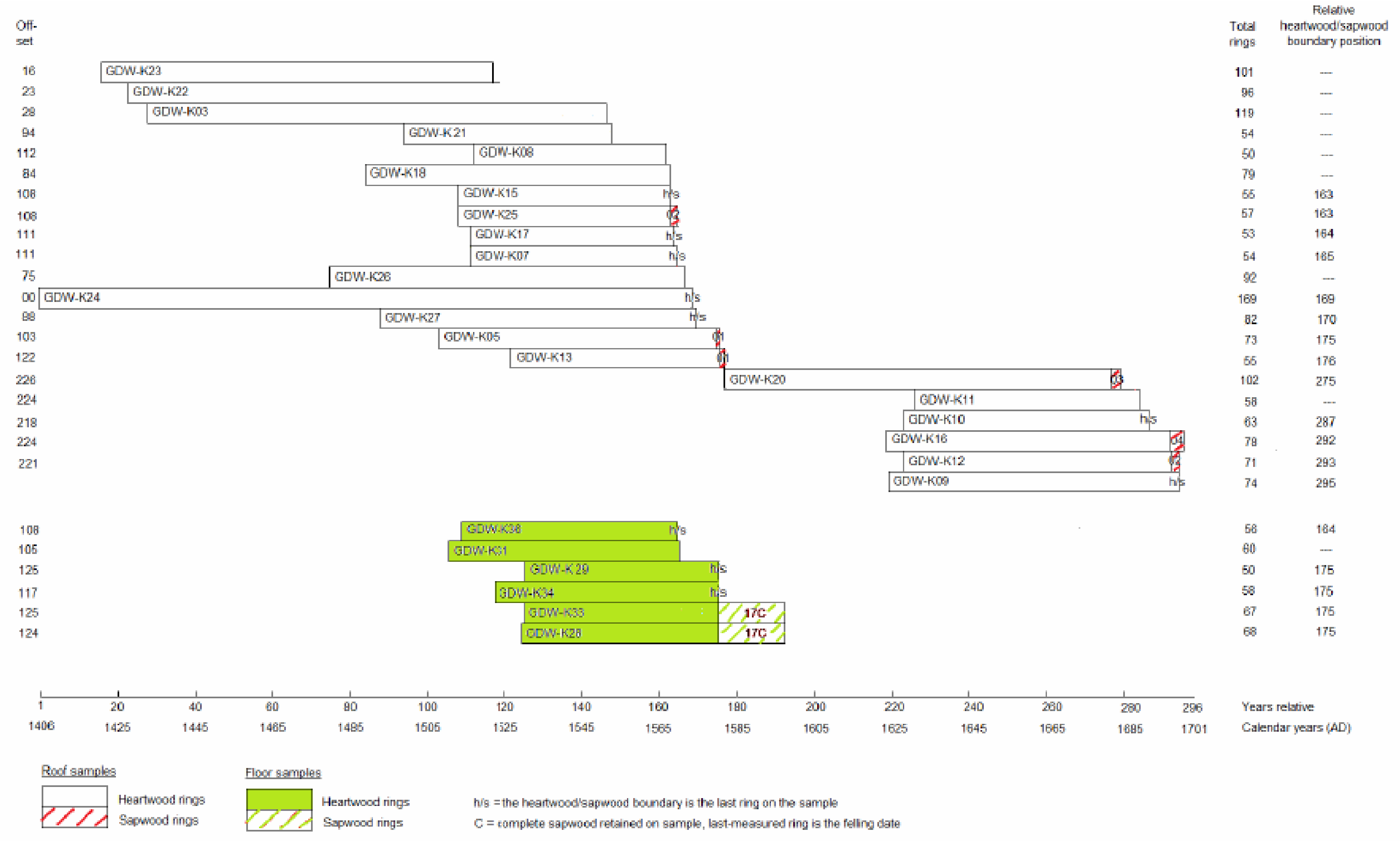


Figure 20: Bar diagram of all dated samples, sorted by heartwood/sapwood boundary and area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

GDW-K03A 119
94 99 127 126 112 98 143 89 73 102 75 57 89 88 81 80 85 101 80 76
92 76 94 70 51 86 97 107 62 97 117 113 177 121 85 139 148 163 122 114
108 119 82 107 136 133 120 164 107 101 86 86 95 119 154 139 108 84 88 102
129 156 174 67 64 97 69 70 89 87 105 99 105 90 93 103 91 123 119 102
93 73 81 58 114 71 73 52 68 57 62 45 61 59 75 64 70 93 61 65
63 61 45 35 32 46 46 58 38 47 51 46 56 52 50 40 43 54 42
GDW-K03B 119
84 108 126 121 117 92 133 94 79 102 63 78 84 84 77 80 84 109 93 82
95 70 108 62 67 67 90 90 61 114 96 107 168 125 78 148 140 160 115 117
117 113 95 105 139 116 115 154 122 91 93 88 101 122 150 133 106 91 77 107
126 156 168 69 64 95 71 72 89 84 103 98 104 96 90 100 96 115 117 104
94 86 73 62 112 65 71 49 70 60 57 46 61 65 73 68 66 97 63 56
76 57 37 31 36 49 56 55 37 48 46 52 46 56 52 45 41 42 42
GDW-K05A 58
308 252 244 235 228 228 183 295 294 327 297 379 243 310 382 435 339 171 108 116
131 218 216 268 305 488 321 256 243 266 286 238 129 111 113 240 392 242 190 127
87 97 111 151 215 165 189 171 147 119 137 129 118 93 109 198 309 186
GDW-K05B 41
157 256 165 93 129 97 94 104 92 144 175 148 212 241 199 290 268 220 241 214
210 190 293 301 338 291 384 240 300 445 446 345 180 113 136 142 221 238 246 283
458
GDW-K07A 54
313 393 435 325 371 286 257 158 257 255 326 289 268 225 380 314 332 340 410 327
373 409 470 484 395 310 285 290 229 182 182 210 234 207 235 239 204 195 221 153
166 196 239 239 145 120 82 110 106 110 122 158 176 193
GDW-K07B 54
309 392 437 329 371 283 262 159 255 265 325 283 260 247 387 331 332 337 394 353
384 427 458 470 365 309 285 269 242 207 177 204 236 204 240 225 207 191 225 158
165 194 232 245 149 124 79 103 124 100 119 159 192 125
GDW-K08A 50
295 640 391 493 446 365 261 314 368 400 335 298 330 453 423 460 440 469 400 410
446 531 651 450 337 304 304 363 389 299 329 438 362 386 296 255 224 237 187 160
216 260 280 212 204 168 130 168 122 151
GDW-K08B 50
398 617 386 526 451 371 243 363 370 396 365 317 364 454 431 457 436 475 402 404
463 527 661 455 329 305 303 359 387 304 329 390 366 375 290 248 225 237 183 154
215 255 270 215 194 161 121 152 151 124
GDW-K09A 74
269 343 454 305 286 338 365 207 268 212 222 308 231 195 195 103 153 138 169 192
158 206 183 148 155 156 201 230 195 206 135 119 91 157 138 112 96 73 73 104
76 85 72 57 73 60 55 40 40 33 69 60 87 95 92 273 180 175 132 223
169 200 183 193 191 152 155 125 130 137 154 168 157 187
GDW-K09B 74
272 344 444 304 282 339 359 212 269 208 228 314 233 191 196 102 166 140 166 192
167 203 190 136 159 157 201 239 213 207 144 115 108 153 146 116 91 77 69 105
76 81 74 57 73 60 58 45 44 31 64 58 85 88 95 261 180 174 142 215
170 200 191 196 200 142 155 133 131 139 146 166 154 184

GDW-K10A 63
166 199 276 275 197 258 247 259 362 266 225 229 118 188 162 244 215 178 208 176
125 152 166 191 250 222 230 162 127 130 147 164 107 101 83 81 97 88 77 72
56 66 60 46 47 36 29 70 55 89 93 102 242 184 177 154 213 179 207 170
186 184 169
GDW-K10B 63
204 191 249 264 209 238 249 261 365 256 240 216 118 185 165 246 190 175 214 163
127 162 162 202 248 249 234 168 140 109 162 148 114 93 86 86 101 73 67 76
57 72 56 63 45 40 29 67 60 82 98 89 218 190 194 163 210 197 207 172
183 178 163
GDW-K11A 58
166 296 195 224 190 161 194 168 146 154 72 139 121 149 165 131 179 169 117 128
127 157 218 209 192 153 123 112 171 147 98 73 59 65 97 68 56 57 48 59
59 61 47 33 42 71 75 123 131 109 263 184 173 138 239 159 166 168
GDW-K11B 58
167 294 194 221 188 162 197 171 147 154 79 140 119 147 164 138 171 165 120 136
133 167 214 212 196 146 132 118 160 147 96 72 70 58 103 64 54 58 53 58
55 62 44 29 44 73 74 117 135 115 261 183 168 154 234 153 168 171
GDW-K12A 71
252 330 390 390 243 230 208 191 251 199 152 189 116 168 130 193 177 151 186 165
131 149 126 158 207 207 214 193 174 124 184 145 102 76 71 85 88 72 55 56
53 43 51 44 40 41 26 66 89 178 161 136 259 191 170 140 249 170 170 161
161 176 136 133 87 100 115 118 159 144 140
GDW-K12B 71
192 325 393 397 234 238 205 199 241 208 167 180 98 167 134 190 201 140 200 173
130 153 138 160 205 207 226 206 181 122 187 142 110 77 77 73 94 62 60 58
44 45 48 51 32 43 23 73 92 178 163 135 272 190 166 140 248 177 164 153
161 178 131 133 90 95 119 120 161 137 141
GDW-K13A 55
446 401 451 391 277 314 341 421 224 219 283 323 432 330 277 236 352 567 556 417
359 510 332 320 298 345 387 453 220 323 260 313 316 253 268 279 225 261 264 255
220 250 203 221 181 198 198 208 191 140 141 159 209 166 128
GDW-K13B 55
476 410 356 394 246 359 341 419 223 214 285 343 417 352 274 234 350 583 529 433
352 510 333 319 302 347 384 457 219 300 260 314 317 250 267 277 228 256 270 244
227 255 202 218 187 197 201 210 193 135 134 152 212 165 133
GDW-K15A 55
265 294 243 152 260 344 216 266 268 274 341 509 429 401 375 268 237 357 364 362
395 426 311 313 387 411 468 470 287 272 252 222 211 171 202 195 177 194 183 176
151 179 123 144 164 205 186 102 132 84 102 93 87 72 103
GDW-K15B 55
268 305 234 148 263 346 216 263 266 265 352 509 437 396 384 278 227 361 362 359
390 425 320 320 367 418 459 461 299 253 253 239 219 170 201 190 182 194 183 182
148 183 124 140 171 207 178 119 134 89 91 93 78 87 104
GDW-K16A 78
275 318 259 310 300 359 233 221 277 215 159 186 193 206 273 253 166 157 103 177
130 205 167 132 197 126 120 135 129 136 164 150 125 88 82 72 115 111 73 66
59 54 85 50 50 51 52 50 53 74 35 42 29 78 56 140 135 99 242 165
140 113 176 99 127 146 145 144 92 143 85 95 132 156 159 98 151 129
GDW-K16B 78
280 304 259 297 311 395 228 216 283 209 159 182 220 218 283 240 159 151 99 178
140 207 173 138 201 133 118 127 135 140 167 149 124 92 75 76 111 113 70 62
59 62 81 54 43 58 51 52 54 66 41 46 31 73 56 136 138 108 243 163

150 110 173 100 128 142 142 148 98 143 84 105 138 144 146 104 159 136
GDW-K17A 53
372 480 572 375 436 443 394 270 317 310 336 269 275 246 374 316 353 346 353 311
359 380 487 469 407 254 270 274 243 325 237 250 266 270 294 263 233 175 208 154
176 233 290 257 173 119 95 106 97 105 96 135 162
GDW-K17B 53
379 471 566 385 429 448 412 281 320 294 355 277 265 248 366 313 355 347 351 301
364 383 485 476 402 258 267 266 250 325 242 248 272 269 299 265 236 175 218 156
180 238 291 247 179 109 99 107 94 93 96 142 168
GDW-K18A 79
206 237 192 347 298 280 312 214 129 180 201 254 225 135 96 157 156 170 189 223
238 287 262 212 226 258 251 142 248 247 187 220 199 159 105 142 183 159 192 153
140 235 148 141 153 205 162 199 177 207 244 183 135 151 172 166 171 182 173 195
168 159 159 201 166 200 160 143 137 165 160 172 187 157 137 131 128 150 188
GDW-K18B 79
199 234 182 271 353 185 369 246 161 166 184 215 209 118 95 147 181 179 201 214
250 262 250 223 218 247 252 143 243 249 176 219 205 146 130 137 188 150 189 153
146 233 152 136 154 205 165 191 176 205 247 170 137 157 177 167 147 181 165 196
172 153 158 197 159 193 160 141 150 163 173 174 197 145 130 127 142 142 169
GDW-K19A 57
209 300 290 227 283 265 183 254 239 341 228 259 274 279 316 286 292 308 479 624
591 307 192 256 215 182 129 168 117 144 98 111 123 106 115 118 161 157 87 72
97 127 155 149 238 236 169 164 251 294 186 160 173 146 181 122 107
GDW-K19B 57
218 301 292 228 282 273 181 251 232 348 230 253 287 271 314 294 291 311 474 630
586 322 186 254 217 180 117 170 129 145 101 113 131 108 114 116 168 148 87 71
104 124 157 150 238 236 170 169 250 293 188 164 174 151 182 127 100
GDW-K20A 102
70 83 129 191 264 222 172 180 149 175 187 211 153 211 174 136 185 172 163 159
135 155 139 71 115 153 166 91 144 113 85 77 56 88 62 94 87 92 62 57
84 48 94 77 75 76 40 55 50 38 68 52 32 50 33 60 99 137 156 130
105 76 84 109 158 137 170 158 80 105 87 69 108 144 101 86 102 109 118 116
78 118 81 73 89 86 67 84 104 108 119 91 69 53 65 122 154 99 141 99
237 196
GDW-K20B 102
68 78 126 197 258 225 171 180 146 174 183 212 148 216 180 138 178 175 166 164
143 142 137 77 115 155 165 91 149 107 87 78 53 92 62 85 94 90 61 66
78 56 85 76 77 76 42 50 54 41 65 40 38 47 38 66 97 132 157 132
93 83 88 105 155 140 172 154 83 105 85 68 114 147 100 85 105 103 122 116
82 126 72 74 82 86 70 80 109 108 115 93 69 63 60 117 152 103 141 98
246 228
GDW-K21A 54
173 266 262 371 138 417 267 330 194 284 202 117 137 104 151 109 113 79 101 124
70 90 94 77 54 85 102 143 120 104 136 132 89 115 100 136 124 138 149 140
143 120 108 105 143 106 99 67 81 105 106 111 146 166
GDW-K21B 54
159 262 261 369 145 402 249 345 189 317 211 104 133 105 165 109 101 85 98 127
64 96 91 76 54 101 102 136 121 107 134 153 110 107 100 136 127 151 145 135
146 112 105 101 147 111 95 64 77 113 97 115 141 170
GDW-K22A 96
128 156 151 160 92 92 100 66 67 103 87 89 57 78 71 108 71 78 76 111
123 110 102 117 112 136 103 137 152 162 132 142 153 143 119 110 102 111 106 93
182 192 216 242 146 132 112 71 80 85 81 121 130 90 69 57 64 76 113 97

75 94 76 72 86 88 87 111 59 56 63 51 77 88 80 91 59 96 80 67
85 92 82 86 88 79 77 84 80 98 81 67 69 98 64 64
GDW-K22B 96
138 152 148 151 103 84 102 62 72 93 96 77 73 74 67 102 68 86 71 112
129 102 112 113 105 142 98 136 146 157 129 138 151 138 125 111 103 119 98 95
186 186 200 242 142 126 118 64 87 84 92 109 121 88 69 50 62 69 116 95
83 103 76 68 83 95 90 116 57 57 58 53 81 83 81 85 65 94 73 73
93 89 78 84 93 76 80 77 86 101 84 59 68 99 61 62
GDW-K23A 101
169 211 202 168 150 171 168 187 200 217 178 121 143 158 171 135 102 88 102 120
130 130 112 99 62 79 84 100 136 129 111 120 110 124 149 124 113 97 126 93
133 115 137 118 151 98 78 141 171 160 155 155 142 145 92 95 97 99 121 148
85 71 73 76 118 225 167 144 137 84 94 119 83 83 120 61 54 52 51 60
80 67 62 60 65 68 74 99 111 82 95 59 63 65 85 69 69 66 65 51
66
GDW-K23B 101
169 202 201 149 166 167 168 188 197 231 178 118 142 144 178 137 95 87 100 137
126 127 114 99 64 79 80 121 143 128 122 128 103 120 154 125 111 92 114 80
129 124 140 116 147 100 96 124 176 157 163 154 133 151 93 96 101 99 120 147
84 71 92 64 111 228 179 139 140 84 91 122 86 82 119 64 44 60 51 57
71 68 67 60 62 71 81 101 103 85 90 65 60 65 80 71 80 58 69 63
69
GDW-K24A 169
250 164 131 117 178 204 107 111 155 124 80 100 177 261 246 185 156 204 176 158
160 119 104 155 179 192 128 113 127 109 107 91 77 79 118 126 149 127 86 70
59 72 81 103 117 128 122 124 139 140 201 174 152 84 92 74 124 152 121 113
146 102 79 116 167 145 163 114 93 97 62 77 76 81 104 116 63 67 72 71
106 148 128 119 108 73 83 101 119 102 93 58 65 74 60 92 95 71 58 65
64 71 84 90 87 87 73 58 67 69 93 73 82 67 61 60 73 47 36 74
84 90 75 73 64 99 58 53 56 103 78 75 75 90 74 83 66 69 64 85
76 61 83 85 74 68 63 78 65 82 48 46 54 66 78 100 111 105 97 110
87 77 116 75 88 43 58 74 72
GDW-K24B 169
228 159 138 120 181 201 108 107 147 124 86 110 163 256 235 191 161 205 170 160
164 106 110 162 178 185 137 106 112 113 99 88 88 74 115 126 146 130 93 56
71 71 86 105 115 128 123 133 132 139 210 173 149 79 88 91 121 154 127 107
133 99 86 98 176 148 172 121 91 99 66 70 82 83 103 111 65 72 67 72
105 143 124 114 114 83 72 101 127 89 106 61 60 78 57 87 99 67 65 66
71 75 79 102 89 75 81 71 64 69 78 75 88 65 61 57 80 49 35 70
84 90 76 68 69 100 51 60 57 98 77 77 79 85 78 79 71 69 66 82
80 59 78 90 67 72 58 82 70 76 49 51 54 57 90 92 121 116 103 105
83 83 104 84 86 48 57 71 70
GDW-K25A 57
231 370 260 246 376 460 321 336 321 270 219 337 314 321 251 244 216 357 305 370
367 426 308 348 437 450 464 407 319 305 271 269 271 225 258 252 231 237 219 233
180 213 140 191 175 216 210 152 129 107 113 114 107 96 143 160 138
GDW-K25B 57
214 362 261 266 372 458 322 344 312 278 217 316 319 324 260 245 213 362 299 371
375 431 320 347 432 473 470 394 285 294 278 270 271 226 267 244 236 238 220 241
187 216 141 194 181 213 221 148 131 109 111 108 107 104 135 165 166
GDW-K26A 92
240 162 164 244 304 268 403 363 262 278 205 222 378 397 352 455 213 204 325 271
365 309 250 207 205 261 308 192 286 293 209 270 240 295 337 247 173 318 275 240

266 230 175 218 207 197 209 212 152 169 227 139 146 194 240 166 205 230 187 240
169 114 189 174 232 144 200 208 256 161 171 189 210 177 201 124 172 187 201 197
202 196 189 147 147 199 214 215 224 221 225 233
GDW-K26B 92
223 190 166 246 305 278 393 347 270 264 206 235 386 396 352 464 215 200 326 278
367 321 246 225 191 255 296 190 233 290 208 271 235 290 340 265 187 294 263 236
216 226 166 199 173 205 193 224 144 156 248 125 143 204 241 183 205 226 176 231
183 104 203 188 241 110 231 195 249 178 162 195 197 183 216 131 159 179 202 173
214 173 201 144 165 196 199 220 259 214 209 240
GDW-K27A 82
321 234 347 177 192 361 292 344 298 215 233 193 213 305 183 170 207 153 208 207
270 276 222 158 262 226 190 180 232 151 166 158 185 212 217 124 145 199 137 111
190 284 215 198 191 226 345 164 103 171 152 192 108 164 161 212 160 113 171 189
161 193 118 117 123 180 173 200 146 154 125 154 159 197 211 217 213 182 179 191
242 225
GDW-K27B 82
331 219 346 196 175 352 304 345 303 218 221 199 223 292 184 180 215 144 225 210
266 280 218 164 260 223 192 180 234 149 162 156 189 215 215 124 142 204 116 128
185 289 209 210 190 219 331 180 101 174 145 207 110 156 155 227 149 129 167 181
160 198 119 105 125 179 172 209 141 160 119 143 150 189 202 245 202 189 196 180
258 214
GDW-K28A 68
344 503 423 339 421 378 418 347 367 515 580 513 391 377 431 503 483 401 335 400
319 428 409 417 399 370 242 219 359 339 354 259 224 143 135 113 168 163 189 231
222 239 231 210 227 191 180 209 180 172 227 140 184 228 232 215 212 195 253 300
200 251 289 277 264 286 274 186
GDW-K28B 68
361 483 406 396 404 348 403 339 367 539 580 522 413 406 442 521 494 392 340 393
318 412 432 410 396 368 243 231 350 330 354 269 214 152 119 124 165 156 199 231
226 235 226 214 217 202 162 210 182 176 224 146 191 228 212 212 229 216 243 326
194 235 275 281 261 273 286 206
GDW-K29A 50
253 190 238 346 335 348 320 343 435 355 266 250 188 536 641 459 387 366 530 435
466 460 416 273 365 267 355 448 420 554 461 581 380 296 248 290 391 476 531 324
182 207 237 657 532 250 300 335 240 223
GDW-K29B 50
276 188 232 343 323 330 327 348 431 347 279 239 188 542 665 460 385 355 520 445
474 448 412 290 375 260 339 433 430 518 461 576 369 292 265 286 390 485 525 330
189 204 236 676 535 255 298 330 238 231
GDW-K31A 60
206 185 257 255 264 269 311 288 215 248 466 563 358 315 293 291 289 293 269 275
371 385 332 311 353 415 331 321 378 341 197 88 170 221 285 225 241 403 611 345
371 244 247 173 253 199 135 162 203 236 211 197 172 103 64 123 94 144 167 157
GDW-K31B 60
205 190 250 264 258 269 303 286 220 247 485 565 355 312 303 290 308 299 270 275
374 385 336 306 346 411 324 327 378 334 195 85 168 227 290 231 238 392 646 368
364 228 263 173 246 203 137 165 196 240 218 186 173 103 67 114 98 139 173 155
GDW-K33A 67
354 247 295 212 368 262 185 196 382 403 241 98 153 237 324 225 245 316 389 324
352 284 324 231 263 108 129 150 213 238 199 139 124 66 81 111 108 97 146 137
112 109 107 143 201 143 141 158 147 227 165 147 106 134 207 166 96 67 110
94 119 150 176 147 160 118 133
GDW-K33B 67

352 260 280 217 366 234 180 203 375 418 240 97 154 216 341 235 247 296 412 321
341 268 319 242 269 119 130 144 224 232 200 143 118 68 78 112 105 104 147 137
107 109 85 157 201 144 132 166 154 218 162 152 129 126 197 152 86 64 118
101 105 152 175 140 162 141 110
GDW-K34A 58
174 210 147 157 228 193 238 137 232 200 176 164 212 164 194 204 270 367 182 80
103 117 166 156 228 253 237 191 151 167 205 166 144 90 65 91 84 125 118 134
115 83 113 126 100 152 90 123 87 65 91 113 138 97 96 107 132 148
GDW-K34B 58
157 211 152 154 192 197 253 149 205 188 164 212 199 165 208 219 267 363 188 82
99 118 167 159 226 252 252 182 167 172 200 166 145 91 61 86 94 110 109 139
112 101 106 122 111 151 92 124 86 71 91 120 145 99 101 95 126 140
GDW-K36A 56
304 244 315 350 468 402 253 210 175 118 173 213 175 122 102 80 67 190 432 557
560 426 382 457 431 602 505 229 105 202 265 301 379 338 361 459 374 299 249 382
256 242 114 122 157 238 251 396 283 284 157 136 122 104 137 180
GDW-K36B 56
300 251 308 336 467 416 241 211 178 117 189 205 177 128 96 78 63 196 452 512
522 424 392 448 444 592 506 228 117 188 276 299 364 343 355 469 358 316 252 387
249 238 119 126 157 232 238 410 281 276 169 128 112 110 144 196

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

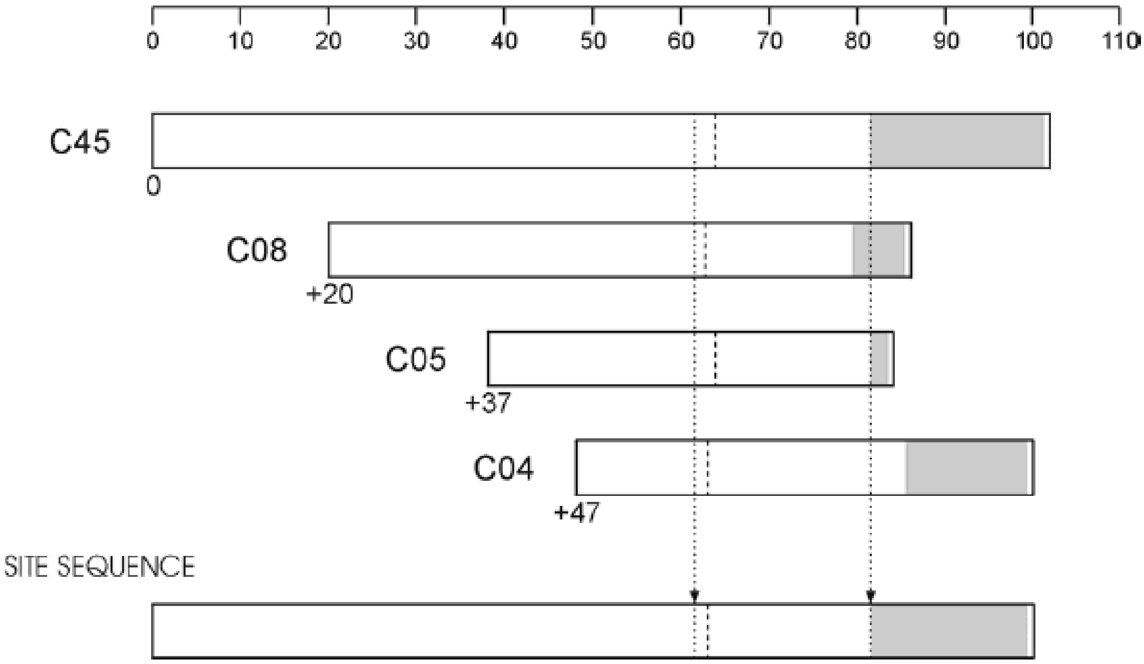


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

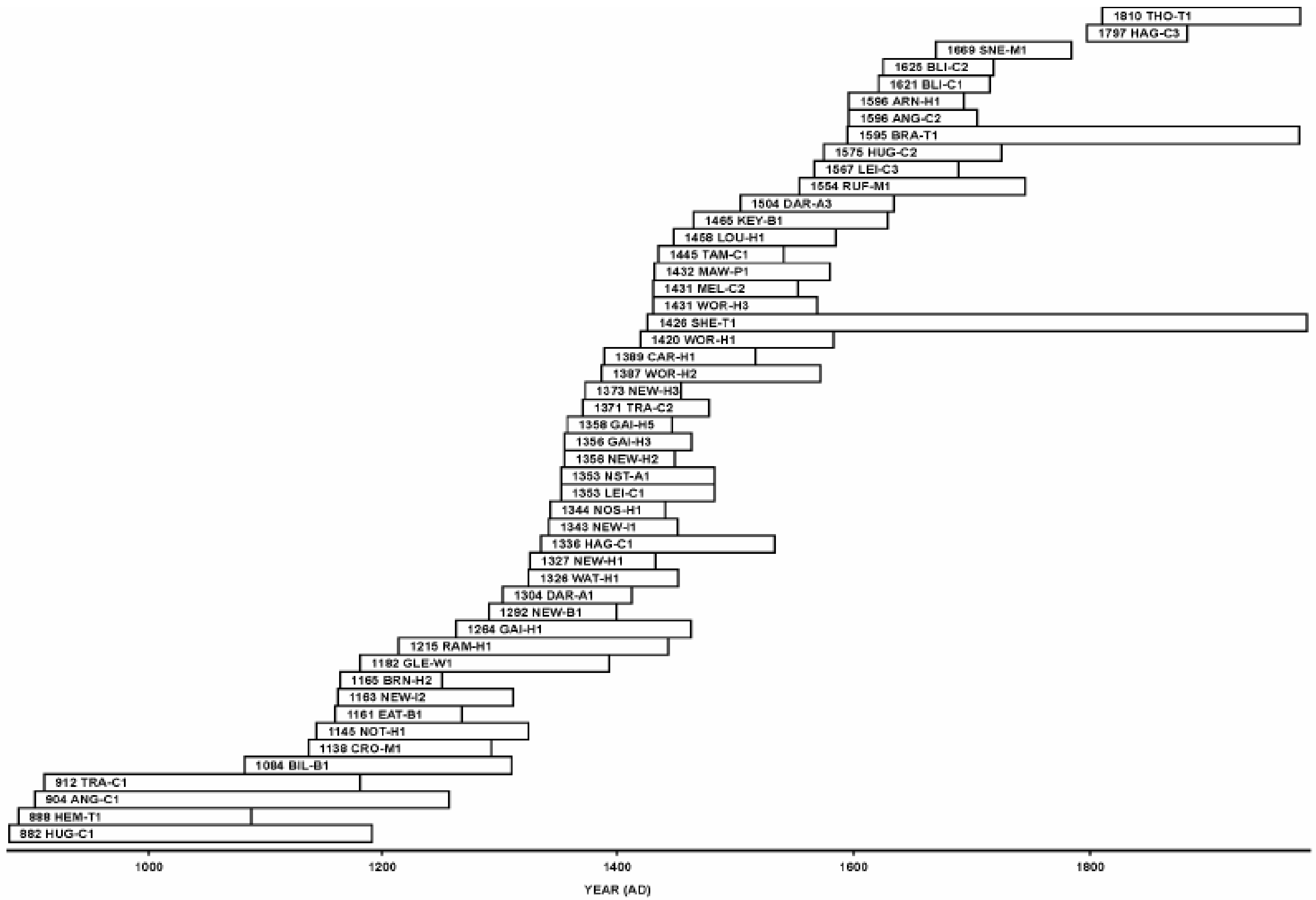
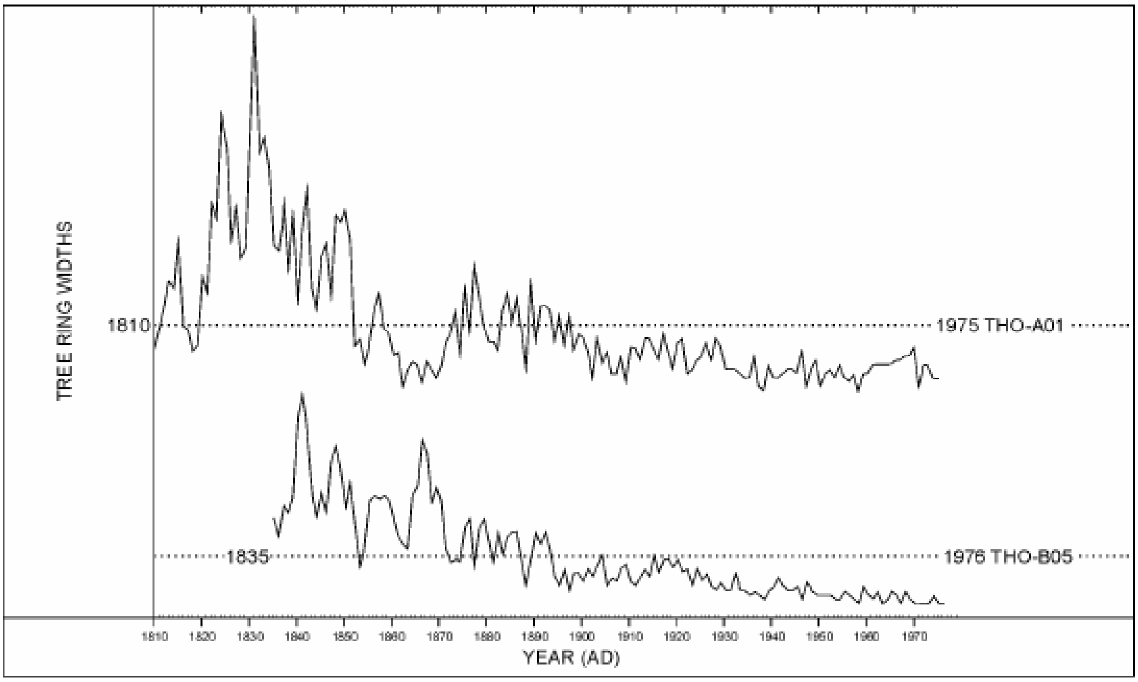


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

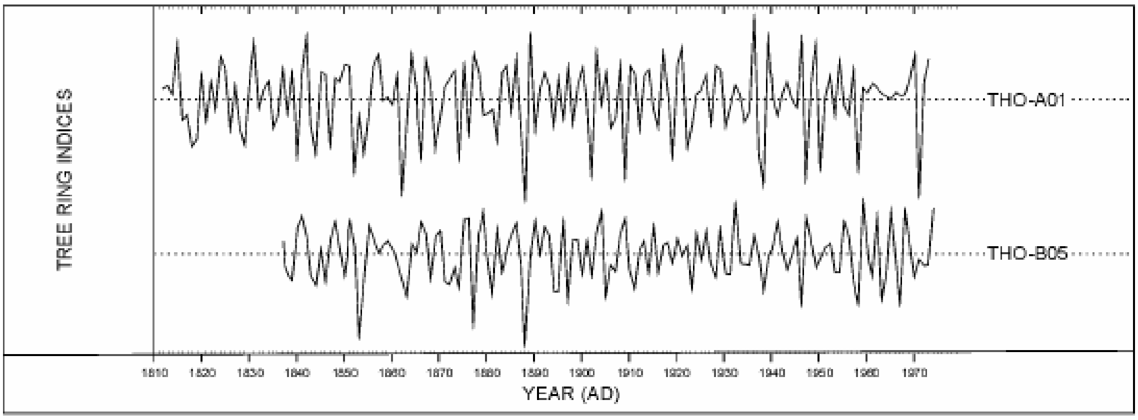


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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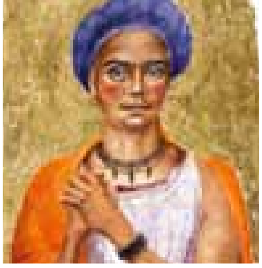


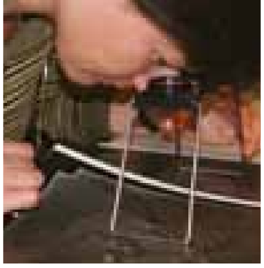


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