St Marys Court, 49–51 North Bar Within
Beverley, East Riding of Yorkshire
Tree-ring analysis of oak timbers

Alison Arnold, Robert Howard and Cathy Tyers

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ST MARYS COURT
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EAST RIDING OF YORKSHIRE

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SUMMARY

Tree-ring analysis was undertaken on samples taken from the roof and timber framing of St Marys Court, 49–51 North Bar Within, Beverley, resulting in the dating of a single site sequence. Site sequence BEVESQ01 contains five samples, all taken from tiebeams in the roof, and spans the period AD 1173–1336. Interpretation of the surviving sapwood suggests all the tiebeams were derived from trees felled in AD 1336.

A second site sequence is undated.

CONTRIBUTORS

Alison Arnold, Robert Howard and Cathy Tyers

ACKNOWLEDGEMENTS

We would like to thank David Cook of the Yorkshire Vernacular Buildings Study Group for facilitating access and the owners and tenants of St Marys Court for allowing the sampling to be undertaken. The drawings and building's description are based on the survey undertaken by the YVBSG. Thanks are also given to Shahina Farid of the Historic England Scientific Dating Team for her advice and assistance throughout the production of this report and to Rebecca Lane of the Historic England Architectural Investigation Team who coordinated this project.

ARCHIVE LOCATION

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DATE OF INVESTIGATION

2015–2020

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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 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 Investigator).

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).

ST MARYS COURT

St Marys Court is located on the west side of North Bar Within and is thought to be associated with the development of Beverley around St Mary's Church and the north end of Saturday Market (Figs 1–3). It is likely to have originally been a lodging or part of a row. It is of two stories and six bays (Fig 4), although it may have once had more bays to the north. It was jettied to the front and south gable end, and possibly the north gable before these outer bay/s were removed. It is also thought to have had a rear wing once, again since demolished. By the early-nineteenth century the building had been divided into three residences before being converted to commercial premises in the early-twentieth century. At this point the majority of the timber framing survived although much of this is now missing or obscured. The building is Grade II* listed (List Entry Number 1084008).

On the evidence of surviving timber (Fig 5), it can be seen that the roof was of common rafter type with at least one crown post, supported on wall posts. Braces curved up from the wall posts to the tiebeams and from the crown post to a collar purlin. The west post of truss IV may have had double bracing to the tiebeam. It has been suggested that it is fifteenth century in date (List Entry Number 1084008).

SAMPLING

A total of 12 core samples were taken from oak (*Quercus* sp) timbers of the roof and timber framing of this building. Each sample was given the code BEV-E and numbered 1–12. The location of all samples was noted at the time of sampling and has been marked on Figures 4 and 6–7. One of the tiebeams (BEV-E11) was sampled twice in an attempt to maximise the length of the ring-width sequence. These two ring-series cross-matched (t = 11.2) and were combined to form the 135-year timber mean reported in Table 1. Further details relating to the samples can be found in Table 1. Trusses have been numbered I–VII from site south to site north, following the numbering scheme used by the Yorkshire Vernacular Buildings Study Group, which in turn adopted that of Humber Archaeology (1982).

ANALYSIS AND RESULTS

Three of the samples, BEV-E02 and BEV-E05 from wall posts and BEV-E04 from a rafter, had too few rings for secure dating and so were rejected prior to measurement. The remaining nine samples were prepared by sanding and polishing and their growth-ring width 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 seven samples matching to form two groups.

Firstly, five samples, all taken from tiebeams, matched at a minimum t-value of 4.7 and were combined at the relevant offset positions to form BEVESQ01, a site sequence of 164 rings (Fig 8). This site sequence was compared against a series of reference chronologies for oak where it was found to match securely and consistently at a first-ring date of AD 1173 and a last-measured ring date of AD 1336. The evidence for this dating is given in Table 2.

Two other samples also matched each other (minimum t-value of 7.2) and were again combined at the relevant offset positions to form BEVESQ02, a site sequence of 93 rings (Fig 9). Attempts to date this site sequence and the remaining ungrouped samples by comparing them against the reference chronologies were unsuccessful and these remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of five samples, all from tiebeams in the roof. Sample BEV-E12 has complete sapwood and the last-measured ring date of AD 1336, the felling date of the timber represented. The other four dated samples have the heartwood/sapwood boundary, which in all cases are broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1307. Using the estimate that 95% of mature oak trees in this region have 15–40 sapwood rings this gives an estimated felling date for the four timbers represented to within the range AD 1322–47, consistent with these timbers also having been felled in AD 1336.

DISCUSSION

Tree-ring analysis has shown that the roof of St Marys Court incorporates timber felled in AD 1336. This would suggest a construction date for the building in the first half of the fourteenth century, somewhat earlier than the fifteenth-century date previously assigned to it, if these five tiebeam are thought to be representative of the primary phase of construction.

In the fourteenth century Beverley was one of the wealthiest towns in the country. Evidence for this has been provided during the course of this project (Cook and Neave 2018) with the identification of major rebuilding and extensions being undertaken at the church (Arnold *et al* 2020a) and the construction of a number of high status buildings, St Marys Court being just one of these, with 19–21 Ladygate, dated to AD 1330 (Arnold *et al* 2020b) being a second.

The highest levels of similarity between the dated site sequence, BEVESQ01, and reference chronologies (Table 2) are generally with those in the surrounding regions with Yorkshire being well represented but also the East and West Midlands. This suggests that the dated timbers are likely to be sourced from woodland within the surrounding region.

The lack of successful dating for site sequence BEVESQ02 and the two ungrouped samples may simply be due to the presence of bands of narrow rings which are masking the overall general climatic signal required for successful dating purposes. It could also be due to these timbers representing different phases of repair or construction and single samples or poorly replicated site sequences are always more problematic to date reliably. However it should be noted that the lack of dating and cross-matching cannot be assumed to either confirm or refute whether these timbers represent the same phase of construction as the five dated tiebeams.

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TABLES

Table 1: Details of tree-ring samples taken from St Marys Court, 49–51 North Bar Within, Beverley, East Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
BEV-E01	Tiebeam, truss VI	79	h/s	1237	1315	1315
BEV-E02	East wall post, truss VI	NM	--	----	----	----
BEV-E03	Tiebeam, truss V	126	h/s	1190	1315	1315
BEV-E04	West rafter, truss V	NM	--	----	----	----
BEV-E05	West wall post, truss V	NM	--	----	----	----
BEV-E06	West brace, crown post to tiebeam, truss V	60	07	----	----	----
BEV-E07	East brace, crown post to tiebeam, truss V	92	13	----	----	----
BEV-E08	Stud post 2, below tiebeam, truss V	97	35C	----	----	----
BEV-E09	Stud post 4, below tiebeam, truss V	89	--	----	----	----
BEV-E10	Tiebeam, truss IV	100	h/s	1193	----	1292
BEV-E11	Tiebeam, truss III	135	h/s	1173	1307	1307
BEV-E12	Tiebeam, truss II	149	31C	1188	1305	1336

NM = not measured
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 BEVESQ01 and the reference chronologies when the first-ring date is AD 1173 and the last-measured ring date is AD 1336

Reference chronology	*t*-value	Span of chronology	Reference
Baxby Man Farm, Baxby, North Yorkshire	7.8	AD 1161–1307	Howard *et al* 1994
Hull (HMC94) coffin, East Yorkshire	7.5	AD 1155–1319	Tyers 1998
64–72 Goodramgate, York, North Yorkshire	7.0	AD 1079–1315	Arnold and Howard 2012a
Polesworth Abbey Gatehouse, Warwickshire	6.7	AD 1095–1342	Arnold and Howard 2007
Ulverscroft Priory, Ulverscroft, Leicestershire	6.5	AD 1219–1463	Arnold *et al* 2008
The Manor House, Abbey Green, Burton-on-Trent, Staffordshire	6.6	AD 1162–1339	Howard *et al* 1998
7–9 Stourport Road, Bewdley, Worcestershire	6.4	AD 1060–1301	Arnold *et al* 2005
32 Goodramgate, York, North Yorkshire	6.4	AD 992–1298	Arnold and Howard 2012b
Bilby bridge, nr Retford, Nottinghamshire	6.0	AD 1084–1311	Morgan 1976
Hall Garth, Beverley, East Yorkshire	5.9	AD 1002–1324	Hillam 1981

FIGURES

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

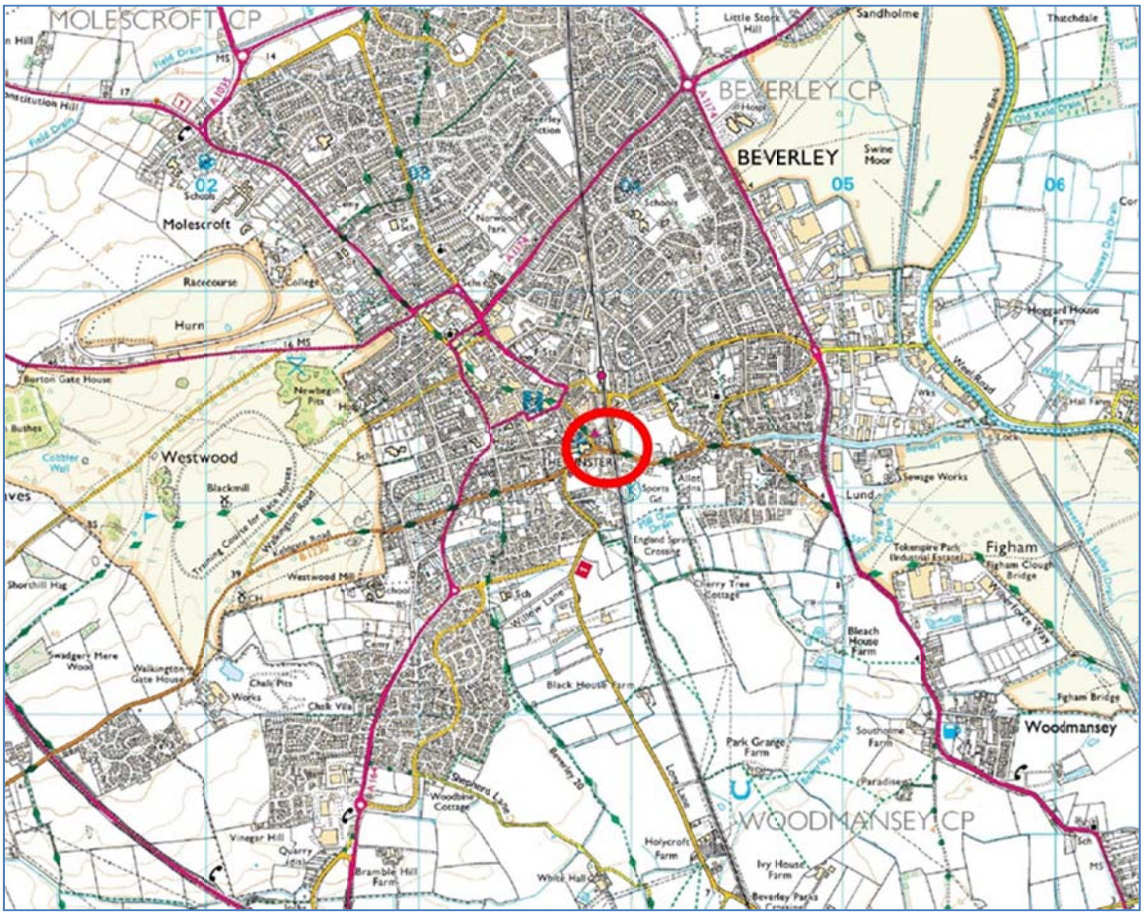

Figure 2: Map to show the general location of St Marys Court in Beverley (red ellipse). © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the location of St Mary's Court, hashed. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

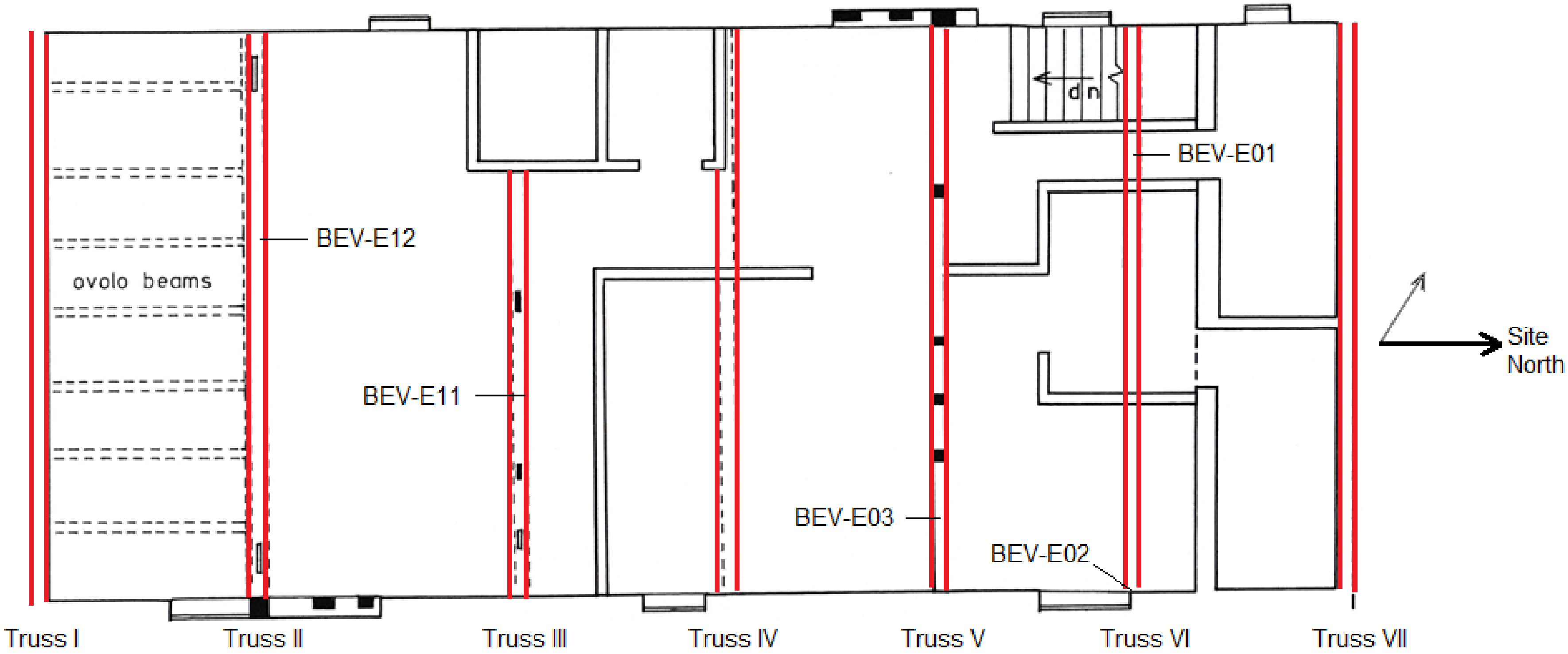

Figure 4: First-floor plan, showing truss numbering and sampled timbers BEV-E01–03, and BEV-E11–12 (YVBSG, 2015)

Figure 5: The west post of truss V, photograph taken from the north-east (Alison Arnold)

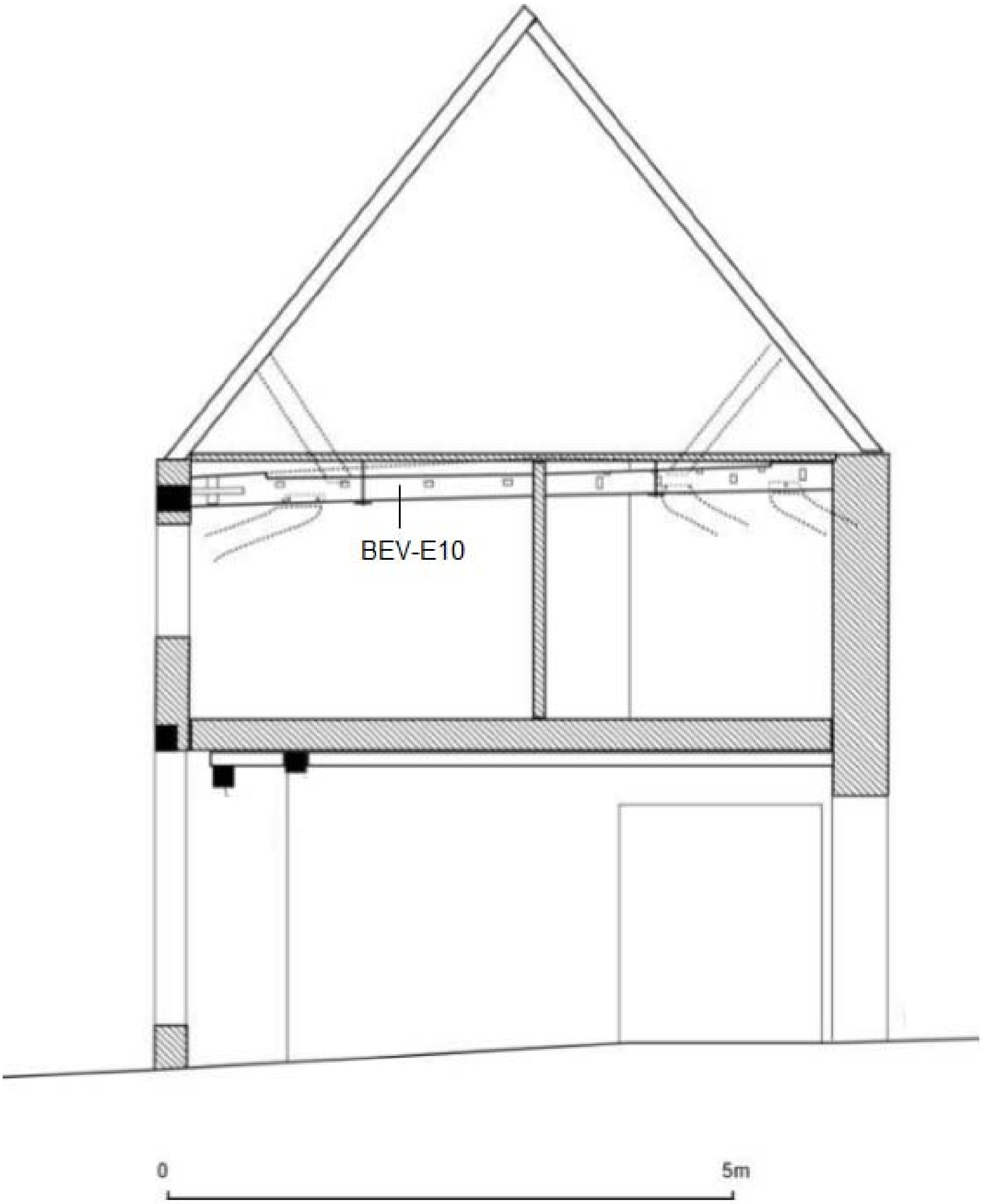

Figure 6: Truss IV (north face), showing the location of sampled timbers BEV-E10 (YVBSG 2015)

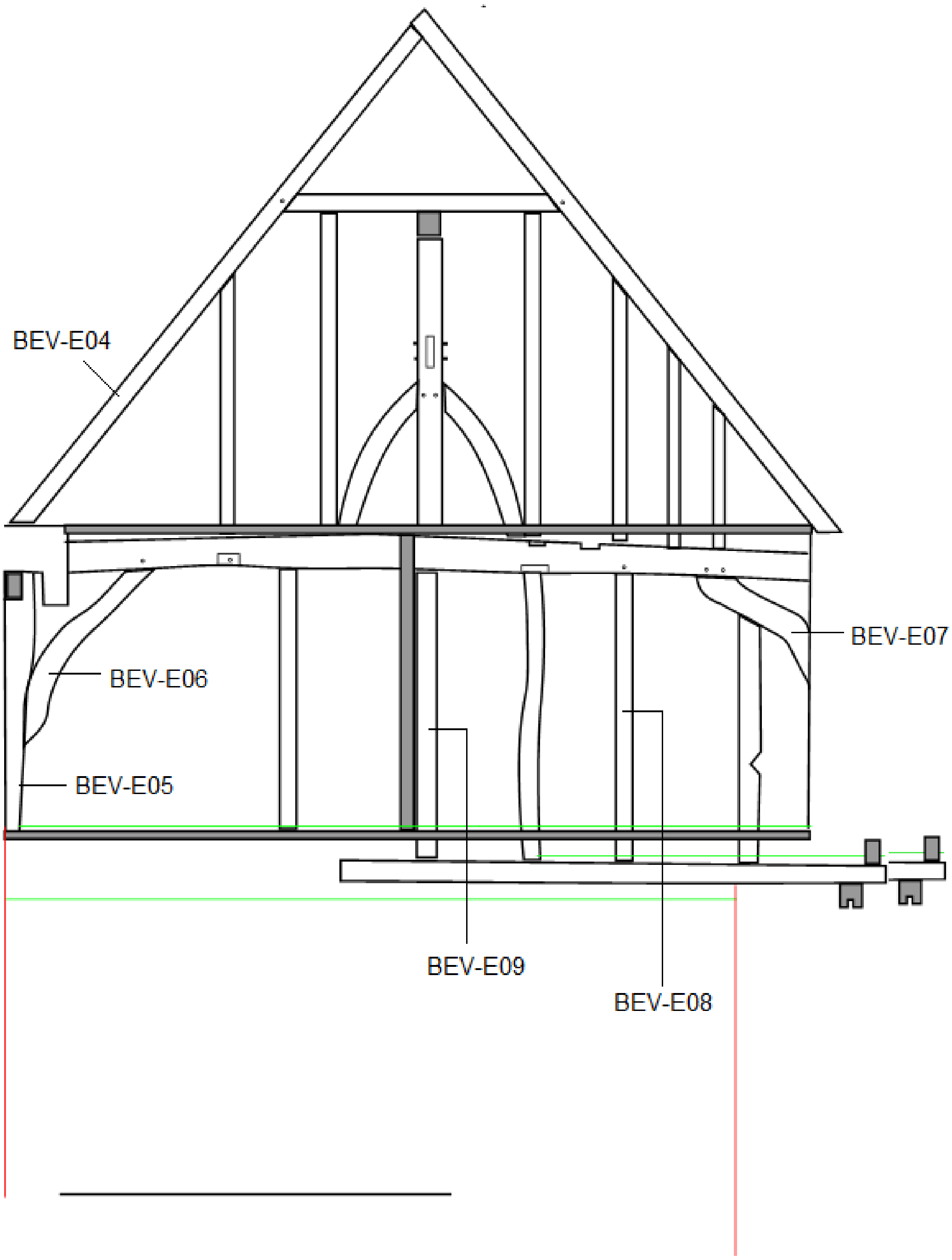

Figure 7: Truss V (south face), showing the location of sampled timbers BEV-E04-09 (YVBSG 2015)

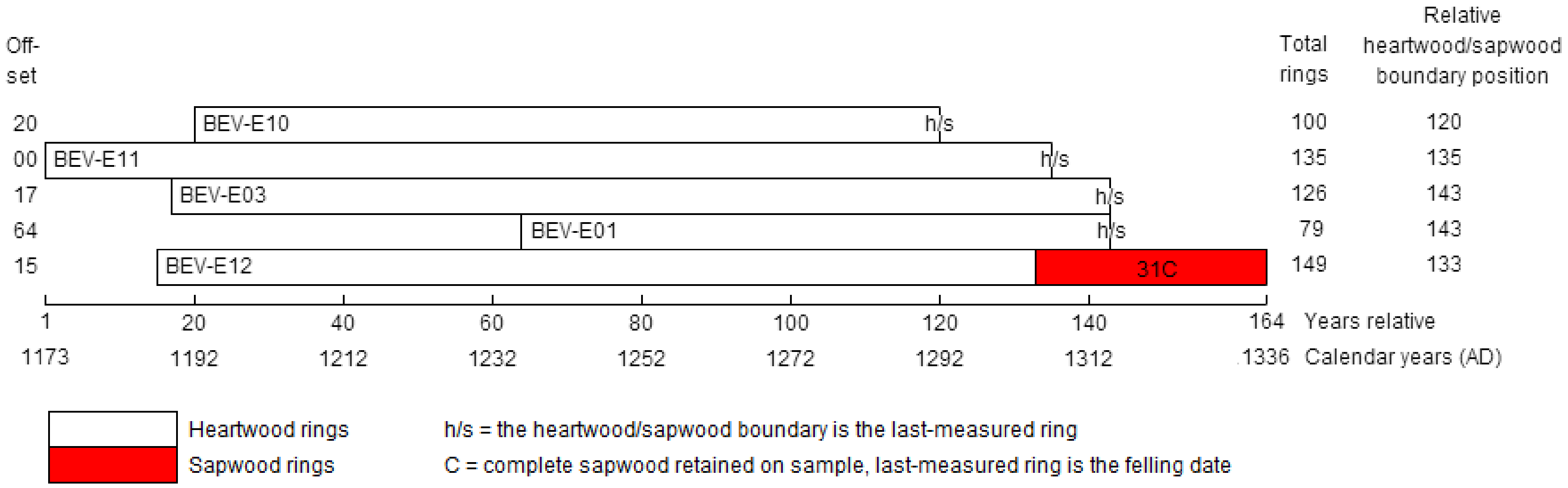

Figure 8: Bar diagram of samples in site sequence BEVESQ01

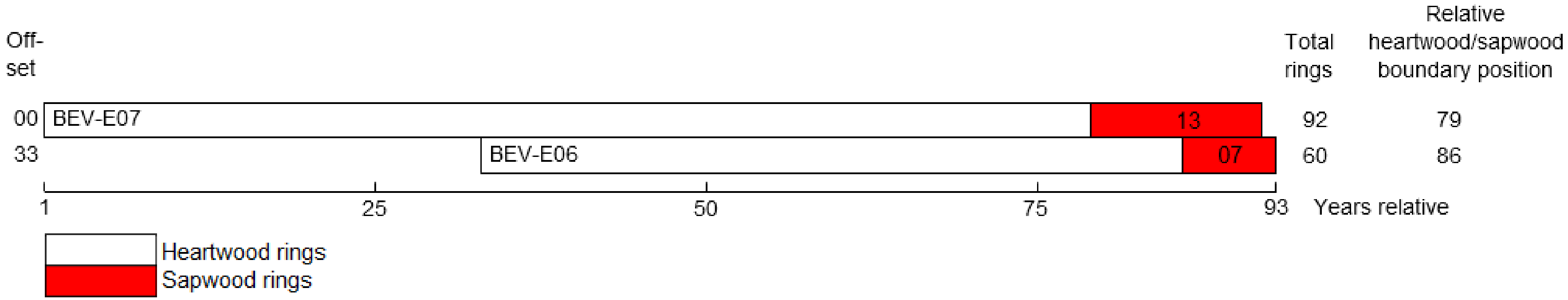

Figure 9: Bar diagram of samples in site sequence BEVESQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

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BEV-E01A 79
 423 520 319 210 247 279 234 183 212 169 217 305 299 175 265 260 217 241 165 153
 112  91  87 142 203 229 209 110  89 143 163 160 113 148 139 124 102 102  93 122
 185 144 172 239 328 158 163 144 124 191 129 134 169 180 236 274 200 219 133 117
 120 104  82  96 117  89  84  75 113 122 129 100  82  85  84  88  73  68 109

BEV-E01B 79
 386 500 332 210 254 283 238 187 201 170 213 303 301 173 260 255 224 232 175 171
 127  92  91 140 203 220 219 116  85 141 161 158 119 149 133 123 106 100  93 125
 183 144 167 242 327 160 164 143 119 191 127 136 165 183 235 271 199 221 141 112
 120  99  80 101 110  97  78  78 112 119 136  95  89  88  80  87  73  67 115

BEV-E03A 126
 380 461 417 481 341 263 247 251 182 204 249 258 201 167 112 125 109  63  72  91
 108 111  78  90  76  83 106  99 122 109 151  95  67 127 115 113 124  99 131 158
 149 127 105  89  87 142 134 193 150 137 120 106  96 102 102  78  64  57  61  71
  67 141 188 191 242 280 249 170  86  89 201 207 262 287 127 125 168 192 210 160
 120 140 105  88  70  69  84 102  92 125 103 167 167 158 137 114 134 116  94 150
 113 115 137 130 204 106 102  84  76  68  77 101  76  69  51  89 102 124 104  94
  99  80 106  71  65  59

BEV-E03B 126
 403 469 413 517 347 274 249 258 175 208 253 260 199 165 116 132 102  66  82  93
 102 115  79  73  60  94 105  91  97 104 151  91  67 129 112 115 132 104 121 156
 159 126 102  90  86 139 128 199 149 135 121 108  89 111  94  81  67  53  61  73
  62 142 189 194 249 278 250 161  73 100 196 198 263 282 132 125 166 191 207 167
 117 135 109  90  75  64  78 100 108 115 103 168 165 155 135 105 138 124  95 149
 114 117 137 128 206 110  88  82  82  70  76 103  74  60  55  91 105 121 103  97
  90  91  98  77  69  50

BEV-E06A 60
 185 230 210 197 272 199 156 202 381 201 181 197 193 264 182 132 164 198 177 145
 230 185 142 202 172 189 161 208 229 337 203 173 283 206 261 249 193 126  94  93
  94 121  56  51  61  79  55  52  85  95  95 106 161 356 278 360 341 335 319 261

BEV-E06B 60
 186 233 210 200 280 190 160 197 388 203 174 198 190 279 177 129 159 205 152 142
 221 182 154 208 174 188 162 203 231 342 206 165 291 199 263 251 203 123  94  85
 104 118  55  53  59  75  49  51  99  93  99 102 153 369 275 372 343 335 324 256

BEV-E07A 92
 457 247 258 229 271 242 317 366 289 246 245 140 149 190 209 237 173 178 152 169
 123 198 190 179 219 180 187 153 158 147 180 123 238 138 116 121 151 186 155 139
 130 196 116 116 118 123 125 136  93 142 142 129 105 139 103 125 122 123 142 127
 157 134 163 119  89 151  73  95 106 163 111 110  97 105 114 115  93 103 136  80
 108 111 163  83 116 145 166 130 164 144 158 187
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BEV-E07B 92
 465 243 263 228 274 235 317 368 293 242 251 132 147 182 213 230 177 171 147 153
 125 190 189 170 216 181 193 147 157 142 187 132 252 138 124 123 144 192 153 138
 132 205 108 108 136 119 145 109  98 147 140 129 104 147 105 112 129 120 149 123
 155 137 165 123  90 144  82 100 110 160 118 114  88 109 111 110 107  99 143  86
 105 120 147  91 120 139 165 136 163 153 159 188

BEV-E08A 97
 105 107  90 136  91 122  77 108 163 135 132 192  85  60  60 109  99  95 128 180
 153 132  60  98  79 138 208 217 120 102 100 143 151  82  94 109  85  83  87 101
 127 185 110 162 132 140 119 194 133 195 176 139 190 158 150 145 183 163  79  69
  78  72  63  62  48  88 114  84 103  92 108  96  80  72  73  52  53  30  67  69
  88  67  63  50  43  64  66  66  77  68  44  60  65  79  64  38  65

BEV-E08B 97
  99 114  84 139  94 107  82 112 159 137 135 198  95  69  47 122  89 103 124 169
 156 138  67  89  90 139 218 210 115  95  98 140 143  87  90 109  90  85  87 102
 133 184 114 160 147 140 131 189 133 190 174 147 186 161 147 144 185 165  81  69
  77  70  70  60  53  85 109  89  96  99 115  90  79  78  65  57  68  34  56  79
  87  63  53  44  54  63  67  71  63  71  36  53  76  72  72  38  71

BEV-E09A 89
 138 385 253 283 275 360 270 273 188 115 227 320 257 204 205 108 145 154 283 291
 281 242 351 300 428 539 350 344 312 394 245 241 326 371 162 268 166 174 157 150
 128 151 182  84  62  54  55  58  52  76  54  74  78  64  89 131  86 130  71  80
 139 120 102 121  55  38  49  80  62 102 105 146 101  78  71  96  94  76  63  95
  90  91  41  94 103 153 118 167 133

BEV-E09B 89
 131 389 250 287 267 360 281 265 182 116 233 315 271 198 204 106 141 162 284 295
 277 250 355 292 429 528 345 347 313 395 245 248 328 373 160 260 169 178 158 148
 130 152 185  84  61  53  54  58  55  67  54  79  74  69  82 131  89 114  87  75
 149 110 100 129  49  36  50  84  60 105 104 146  98  80  72  90 108  66  74  97
  92  90  41  91 108 158 115 165 136
BEV-E10A 100
 411 346 296 304 321 318 343 287 284 279 340 203 277 236 173 205 165 211 254 129
  87 143 147 161 164 134 130 168 122 105 139 120 143 102 109 116 112 121  91  94
  57  91  95  80 133 111  60  50  83  84 103  93 110 112 125  45  93 116 126  83
  56 116 134 110  80  57  44  66  67  67  67  33  50  55  48  59  40  55  55  38
  54  32  35  49  44  26  38  47  69  52  36  34  61  49  49  62  69  61  79  60

BEV-E10B 100
 417 355 294 299 313 315 343 300 289 259 338 193 274 232 177 206 169 210 252 130
  91 144 147 157 165 132 134 167 123 102 141 115 146 103 108 117 110 123  94  87
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  65 115 128 111  81  52  55  63  65  69  61  35  54  63  36  67  36  56  57  38
  52  32  35  49  48  24  41  51  64  53  39  38  55  50  53  50  77  58  78  53

BEV-E11A 122
 189 274 387 353 262 284 365 259 231 262 270 184 250 229 272 269 284 258 324 292
 353 199 254 230 229 205 242 190 229 228 222 126 186 173 124 136 119 182 158 100
  52 148  96 118 117  93 121 120  88  92 100 112 115  91  80  98 105 146  80 103
  71  89 104  65 115  88 102  74  90  69 126  90  99 140 128  48 110  89 107  63
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 56  40

BEV-E11B 87
150 147 168 166 174 149 143 167 154 185 134 123 107 121 154  95 147 132 139 105
117 108 155 121 140 167 170  66 120 129 130  65 101 116 160 128 139  68  51  92
 95  84  76  50  79  58  39  59  44  46  64  44  64  51  42  58  71  35  50  50
 51  45  35  45  44  53  41  36  27  25  56  46  29  23  25  30  24  23  23  18
 23  23  30  33  29  41  51

BEV-E12A 149
622 589 774 763 811 680 465 479 418 383 243 318 309 235 165 218 177 198 146  96
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110  60  63  41  48  55  45  46  38

BEV-E12B 149
630 582 780 756 817 681 466 468 426 383 239 305 306 228 174 226 191 193 151  85
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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.

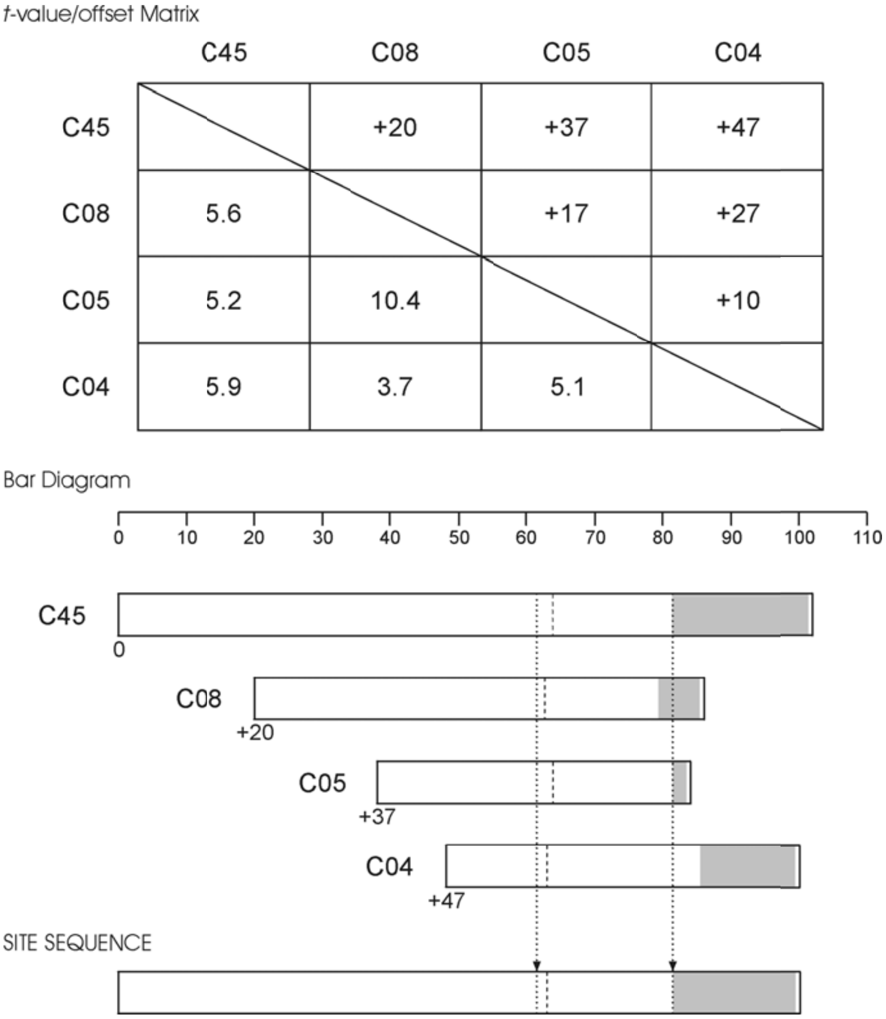
There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges 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.

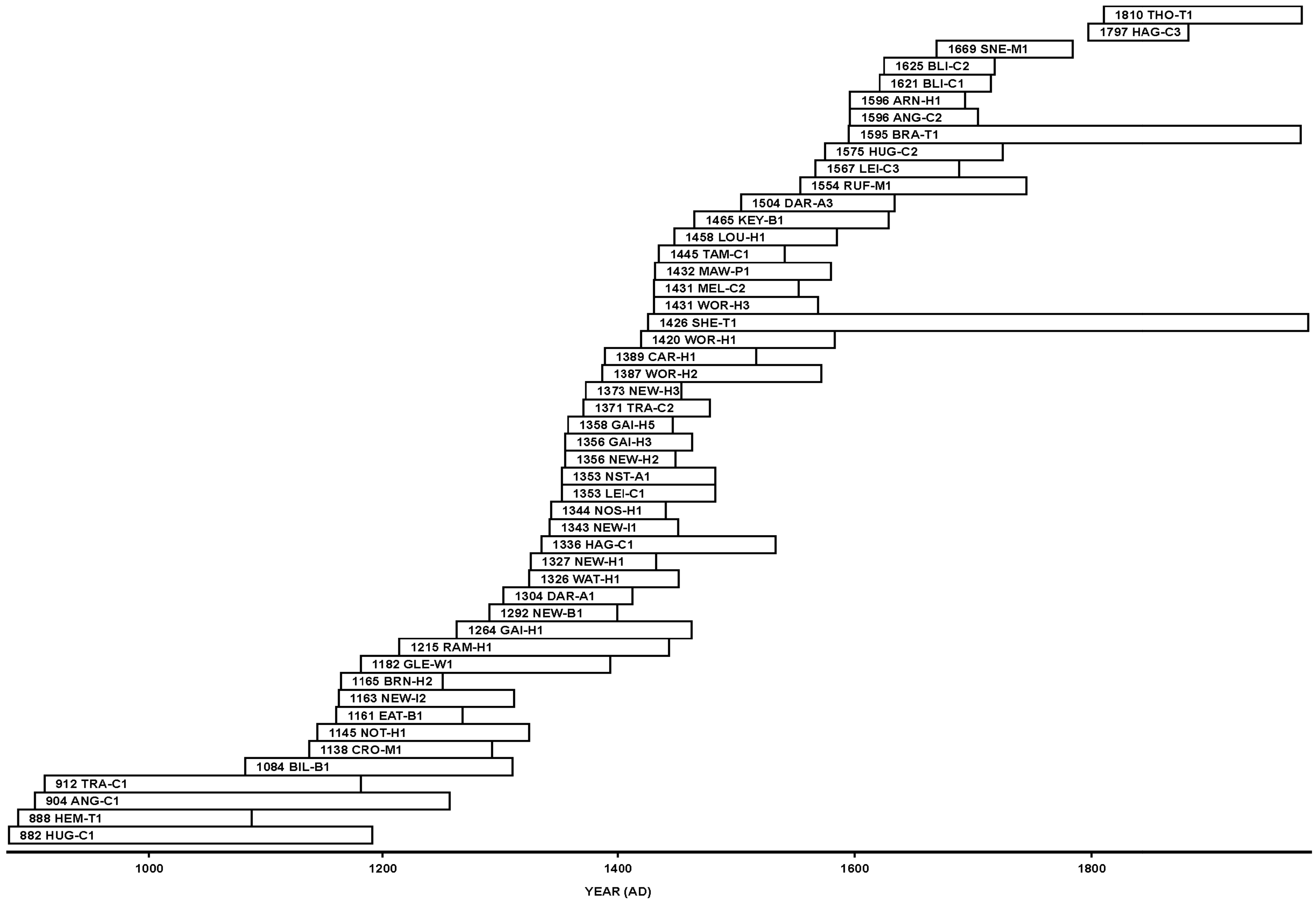
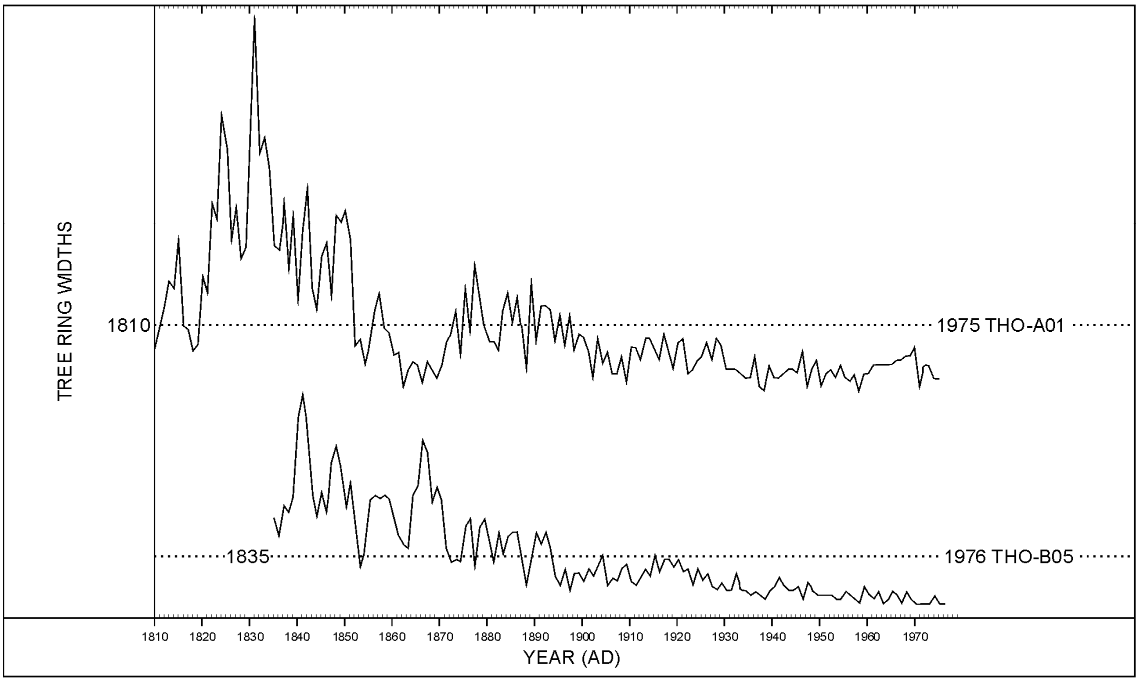


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

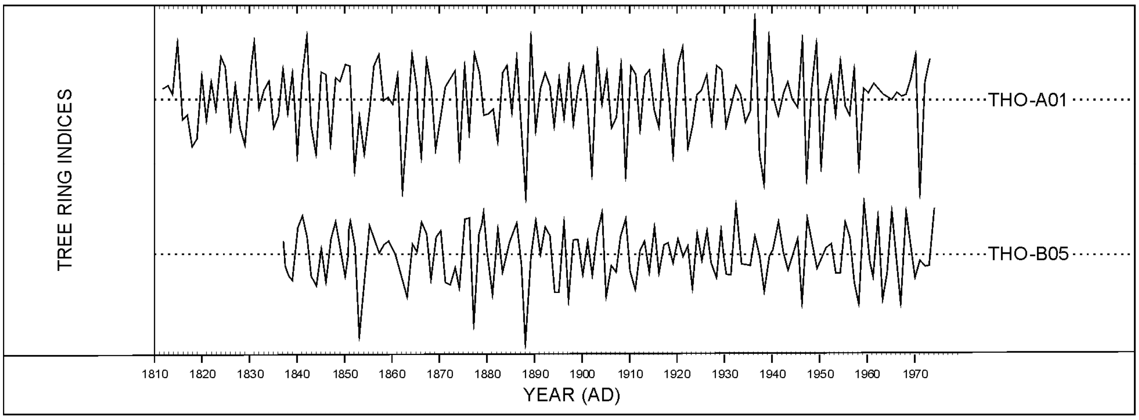


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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