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Choir roof, The Minster Church of St John, Beverley, East Riding of Yorkshire
Tree-ring dating of oak timbers

Alison Arnold, Robert Howard and Cathy Tyers

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CHOIR ROOF
THE MINSTER CHURCH OF ST JOHN
BEVERLEY
EAST RIDING OF YORKSHIRE

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SUMMARY
Tree-ring analysis was undertaken on samples taken from oak timbers of the Choir roof of The Minister Church of St John, Beverley, resulting in the construction of a single site sequence. Site sequence BEVKSQ01 contains 24 samples and spans the period AD 1573–1736. Interpretation of the surviving sapwood suggests felling of timbers in the mid-AD 1730s, some timbers having precise felling dates of AD 1735 and AD 1736, with construction likely to have followed shortly after. This would indicate the roof relates to part of the restorations undertaken by Hawksmoor.

CONTRIBUTORS
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CONTENTS

INTRODUCTION

The *Early Fabric in Historic Towns: Voluntary Group Projects*, funded by Historic England, have been developed in the recognition and acknowledgement of the excellent work being undertaken by local vernacular groups in the study of local architectural trends and fabrics. The project's intention is to encourage this type of study through the provision of support and to facilitate training of more people in building analysis and recording. The local projects were coordinated by Rebecca Lane (Historic England South West Region: Senior Architectural Investigation).

Early Fabric in Beverley Project

Whilst there is a corpus of research on form and age of the town of Beverley, it does not cover detailed examination of early fabric or aspects of typology, with analysis and interpretation of existing buildings until now not having benefited from dendrochronology, with the exception of some limited work on the Minster.

Initially, 13 properties were identified that were thought to be key to understanding the town's architectural development for a programme of comprehensive investigation. These properties were assessed for their suitability for tree-ring dating and those found to contain timbers potentially suitable for analysis were sampled. As the project progressed and some of the original buildings identified were rejected as unsuitable for tree-ring dating, further candidates for tree-ring analysis were assessed and sampled if appropriate.

It was hoped that successful dating of these buildings would extend the knowledge of early fabric and selected buildings in the historic town of Beverley in support of Historic England's responsibility to identify and understand the urban vernacular and historic environment of a market town. The reports produced on the buildings recorded as part of this project by the Yorkshire Vernacular Buildings Study Group, led by David Cook, will be held in the YVBSG archive and will be available through their website (www.yvbsg.org.uk), whilst a summary of the project is presented in Vernacular Architecture (Cook and Neave 2018).

THE MINSTER CHURCH OF ST JOHN

The Minster Church of St John (List Entry No 1084028), Beverley (Figs 1–3) is built on the site of a seventh-century monastery. Its nave is constructed of Tadcaster magnesian limestone and the choir and transepts from oolitic limestone. It is of cruciform plan with a seven-bay, aisled chancel with square east end and single-bay eastern transepts, aisled to the east, three bay double aisled main transepts and central tower. The west front has twin towers with offset angled buttresses (Fig 4). Building of the eastern arm began after a fire destroyed parts of the earlier Romanesque church in AD 1188. In *c* AD 1219 a tower collapsed causing substantial damage to the Minster and necessitating rebuilding of parts of the building, work thought to have commenced after c AD 1225. The 11-bay nave dates to *c* AD 1308–50, the north porch and west front to *c* AD 1390–1420, and the north-east chapel to *c* AD 1490. The Minster was in a poor state of repair by the early-eighteenth century and in AD 1716 the architect Nicholas Hawksmoor devised an extensive programme of restoration; other works were undertaken in the nineteenth century (Miller *et al* 1982).

Choir roof

The roof over the Choir consists of 15 trusses of principal rafters, collars, tiebeams, queen posts, king posts, braces, and struts (Fig 5). Between these trusses are common rafters, a large number of which show signs of reuse, and purlins. Previous research on the Choir roof, undertaken on behalf of the Friends of Beverley Minster, had dated two tiebeams as likely to have been felled in the mid-AD 1730s (Tyers 2012) and identified the use of reused common rafters of AD 1234–59 (Arnold and Howard 2016).

SAMPLING

A total of 24 core samples was taken from oak (*Quercus* sp.) timbers of the Choir roof. Each core sample was given the code BEV-K and numbered 01–24. The location of all samples was noted at the time of sampling and has been marked on Figure 6. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

All 24 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 programme (see Appendix), resulting in 24 samples matching at a minimum *t*-value of 5.0 to form a single group.

These 24 samples were combined at the relevant offset positions to form BEVKSQ01, a site sequence of 164 rings (Fig 7). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1573 and a last-measured ring date of AD 1736. The evidence for this dating is given in Table 2.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of all 24 samples taken from the Choir roof. Where sapwood is incomplete or missing felling date ranges or *terminus post quem* dates for felling have been calculated using the estimate that 95% of mature trees in this region have 15–40 sapwood rings. Five of these samples have complete sapwood. One, BEV-K16, has the last-measured ring date of AD 1736, the felling date of the timber represented. The other four samples with complete sapwood have the last-measured ring date of AD 1735, and so were felled the previous year (AD 1735).

Eighteen of the other samples have the heartwood/sapwood boundary ring which in all cases is broadly contemporary, ranging from AD 1707 (BEV-K10, BEV-K13, BEV-K14) to AD 1723 (BEV-K18), and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1717 allowing an estimated felling date to be calculated for the 18 timbers represented to within the range AD 1735–57, consistent with these timbers also having been felled in the mid-AD 1730s. This allows for sample BEV-K21 having the last-measured ring date of AD 1734 with incomplete sapwood.

The final dated sample, BEV-K02, does not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated for it, except to say that with a last-measured heartwood ring date of AD 1702, this would be estimated to be after AD 1717, at the earliest, making the timber represented also likely to have been felled in the mid-AD 1730s.

DISCUSSION

Tree-ring analysis has successfully dated timbers utilised within the Choir roof as having been felled in AD 1735 and AD 1736. The level of cross-matching within 24 sample group is sufficiently high to suggest that the timbers represented were felled as part of a single felling event in the mid-AD 1730s. The two tiebeams dated previously by Tyers (2012) have last measured ring dates of AD 1733 and AD 1734. Both were thought to have lost only a ring or two of the complete sapwood during the sampling process and hence it had been concluded that they were both felled in the mid-AD 1730s, an interpretation that is supported by this more extensive analysis of timbers from the Choir roof. Construction of this roof is likely to have been undertaken as part of the renovations directed by Nicholas Hawksmoor.

There are a several probable same tree matches amongst the timbers: the north and south principal rafters of truss 11 (represented by samples BEV-K13 and BEV-K14 which match each other at t = 19.2) and those of truss 15 (samples BEV-K22 and BEV-K23 which match at t = 17.3). There are other potential same tree matches as well, all of which supports the likelihood that this group of dated timbers representing a single felling event.

This analysis has produced, in BEVKSQ01, a long and well replicated site chronology. It can be seen to match well against a disparate group of reference chronologies from Derbyshire, Nottinghamshire, Cheshire, Northamptonshire, and Warwickshire (Table 2) and is likely to be a robust and useful reference chronology for the period it encompasses.

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TABLES

Table 1: Details of tree-ring samples from the Choir roof, The Minster Church of St John, Beverley, East Riding of Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
BEV-K01	Tiebeam, truss 3	99	22C	1637	1713	1735
BEV-K02	Tiebeam, truss 4	130	--	1573	----	1702
BEV-K03	Tiebeam, truss 6	79	14	1653	1717	1731
BEV-K04	North principal rafter, truss 7	151	22C	1585	1713	1735
BEV-K05	South principal rafter, truss 7	125	11	1603	1716	1727
BEV-K06	Tiebeam, truss 7	131	23C	1605	1712	1735
BEV-K07	North principal rafter, truss 8	98	09	1632	1720	1729
BEV-K08	South principal rafter, truss 8	87	08	1642	1720	1728
BEV-K09	Tiebeam, truss 8	62	22C	1674	1713	1735
BEV-K10	North principal rafter, truss 9	84	h/s	1624	1707	1707
BEV-K11	Tiebeam, truss 9	90	h/s	1631	1720	1720
BEV-K12	Tiebeam, truss 10	86	13	1643	1715	1728
BEV-K13	North principal rafter, truss 11	121	15	1602	1707	1722
BEV-K14	South principal rafter, truss 11	123	20	1605	1707	1727
BEV-K15	Tiebeam, truss 11	81	h/s	1640	1720	1720
BEV-K16	Tiebeam, truss 12	124	22C	1613	1714	1736
BEV-K17	North principal rafter, truss 13	101	h/s	1622	1722	1722
BEV-K18	South principal rafter, truss 13	119	01	1606	1723	1724
BEV-K19	Tiebeam, truss 13	110	03	1612	1718	1721
BEV-K20	North principal rafter, truss 14	121	09	1610	1721	1730
BEV-K21	Tiebeam, truss 14	127	16	1608	1718	1734
BEV-K22	North principal rafter, truss 15	113	h/s	1605	1717	1717
BEV-K23	South principal rafter, truss 15	108	h/s	1610	1717	1717
BEV-K24	Tiebeam, truss 15	111	h/s	1607	1717	1717

h/s = heartwood/sapwood boundary is the last-measured ring
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BEVKSQ01 and reference chronologies when the first-ring date is AD 1573 and the last-measured ring date is AD 1736

Reference chronologies	*t* - value	Span of chronology	Reference
Bolsover Castle Riding House, Bolsover, Derbyshire	11.3	AD 1494–1744	Howard *et al* 2005
Bingham, Nottinghamshire	10.9	AD 1445–1752	Arnold and Howard 2014 unpubl
Kirby Hall, Northamptonshire	10.2	AD 1509–1795	Arnold *et al* forthcoming
Middleton Hall, Warwickshire	10.0	AD 1593–1718	Arnold *et al* 2006
Castle House, Melbourne, Derbyshire	10.0	AD 1583–1720	Arnold and Howard 2009
The Minster Choir tiebeams, Beverley, East Yorkshire	9.8	AD 1632–1734	Tyers 2012
Muniment Room, Melbourne Hall, Derbyshire	9.8	AD 1601–1708	Arnold and Howard 2013
Combermere Abbey, Whitchurch, Cheshire	9.6	AD 1602–1727	Howard *et al* 2003
St Giles Church bellframe, Elkesley, Nottinghamshire	9.5	AD 1628–1722	Arnold *et al* 2003a
Bolsover Castle The Keep/Little Castle, Bolsover, Derbyshire	9.3	AD 1532–1749	Arnold *et al* 2003b
Potterdike House, Newark-on-Trent, Nottinghamshire	8.7	AD 1603–1740	Arnold *et al* 2002

FIGURES

Figure 1: Map to show the general location of Beverley (red ellipse). © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900.

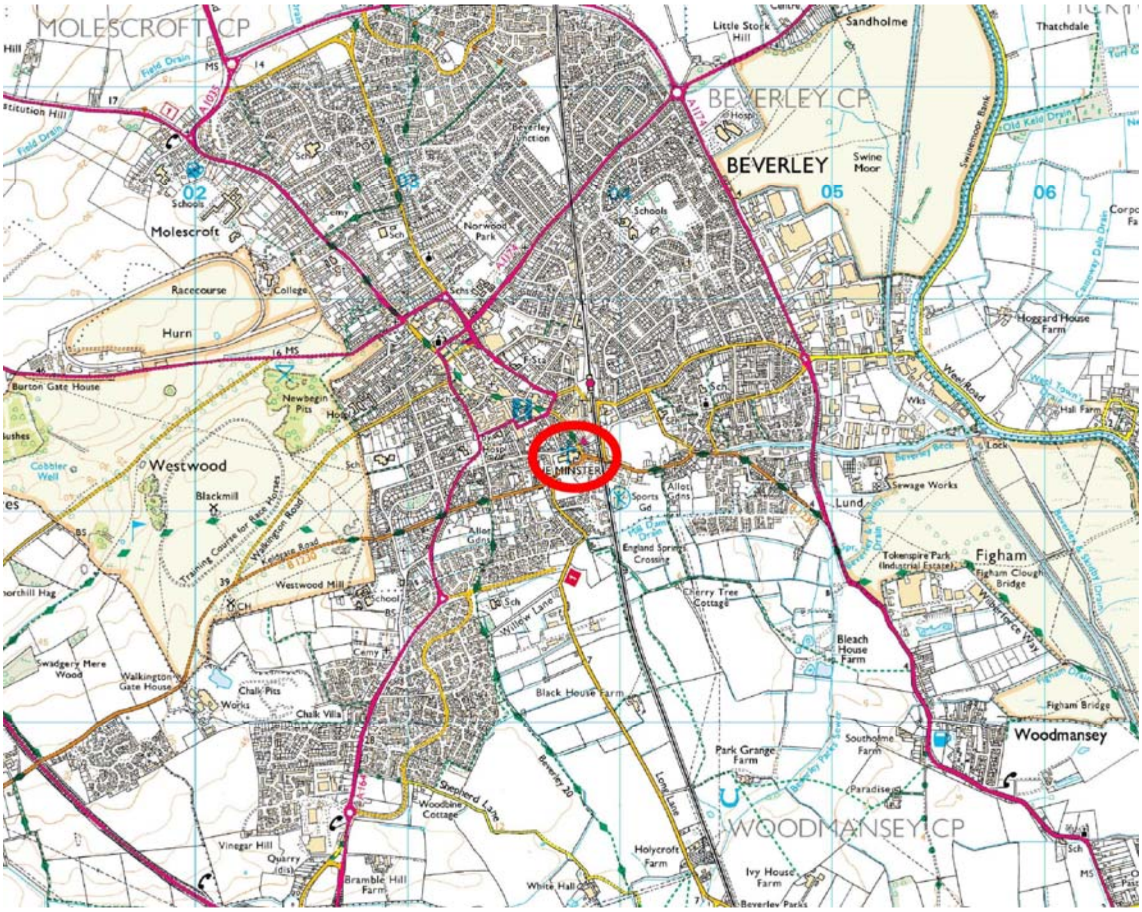

Figure 2: Map to show the general location of The Minster (red ellipse). © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the location of The Minster, centre. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

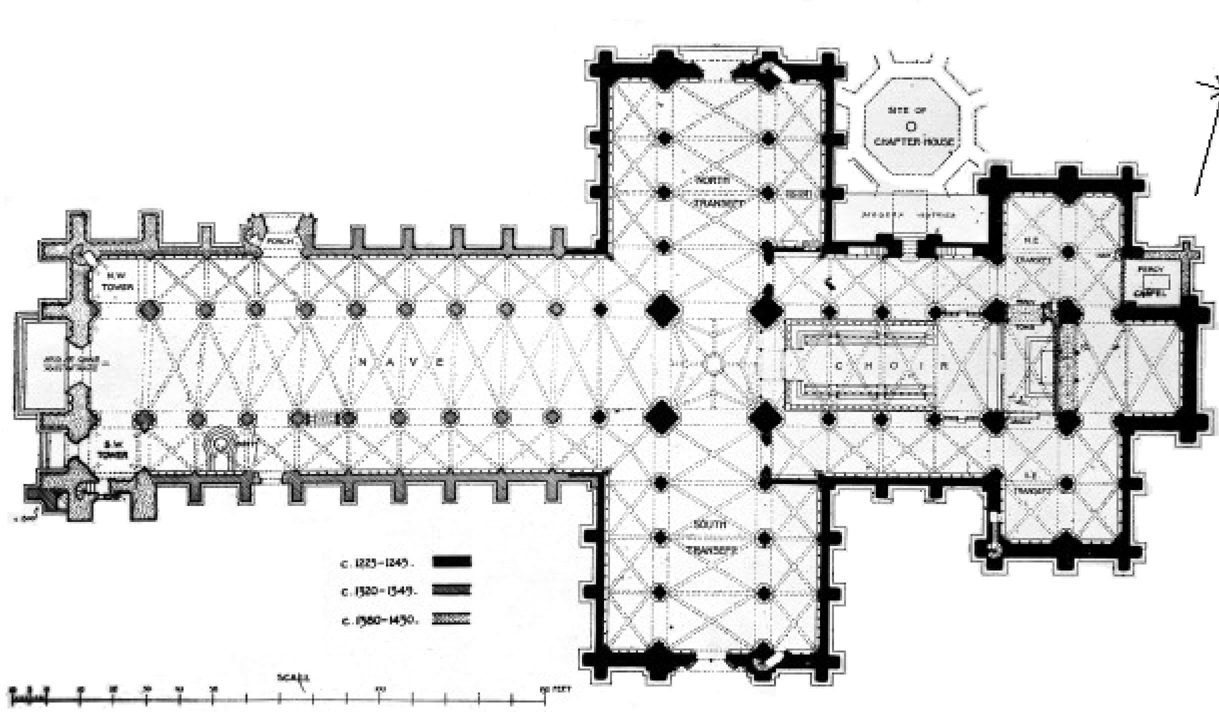

Figure 4: Plan of The Minster (John Bilson)

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Figure 5: The Choir roof, photograph taken from the east (Alison Arnold)

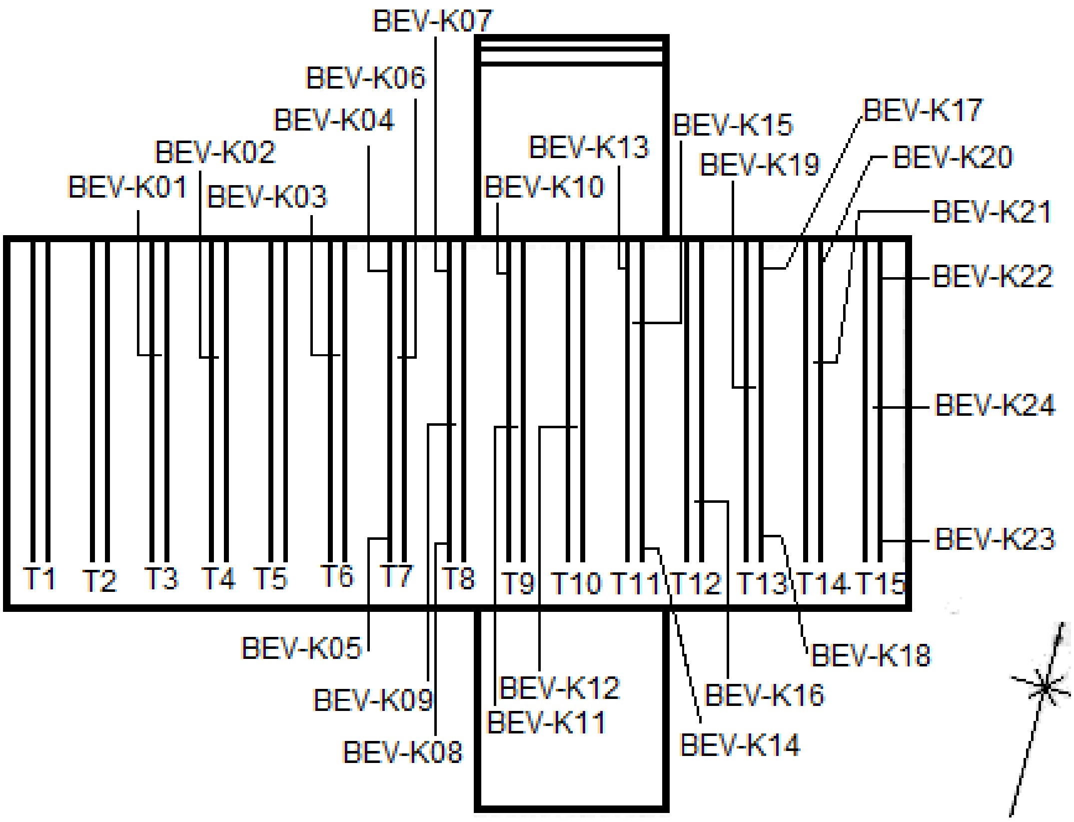

Figure 6: Sketch plan, showing the location of the samples BEV-K01– BEV-K24

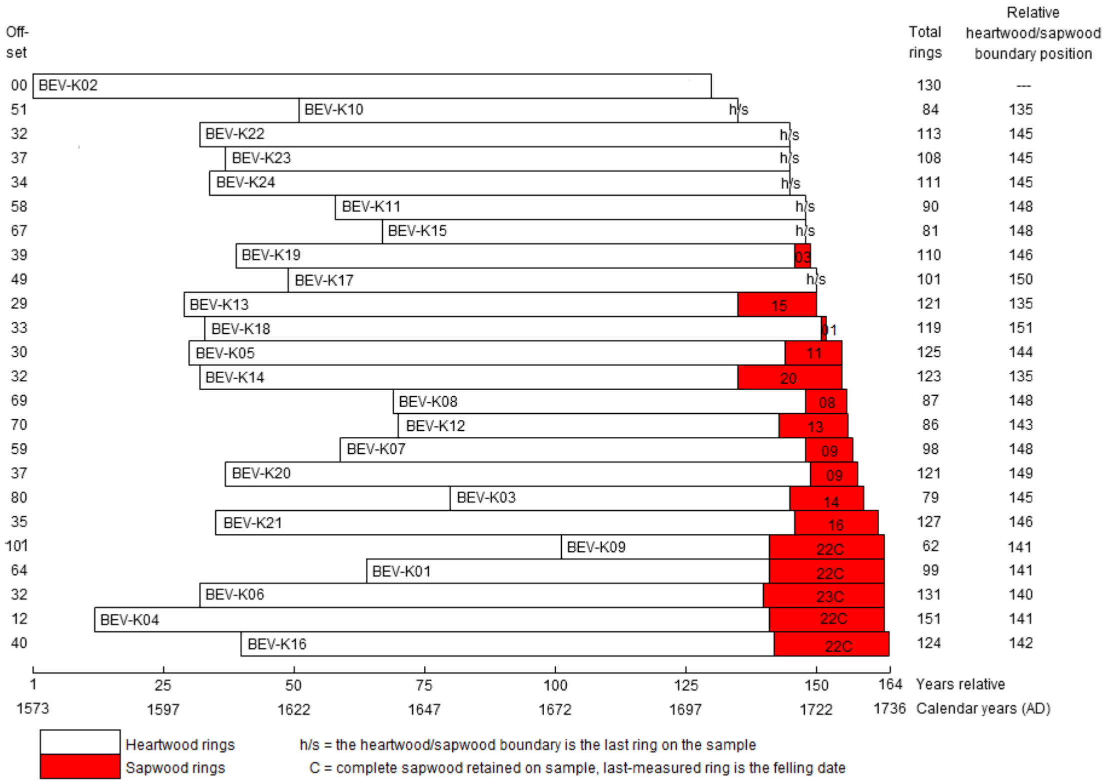

Figure 7: Bar diagram of samples in site sequence BEVKSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BEV-K01A 99
139 196 97 158 216 109 145 128 168 238 129 164 146 104 135 140 136 229 250 186
144 161 166 143 109 110 120 112 121 150 152 143 158 192 128 154 136 128 88 107
180 162 161 163 92 266 163 123 96 275 218 179 190 130 160 160 173 147 160 94
159 143 125 106 110 97 154 198 118 130 127 144 137 58 107 131 141 107 95 105
104 79 102 71 106 124 117 94 82 109 155 120 134 111 98 98 94 96 93

BEV-K01B 99
147 194 98 154 217 109 151 121 169 216 128 156 144 92 140 158 119 239 243 175
140 162 164 145 100 115 108 110 119 157 153 139 170 190 131 161 137 132 88 111
191 165 169 167 91 267 161 123 101 273 217 181 187 132 160 157 172 150 156 96
159 148 122 107 115 97 156 210 130 117 126 135 123 67 110 134 135 100 98 105
103 80 97 72 106 125 112 99 79 108 157 119 177 105 116 104 88 89 97

BEV-K02A 130
302 337 317 390 279 267 289 334 296 311 332 284 328 304 325 226 223 200 179 180
207 220 257 209 182 176 176 163 157 164 188 175 117 182 149 129 127 99 107 109
102 67 62 92 86 161 104 123 168 209 131 115 135 120 208 179 192 165 145 206
148 114 136 127 162 187 112 133 130 118 119 110 95 117 155 192 164 112 130 147
140 147 147 131 133 161 142 138 131 113 95 92 106 133 139 89 101 108 148 148
149 136 112 175 228 182 183 139 102 153 106 119 117 158 147 124 137 113 119 115
94 111 101 93 101 108 94 82 66 64

BEV-K02B 130
299 334 324 368 290 262 299 307 303 315 323 298 330 301 325 222 227 195 178 183
209 224 255 209 182 178 174 162 159 166 189 173 119 180 155 126 127 98 105 106
102 75 65 91 84 161 103 114 177 228 132 113 141 121 209 184 182 163 146 200
154 110 139 123 168 188 111 135 128 129 109 98 93 121 147 204 158 114 134 147
145 149 150 134 130 162 149 136 122 109 101 84 109 132 133 91 97 117 151 143
149 133 113 173 235 180 181 132 112 149 102 133 125 156 148 121 144 117 114 108
110 104 106 93 99 98 105 78 64 57

BEV-K03A 79
150 315 367 316 198 269 202 173 138 84 113 101 107 167 114 95 201 191 265 238
261 249 220 304 432 503 517 441 425 348 241 241 228 446 394 333 371 188 247 223
320 326 328 248 284 388 359 294 264 283 252 323 261 319 325 294 161 177 209 198
180 149 220 178 223 185 186 116 129 135 90 124 164 108 146 183 187 127 131

BEV-K03B 79
261 317 346 321 177 262 181 192 139 102 104 106 103 168 120 90 206 197 262 247
261 247 220 324 460 524 516 441 420 354 244 238 237 459 403 353 370 189 246 216
318 327 334 240 284 378 358 298 263 292 257 316 257 311 329 298 170 170 209 199
180 152 216 187 202 194 175 121 132 108 113 122 163 117 143 174 193 144 113

BEV-K04A 151
250 227 220 133 190 186 209 220 188 208 171 171 142 248 230 247 229 193 273 300
295 363 352 220 271 322 244 311 327 211 189 227 264 344 306 301 283 292 300 185
213 284 279 250 301 234 240 227 215 166 123 172 201 264 167 133 192 131 146 119
147 139 121 133 122 75 70 91 115 111 123 86 102 86 97 100 92 93 78 53

53 50 60 63 70 56 59 74 56 49 41 39 52 74 98 64 82 109 70 69
89 97 144 119 100 73 64 56 61 78 73 79 84 103 85 71 68 76 100 115
86 88 99 101 57 43 85 113 80 75 79 89 111 91 96 96 109 93 63 74
75 49 98 68 72 40 37 35 34 39 35

BEV-K04B 151
240 200 235 140 176 182 217 225 184 200 177 169 139 242 234 248 227 194 285 299
283 369 342 217 268 329 241 303 325 220 168 221 241 350 306 298 283 297 304 188
212 282 290 256 305 234 231 228 219 175 121 168 207 271 176 143 206 134 155 124
145 137 123 136 115 74 72 85 124 101 125 86 89 97 81 103 94 97 66 57
60 51 65 59 67 72 63 66 68 54 39 46 46 73 89 78 82 107 71 67
88 111 132 112 110 88 61 67 46 85 77 84 85 113 87 76 68 70 99 115
93 78 97 99 64 42 86 109 80 82 64 101 108 92 96 101 103 86 66 77
68 60 88 81 63 50 37 35 28 37 37

BEV-K05A 125
292 312 287 337 403 269 329 366 292 286 320 164 157 185 249 360 244 232 220 242
276 137 135 172 187 180 226 141 162 145 155 151 108 144 143 220 175 154 201 106
148 132 128 164 145 160 159 114 123 141 166 183 153 126 160 124 127 116 117 141
115 87 63 103 114 108 123 119 92 100 100 64 55 75 113 127 112 100 80 164
65 70 110 113 131 108 90 75 64 57 88 95 69 55 68 96 75 81 57 65
84 84 81 74 84 87 51 73 101 105 87 92 51 107 88 81 91 93 98 107
68 78 75 70 75

BEV-K05B 125
282 323 251 341 413 259 308 349 286 281 322 173 173 187 257 363 239 223 229 243
278 138 138 171 195 179 221 146 161 147 139 159 108 148 149 219 177 151 196 91
165 127 127 166 157 168 163 119 119 138 172 177 158 127 161 129 124 116 120 139
117 86 67 89 112 116 125 118 94 105 98 62 59 70 114 111 114 97 76 157
68 68 109 114 128 109 91 71 66 53 88 83 80 56 70 95 82 65 63 60
89 76 85 65 100 80 47 71 108 105 86 91 55 103 87 86 94 98 103 104
68 84 78 70 83

BEV-K06A 131
184 298 442 276 254 307 301 367 308 220 188 242 420 403 356 415 263 391 212 143
136 204 216 189 248 198 252 294 257 168 213 143 354 511 231 285 355 203 282 302
378 394 254 268 206 173 272 225 190 296 294 282 183 267 292 290 182 188 171 153
146 152 171 169 203 301 187 235 171 177 120 170 189 145 134 103 117 216 168 125
124 218 269 226 276 162 184 202 212 175 182 129 164 171 161 121 118 89 147 139
129 159 174 158 134 84 129 162 145 121 128 120 143 118 120 81 123 133 112 99
101 92 119 102 118 100 104 99 76 88 74

BEV-K06B 131
203 280 433 291 270 311 294 371 308 220 189 243 421 398 359 416 264 392 210 137
140 210 210 180 229 200 256 294 237 165 202 151 351 514 238 273 349 199 278 308
379 389 252 276 208 180 262 234 191 293 297 281 183 265 297 288 181 193 168 160
149 167 180 167 205 296 193 234 172 174 122 173 190 148 125 123 93 224 158 134
123 219 277 225 275 159 185 202 207 171 184 132 164 165 163 126 121 87 148 140
126 168 170 161 135 85 128 160 152 105 130 118 148 101 101 91 117 132 111 98
101 91 121 102 121 98 103 98 72 93 73

BEV-K07A 98
175 216 209 161 194 269 260 247 238 334 244 257 257 264 252 272 279 193 121 107

96 174 206 318 296 262 325 260 266 209 231 298 187 131 215 235 252 227 243 158
146 128 100 58 53 106 164 252 320 289 249 152 112 105 166 220 250 68 49 82
60 56 101 100 84 73 113 97 131 105 136 188 231 200 218 237 176 126 93 122
125 170 167 124 145 152 157 149 116 151 142 160 158 114 167 254 153 258

BEV-K07B 98
186 216 202 158 179 260 262 241 231 312 243 260 258 254 264 263 292 189 123 101
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138 130 92 66 49 112 164 257 317 295 246 153 124 105 160 215 251 64 53 73
47 76 95 105 60 81 110 95 122 107 137 183 247 196 224 227 180 130 94 119
134 171 169 115 134 158 145 156 115 141 170 146 158 121 170 286 179 262

BEV-K08A 87
242 247 295 299 243 252 252 171 156 159 153 209 295 343 294 242 273 230 249 185
186 242 150 105 203 204 224 269 288 141 96 88 54 22 27 80 152 205 251 249
208 98 75 84 162 244 217 138 83 81 67 59 112 74 62 63 99 84 106 139
117 208 290 210 255 256 213 136 90 138 135 193 145 115 168 138 143 179 134 150
202 183 153 150 185 214 157

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260 244 299 292 240 250 247 165 162 154 155 208 302 343 301 240 275 248 255 186
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184 202 153 158 174 187 129

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156 292 378 357 444 365 424 202 440 315 217 223 409 338 259 232 146 212 125 191
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79 102 98 115 107 84 95 71 57 58 63 55 60 72 52 51 44 75 103 87
54 67

BEV-K09B 62
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164 159 134 189 175 178 145 163 109 165 166 133 126 144 124 98 93 115 100 99
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47 54

BEV-K10A 84
230 251 257 285 244 235 192 238 232 258 128 155 173 120 174 224 238 270 176 245
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222 189 164 194 257 233 188 230 223 300 199 159 190 343 288 251 233 186 287 219
127 91 233 228 155 130 115 117 87 132 122 99 101 172 264 234 170 185 157 220
164 101 145 154

BEV-K10B 84
232 256 258 292 245 243 185 235 235 256 130 158 164 121 172 228 238 281 170 245
294 191 235 165 237 239 290 444 347 296 312 389 285 296 301 258 333 284 256 320
222 187 165 198 264 232 181 233 218 309 219 158 192 336 287 257 231 181 292 200
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162 104 145 144

BEV-K11A 90

351 314 267 236 271 339 326 196 228 236 382 231 443 417 412 427 350 294 229 148
201 153 163 197 319 368 317 406 586 447 378 313 279 326 195 314 340 441 408 511
455 428 356 312 149 257 385 432 414 411 370 430 233 172 136 227 247 273 284 170
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120 166 209 242 161 173 170 134 149 185

BEV-K11B 90
304 323 275 252 263 341 329 200 236 236 387 233 452 421 417 429 360 299 231 154
202 152 166 198 302 376 315 411 593 441 379 313 278 329 194 315 345 442 407 506
445 423 368 304 144 266 390 434 414 412 375 434 222 173 136 225 252 264 294 175
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BEV-K12A 86
307 285 294 244 185 132 127 88 87 96 82 186 293 232 141 154 107 127 105 84
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195 132 140 389 406 384 406 287 282 164 182 316 260 164 272 302 281 255 366 222
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142 144 166 159 155 154

BEV-K12B 86
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136 166 156 170 180 273 245 240 272 205 203 256 211 206 196 247 284 337 236 260
196 131 139 404 388 356 400 293 311 167 186 315 252 162 274 299 281 257 374 233
234 378 264 280 349 306 341 138 258 313 329 275 224 240 201 152 195 163 170 168
153 136 155 157 139 159

BEV-K13A 121
52 114 164 348 351 456 380 374 298 165 187 197 180 137 241 221 223 158 142 149
157 142 122 172 172 205 187 208 115 87 149 206 105 121 138 142 187 254 269 255
212 225 229 176 185 142 170 154 107 142 188 158 195 260 172 180 209 129 212 159
121 204 162 121 98 137 204 159 154 180 172 228 173 129 129 286 212 200 321 144
268 138 124 116 218 190 198 136 99 81 89 157 150 130 110 176 183 143 121 164
86 140 131 87 158 130 141 169 67 71 79 83 66 114 71 54 85 96 128 177
139

BEV-K13B 121
106 118 156 345 349 458 380 374 297 165 192 193 177 137 219 194 253 170 161 145
162 122 130 193 181 202 191 198 120 91 146 189 107 118 155 143 190 246 259 272
223 238 222 178 182 146 167 148 108 146 174 173 192 262 175 177 211 120 214 151
122 208 165 136 88 139 206 161 148 173 178 230 181 128 120 297 213 205 315 142
269 140 122 115 226 189 192 138 102 82 89 153 149 124 104 181 183 144 131 159
89 143 127 97 148 142 129 132 74 73 78 88 67 93 66 67 83 103 113 195
125

BEV-K14A 123
286 446 450 343 386 314 166 159 212 208 182 254 275 276 185 155 153 155 143 130
178 200 234 204 219 144 147 207 209 112 126 167 119 125 237 223 259 193 253 215
177 177 134 170 127 88 120 161 183 186 270 188 182 192 124 159 95 112 194 196
109 95 130 181 159 133 172 139 163 131 69 100 220 166 149 215 125 246 147 91
91 152 159 156 90 66 72 71 122 113 83 72 150 138 122 83 135 65 147 130
90 127 111 132 120 55 61 71 67 70 64 63 49 55 93 77 102 171 76 114
122 146 176

BEV-K14B 123
278 433 438 337 390 306 167 157 214 206 181 257 276 278 185 157 148 159 143 137
174 194 236 209 221 144 142 208 212 104 120 164 118 127 235 221 261 188 271 213
171 168 136 177 127 88 118 157 187 182 274 191 179 193 120 163 90 114 202 188
106 91 117 176 172 146 180 146 152 127 70 99 216 166 147 228 117 240 152 100
89 155 147 154 92 71 67 82 109 116 89 71 144 140 113 85 138 78 138 116
92 131 104 131 124 59 71 62 59 56 70 61 66 58 80 83 112 170 73 96
131 149 176

BEV-K15A 81
289 407 281 488 518 529 504 486 495 417 328 400 314 331 484 482 579 479 429 485
375 324 293 229 229 189 410 374 388 313 493 394 353 342 311 120 182 229 245 324
269 161 248 137 100 89 149 172 260 257 165 195 109 246 222 188 147 126 146 152
130 192 118 183 223 176 181 182 178 123 77 100 156 230 201 141 98 123 95 94
174

BEV-K15B 81
312 402 270 478 509 502 494 500 492 408 338 387 326 329 477 483 579 493 430 512
390 305 292 232 235 194 410 369 370 304 485 388 356 350 315 113 186 232 249 316
261 164 247 133 103 88 129 175 258 251 165 194 115 240 206 211 149 129 157 133
126 190 114 183 227 173 181 180 179 125 74 95 165 224 201 136 106 104 110 104
163

BEV-K16A 124
341 404 404 432 410 445 359 318 311 348 293 169 134 82 60 72 121 102 116 158
156 126 112 151 187 286 328 284 322 162 191 183 268 320 306 292 242 129 224 165
191 205 177 149 112 164 104 83 73 99 104 115 90 116 115 105 117 132 92 102
69 85 67 80 123 126 118 91 102 117 78 72 107 161 177 138 105 84 88 85
107 94 96 94 129 124 115 66 124 101 99 113 80 85 104 96 63 77 104 102
92 87 146 134 113 94 135 125 108 115 69 85 91 101 121 118 99 112 97 135
131 112 134 90

BEV-K16B 124
379 408 402 397 416 435 355 325 331 385 320 169 153 70 78 75 116 101 120 150
157 129 108 153 183 288 328 281 324 172 192 181 261 322 321 306 247 133 229 165
180 201 183 150 117 164 106 84 71 91 102 115 93 107 118 103 122 122 83 103
60 86 60 78 122 128 111 111 101 117 82 85 105 163 179 145 95 80 93 81
108 90 94 102 125 127 122 65 121 110 96 112 77 85 113 107 74 74 102 106
102 76 134 138 122 99 126 110 138 101 77 77 95 104 113 125 102 120 90 138
135 118 143 98

BEV-K17A 101
349 365 99 64 54 107 120 193 131 107 143 170 118 54 37 81 187 474 473 300
128 86 153 177 324 389 444 369 437 302 150 195 279 325 303 159 223 189 172 128
115 173 238 191 147 179 184 227 195 105 149 151 131 69 110 141 168 142 173 180
199 119 92 99 224 194 130 66 84 116 106 110 170 116 123 152 170 147 132 151
104 107 87 97 86 129 126 112 61 70 80 98 87 195 174 191 168 117 138 190
131

BEV-K17B 101
352 350 97 64 69 128 136 188 133 105 137 166 120 48 40 80 195 488 467 286
118 88 145 172 321 386 442 380 442 297 159 188 271 326 311 160 219 187 166 129

118 178 231 181 152 186 176 226 195 109 142 167 121 68 106 146 171 148 160 177
196 126 92 102 223 193 129 63 88 116 103 114 162 121 125 163 153 150 135 144
106 106 86 98 83 127 128 96 68 80 79 97 84 205 179 196 163 114 136 191
146

BEV-K18A 119
221 177 164 222 155 156 116 210 212 105 187 231 372 212 283 296 333 319 88 58
51 171 162 194 148 118 176 161 103 48 44 102 211 180 295 187 108 106 155 201
307 297 311 256 292 155 140 177 239 289 255 139 196 126 137 100 78 152 180 145
112 173 151 198 149 92 124 141 124 70 74 136 147 126 144 135 137 82 68 77
124 163 107 57 77 102 101 118 156 125 97 136 158 126 127 159 106 86 92 102
91 140 135 120 55 79 82 130 72 173 162 144 154 100 146 205 254 122 99

BEV-K18B 119
238 182 142 211 159 160 120 229 206 113 185 225 369 212 289 300 340 321 86 58
51 167 160 192 147 120 183 159 101 47 55 89 219 180 308 192 103 103 153 201
300 298 313 265 286 154 139 178 239 290 254 138 194 131 134 101 79 155 174 141
117 158 145 195 146 98 120 142 126 68 76 142 140 128 149 132 133 78 63 63
153 159 108 57 83 94 102 116 155 129 97 135 160 124 129 157 108 84 92 103
88 148 132 121 53 81 85 129 71 177 156 145 154 101 137 211 249 120 95

BEV-K19A 110
332 470 381 291 259 183 273 209 284 193 276 310 153 91 122 212 227 231 167 151
197 223 167 171 161 183 242 193 151 167 104 54 67 126 207 242 241 132 82 75
55 103 153 190 221 84 143 132 154 103 96 164 159 89 63 74 109 142 100 81
81 73 84 64 81 134 166 110 109 140 174 112 60 78 174 202 210 156 90 99
56 50 99 95 158 195 178 144 153 143 173 156 115 95 136 144 117 69 44 65
124 172 82 204 182 261 174 141 106 116

BEV-K19B 110
321 455 383 301 259 188 272 218 310 202 285 315 155 87 123 210 223 234 168 155
219 229 166 178 161 186 241 201 151 170 101 56 70 120 217 247 242 137 73 74
59 106 150 192 220 84 146 133 159 100 99 159 159 85 68 71 97 142 110 83
85 71 78 67 85 142 167 111 105 140 172 115 65 81 165 224 220 151 100 90
63 61 103 104 159 198 170 127 145 142 161 138 118 107 139 127 122 70 37 68
116 174 83 207 177 256 200 125 124 165

BEV-K20A 121
168 133 160 270 241 195 212 72 133 113 160 187 181 163 79 49 64 130 126 226
113 118 148 209 131 133 129 103 162 178 172 260 170 78 89 151 263 259 276 204
180 162 141 231 314 429 386 184 222 261 183 134 142 211 271 226 163 181 208 219
225 172 162 126 83 72 77 124 134 119 127 128 108 76 61 65 98 79 85 75
68 62 64 49 58 45 55 60 75 49 52 55 53 56 43 52 35 41 38 43
32 35 46 60 43 86 81 79 78 98 82 113 152 110 117 165 197 221 180 240
180

BEV-K20B 121
171 131 160 274 250 199 216 76 129 108 181 189 198 154 83 54 83 143 124 209
116 110 134 215 140 145 134 118 152 172 171 252 144 85 87 148 274 246 283 206
182 174 146 213 292 433 375 185 221 252 187 125 152 209 257 217 164 184 200 222
226 162 160 127 75 71 79 126 130 115 147 133 112 77 68 62 108 102 97 66
77 51 70 49 54 39 49 55 69 42 65 47 50 62 42 41 34 45 36 37
40 34 54 52 35 91 75 83 73 91 84 120 143 110 117 160 185 219 175 233

171

BEV-K21A 127
327 333 432 355 463 349 291 333 285 295 337 250 231 207 266 265 131 125 68 75
79 112 79 91 110 176 121 99 118 139 258 239 253 295 161 153 201 251 284 217
255 238 148 229 185 205 258 273 220 151 172 121 121 127 122 143 146 127 164 138
142 181 165 121 132 96 143 85 120 163 158 144 137 146 193 152 123 154 282 275
220 155 100 137 144 199 143 133 134 176 189 169 98 147 113 124 140 101 113 137
131 115 119 176 174 170 123 266 187 197 167 170 154 224 184 99 131 157 217 226
221 200 173 124 173 178 145

BEV-K21B 127
318 343 427 356 473 346 289 330 285 301 333 247 233 209 270 250 135 128 75 64
77 111 81 90 113 169 125 103 119 145 247 233 249 311 147 155 179 243 251 221
268 237 171 232 184 205 253 267 225 146 177 115 118 124 125 135 150 122 162 137
150 172 172 116 133 91 151 77 132 167 155 141 137 144 189 154 135 146 284 275
232 142 100 140 144 199 144 131 133 184 183 167 101 148 109 130 134 99 110 139
141 108 125 176 171 164 129 263 195 196 143 193 156 219 183 97 132 156 217 227
221 201 174 122 173 180 141

BEV-K22A 113
132 218 300 237 255 234 198 188 222 158 124 156 111 227 162 136 93 153 119 45
43 44 82 45 88 57 34 56 51 37 31 41 52 78 87 122 232 89 233 288
405 381 261 245 168 130 237 150 216 344 353 276 88 194 204 154 93 162 192 185
125 85 211 189 244 181 76 214 110 105 62 173 180 188 197 171 133 225 113 120
100 218 213 203 66 85 68 86 198 140 83 157 130 164 135 63 107 84 119 123
111 73 125 95 69 99 91 122 177 122 259 167 199

BEV-K22B 113
136 222 335 165 259 231 203 216 217 164 119 134 87 222 161 137 98 134 109 44
50 53 67 52 87 43 38 55 51 44 27 38 67 75 85 125 238 81 224 302
394 377 274 250 166 142 237 152 213 345 355 260 83 201 206 139 89 168 176 190
119 92 212 189 246 188 71 213 106 107 59 194 160 193 197 169 137 227 102 121
100 212 219 206 67 83 70 81 204 134 93 154 128 158 144 53 110 83 121 121
113 66 118 110 69 93 102 110 170 142 257 173 227

BEV-K23A 108
266 236 274 210 177 222 211 71 290 199 197 116 174 79 38 41 31 79 42 68
57 37 39 39 35 34 37 52 87 88 123 219 81 270 303 361 383 225 220 169
109 185 137 180 286 374 318 86 207 251 163 82 136 158 205 154 158 270 286 368
305 93 210 132 98 58 176 178 231 221 167 182 274 184 160 150 306 288 214 86
96 122 90 144 160 102 158 138 153 155 68 98 78 115 91 89 87 120 140 67
98 92 135 123 137 268 194 221

BEV-K23B 108
256 235 281 215 186 224 231 79 270 202 188 114 178 83 27 39 38 80 43 83
52 27 27 48 43 32 31 57 91 87 133 234 82 278 304 367 391 227 214 170
120 191 139 187 289 392 327 85 211 254 165 86 135 151 194 161 166 271 298 374
290 94 210 131 93 60 172 196 243 214 176 180 277 186 163 151 295 301 230 86
93 129 88 147 159 106 156 130 154 159 70 99 78 127 89 92 87 116 146 68
102 95 131 124 136 281 183 263

BEV-K24A 111

305 376 588 612 525 561 506 379 396 406 283 380 317 297 195 267 170 138 111 152
186 145 160 135 77 146 123 97 67 85 162 268 158 256 255 130 140 154 322 507
507 429 325 211 198 205 290 339 321 271 138 146 189 105 110 154 204 220 129 168
181 182 227 102 107 130 75 89 62 187 203 142 148 140 223 130 110 103 151 250
222 183 89 105 127 92 119 199 158 142 145 213 152 144 169 144 133 124 118 91
181 110 83 65 94 147 108 76 159 112 157

BEV-K24B 111
305 365 585 634 525 502 479 393 403 407 280 356 282 289 201 267 168 140 109 146
191 143 165 137 70 150 123 98 65 93 158 269 152 251 259 129 137 154 322 512
501 444 335 232 195 194 289 340 317 283 106 176 183 112 104 156 209 208 127 167
182 175 238 91 115 126 72 85 70 186 203 137 156 140 217 132 103 99 161 242
214 198 86 117 110 97 122 203 151 141 140 226 156 128 154 141 133 117 112 100
178 110 86 70 91 141 112 78 156 113 130

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 Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (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 Figure 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	

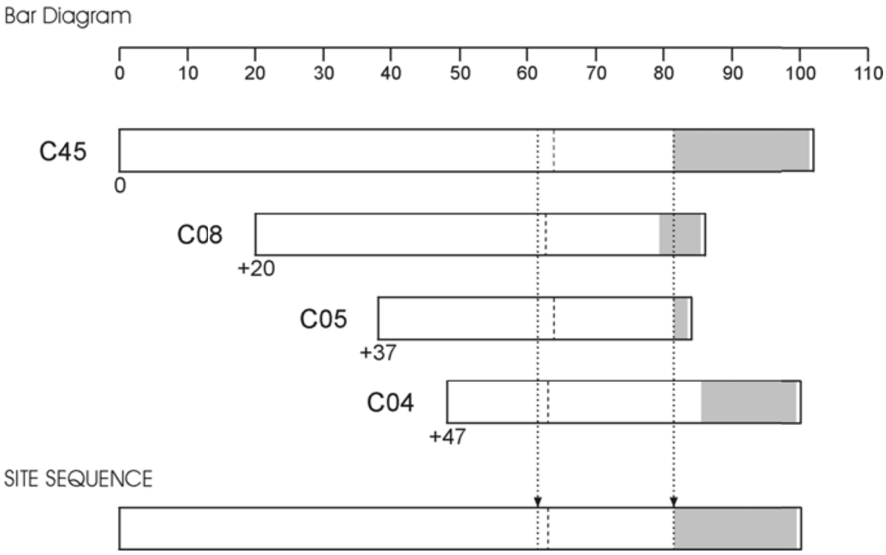


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

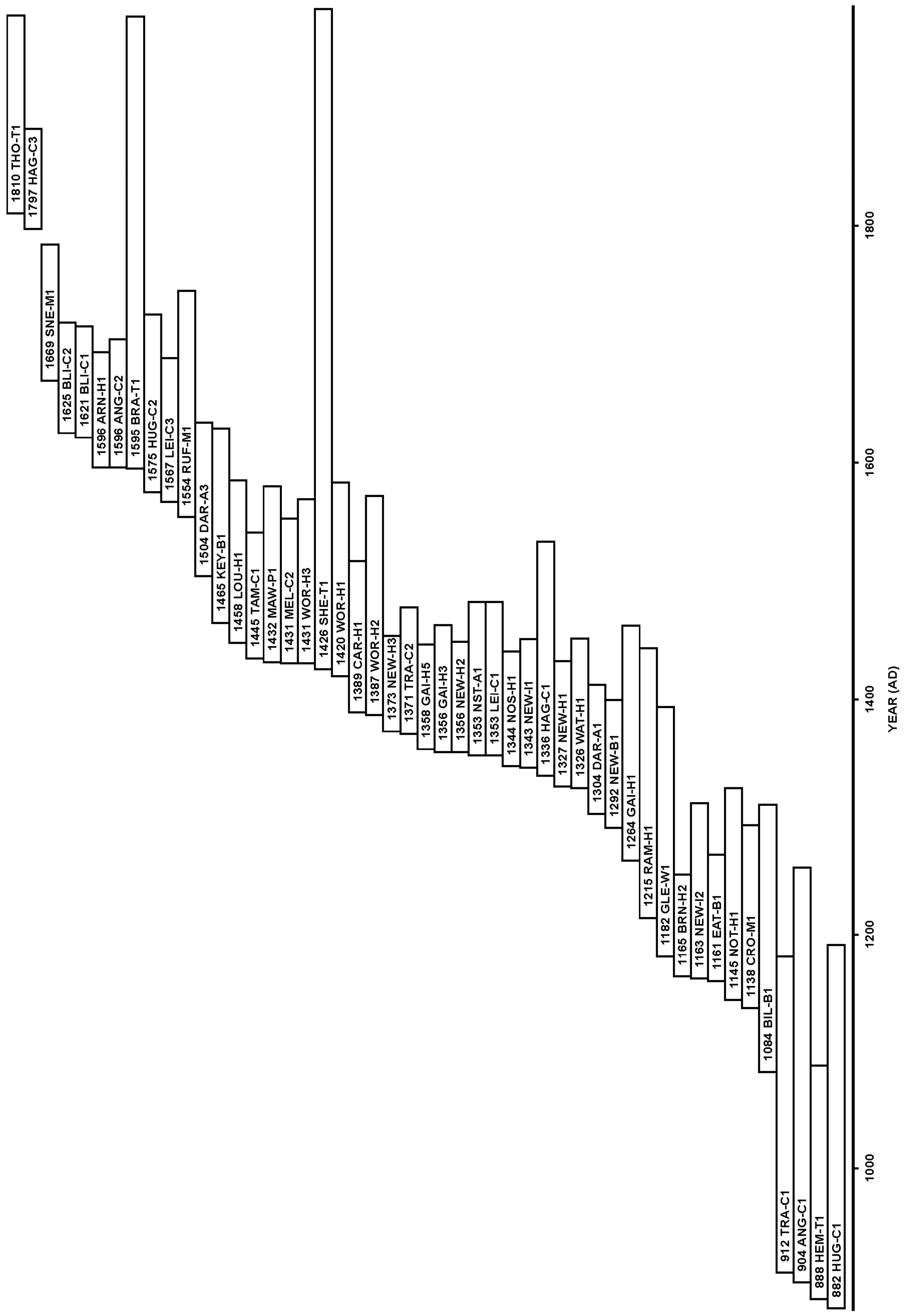
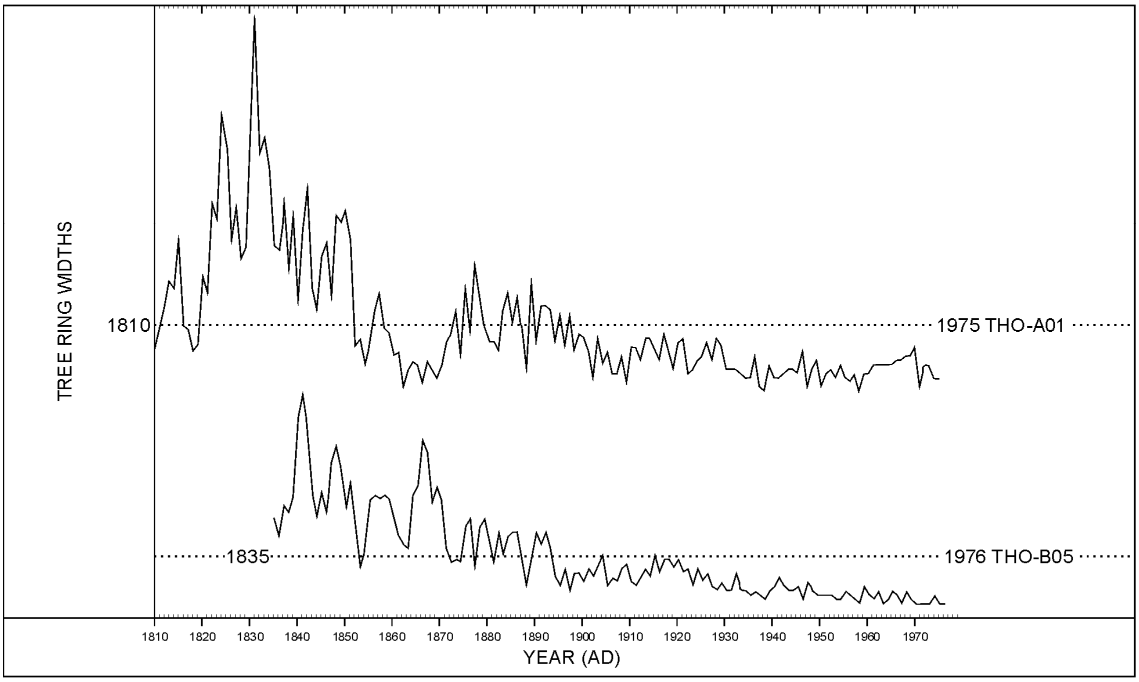


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

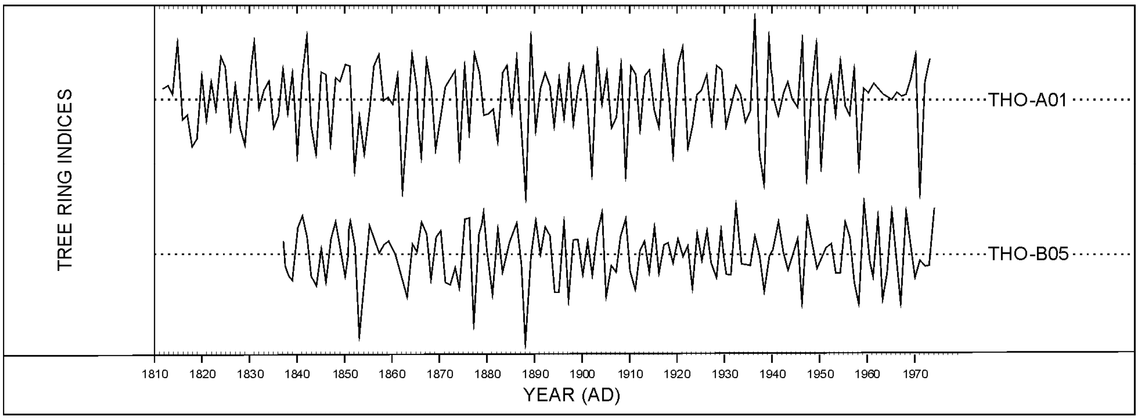


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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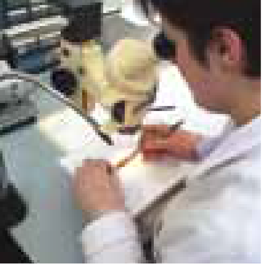 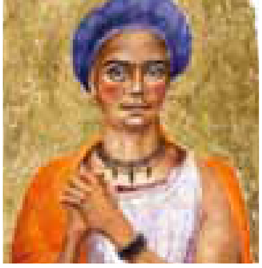   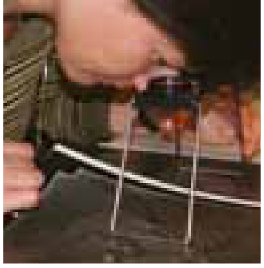 

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