ST FIRMIN CHURCH, THURLBY, LINCOLNSHIRE
TREE-RING ANALYSIS OF TIMBERS OF THE BELLFRAME AND TOWER

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

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SUMMARY

Samples were taken from the dismantled bellframe and supporting beams, and from *in-situ* tower timbers. All 12 bellframe samples grouped and were combined to form THUBSQ01, a site sequence of 194 rings. This was found to span the period AD 1599–1792, with the timbers represented all probably being felled in AD 1792.

Only one of the supporting beams could be dated, to a felling of AD 1455. Little can be deduced from a single sample as it is unclear whether it is reused, primary, or inserted.

Three of the lower *in-situ* timbers, all corbels, grouped to form a site sequence, THUBSQ03, which has a last-measured ring date of AD 1547. These samples have *termini post quos* of AD 1540, AD 1555, and AD 1562.

Two further site sequences are undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ARCHIVE LOCATION

Lincolnshire Historic Environment Record
Planning and Conservation Group
Lincolnshire County Council
City Hall
Beaumont Fee
Lincoln LN1 1DN

DATE OF INVESTIGATION

2009–10

CONTACT DETAILS

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CONTENTS

INTRODUCTION

The parish church of St Firmin is located in the Lincolnshire village of Thurlby (Figs 1 and 2; TF 10503 16800). It is thought to have had its origins in the eleventh century, with work being undertaken in the twelfth, thirteenth, fourteenth, and fifteenth centuries, as well as being restored in AD 1856. It consists of a three-stage tower with fourteenth-century spire, clerestoried nave, chancel, aisles, transepts, north and south chapels, and porches (www.lbonline.english-heritage.org.uk).

Bellframe and supporting beams

The bellframe was removed from the tower in late 2009 in order for a new metal frame to be installed. The timbers of the frame and the six supporting beams upon which it had sat were given to a local farmer, Roger Osborne, and when seen by the Laboratory were residing on a trailer.

From sketches found by George Dawson and from looking at the timbers it is possible to reconstruct the original form of the frame. It had five bells, hung in four pits: three parallel pits orientated north-south and a transverse pit across the north end of the other pits (Fig 3). The main trusses consisted of sill, long head, and braces which ran from sill to head. This frame sat upon six longitudinal beams which spanned the tower east-west (Fig 4).

In-situ timbers

These can be divided into lower and upper timbers (Fig 4). The lower timbers consist of six north-south beams, two of which are supported on posts and corbels and have braces from beam to post (Fig 5). The upper timbers consist of two east-west beams, supported on posts and with a brace running between the post and the beam. One of these trusses is against the north wall and one against the south wall (Fig 6).

SAMPLING

Sampling was requested by Graham Pledger, bellframe advisor for English Heritage, to provide a precise date for the construction of the *ex-situ* bellframe and associated support beams. In addition it was hoped that the analysis of the timbers still *in-situ* in the tower would allow a greater understanding of their historical context and potential purpose.

A total of 30 timbers was sampled. Each sample was given the code THU-B (for Thurlby Church) and numbered 01–30. Sixteen of these samples are slices taken from the bellframe (THU-B01–12) and supporting beams (THU-B13–16). The other 14 samples are cores taken from the *in-situ* timbers (THU-B17–30). The location of core samples was noted at the time of sampling and has been marked on Figures 7–11. Those

components of the dismantled bellframe which were sampled and an example of one of the supporting beams were photographed (Figs 12–17). Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

All 30 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).

Bellframe and supporting beams

All 12 samples taken from the timbers of the bellframe matched each other at a value of $t=4.5$. These 12 samples were combined at the relevant offset positions to form THUBSQ01, a site sequence of 194 rings (Fig 18). 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 1599 and a last-measured ring date of AD 1792. The evidence for this dating is given in Table 2. One of these samples (THU-B08) has complete sapwood and the last-measured ring date of AD 1792, the felling date of the timber represented. A further five dated samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1766, which allows an estimated felling date to be calculated for the five timbers represented to the range AD 1788–1806 (this allows for sample THU-B09 having a last-measured ring date of AD 1787 with incomplete sapwood), consistent with a felling of AD 1792. The other six dated samples do not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated, except to say with last-measured heartwood ring dates ranging from AD 1708 (THU-B03) to AD 1767 (THU-B04), it is also possible these were felled in AD 1792.

Two samples taken from the supporting beams matched each other and were combined at the relevant offset positions to form THUBSQ02, a site sequence of 69 rings (Fig 19). Attempts to date this site sequence by comparing it against the reference material were unsuccessful and it remains undated.

A third sample (THU-B14) was compared individually against the reference material where it was found to span the period AD 1389–1455. The evidence for this dating is given by the t-values in Table 3. This sample has complete sapwood, demonstrating the timber represented was felled in AD 1455.

The fourth sample, THU-B13, is too short to be individually dated securely.

In-situ timbers

Three of the samples taken from the lower timbers matched each other and were combined at the relevant offset positions to form THUBSQ03, a site sequence of 90 rings (Fig 20). 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 1458 and a last-measured ring date of AD 1547. The evidence for this dating is given by the *t*-values in Table 4. None of these samples has the heartwood/sapwood boundary ring date and, therefore, it is not possible to calculate an estimated felling date for the timbers represented, except to say, that with last-measured ring dates of AD 1525 (THU-B19), AD 1540 (THU-B26), and AD 1547 (THU-B24), these would be estimated to be AD 1541, AD 1556, and AD 1563 at the earliest, respectively.

Eight other samples, from both the upper and lower timbers, matched each other and were combined at the relevant offset positions to form THUBSQ04, a site sequence of 76 rings (Fig 21). Attempts to date this site sequence by comparing it against the relevant reference material were unsuccessful and it remains undated.

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

DISCUSSION

Prior to tree-ring analysis being undertaken the bellframe was believed, on documentary sources, to date to AD 1713, the date of two of its bells. However, the dendrochronological research has demonstrated that it was constructed from timber felled in AD 1792, making it about 80 years older. Notes attached to the drawings found by George Dawson list the dates of the five bells. In addition to the two dated to AD 1713, there are a further two dated to AD 1908, and one dated to AD 1790. It now seems likely that the bellframe was constructed just after the casting of this last bell.

Only one of the supporting beams has been successfully dated, to a felling of AD 1455. Unfortunately, as a single dated timber that is not an integral part of an extant structure there is little that can be deduced from its dating. This beam could be primary or reused and may have been a later insertion into the supporting framework. As well as the interpretation, the dating of individual samples can be problematic, especially when the tree-ring sequence is relatively short, as in this case. However, it matches well and consistently at AD 1455 and is considered a secure date.

Only three of the *in-situ* timbers have been successfully dated, within site sequence THUBSQ03. The three lower timbers, all corbels, have *termini post quos* for felling of AD 1540, AD 1555, and AD 1562. All three samples show periods of severe growth retardation, which may explain the slightly lower matches against the reference material than might be hoped for. Having said this, the site sequence does match consistently and at a level deemed secure against the reference chronologies.

It is unfortunate that site sequence THUBSQ04, containing eight of the *in-situ* timbers, from both the upper and lower structures, could not be dated. This is most likely due to the short ring-width sequences of many of these samples, with the overall site sequence only being 76 rings. From studying the relative heartwood/sapwood boundary positions, it is possible to say that all the lower timbers represented were most likely felled at the same time. Unfortunately, none of the upper timbers retained the heartwood/sapwood boundary and so it is not possible to say whether both the upper and lower structures are contemporary or even that all upper timbers were felled at the same time.

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TABLES

Table 1. Details of tree-ring samples from the bellframe and bell tower at Thurlby Church, Thurlby, Lincolnshire

Sample Number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Bellframe						
THU-B01	Top sill	108	22	1679	1764	1786
THU-B02	Bottom sill	149	--	1616	----	1764
THU-B03	Unidentified	99	--	1610	----	1708
THU-B04	Top sill	70	--	1698	----	1767
THU-B05	Bottom sill	107	--	1650	----	1756
THU-B06	Unidentified	154	--	1599	----	1752
THU-B07	Bottom sill	89	--	1644	----	1732
THU-B08	Bottom sill	156	22C	1637	1770	1792
THU-B09	Top sill	138	13	1650	1774	1787
THU-B10	Top sill	88	10	1688	1765	1775
THU-B11	Brace	104	06	1666	1763	1769
THU-B12	Brace	123	18	1659	1763	1781
Supporting beams						
THU-B13	Beam	48	--	----	----	----
THU-B14	Beam	67	17C	1389	1438	1455
THU-B15	Beam	69	--	----	----	----
THU-B16	Beam	49	--	----	----	----

Table 1 (contd)

Sample Number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
In-situ timbers – lower						
THU-B17	North-south beam (easternmost)	55	12	----	----	----
THU-B18	North-south beam (westernmost)	53	07	----	----	----
THU-B19	East truss, north corbel	68	--	1458	----	1525
THU-B20	West truss, north post	41	h/s	----	----	----
THU-B21	East truss, north post	55	15	----	----	----
THU-B22	East truss, north brace	45	04	----	----	----
THU-B23	West truss, north brace	70	25C	----	----	----
THU-B24	East truss, south corbel	88	--	1460	----	1547
THU-B25	East truss, south post	68	18	----	----	----
THU-B26	West truss, south corbel	54	--	1487	----	1540
In-situ timbers – upper						
THU-B27	North truss, east post	44	--	----	----	----
THU-B28	South truss, west post	46	--	----	----	----
THU-B29	South truss, east post	48	--	----	----	----
THU-B30	North truss, east brace	46	--	----	----	----

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

C = complete sapwood retained on the sample

Table 2: Results of the cross-matching of site sequence THUBSQ01 and relevant reference chronologies when the first ring date is AD 1599 and the last-ring date is AD 1792

Reference chronology	t-value	Span of chronology	Reference
East Midlands	9.4	AD 882–1981	Laxton and Litton 1988
Church Farm, Bringhurst, Leicestershire	10.9	AD 1664–1781	Groves et al 2004
Thaxted Church, Essex	8.7	AD 1644–1813	Tyers 1990
Bradgate Trees, Leicestershire	7.8	AD 1595–1975	Laxton and Litton 1988
Clothall Bury Farmhouse, Hertfordshire	7.8	AD 1636–1753	Arnold et al 2003a
Green's Mill, Sneinton, Nottinghamshire	7.6	AD 1664–1787	Laxton et al 1982
Worcester Cathedral, Worcestershire	7.6	AD 1484–1772	Arnold et al 2003b

Table 3: Results of the cross-matching of sample THU-B14 and relevant reference chronologies when the first-ring date is AD 1389 and the last-measured ring date is AD 1455

Reference chronology	t-value	Span of chronology	Reference
Little Morton Hall, Cheshire	7.2	AD 1377–1462	Howard 2003 unpubl
Thaxted Church, Essex	5.8	AD 1345–1526	Tyers 1990
Nevill Holt, Leicestershire	5.5	AD 1274–1534	Arnold et al 2008
Combermere, Cheshire	5.3	AD 1363–1564	Howard et al 2003
Dog and Duck, Shardlow, Derbyshire	5.3	AD 1380–1455	Howard et al 1993
23 Church Street, Eckington, Derbyshire	5.3	AD 1381–1474	Esling et al 1989
Auld Cottage, Norwell, Nottinghamshire	5.2	AD 1335–1512	Hurford et al 2010

Table 4: Results of the cross-matching of site sequence THUBSQ03 and relevant reference chronologies when the first-ring date is AD 1458 and the last-ring date is AD 1547

Reference chronology	*t*-value	Span of chronology	Reference
East Midlands	4.8	AD 882–1981	Laxton and Litton 1988
Otley Hall (structural), nr Ipswich, Suffolk	5.7	AD 1415–1587	Bridge 2001
Shifnal Manor Gazebo, Shropshire	5.4	AD 1455–1628	Arnold *et al* 2005
Dower House, Fawsley, Northamptonshire	5.0	AD 1427–1575	Howard *et al* 1999
Lowdham Old Hall (barn), Lowdham, Nottinghamshire	5.0	AD 1422–1527	Howard *et al* 1997
Flores House, Oakham, Rutland	5.0	AD 1408–1591	Hurford *et al* 2008
Auld Cottage, Norwell, Nottinghamshire	5.0	AD 1335–1512	Hurford *et al* 2010

FIGURES

Figure 1: Map to show the general location of Thurlby
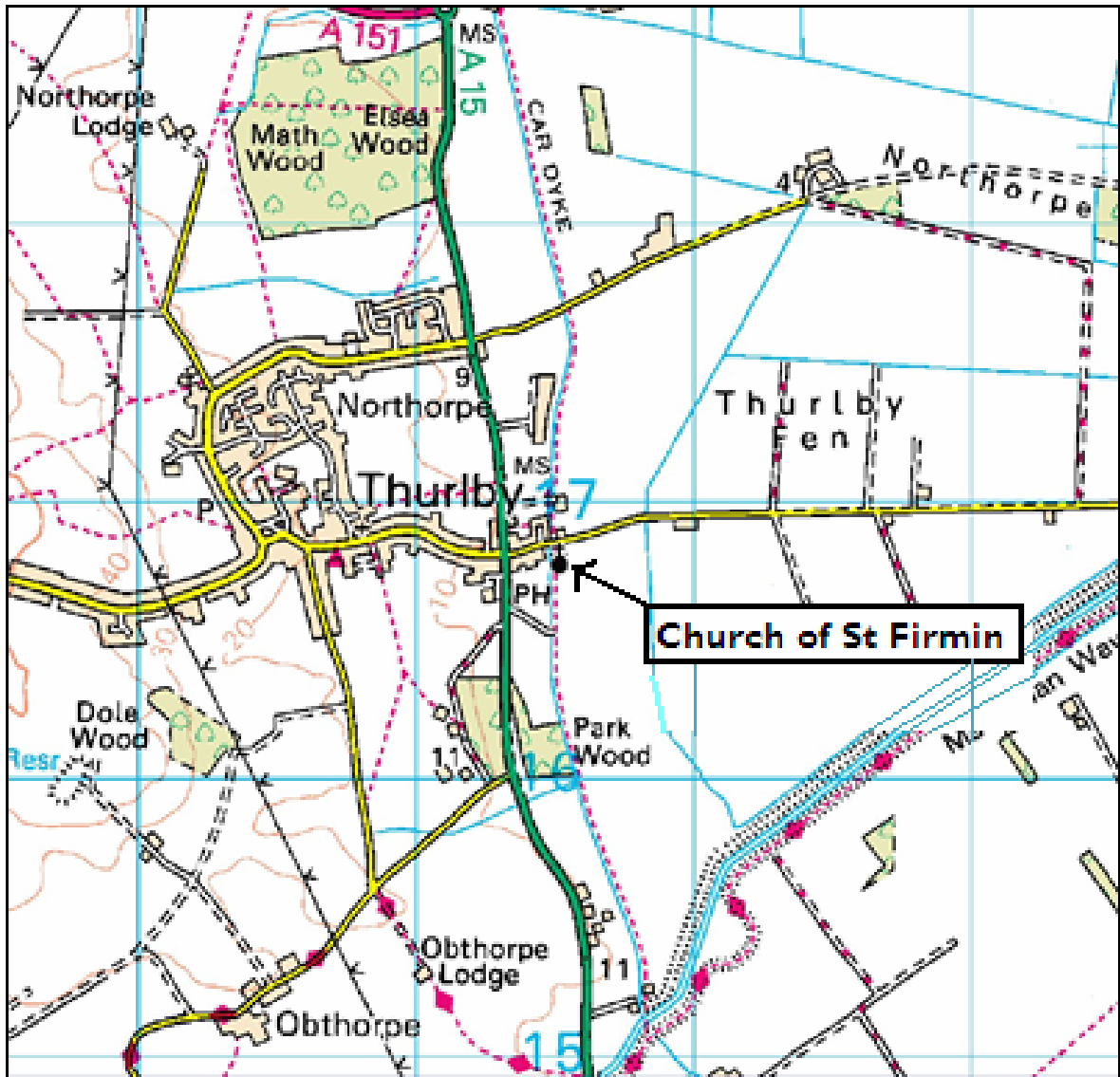
Figure 2: Map to show the location of St Firmin
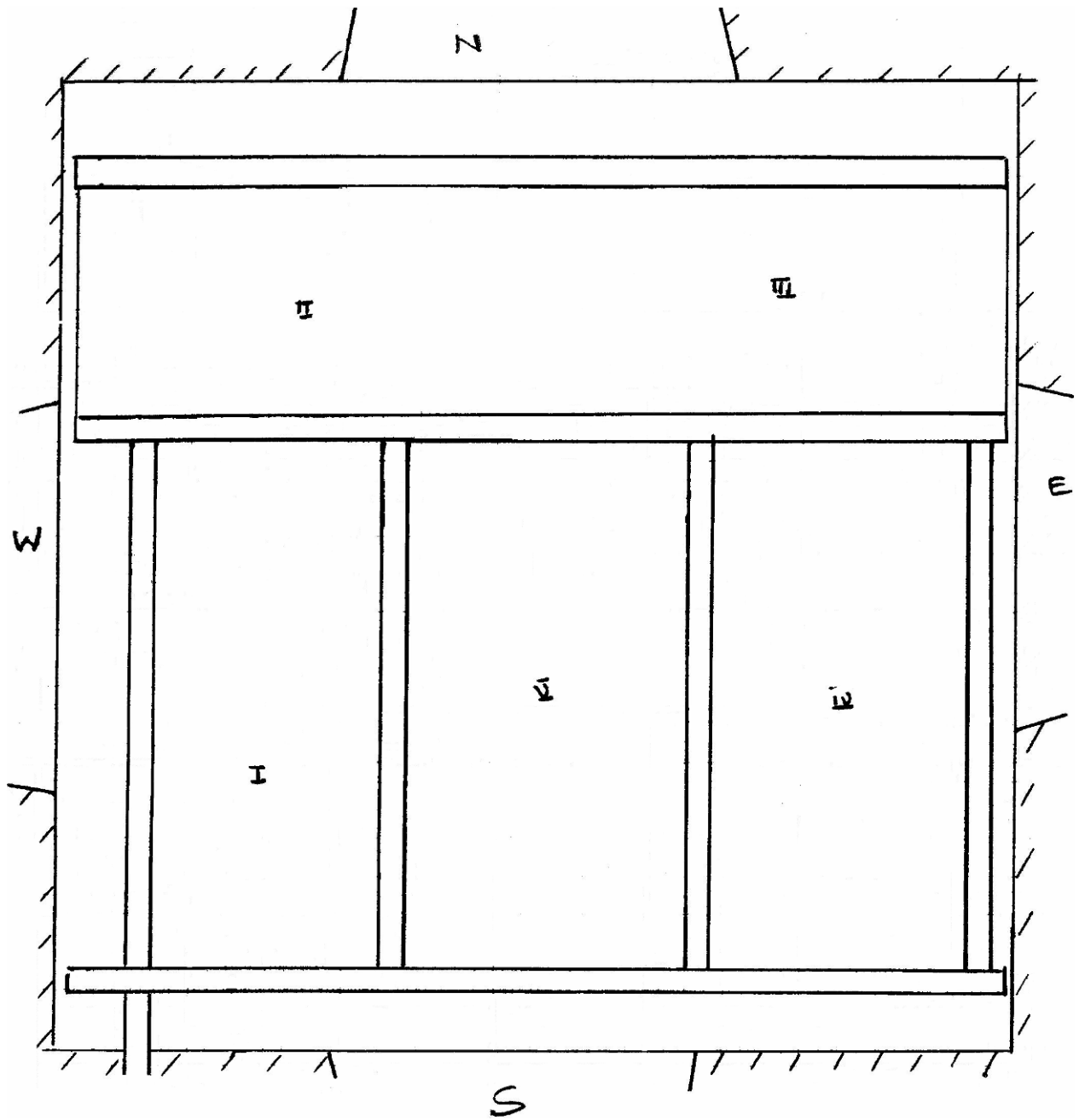
Figure 3: Thurlby Church; tower plan (provided by George Dawson)

S   N

approximate level of
upper timbers

E   W
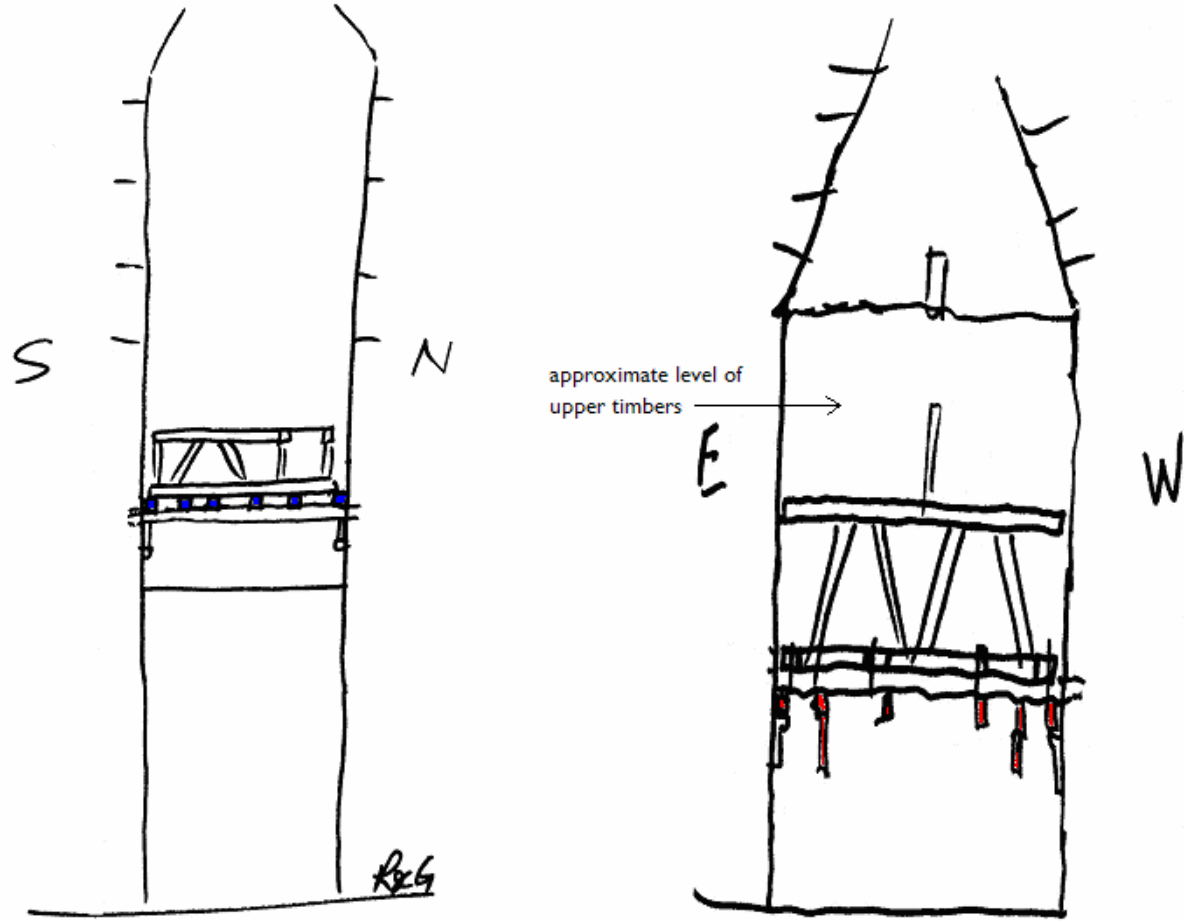
Figure 4: Sketch drawings which show the bellframe design, six supporting beams in blue on the drawing to the left, and lower in-situ timbers in red and approximate level of upper in-situ timbers marked on the drawing to the right (provided by George Dawson)

Figure 5: Lower in-situ timbers (east truss, north side)

Figure 6: Upper in-situ timbers (south truss, west side)
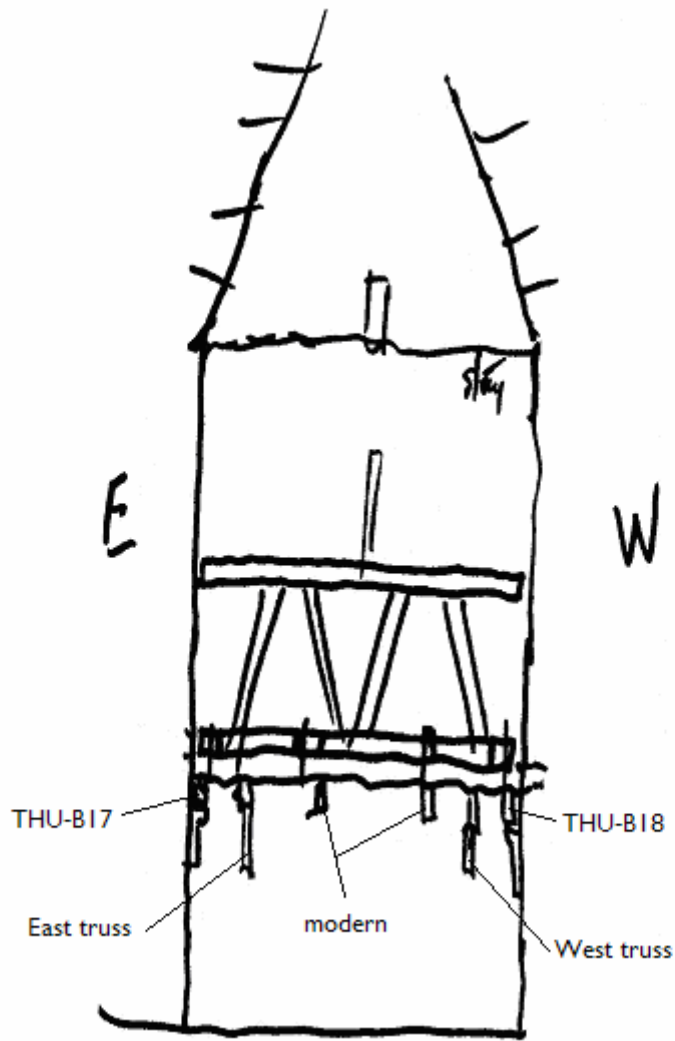
Figure 7: Sketch drawing showing the location of samples THU-B17 and THU-B18 and the position of the east and west truss
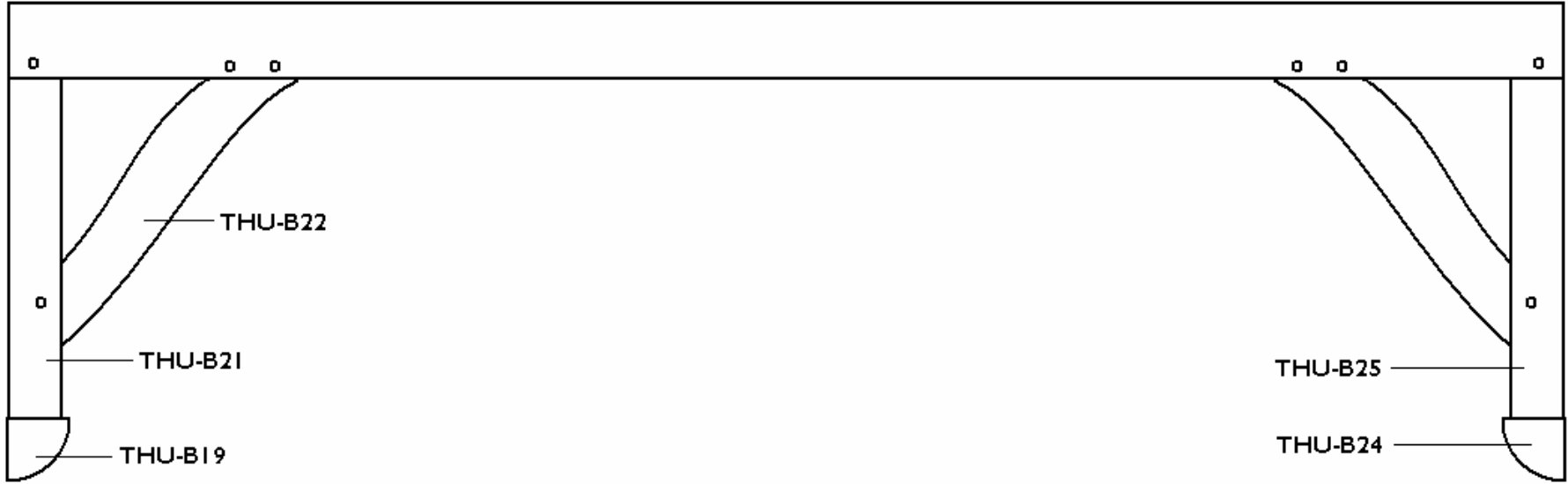
Figure 8: Lower in-situ timbers; sketch of east truss, showing the location of samples THU-B19, THU-B21-2, and THU-B24-5

Figure 9: Lower in-situ timbers; sketch of west truss, showing the location of samples THU-B20, THU-B23, and THU-B26
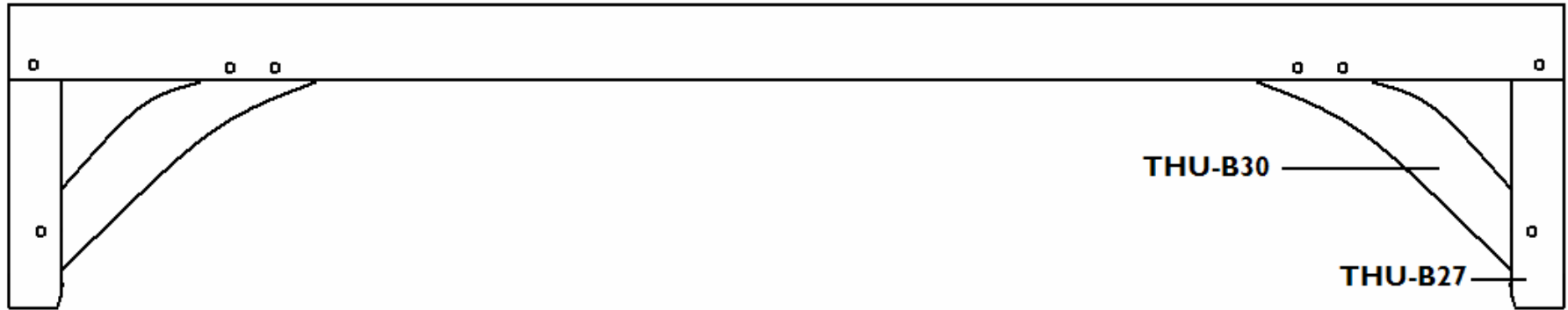
Figure 10: Upper in-situ timbers; sketch of north truss, showing the location of samples THU-B27 and THU-B30
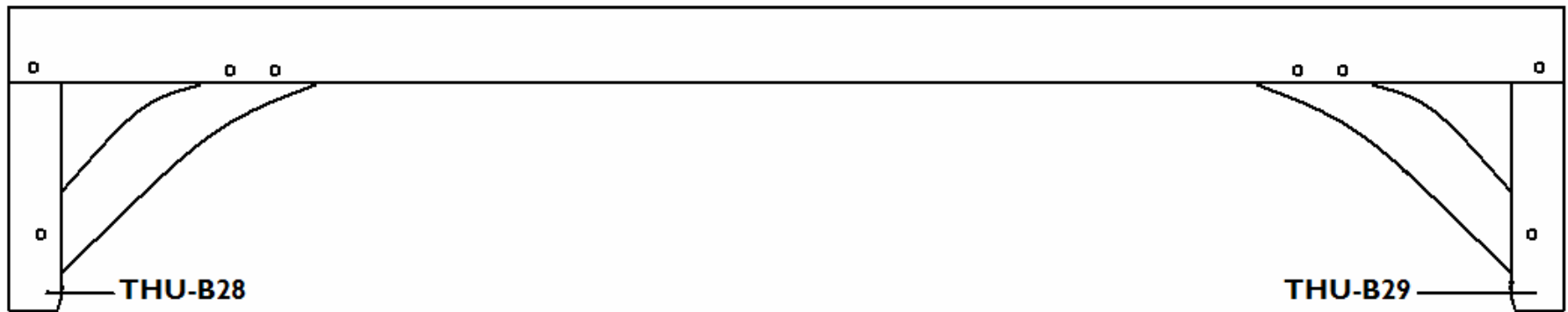
Figure 11: Upper in-situ timbers; sketch of south truss, showing the location of samples THU-B28 and THU-B29

Figure 12: Samples THU-B01 and THU-B11

THU-B02

Figure 13: Sample THU-B02

THU-B04

THU-B03

THU-B09

THU-B10

Figure 14: Samples THU-B03, THU-B04, THU-B09, and THU-B10

THU-B05

THU-B06

THU-B07

Figure 15: Samples THU-B05, THU-B06, and THU-B07

Figure 16: Samples THU-B08 and THU-B12

Figure 17: One of the supporting beams
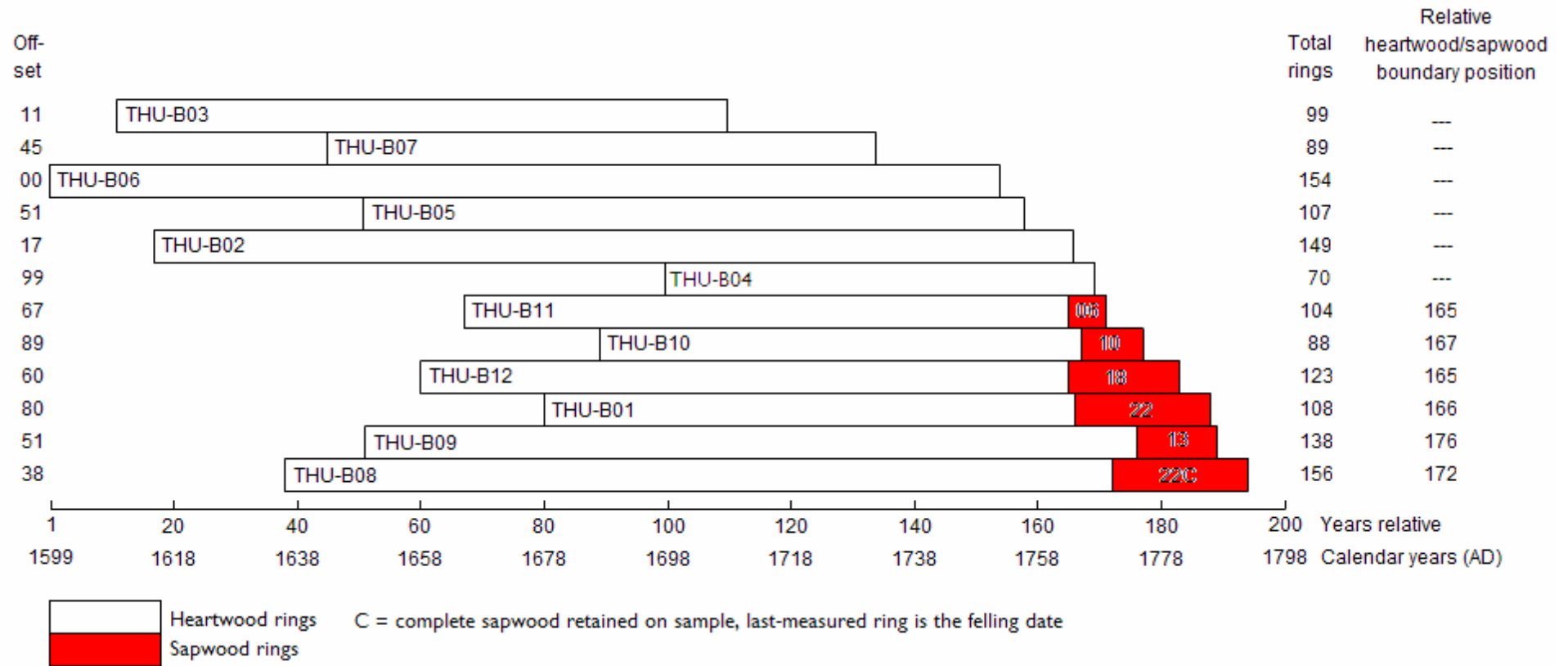
Figure 18: Bar diagram of samples in site sequence THUBSQ01
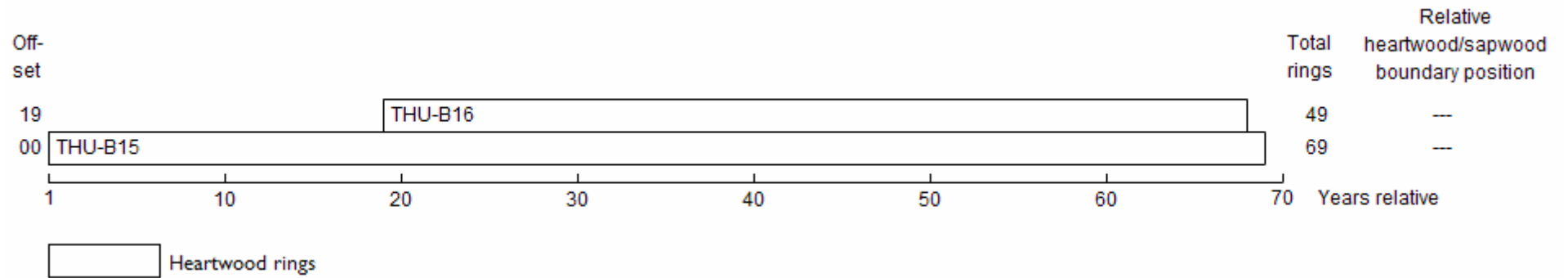
Figure 19: Bar diagram of samples in undated site sequence THUBSQ02
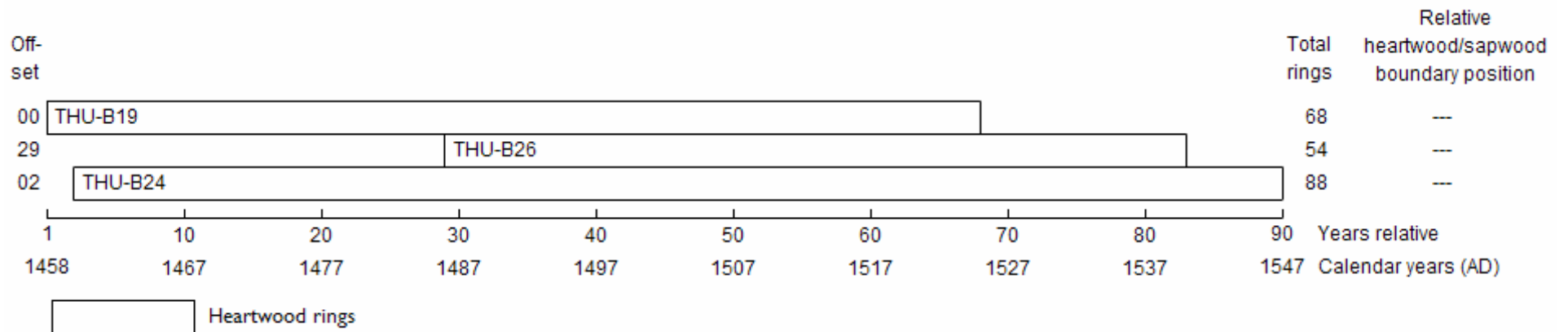
Figure 20: Bar diagram of samples in site sequence THUBSQ03
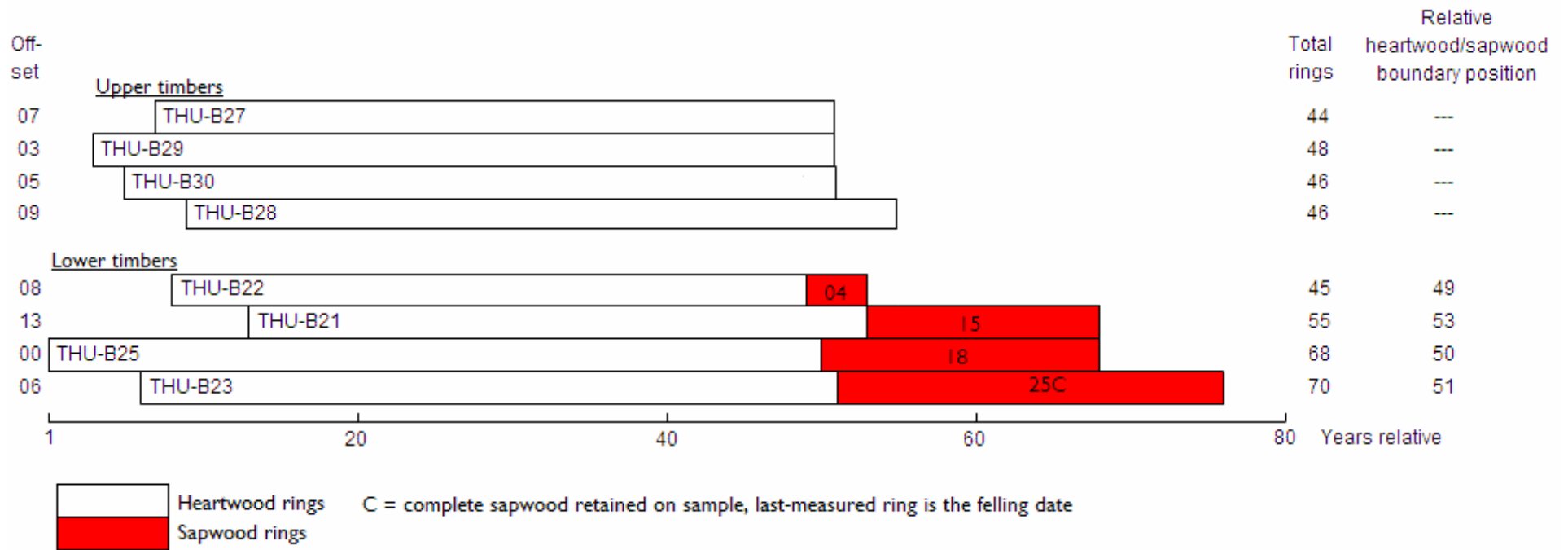
Figure 21: Bar diagram of samples in site sequence THUBSQ04

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

THU-B01A 108
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158 167 107 101  78  67  92 164 189 196 146 116 107 158 163 167  86 141 160 221
162 224 204 132 182 231 185 241 191 200 156  92 172 193 214 156 218 211 247 178
138 227 236 236 192 279 282 245 307 238 258 187 222 204 177 153 231 149 106 181
220 176 126 147 127 141 164 179 215 133 129 135 171 159 166 187 179 146 124 152
158 161 187 151 146 140  88 110  75  65  99 140 109 118 147 171 140 135 144 154
121 107 108 112  93 100  85  82
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THU-B01B 108
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173 175  96 119  70  79  82 145 173 186 140 125 100 160 166 157 109 116 182 240
189 185 176 153 188 212 165 231 176 215 152 103 168 190 219 159 222 213 250 186
154 237 258 230 185 288 284 250 296 238 237 209 211 214 174 142 219 147 104 191
214 180 136 144 125 159 164 170 211 168 129 154 182 163 168 194 174 145 126 151
160 166 184 152 155 137  82 116  92  75 102 147 112 114 156 153 165 116 139 168
128 106 114 108  83 106  82 109
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THU-B02A 149
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149 188 132 270 300 283 239 200 139 134 103 120 283 229  67  46 129 124  73  81
228 136 158 131 125 137  56 180 190 173 198 176 224 129 119 149  69 130 164 144
182  69 138 100 198 118 182 101 125 131  48 130 178 148 181 102 209 135 103 100
161 181 140 243 154 134 214 166 103  59 172 213 182 126  66 120 105 189 113 112
171 232 169 143  80 109  59 132 138 110 163 107 165 117 107  97 136 194  89 169
163 126  85 126 140 187  89  74 171 103 129 153 116 102 175 140 119 111  69 280
203  65  97 124  56  83  79  91 117  99 201 119 153 130 122 129 116 495 163 194
121 147  96 168 113 129  98 268 162
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221 140 164 132 118 147  55 191 210 190 198 171 228 113 126 131  75 113 153 150
168  68 135  97 179 129 185  92 128 132  59 117 170 148 183 103 211 145 104  88
166 190 125 250 142 142 209 167 108  55 174 216 175 129  58 127 101 186 117 115
179 217 165 145  75 112  61 128 140 113 162 109 168 120  98  95 139 196  90 174
159 127  86 123 143 190  88  81 176 112 139 150 113 110 173 133 133 103  71 291
215  55 104 116  65  88  75  85 125 105 198 125 161 123 122 137 107 478 151 192
134 132  84 168 121 128  93 268 170
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THU-B03A 99
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173 276 195 197 156 215 191 179 178 125 134  68 129 214  93 132 146 158 196 217
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219 258 163 182 216 217 251 189 268 342 360 298 429 188 184 157 347 299 529 232
454 296 514 376 205 161 312 373 286 393 269 336 613 417 184 163 370 283 343 188
160 240 138 324 135 216 231 235 297 370 186 133 200 260 471 205 252 266 364
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240 274 210 199 152 190 168 170 155 123 134  68 132 193  92 110 137 150 164 187
160 164 181 211 171 274 446 302 359 203 223 247 159 172 215 233 321 201 293 146
216 272 163 185 200 221 264 205 265 323 356 284 419 164 190 144 336 303 522 265
476 291 505 387 211 159 331 368 291 402 241 327 601 419 200 171 387 289 341 189
160 250 151 313 128 213 223 234 276 348 189 127 203 264 459 199 245 273 371
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THU-B04A 70
 62 72 154 215 193 234 340 282 393 322 280 151 114 182 313 389 281 331 439 334
201 272 332 428 479 394 445 304 509 432 345 399 245 374 495 373 288 210 289 147
193 254 201 169 153 150 165 133 171 173 116 141 166 196 127 175 139 138 75 112
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THU-B04B 70
 66 66 153 213 191 243 321 279 420 293 282 182 103 180 287 363 249 310 441 323
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245 243 181 193 182 160 155
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248 211 184 214 151 157 156
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264 145 41 38 32 36 50 104 104 126 88 82 86 65 100 106 113 129 141 115
130 242 155 125 117 88 123 94 141 182 147 180 111 213 146 104 93 115 159 136
158 139 105 149 110 99 45 113 80 114 69 56 49 58 107 64 46 49 91 89
 66 43 106 72 91 115 93 122 82 104 88 71 79 119 172 96 188 156 130 97
103 156 188 155 122 170 135 157 187 141 148 146 126 141 98 85 156 115 67 120
115 116 79 68 95 83 117 147 124 127 94 109 94 126
THU-B06B 154
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263 134 44 49 38 28 53 102 101 101 86 86 93 66 102 103 117 119 132 111
135 232 162 129 112 92 118 93 150 179 147 194 110 197 142 102 101 110 152 140
164 151 98 141 120 84 56 113 83 104 76 53 50 61 100 63 40 49 94 81
 71 47 102 76 89 116 86 119 93 98 95 61 94 112 174 98 187 156 141 92
108 151 187 151 123 153 135 170 183 142 163 144 115 138 95 86 170 114 64 114
122 109 86 74 89 84 123 135 122 129 86 113 93 115
THU-B07A 89
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211 126 189 189 296 158 117 128 132 200 154 87 67 146 181 210 147 220 120 227
336 212 190 237 136 114 79 95 161 232 210 178 196 166 125 118 208 201 303 248
422 311 294 314 303 294 237 233 208

THU-B07B 89
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136 202 320 286 386 288 350 321 294 181 108  77  91 266 313 285 240 332 388 212
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319 227 232 257 156 107  85  96 174 234 207 160 172 152 105 130 209 208 267 299
342 298 308 314 346 295 225 233 221
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THU-B08A 156
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152 161 172 179  92 200 177 174 126 214 173 245 198 140 124 128 154 121  68 103
112 164 138 159 153 119 176 214 144 174 150 152 108 109 144 175 232 167 223 192
221 165 114 187 221 206 174 271 225 216 242 253 194 185 206 225 131 122 284 186
104 170 228 171 118 148 121 189 191 278 263 174 149 173 227 245 194 242 199 203
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THU-B08B 156
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124 175 150 146 156 123 169 214 145 177 162 160  99 101 137 185 233 153 214 206
203 160 119 199 210 214 151 254 242 195 240 241 184 188 213 215 163 128 287 158
104 147 196 171 113 134 127 192 185 251 284 173 150 174 215 233 224 266 206 197
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140 193 167 134 134 194 109 125  84 102  62  87 134 143 129 122
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THU-B09A 138
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155 245 285 274 138 172 130 130  76  76 130 155 165 119 147 135 113 137 114 114
104  97 125  89 106  91  74  73 107 122 127  82  69  55  78  77 114  81  93 125
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100  94 111 121 122  80 102 103  94  78  76  95 100  99  70  75  68  79
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THU-B09B 138
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THU-B10A 76
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106  78 108 132 185 106  85 116  99 121 143 122  99 108  90 121
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THU-B10B 83
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130 114 132 137 129 146 132  96 138  88 218 207 120 147 138 206 172 120 110 170
199 189 183
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THU-B11A 104
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164 127 144 107 128 177 159 118 100 168 102 136 187 136 118 156 93 227 162 76
139 89 178 135

THU-B11B 104
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149 93 182 145

THU-B12A 123
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 94 139 153 142 92 132 52 109 140 88 133 127 110 112 158 105 111 57 73 108
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115 106 128 90 165 136 68 146 65 146 100 98 95 127 126 136 127 114 89 115
112 94 96

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 85 137 141 147 89 127 46 120 120 108 123 134 102 103 150 95 128 60 80 102
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118 124 101

THU-B13A 48
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THU-B13B 48
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THU-B14A 67
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THU-B15A 69

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THU-B15B 69

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THU-B16A 49

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THU-B16B 49

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THU-B17A 55

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241 235 242 250 225 183 206 206 118 75 116 130 118 101 99

THU-B17B 55

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THU-B18A 53

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THU-B18B 53

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THU-B19B 68

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THU-B20A 41

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230

THU-B20B 41

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227

THU-B21A 55

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THU-B22B 45
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251 178 133 184 193
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THU-B24B 88
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THU-B26A 54
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THU-B26B 54
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136 237 176 221
THU-B28A 46
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226 289 356 293 326 267
THU-B28B 46
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219 270 375 298 329 285
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314 173 258 152 163 275 153 98
THU-B29B 48
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THU-B30B 46
 76 83 39 29 60 208 271 215 249 366 410 323 448 391 466 289 323 290 239 286
293 138 94 150 274 308 283 161 225 207 230 222 198 235 311 183 332 254 393 237
281 248 227 404 215 212

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It

also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

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

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

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

t-value/offset Matrix

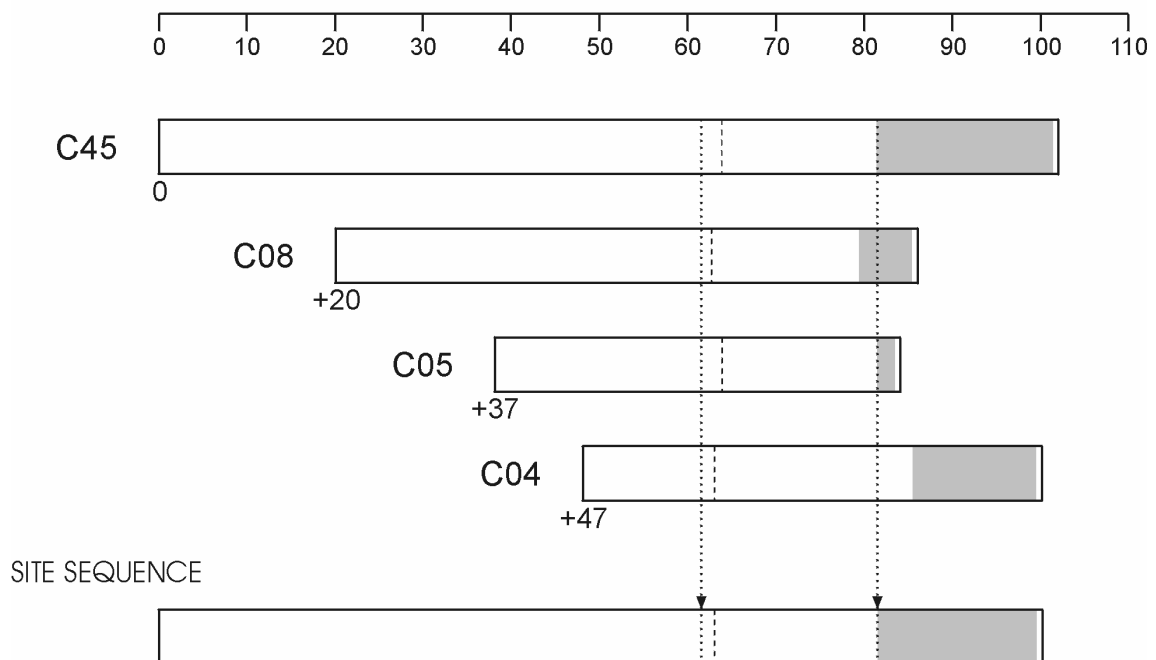|	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

SITE SEQUENCE

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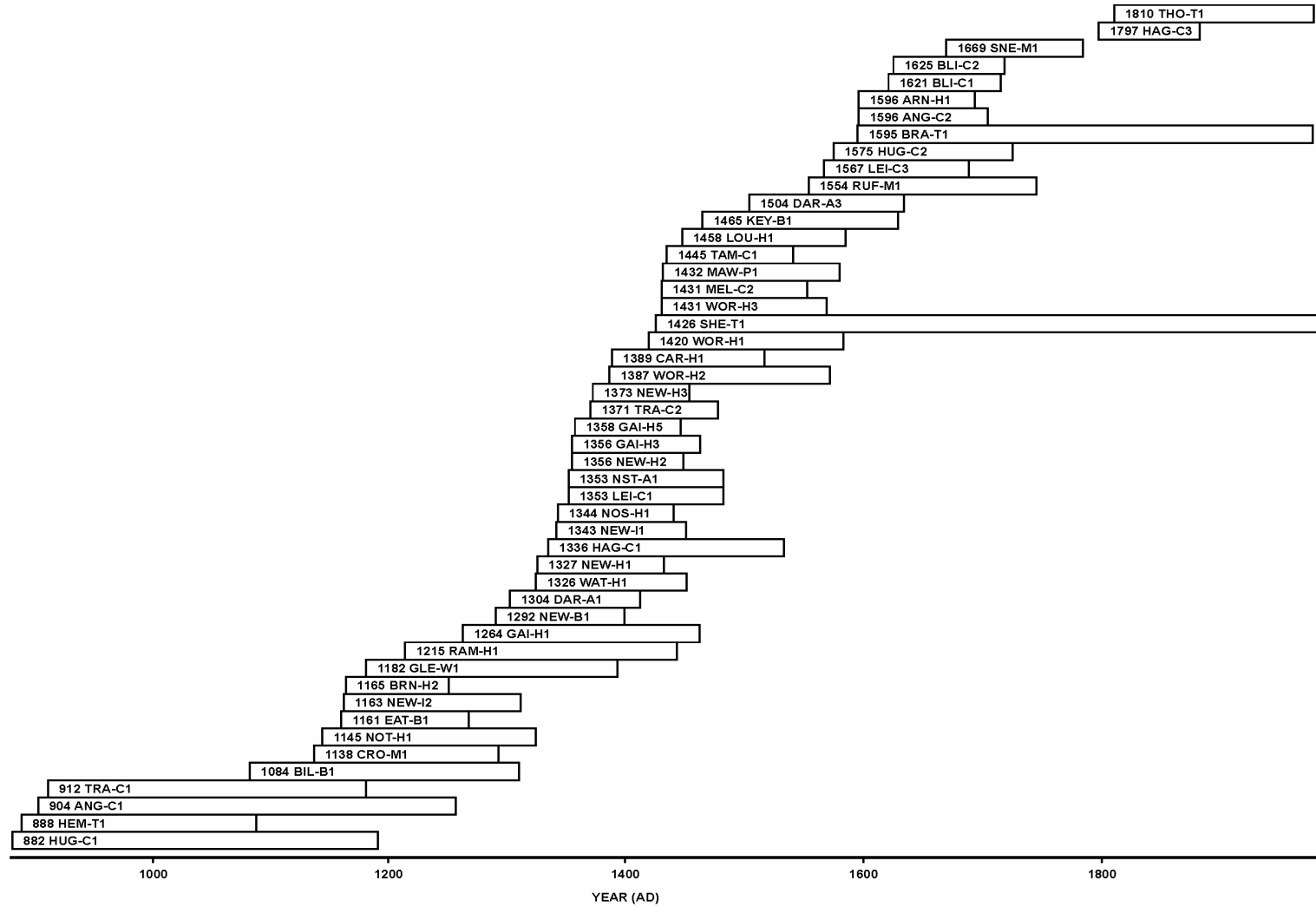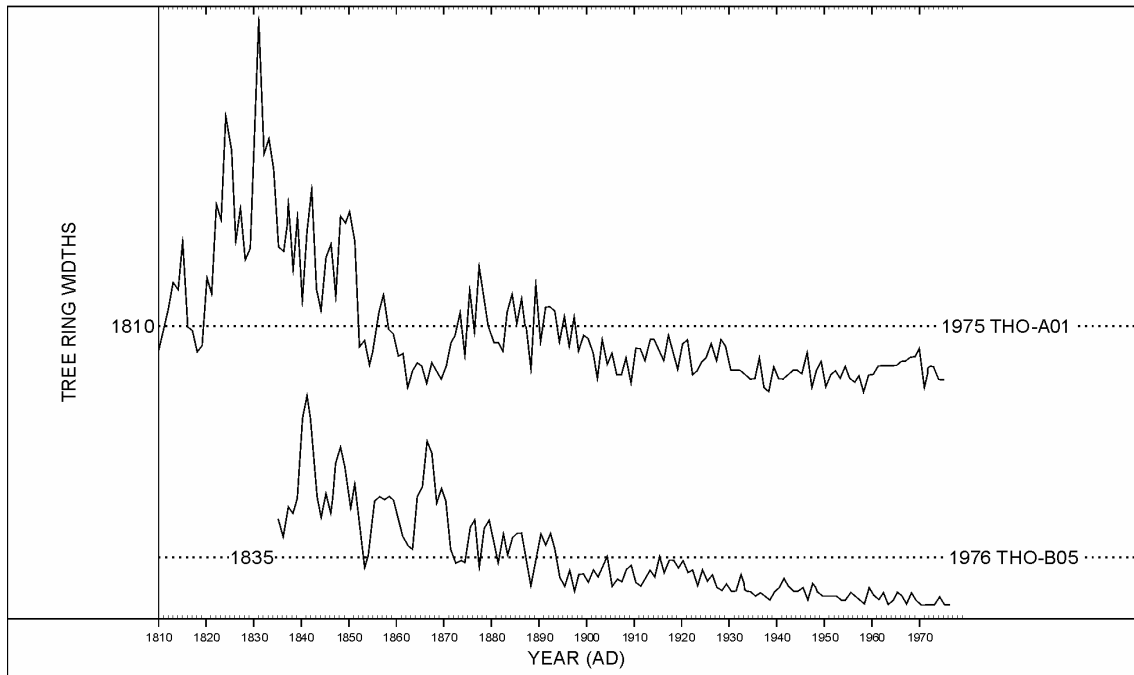
Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87
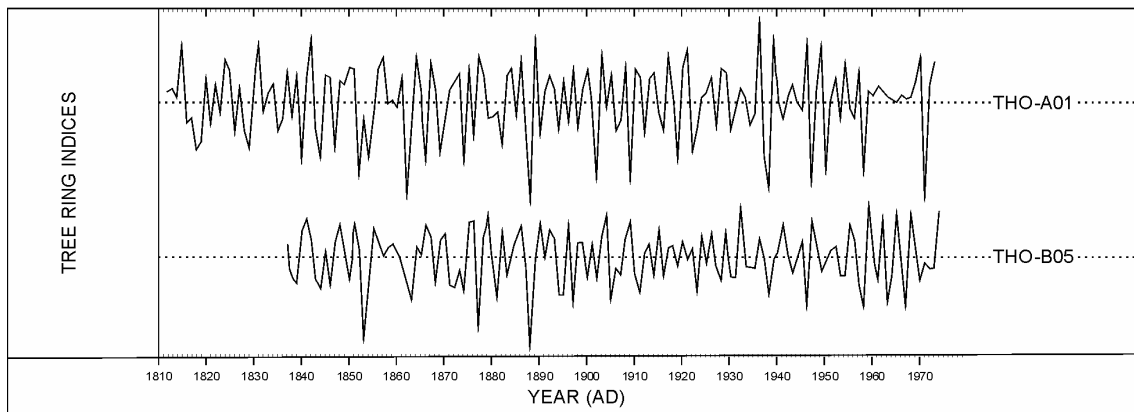
(a)

(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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