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15 Flemingate, Beverley, East Yorkshire Tree-Ring and Radiocarbon Analysis of Oak Timbers

Alison Arnold, Robert Howard, Cathy Tyers,
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15 FLEMINGATE
BEVERLEY, EAST YORKSHIRE

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SUMMARY
Tree-ring analysis of samples taken from 15 Flemingate, Beverley, resulted in the construction of two site sequences: BEVGSQ01, a site sequence of 92 rings containing four samples, and BEVGSQ02, a 177-ring site sequence from two samples. Neither of these, nor any of the ungrouped individual series, could be securely dated using tree-ring analysis.

Tree-ring analysis did, however, identify that BEVGSQ02 cross-matched with an undated site master chronology, BEVJSQ01, from reused timbers in The Guildhall in Beverley. Two dendrochronological samples, one from BEVJSQ01 and one from BEVGSQ01, were sub-sampled for radiocarbon dating. The combined master sequence, BEVGJSQ01, of 197 rings, was subsequently dated by a combination of dendrochronology and radiocarbon analysis to the period AD 1245–AD 1441_{DR}, with BEVGSQ02 being dated to AD 1255–1431_{DR}.

The two dated timbers from 15 Flemingate were felled in AD 1431_{DR}, suggesting construction of the building may have taken place in the second quarter of the fifteenth century.

CONTRIBUTORS
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ACKNOWLEDGEMENTS
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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).

BUILDING DESCRIPTION

Flemingate is a street to the south of Beverley town centre, with number 15 lying on the north side of the street, less than 100m east of the Minster (Figs 1 –3). Number 15 Flemingate has an associated YVBSG archive report (YVBSG 2015) from which this description is summarised. Further information can also be found in the unpublished report by Ed Dennison Archaeological Services 2008.

Number 15 Flemingate is a two-storey plus attic, four-bay building, situated gable end onto Flemingate and running broadly north-south (Fig 4). It is one of a pair with the adjoining 13 Flemingate (The Lord Nelson Public House), in the same ownership as 15 Flemingate until *c* AD 1984. This pair of buildings are Grade II* listed (Listing Entry Number: 1346325). To the north of the main building are single-storey brick outbuildings.

The surviving medieval roof over 15 Flemingate consists of four crown-post trusses, although on the basis of carpenter's marks it has been suggested that the building may have once continued further north. Truss III, separating bays 3 and 4 (Fig 4), comprises wall posts with slightly splayed heads rising to a cambered tiebeam which supports the crown-post structure (Fig 5). The crown post is flanked by curved, downward braces with vertical outer studs. The head of the crown post is also slightly splayed below the collar. Braces rise from the crown post to the collar purlin which supports the collars.

To the south of truss III, is another truss (truss IIII), of the same form (Fig 6) but utilising timber of better quality and greater scantling. The tiebeam of this truss has a more pronounced camber and has stopped and barred chamfers to the soffits and a carved, central boss in the form of a rose.

Remains of two further crown-post trusses survive in the north gable wall (north of truss III) and within the attic space to the south of truss IIII (Fig 7). There may have been a fifth truss at the south end of the building, removed when the present hip was created and possibly a sixth one to the north of the present north gable wall. This latter suggestion is on the basis of the carpenter's marks.

Documentary evidence can place the building back to the seventeenth century, although the crown-post roof would suggest a late fourteenth- or early fifteenth-century date. Other modifications such as the staircase were undertaken in the first half of the eighteenth century.

SAMPLING

A total of 11 samples was taken from oak (*Quercus* sp) roof timbers and a door head; each sample was given the code BEV-G and numbered 01–11. The location of all samples was noted at the time of sampling and has been marked on Figures 8–10. Further details relating to the samples can be found in Table 1. Trusses and bays have been numbered following the report produced by YVBSG (2015) and nomenclature used in this report also follows that in the YVBSG (2015) report.

TREE-RING ANALYSIS AND RESULTS

All 11 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in six samples cross-matching to form two groups.

Four samples cross-matched each other at a minimum *t*-value of 5.5 and were combined at the relevant offset positions to form BEVGSQ01, a site sequence of 92 rings (Fig 11). Two further samples matched each other at *t*=16.5 and were combined to form BEVGSQ02, a site sequence of 177 rings (Fig 12). Attempts to date these two site sequences and the ungrouped samples by comparing them against a series of relevant reference chronologies for oak were unsuccessful.

Combining the undated site sequences from 15 Flemingate and The Guildhall

Analysis of all the tree-ring data obtained as part of the Early Fabric in Beverley Project subsequently revealed that BEVGSQ02 cross-matched a site sequence from

The Guildhall (BEVJSQ01), which lies approximately 500m northwest of 15 Flemingate (Fig 13), with a very high level of similarity (*t* = 9.7). A further combined sequence, BEVGJSQ01, of 197 rings, containing the components of both BEVGSQ02 and BEVJSQ01 was then constructed at the relevant offset positions (Fig 14). This combined sequence cross-dated consistently with the reference material at a first measured ring date of AD 1245 and a last-measured ring date of AD 1441. The evidence for this is given in Table 2 but, as can be seen, the levels of similarity with the reference chronologies were, combined with the geographical spread, considered insufficient to allow secure dating of this combined sequence by dendrochronology alone.

RADIOCARBON WIGGLE-MATCHING

Following the tree-ring analysis, the dating of the combined sequence comprising six samples from two sites in Beverley, BEVGJSQ01, remained uncertain. Thus single-year tree-rings were sampled from timbers BEV-G04 (15 Flemingate) and BEV-J04 (The Guildhall) (Table 3). These samples were selected on the basis of the secure cross-matching between the two site sequences and hence the tentative tree-ring dates identified for the final rings of the undated individual site sequences: AD 1441 (BEVJSQ01) and AD 1431 (BEVGSQ02). The samples selected for radiocarbon dating, both thought to represent the growth-ring for AD 1419, were deliberately chosen from a steep part of the calibration curve where the radiocarbon content of the atmosphere was rapidly changing (Fig 15).

Radiocarbon dating is based on the radioactive decay of carbon-14 and can be used to date organic materials, including wood. A small proportion of the carbon atoms in the atmosphere are of a radioactive form, carbon-14. Living plants and animals take up carbon from the environment, and therefore contain a constant proportion of carbon-14. Once a plant or animal dies, however, its carbon-14 decays at a known rate. This makes it possible to calculate the date of formerly living material from the concentration of carbon-14 atoms remaining. Radiocarbon measurements, like those in Table 3 are expressed in radiocarbon years BP.

Laboratory methods

Single-year tree-ring samples were submitted to the Oxford Radiocarbon Accelerator Unit (ORAU) and Scottish Universities Environmental Research Centre (SUERC) for Accelerator Mass Spectrometry (AMS) dating. The sample submitted to the Oxford University Radiocarbon Accelerator Unit was pretreated using the acid-base-acid protocol followed by bleaching with sodium chlorite (Brock *et al* 2010, Table 1 (UW)). It was combusted and graphitised as described by Brock *et al* (2010, 110) and Dee and Bronk Ramsey (2000) and dated by AMS (Bronk Ramsey *et al* 2004). The sample submitted to SUERC was converted to α-cellulose, combusted, graphitised, and dated by AMS as described by Dunbar *et al* (2016).

Both facilities maintain continual programmes of quality assurance procedures in addition to participation in international inter-comparison exercises (Scott *et al* 2010). The two results are statistically consistent (Table 3) and a weighted mean has been taken of them before calibration. This demonstrates the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Table 3), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986).

Calibration

Calibration is an essential step in using radiocarbon measurements to estimate the calendar date of samples. It is necessary because the production rate of radiocarbon in the atmosphere is not constant, but varies through time. This means that we need to convert the radiocarbon measurement of a sample to the calendar scale using a calibration curve made up of radiocarbon ages on samples of known calendar date.

That independent scale is the IntCal13 calibration curve (Reimer *et al* 2013) constructed from radiocarbon measurements on tree rings, plant macrofossils, speleothems, corals, and foraminifera. The calibrations which relate the radiocarbon measurements directly to the calendrical time scale have been calculated using IntCal13 and the computer program OxCal v4.2 (https://c14.arch.ox. ac.uk/oxcal/; Bronk Ramsey 2009).

Bayesian wiggle-matching

Wiggle-matching uses information derived from tree-ring analysis, in combination with radiocarbon measurements to provide a revised understanding of the age of a timber; a review is given by Galimberti *et al* (2004). In this technique, the shapes of multiple radiocarbon distributions can be "matched" to the shape of the radiocarbon calibration curve. The exact interval between radiocarbon results can be derived from tree-ring analysis.

Although the technique can be done visually, Bayesian statistical analyses (including functions in the OxCal computer program) are now routinely employed. A general introduction to the Bayesian approach to interpreting archaeological data is provided by Buck *et al* (1996). The approach to wiggle-matching adopted here is described by Christen and Litton (1995).

Details of the algorithms employed in this analysis — a form of numerical integration undertaken using OxCal — are available from the on-line manual or in Bronk Ramsey (2009).

BEVGSQ02 and BEVJSQ01

The chronological model for the dating of site sequences BEVGSQ02 and BEVJSQ01 is shown in Figure 16. As the two single-ring samples formed in the same year and the measurements are statistically consistent, the radiocarbon ages can be combined before calibration by taking a weighted mean (Ward and Wilson 1978; Table 3). The model shows good agreement between the radiocarbon dates and the relative number of years derived from the tree-ring analysis to the tentative tree-ring date of AD 1441 for the formation of the final ring of the combined sequence BEVGJSQ01 (Acomb = 72.7; An = 50.0; n=2; Fig 16). The radiocarbon dating therefore supports the tentative tree-ring dating that had been identified but considered to be insufficiently statistically robust (Table 2).

INTERPRETATION

Two of the samples taken from this building have now been securely dated (Table 1: Fig 16) using a combination of dendrochronology and radiocarbon analysis. Both of these, BEV-G04 and BEV-G08, have complete sapwood and the last-measured ring date of AD 1431_{DR} (these are distinguished from a date derived from ring-width dendrochronology alone by the subscript $_{DR}$), the felling date of the two timbers represented (Fig 16). These two samples match each other at a value of t = 16.5, a level high enough to say that they are likely to have been cut from the same tree.

DISCUSSION

A door head and a crown post at 15 Flemingate are now known to have been felled in AD 1431_{DR}. Stylistically, the roof of this building was thought to be of the later fourteenth- or early fifteenth-century date. The scientific dating has provided support for this dating, suggesting construction occurred in the second quarter of the fifteenth century. A caveat to this is that only two timbers have been dated which allows for the possibility that the two timbers may not be representative of the primary construction phase. With such few dated timbers it remains a possibility that they were reused or represent repairs, although based on the building survey undertaken by the YVBSG (2015) this is thought unlikely.

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YVBSG 2015 *15 Flemingate*, Yorkshire Vernacular Buildings Study Group rep 1847

TABLES

Table 1: Details of tree-ring samples from 15 Flemingate, Beverley, East Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD_{DR})	Last heartwood ring date (AD_{DR})	Last measured ring date (AD_{DR})
BEV-G01	North brace, crown post to collar purlin, truss III	88	35	----	----	----
BEV-G02	Collar, truss III	77	h/s	----	----	----
BEV-G03	South brace, crown post to collar purlin, truss III	65	07	----	----	----
BEV-G04	Door head, truss III	177	22C	1255	1409	1431
BEV-G05	North brace, crown post to collar purlin, truss IIII	55	15	----	----	----
BEV-G06	Tiebeam, truss IIII	131	21	----	----	----
BEV-G07	West wall post, truss IIII	152	h/s	----	----	----
BEV-G08	Crown post, truss IIII	143	21C	1289	1410	1431
BEV-G09	Crown post, truss IV	106	h/s	----	----	----
BEV-G10	South brace, crown post to collar purlin, truss IV	75	h/s	----	----	----
BEV-G11	Collar purlin, truss IV to south end	64	h/s	----	----	----

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 the combined sequence BEVGJSQ01 and the reference chronologies when the first-ring date is AD 1245$_{DR}$ and the last-measured ring date is AD 1441$_{DR}$

Reference chronologies	*t*–value	Span of chronology	Reference
Ulverscroft Priory, Charnwood Forest, Leicestershire	5.6	AD 1219–1463	Arnold *et al* 2008a
The Guildhall, Boston, Lincolnshire	5.5	AD 1244–1380	Arnold *et al* 2008b
Central Tower, York Minster, North Yorkshire	5.2	AD 1214–1462	Hillam pers comm 1997
Castle House, Buckinghamshire	5.2	AD 1272–1406	Miles *et al* 2007
Blackmore Church, Essex	5.1	AD 1266–1399	Miles *et al* 2005
Clothall Bury Farmhouse, Hertfordshire	4.8	AD 1253–1367	Arnold *et al* 2003
St Anthony's Hall, York, North Yorkshire	4.7	AD 1215–1443	Arnold and Howard 2009
Church of St James, Bristol, Somerset	4.7	AD 1209–1396	Arnold and Howard 2011
Old Vicarage, New Buckenham, Norfolk	4.7	AD 1271–1451	Tyers 2004
Gothelney Hall, Charlynch, Somerset	4.6	AD 1238–1411	Arnold *et al* 2010

Table 3: Beverley: The Guildhall and 15 Flemingate radiocarbon and stable isotope results

Laboratory number	Sample reference	Material & context	$\delta^{13}C_{IRMS}$ (‰)	Radiocarbon Age (BP)
OxA-33690	BEV-J04: Ring 175	*Quercus* sp. sapwood, relative year 175 of the 197 year chronology BEVJSQ01 (The Guildhall)	−25.1±0.2	450±29
SUERC-66737	BEV-J08: Ring 165	*Quercus* sp. sapwood, relative year 165 of the 177 year chronology BEVGSQ02 (15 Flemingate)	−25.9±0.2	521±28
	Weighted mean: AD 1419	T'=3.1; ν=1; T'(5%)=3.8; (Ward and Wilson 1978)		487±21

FIGURES

Figure 1: Map to show the location of Beverley (red ellipse).

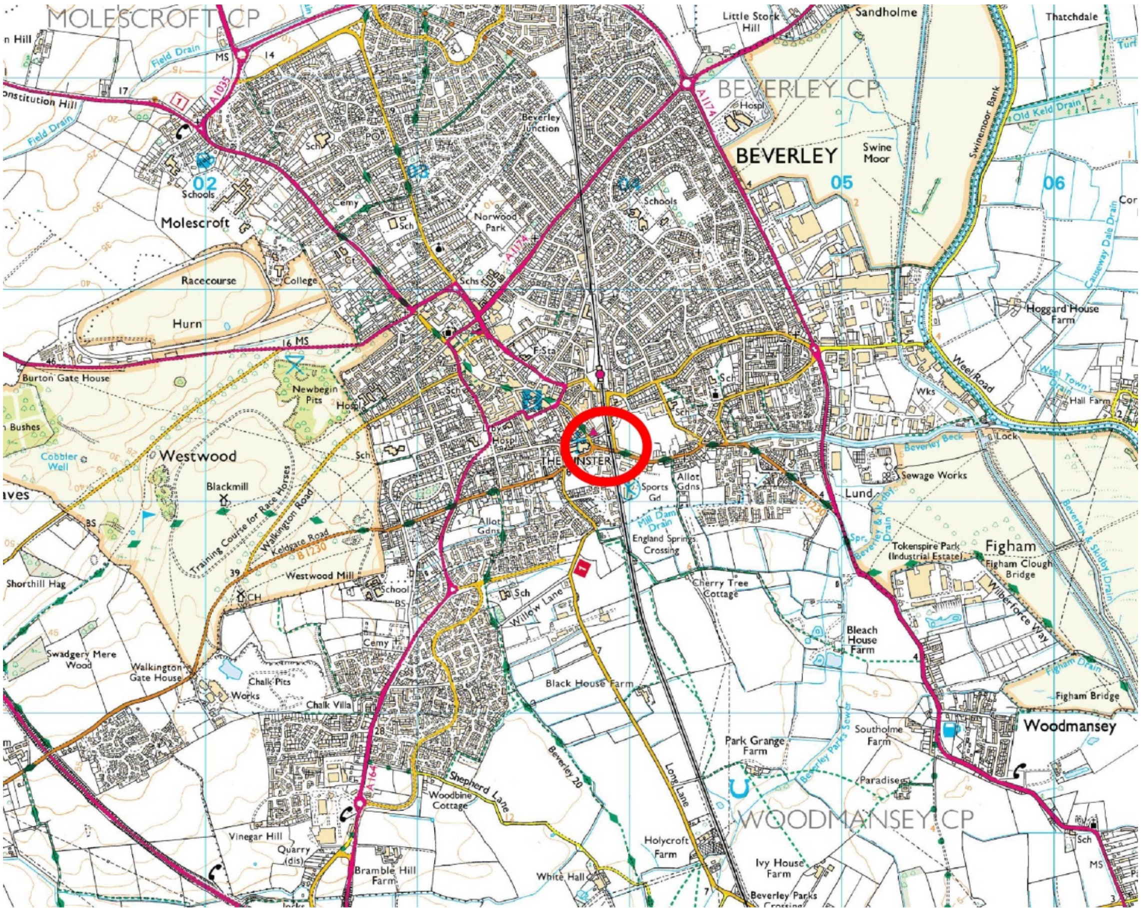


Figure 2: Map to show the general location of 15 Flemingate in Beverley (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

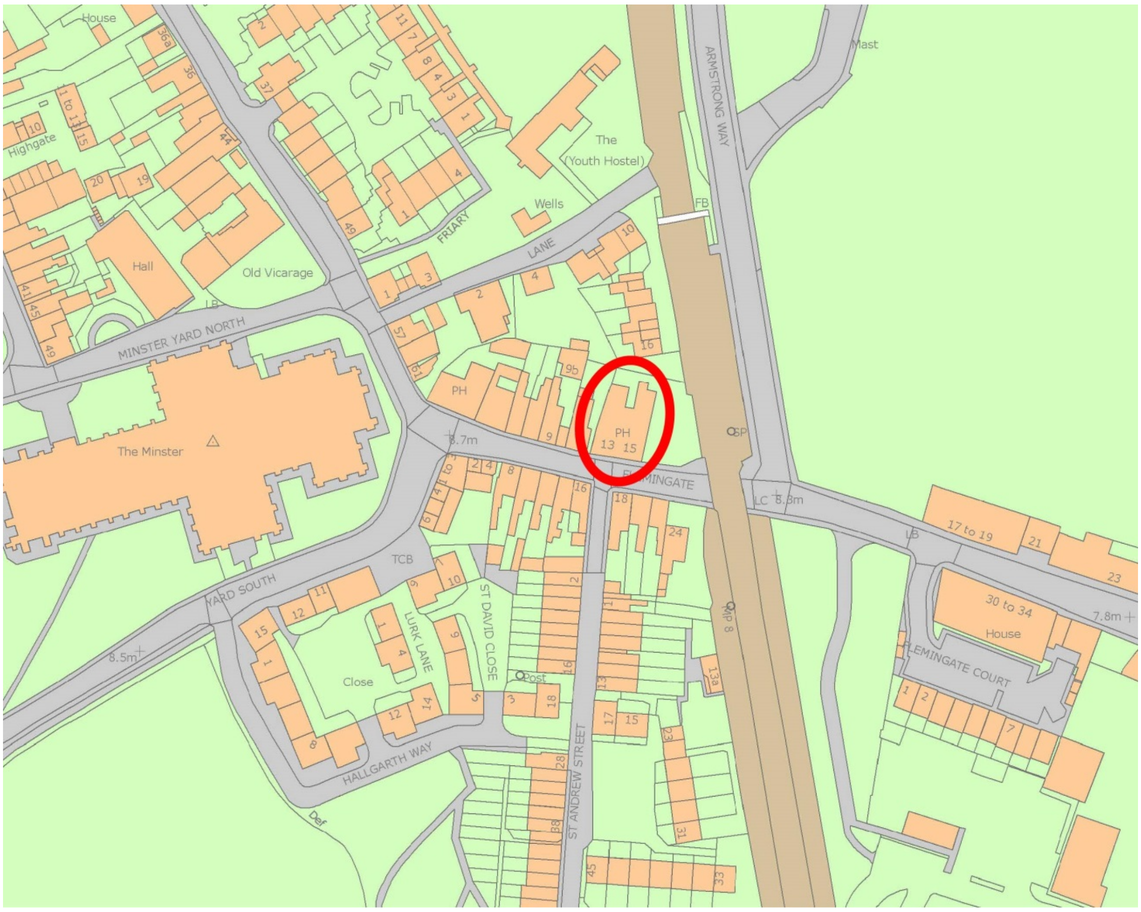


Figure 3: Map to show the precise location of 15 Flemingate, the eastern of the two buildings highlighted (red ellipse), in Beverley. © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

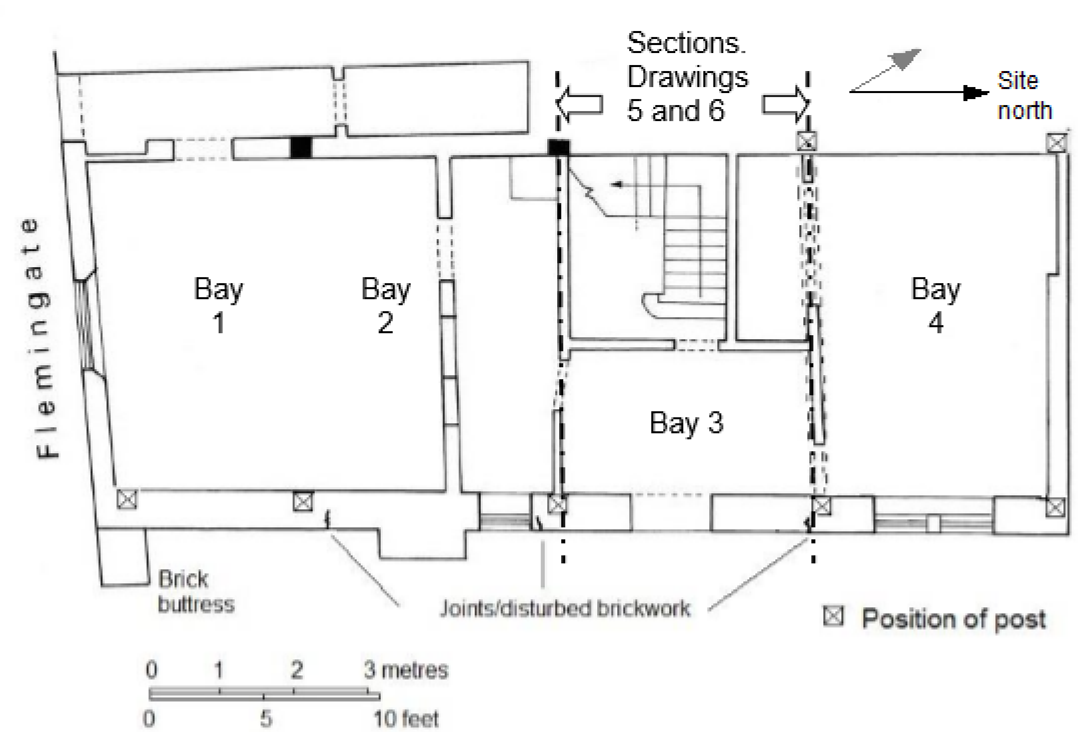


Figure 4: Ground-floor plan of 15 Flemingate (YVBSG 2015)

Figure 5: Truss III, photograph taken from the south (Robert Howard)

Figure 6: Truss IIII, photograph taken from the north (Robert Howard)

Figure 7: Truss IV, photograph taken from the north (Robert Howard)

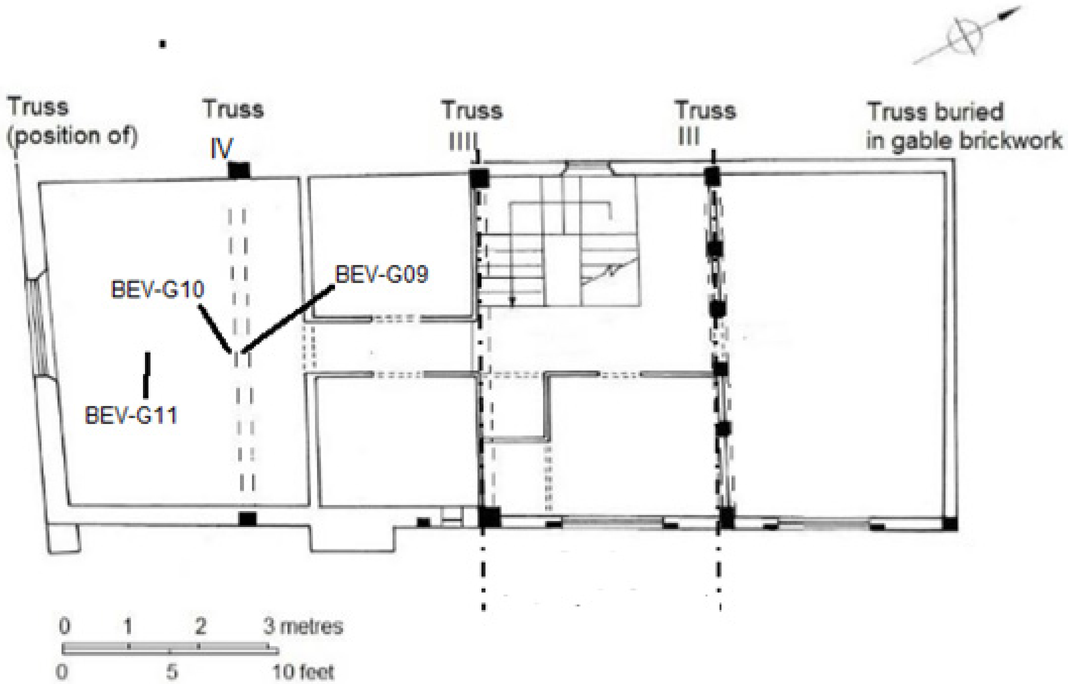


Figure 8: First-floor plan, showing truss positions and the location of samples BEV-G09–11 (YVBSG 2015 based on Ed Dennison Archaeological Services Ltd 2008)

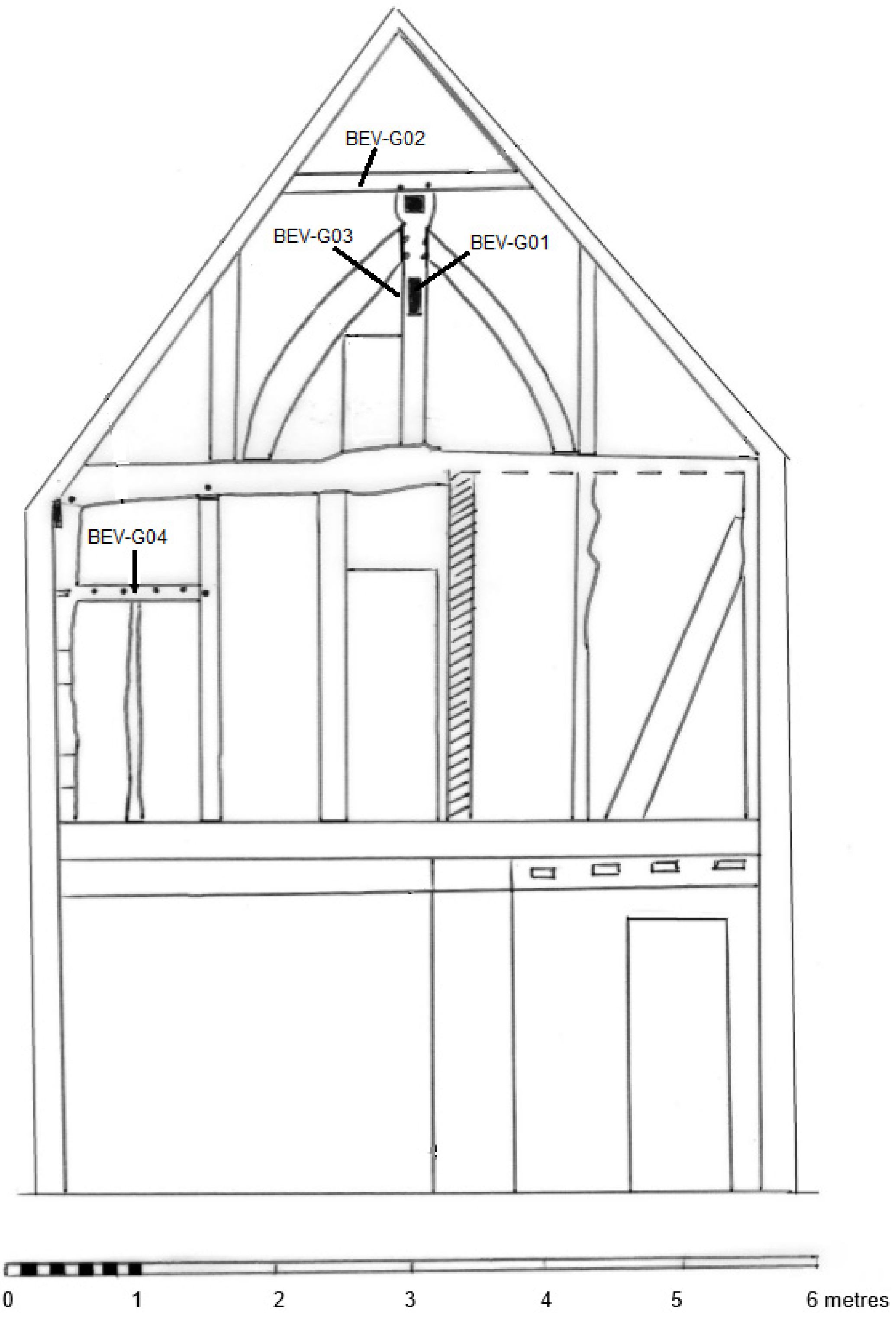


Figure 9: Section through truss III, looking north, showing the location of samples BEV-G01–04 (YVBSG 2015)

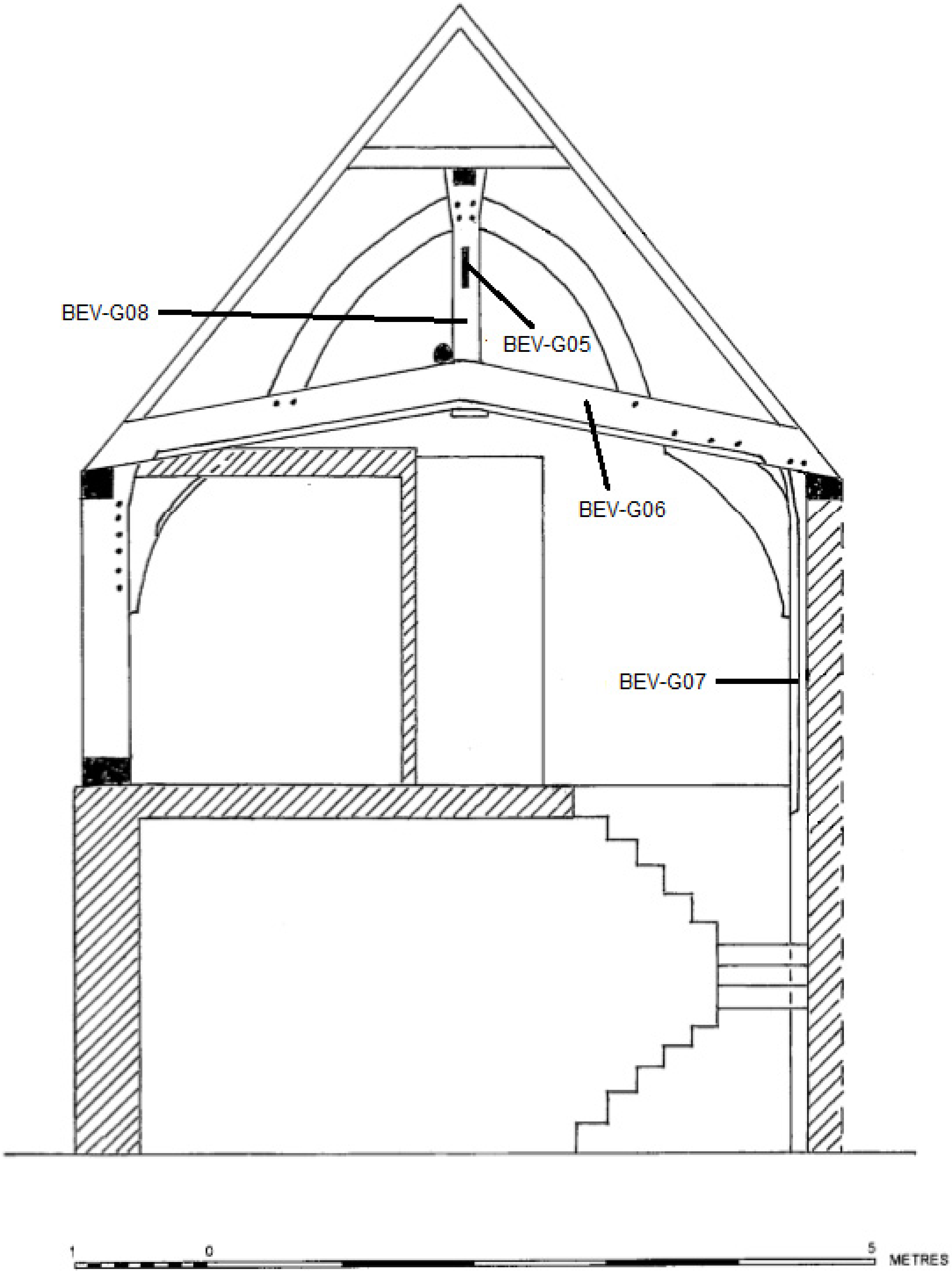


Figure 10: Section through truss IIII, looking south, showing the location of samples BEV-G05–08 (YVBSG 2015)

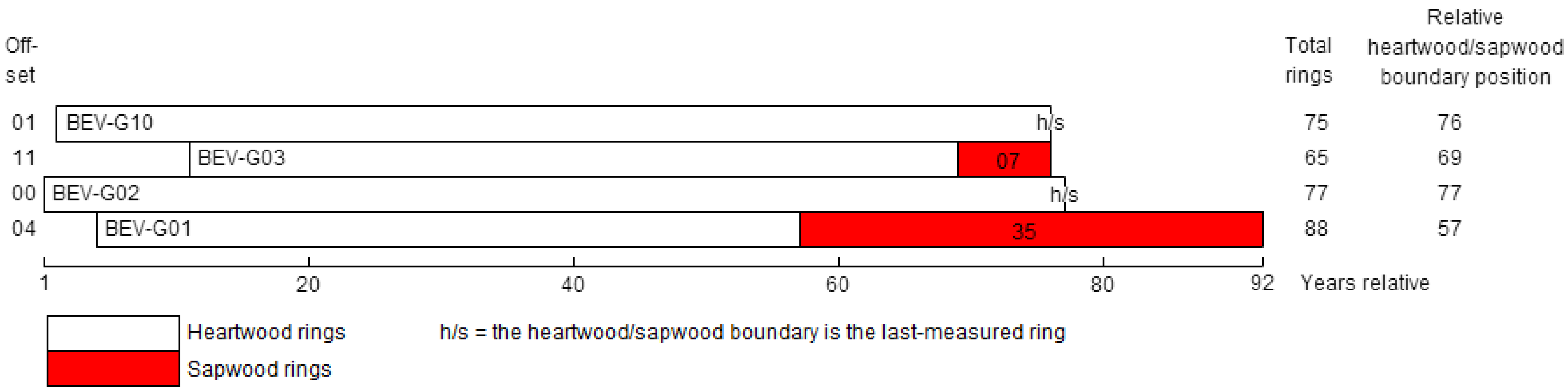


Figure 11: Bar diagram to show the relative position of samples in site sequence BEVGSQ01

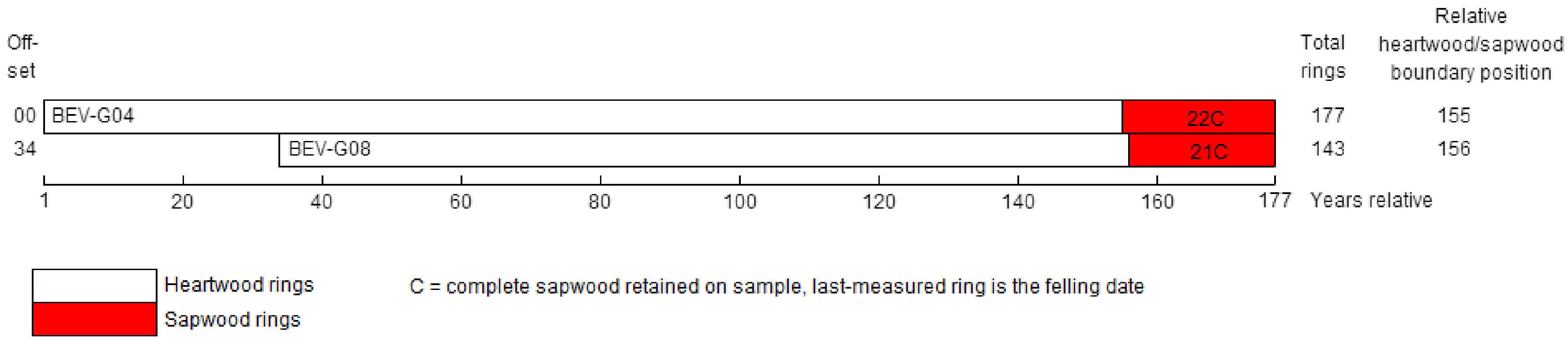


Figure 12: Bar diagram to show the relative position of samples in site sequence BEVGSQ02

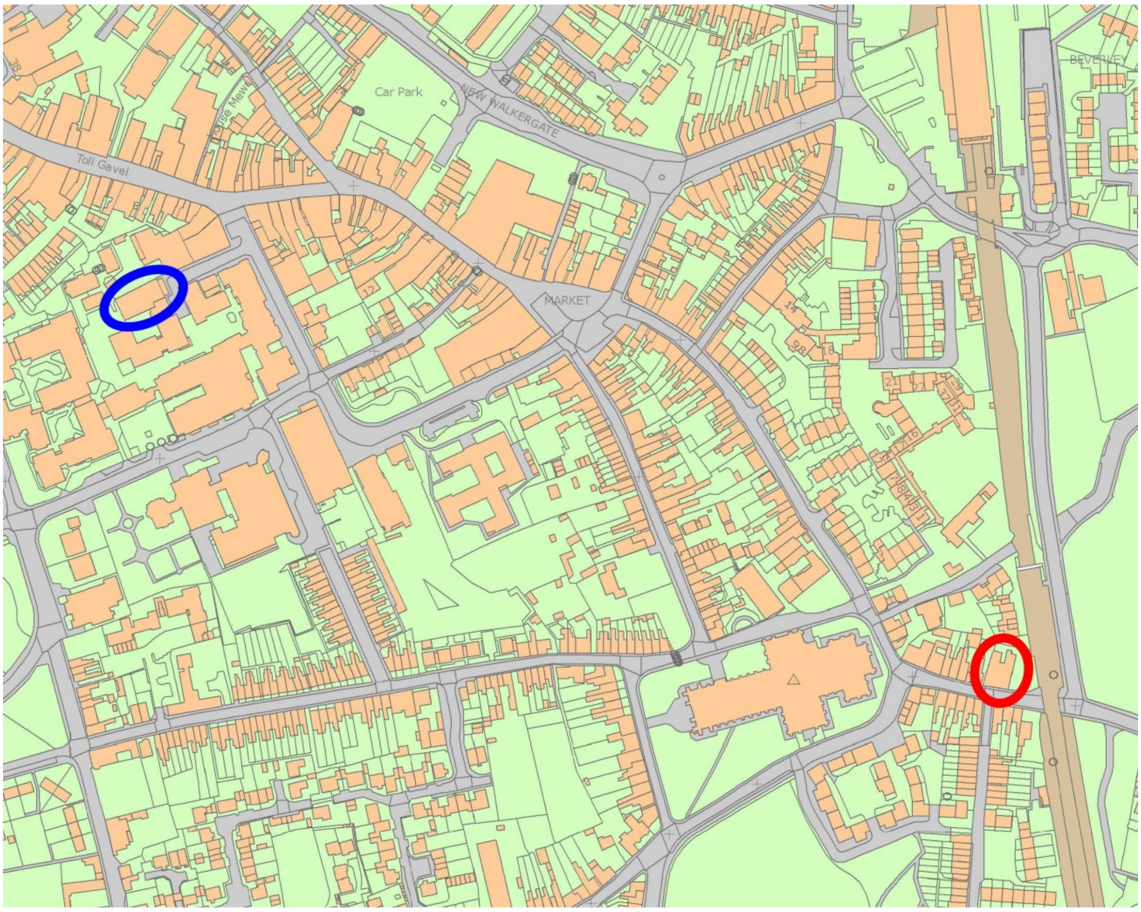


Figure 13: Map to show the proximity of The Guildhall (blue ellipse) to 15 Flemingate, the eastern of the two buildings (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

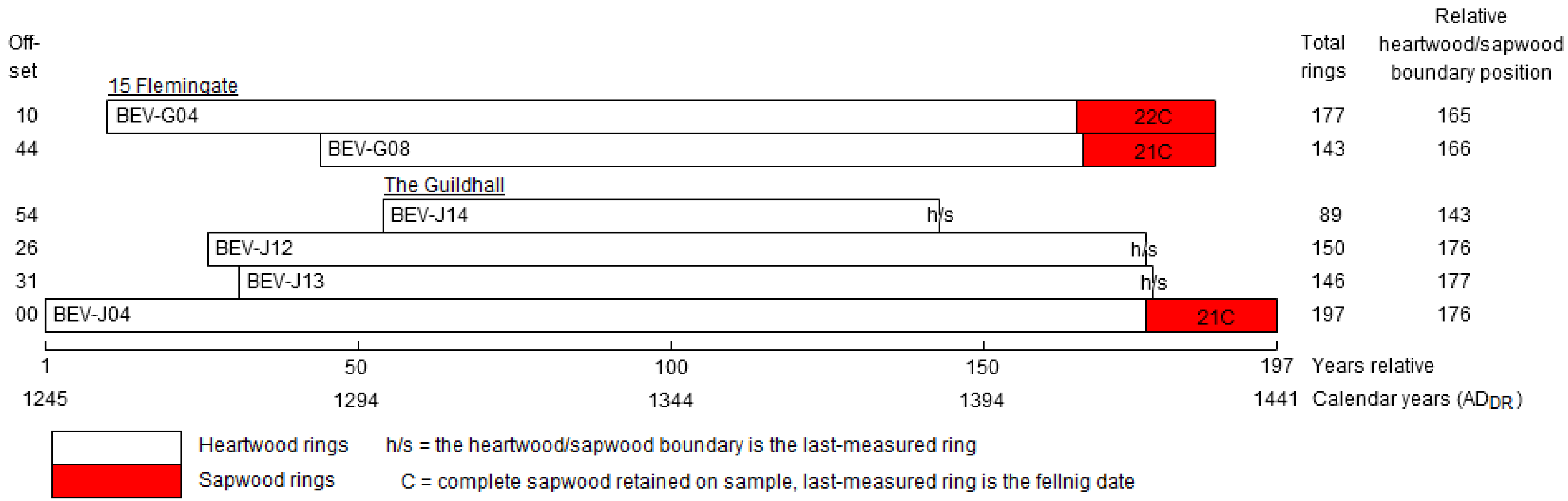


Figure 14: Bar diagram to show the relative position of samples in the combined sequence BEVGJSQ01, sorted by building, dated by a combination of dendrochronology and radiocarbon analysis

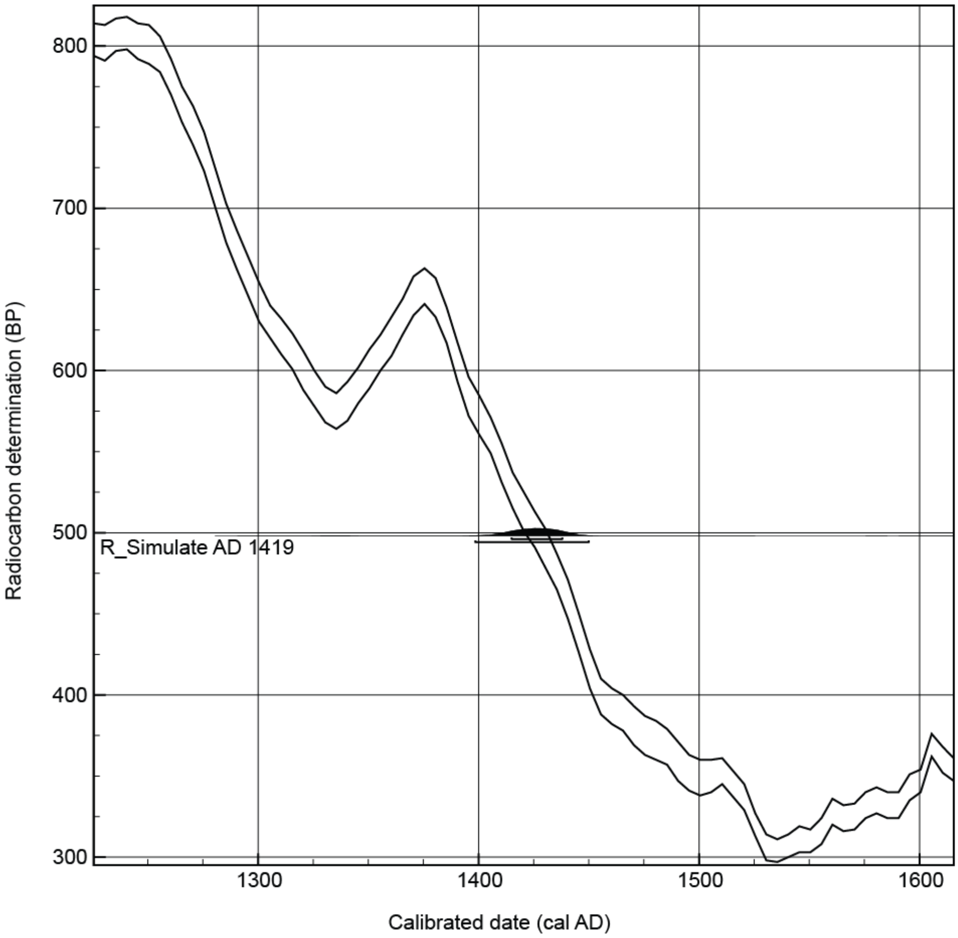


Figure 15: Probability distribution of a simulated radiocarbon date of AD 1419 plotted on the IntCal13 (Reimer et al *2013) calibration curve*

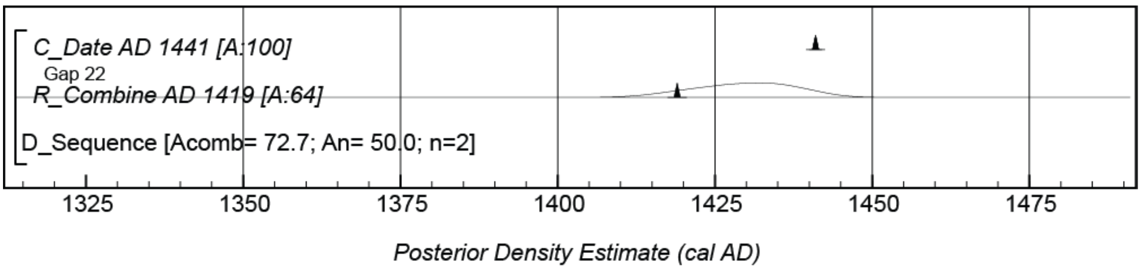


Figure 16: Probability distribution of the date of the radiocarbon sample with a potential tree-ring date of AD 1419 from BEVJSQ01 (ring 175) and BEVGSQ02 (ring 165). The distribution represents the relative probability that an event occurs at a particular time. For the date two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence incorporating the potential tree-ring date for the final ring of undated site sequence BEVJSQ01 - AD 1441. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BEV-G01A 88
49 89 47 59 114 111 155 172 229 289 271 228 297 253 215 200 197 183 121 122
172 218 157 188 181 151 135 100 65 123 117 103 99 83 92 71 62 63 33 100
78 76 91 60 42 64 52 78 115 124 55 56 90 103 80 74 77 41 35 29
24 24 31 32 47 34 29 30 24 39 35 41 36 38 25 31 31 45 44 46
43 44 44 35 29 29 36 35
BEV-G01B 88
66 53 48 48 114 110 161 173 224 263 277 229 296 239 189 205 200 182 121 126
171 218 161 190 178 148 138 100 68 126 116 101 97 86 90 70 57 61 41 89
84 72 93 59 39 73 55 81 118 114 56 54 91 103 87 81 77 42 33 29
26 25 28 34 42 36 35 25 27 33 35 47 31 34 33 30 32 41 47 39
53 41 41 31 26 29 35 33
BEV-G02A 77
229 172 151 195 273 248 282 255 127 183 192 194 203 228 241 202 213 105 109 107
127 128 85 87 108 120 80 104 104 96 84 93 54 92 88 60 101 92 92 94
53 58 65 116 87 75 70 50 44 45 48 78 78 101 58 48 86 85 92 98
105 95 60 44 32 33 45 49 50 44 50 38 50 50 56 81 68
BEV-G02B 77
238 170 154 194 284 241 276 279 125 179 201 194 208 215 249 206 214 102 110 112
120 132 81 85 110 118 84 101 105 97 80 96 54 98 88 60 102 98 86 95
52 61 66 103 84 59 68 47 39 44 42 67 75 102 44 58 79 83 94 90
107 88 57 37 41 36 44 51 48 38 57 43 40 55 59 83 57
BEV-G03A 65
419 354 402 363 341 337 239 250 191 220 172 123 164 210 200 117 201 232 206 148
110 64 106 144 119 122 97 96 80 63 57 51 123 108 104 113 67 39 70 81
82 127 104 57 58 109 103 137 114 124 77 57 60 39 41 67 76 86 96 100
54 45 67 98 108
BEV-G03B 65
416 344 380 341 327 318 199 241 192 229 172 112 149 216 211 108 192 233 203 144
101 74 95 140 125 124 97 118 75 63 59 52 134 90 101 111 64 36 73 76
77 127 117 54 53 113 101 128 110 122 77 59 61 34 41 72 76 81 90 103
61 40 61 95 108
BEV-G04A 177
133 137 131 140 123 141 123 151 187 90 63 40 46 69 51 52 66 82 75 49
48 70 104 75 65 54 71 61 95 106 102 79 56 54 52 85 77 90 95 94
85 90 110 100 110 193 131 157 87 121 147 132 158 132 126 85 69 82 124 92
79 118 95 77 90 96 99 63 100 90 105 85 84 116 60 123 102 133 132 125
119 89 61 52 85 96 101 95 57 80 109 85 77 94 73 49 70 73 58 78
99 89 74 64 70 70 73 107 142 118 128 106 83 69 64 78 100 106 89 70
68 42 39 44 77 95 65 89 78 66 95 101 106 113 84 56 63 55 119 116
102 129 61 44 43 41 35 79 55 58 48 77 77 70 76 61 88 91 113 92
150 105 84 117 109 126 132 105 63 55 55 53 58 63 70 72 68
BEV-G04B 177
136 133 130 132 134 153 118 150 182 98 54 39 49 61 59 59 54 87 75 48
49 73 105 72 63 59 67 63 92 118 92 82 58 51 54 78 85 81 95 90
90 82 121 93 112 188 137 152 79 128 144 131 154 135 120 94 70 78 117 85
86 111 98 81 85 96 92 69 98 91 103 89 78 119 56 132 104 136 136 145
121 87 67 47 97 98 92 98 54 80 110 81 80 91 77 51 65 70 64 79
93 90 80 64 62 73 75 108 146 128 127 110 79 72 61 80 106 99 92 71

69 40 36 41 84 84 74 88 80 58 94 111 105 118 68 59 66 50 127 116
102 129 56 41 42 46 35 75 61 58 48 76 76 72 75 61 85 89 116 92
154 118 77 113 112 126 128 98 63 55 53 49 60 70 68 70 65
BEV-G05A 55
194 203 202 128 112 100 54 66 64 110 130 111 111 110 100 117 117 113 162 177
118 118 104 172 208 188 272 233 300 176 236 196 194 197 184 158 164 148 215 140
84 53 75 72 71 108 101 144 146 121 138 78 85 95 73
BEV-G05B 55
186 184 203 102 118 111 54 65 64 110 125 118 116 111 94 106 127 109 166 176
118 127 105 169 216 193 268 222 296 171 234 194 197 176 161 157 154 147 201 144
82 53 79 74 70 104 106 142 147 123 138 91 87 91 74
BEV-G06A 131
386 319 316 251 253 311 256 248 229 243 338 251 215 217 147 231 263 259 369 331
358 262 181 198 193 225 170 162 177 206 258 258 195 243 189 167 124 112 142 139
158 197 151 270 295 172 178 267 329 299 327 242 248 355 211 235 301 326 250 270
272 306 248 197 317 347 421 398 299 350 349 352 325 280 258 264 170 188 197 156
201 228 342 225 276 197 347 305 314 255 176 211 212 331 259 256 247 232 199 238
197 200 194 156 190 211 214 160 191 150 146 194 187 141 158 160 191 178 178 132
156 123 120 117 88 104 85 72 117 122 100
BEV-G06B 131
344 317 311 221 261 305 225 255 238 240 336 268 219 204 157 246 237 236 370 334
338 277 186 202 201 227 164 158 174 213 265 257 197 246 184 168 146 112 133 147
157 187 151 260 296 175 169 270 334 293 320 245 242 364 218 242 314 331 254 262
275 304 242 193 327 337 408 406 301 352 317 370 313 284 257 257 173 191 193 151
194 219 346 228 268 202 344 309 308 260 143 241 214 327 258 252 258 244 201 234
195 197 182 160 193 198 214 156 190 145 149 182 182 160 159 154 193 178 178 120
159 120 115 119 98 98 81 77 105 121 101
BEV-G07A 152
406 289 233 196 90 103 184 286 248 296 206 198 105 143 242 211 113 99 91 76
88 94 106 199 248 168 202 112 118 91 122 156 164 169 122 136 114 111 97 79
87 111 75 62 74 104 142 101 120 85 106 67 70 49 76 94 111 80 71 69
80 68 66 64 70 125 92 85 155 138 172 138 236 178 84 105 71 78 113 134
122 86 80 46 52 103 111 70 92 57 66 67 126 117 147 111 137 136 105 73
74 72 192 287 166 169 177 145 102 89 69 80 99 133 169 109 46 53 62 106
165 130 103 102 62 77 85 74 97 68 58 58 56 71 103 121 149 98 120 107
132 103 75 71 60 53 48 42 57 56 52 48
BEV-G07B 152
392 311 230 209 103 97 162 339 321 320 159 215 115 142 230 214 116 109 80 90
77 100 95 196 251 169 198 113 115 96 127 148 165 167 123 141 111 102 97 74
93 101 80 61 67 103 137 100 115 80 101 71 65 44 78 91 117 78 68 69
80 65 59 63 61 139 83 96 162 135 175 142 230 168 85 108 72 76 110 135
115 88 79 54 46 111 105 72 93 56 65 63 129 116 149 110 137 136 100 70
69 71 177 291 157 166 180 149 103 82 68 80 101 137 162 104 51 55 67 118
151 125 98 111 74 80 79 85 97 81 62 52 60 67 99 123 132 100 123 102
134 105 71 78 58 50 45 45 59 50 54 53
BEV-G08A 143
65 90 111 116 127 94 98 93 123 112 111 170 141 132 99 130 147 120 150 173
160 106 88 98 133 124 110 117 113 107 110 132 116 85 102 103 124 108 89 137
74 144 131 152 137 136 127 91 77 54 125 136 124 111 63 96 129 108 98 118
97 63 78 89 81 88 112 90 96 84 85 80 85 123 178 157 145 120 92 88
81 97 116 124 91 87 75 47 52 54 93 91 103 93 97 72 109 126 129 157
111 68 76 64 134 152 117 141 118 168 122 126 112 104 90 61 71 73 81 59
72 62 70 78 94 74 96 94 82 114 113 137 151 132 75 76 62 58 64 72

76 80 64
BEV-G08B 138
61 96 110 118 115 92 101 88 127 103 105 177 136 143 83 138 142 129 144 168
164 113 90 97 135 121 107 127 100 108 118 129 117 86 95 108 122 107 93 136
76 147 128 149 137 137 123 93 80 59 119 135 125 103 66 99 126 107 95 121
103 57 92 89 89 89 113 85 97 84 85 76 84 128 174 153 157 126 92 90
74 101 117 117 99 78 80 44 49 50 96 104 93 102 84 79 105 124 135 154
98 75 82 62 128 152 124 146 116 215 116 131 110 107 89 66 67 80 97 92
96 68 77 89 114 77 136 97 89 115 126 124 163 123 60 64 57 51
BEV-G09A 106
377 234 296 248 289 292 276 281 317 368 292 314 248 202 291 354 414 328 299 232
199 202 209 177 122 122 110 54 74 62 76 82 74 77 61 38 67 82 101 118
91 79 100 122 152 138 162 178 142 51 36 49 43 41 53 92 95 80 33 29
57 47 78 93 83 38 42 46 57 34 45 37 50 76 99 109 63 77 72 54
119 41 39 35 27 30 44 67 73 89 82 86 51 93 49 65 91 140 156 111
74 54 103 76 66 108
BEV-G09B 106
377 242 280 277 292 261 274 291 324 372 287 312 248 198 304 349 415 323 301 232
202 198 230 178 143 116 111 49 82 56 84 84 76 70 61 48 64 100 102 135
81 71 100 133 170 140 152 171 142 65 37 50 47 42 59 81 99 88 36 33
50 43 78 88 87 36 37 48 49 35 40 37 48 81 104 103 60 64 67 54
101 53 37 22 33 14 53 64 80 89 83 77 59 87 50 70 80 145 162 104
64 45 88 59 64 106
BEV-G10A 73
258 181 108 312 124 295 200 207 200 234 202 216 229 212 174 146 93 130 161 154
152 81 146 131 146 146 220 189 161 138 98 72 121 145 173 171 123 115 84 54
68 55 65 77 55 35 30 21 37 43 47 59 71 35 36 71 64 73 82 63
52 51 31 39 38 71 75 65 34 34 24 28 24
BEV-G10B 75
238 171 97 303 124 285 184 192 191 229 202 210 171 181 149 149 87 128 155 146
162 84 142 134 145 152 228 191 172 140 108 76 118 145 181 175 129 132 86 46
73 59 63 71 47 42 34 25 34 38 52 55 70 26 49 63 72 64 82 77
48 48 37 42 41 64 89 61 31 34 29 29 28 30 29
BEV-G11A 64
143 224 192 338 258 139 203 178 202 246 233 368 155 146 142 132 117 66 82 99
73 55 51 60 73 29 35 33 44 29 81 191 153 99 95 45 53 52 65 100
63 37 38 72 77 48 45 47 52 50 39 115 104 84 100 103 78 49 28 21
30 46 62 95
BEV-G11B 64
140 227 182 340 248 143 205 166 194 258 223 353 155 149 141 109 123 64 81 104
73 50 51 59 61 37 46 36 36 34 80 193 139 96 104 44 45 52 67 97
59 43 35 81 65 54 47 34 57 50 49 112 97 93 98 107 66 57 26 23
25 45 65 84

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

1. **Inspecting the Building and Sampling the Timbers**. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings;

about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

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

Bar Diagram

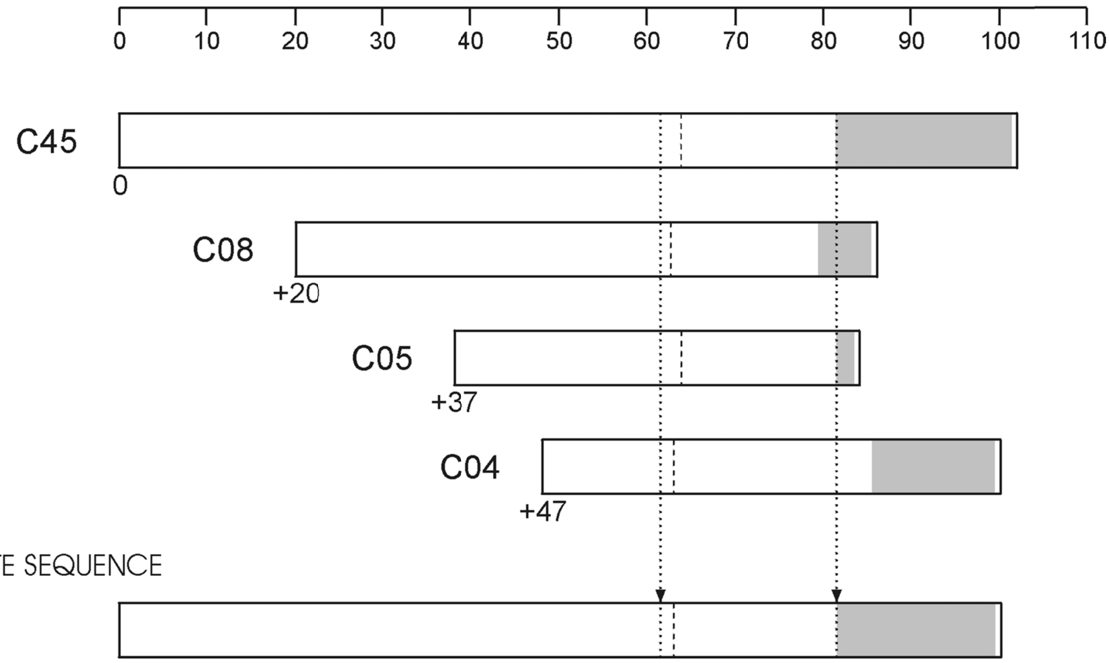


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

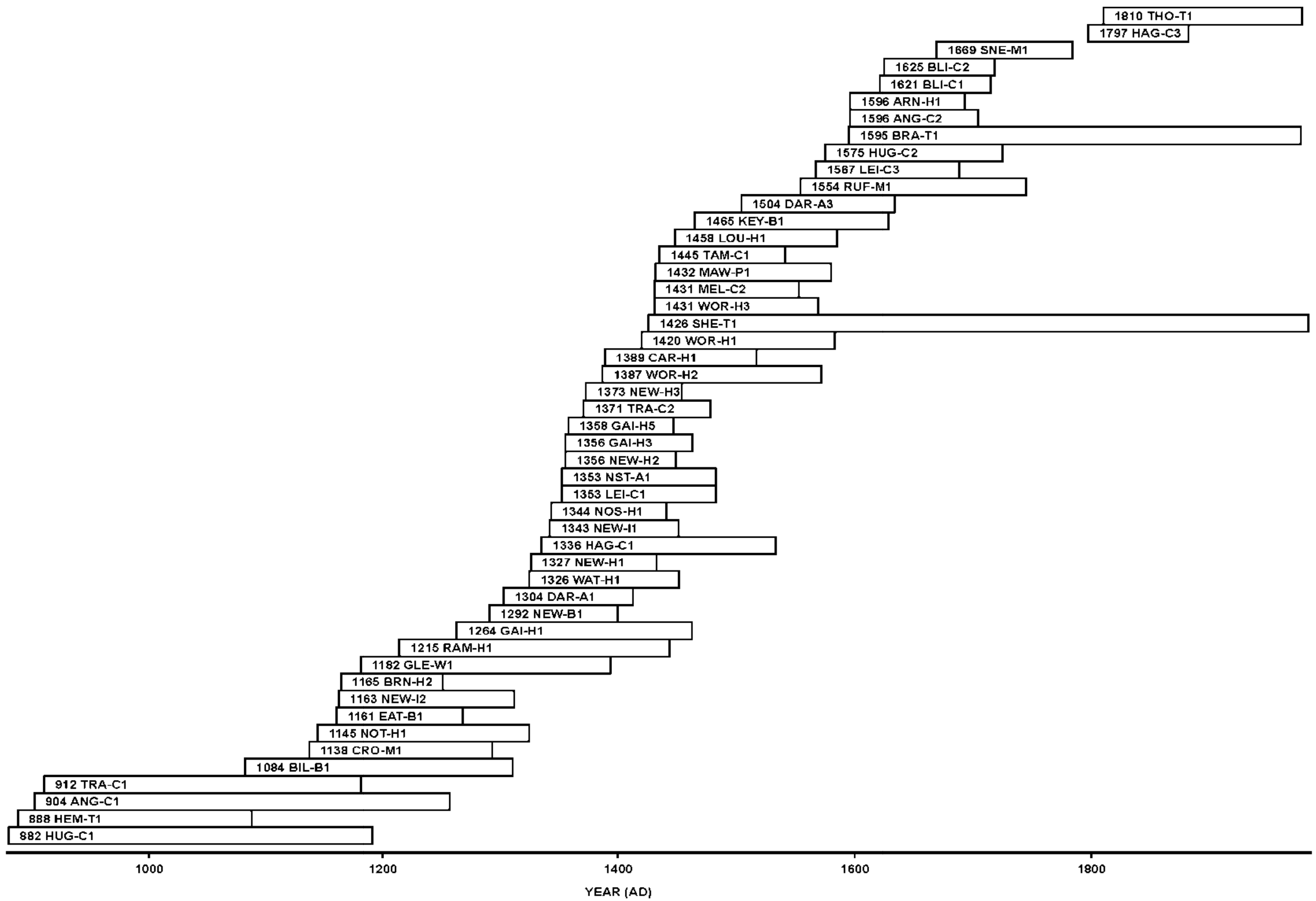
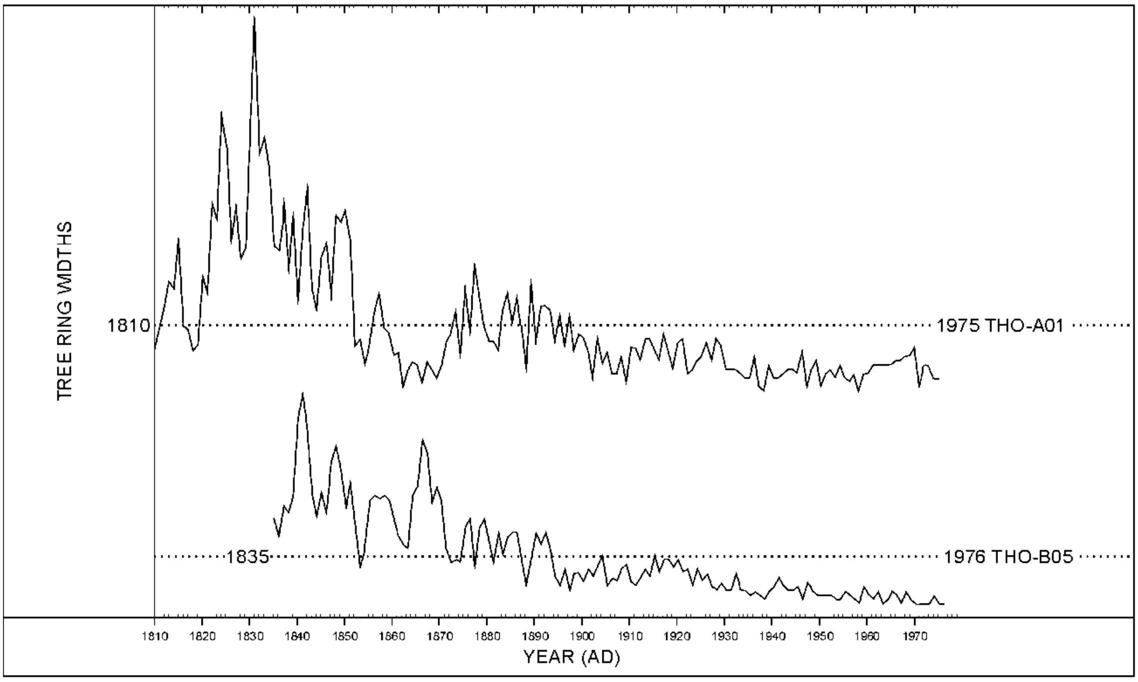


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

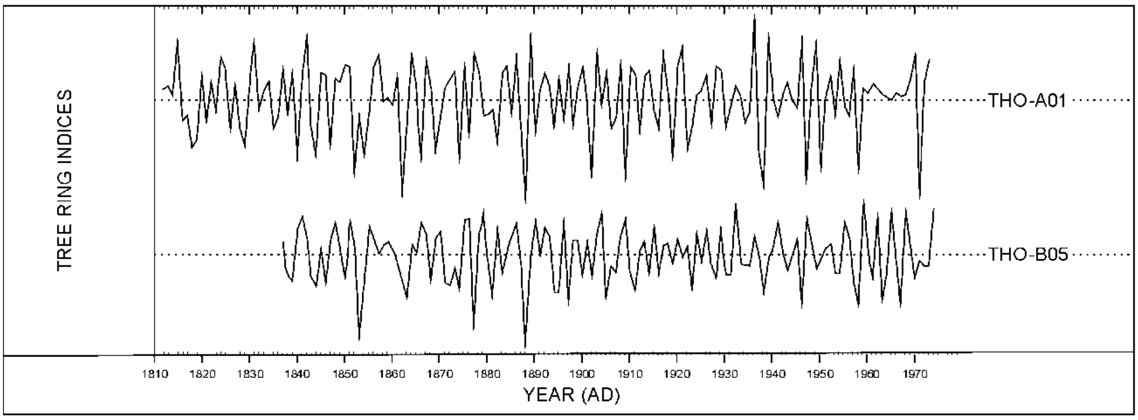


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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