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5/7 West Street and 15/16 Stepcote Hill Exeter Devon

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

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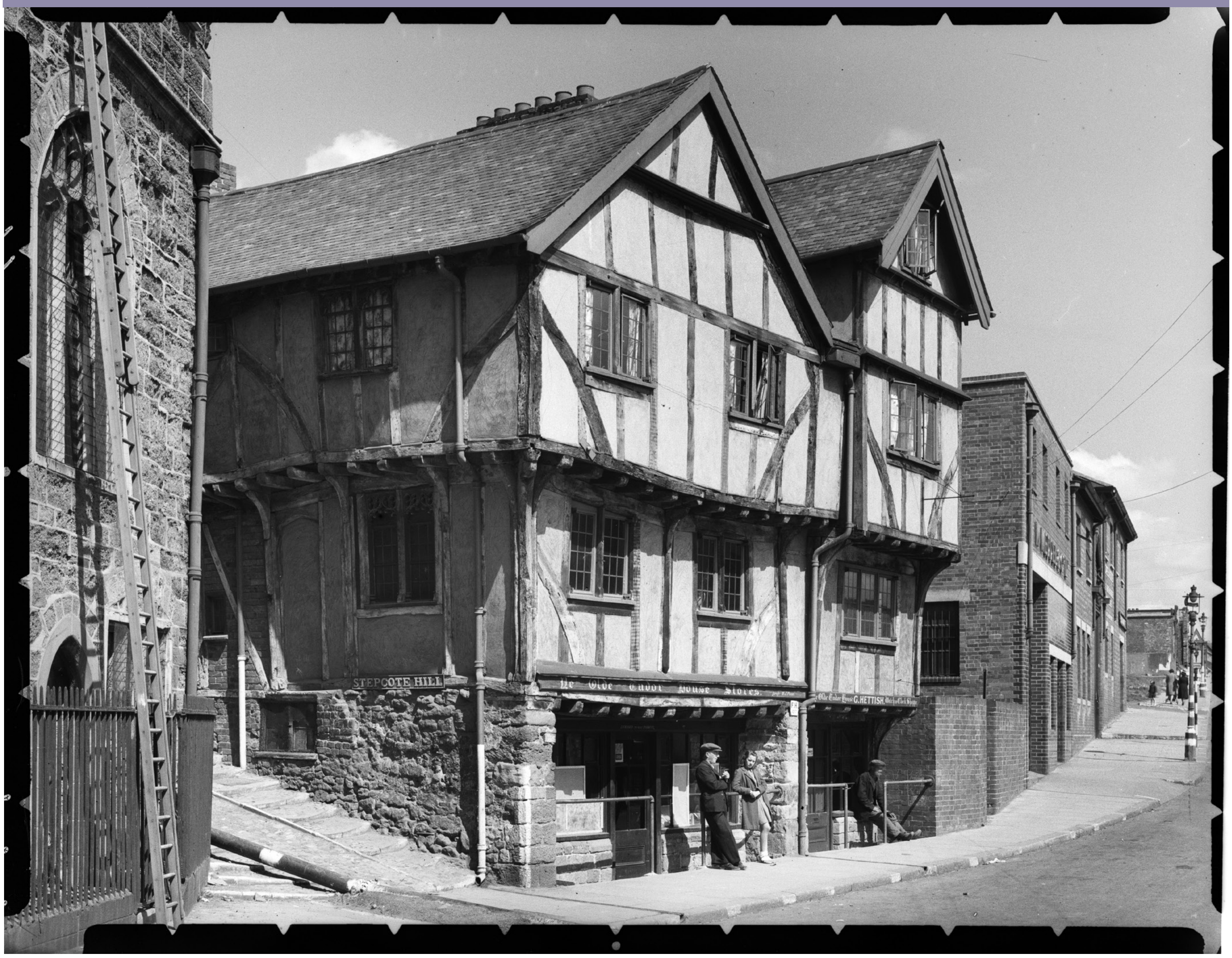

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Front Cover: 5 and 7 West Street at the corner of Stepcote Hill, Exeter, Devon 1942. © Historic England Archive Reference: BB42/00759

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5/7 WEST STREET AND 15/16 STEPCOTE HILL
EXETER
DEVON

Tree-ring Analysis of Oak Timbers

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SUMMARY
Dendrochronological analysis was undertaken on cores from 37 of the 38 timbers sampled on the ground, first, and second floors, and in the roof of this group of properties. This analysis produced a single site chronology comprising samples from 34 timbers with an overall length of 158 rings, these rings dated as spanning the years AD 1282–1439. Interpretation of the sapwood on the 34 dated samples, representing timbers in 5 West Street, 15 Stepcote Hill, and 16 Stepcote Hill, indicates that all of them are contemporary. The presence of complete sapwood on two samples indicates that these two timbers were felled in AD1439, with it being highly likely that all the other dated timbers were cut at, or about, the same time as part of a single programme of work. None of the three samples obtained from 7 West Street could be dated.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

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We would first like to thank the owner of the buildings for his unstinting help and cooperation with the visits to site for assessment and sampling. We would also like to thank Simon Cartlidge (Simon Cartlidge | Architect) for his help in arranging sampling and for the use of his plans and drawings in this report, along with those from Exeter City Council. Thanks too to Stuart Blaylock for the image sourcing of Figure.3. Finally we would like to thank Shahina Farid (Historic England Scientific Dating Team) for commissioning and facilitating this programme of tree-ring analysis.

ARCHIVE LOCATION
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DATE OF INVESTIGATION
2016–18

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CONTENTS

INTRODUCTION

Numbers 5 and 7 West Street and 15 and 16 Stepcote Hill, Exeter, comprise what were originally a parallel pair of timber-framed buildings, each above a stone-built lower (ie ground) floor terraced into the hillside. The buildings are Grade II* listed (List Entry Number 1266893) and occupy a corner plot where the steeply sloped Stepcote Hill runs approximately northwards from West Street towards the city centre (Fig 1). The following information is summarised from Portman (1966), Dunkley *et al* (1985), Parker and Allan (2015), and Cartlidge (2016).

The sloping nature of the site combined with modern internal divisions and recent tenure of the properties, means that 5 West Street comprises only the lower (ground) floor of the western building of the pair, while 7 West Street occupies only the eastern building at both ground- and first-floor levels (Figs 2a and 2b). Number 15 Stepcote Hill (accessible only from Stepcote Hill) comprises the first-floor level of the western building, while 16 Stepcote Hill (accessible only via a rear alleyway off Stepcote Hill) occupies the second floor to both east and west buildings but includes a modern third floor in the east building only (Figs 2b and 2c). An etching, probably by the Exeter artist John Gendall, dated 1834, shows a view of 5 West Street/Stepcote Hill in Figure 3.

In general, the ceilings of all rooms, where visible, appear to be formed of main bridging beams from which run smaller, although still substantial, common joists (Fig 4a). The timber-framing to both original buildings is formed of main posts and vertical studs above jetty plates, there being slightly curved braces from posts to plates (Figs 4b and 4c). The extant original roof trusses, only found in the western building as the roof to the eastern building was replaced when the third floor was inserted, are of principal-rafter with tiebeam and collar form (Fig 4d).

On the basis of stylistic evidence it has been previously suggested that this pair of buildings was originally constructed in the fifteenth century but an early- to mid-sixteenth century date has also been proposed. It is known that the buildings underwent major restoration in the 1930s, including the substantial rebuilding of 7 West Street, during which it is thought that much of the original timber-framing to the West Street elevation was replaced.

SAMPLING

Dendrochronological analysis was requested by Stephen Guy, Inspector of Historic Buildings and Areas for Historic England, to inform advice in relation to listed building consent for the planned repair and refurbishment of the upper floors. It was hoped that the dendrochronological dating evidence would enhance the understanding of these historic houses and hence inform their significance.

Although many of the timbers were covered in heavy black paint and varnish, an initial assessment of dendrochronological potential of all parts of the two buildings determined that, as far as could be seen, the majority of timbers generally appeared to contain sufficient rings for analysis. The exception to this, however, were the timbers to 7 West Street. There were fewer timbers in this part of the building, the roof and upper floor timbers (part of 16 Stepcote Hill) having been replaced in the 1930s refurbishment, and those which remained appeared to be derived from faster grown trees with lower ring numbers (generally less than 40 rings). As such, these timbers were considered to be generally unsuitable for tree-ring analysis.

Core samples were therefore taken from 38 timbers assessed as likely to be suitable. Each sample was given the code EXT-K (for Exeter, site 'K') and numbered 01–38 (Table 1). The majority of these (EXT-K01 – EXT-K35) were obtained from 5 West Street (ground floor), 15 Stepcote Hill (first floor) and the western half of 16 Stepcote Hill (roof), with only three samples, EXT-K36 – EXT-K38, being obtained from 7 West Street (ground floor), The trusses, bays, and individual timbers number from either site north to south, or east to west as appropriate, and the sampled timber locations shown on plans, sections, or annotated photographs in Figures 5a–f.

ANALYSIS AND RESULTS

All of the samples obtained were prepared by sanding and polishing. It was seen at this time that one sample, EXT-K23, had too few rings for reliable dating, and it was rejected from this programme of analysis. The annual growth ring widths of the samples from the remaining 37 timbers were, however, measured, the data of the measurements being given at the end of this report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process showing that 34 measured samples cross-matched with each other (with a minimum *t*-value of 5.6) at positions as shown in Figure 6.

These 34 cross-matched samples were combined at their indicated offset positions to form site chronology EXTKSQ01, this having an overall length of 158 rings. Site chronology EXTKSQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a series of reference chronologies when the date of its first ring is AD 1282 and the date of its last ring is AD 1439 (Table 2).

Site chronology EXTKSQ01 was then compared with the three remaining measured but ungrouped samples, all of them from 7 West Street, but there was no further conclusive, reliable, cross-matching. The three remaining samples were, therefore, compared individually with the full corpus of reference data for oak. There was no conclusive, reliable, cross-dating, and these three individual samples must remain undated.

INTERPRETATION

Timbers from three of the properties within this complex have been dated by dendrochronological analysis, all of which appear broadly coeval (Figs 6 and 7). Samples from two of the timbers, EXT-K15 and EXT-K16, retain complete sapwood, this meaning that they each have the last ring produced by the trees represented before they were felled. In both cases this last complete sapwood ring, and thus the felling of the trees, is dated to AD 1439. Samples from 29 of the remaining dated timbers retain some sapwood, or at least the heartwood/sapwood boundary (Table 1; Figs 6 and 7), this latter indicating that it is only the sapwood rings that have been lost. Given that the relative positions and dates of the heartwood/sapwoods boundaries on these other samples is very similar, and sometimes identical, to those on the timbers whose felling dates are known precisely (EXT-K15 and EXT-K16), this would suggest that these other timbers were felled in, or about, AD 1439 as well. Taken overall, this boundary varies by 22 years, from relative position 123 (AD 1404) on sample EXT-K09 to relative position 145 (AD 1426) on samples EXT-K27 and K30. While such a variation might not suggest an identical year of felling for all timbers, it would indicate that they were felled over a relatively short period of time as part of a single programme of work. The samples from the remaining three dated timbers do not retain any trace of sapwood but with felled after dates of AD 1373 (EXT-K08), AD 1379 (EXT-K22), and AD 1396 (EXT-K19), combined with the level of similarity that these series show with all other dated series, suggests that they were also felled in, or around, AD 1439.

Examination of the timbers by sample location shows that the timbers from the 5 West Street (ground floor) have an average heartwood/sapwood boundary date of AD 1412 with individual heartwood/sapwood boundary dates ranging from AD 1407 (EXT-K05) to AD 1417 (EXT-K07), those from 15 Stepcote Hill (first floor) an average of AD 1413 and a range varying from AD 1404 (EXT-K09) to AD 1424 (EXT-K12), and those from 16 Stepcote Hill (roof) an average of AD 1415 and a range varying from AD 1406 (EXT-K25) to AD 1426 (EXT-K30). It is tempting to suggest that this possible minor progression of felling date range for each property rising from ground floor to roof level provides some indication of the length of the period of felling. However, this is more speculation than fact.

DISCUSSION AND CONCLUSION

The dendrochronological analysis thus indicates that the timbers used at 5 West Street, 15 Stepcote Hill, and the roof of the western building (part of 16 Stepcote Hill), were felled over a short period of time in, or around, AD 1439, and that these properties, originally a parallel pair of timber-framed buildings, are the product of a single phase of construction. This supports the fifteenth-century date proposed on stylistic evidence and refines the dating of these buildings.

As may be seen from Table 2, although site chronology EXTKSQ01 has been compared with reference data from across the United Kingdom and Ireland, the highest levels of similarity are to be found with chronologies from sites elsewhere in Devon and other counties in the south-west, excluding Cornwall. This could suggest that the dated timbers used at West Street/Stepcote Hill were not sourced from the immediate environs of Exeter, but from somewhere slightly further afield in this area to the north-east of Exeter.

Wherever the source woodland was, it seems likely that many trees utilised here were all growing in the same woodland. With numerous examples of cross-matches with values of *t*=7.0+. *t*=8.0+, and *t*=9.0+, it is clear that many trees were growing close to each other, such values being found between samples from different parts of the complex. Indeed, with even higher values, *t*=11.4 between EXT-K01 and EXT-K17, or *t*=12.4 between EXT-K4 and EXT-K11, it is likely that some timbers have been derived from the same tree. The highest cross-match is between samples EXT-K04 and EXT-K05 which match with a value of *t*=17.0.

These cross-matches again support the view that all the trees were felled as part of a single short programme of felling, it being considered something of a coincidence that trees originally growing close to each other, but felled at quite different times, should come to be used in the same building.

Three samples, EXT-K36 – EXT-K38, all from the ground floor ceiling of 7 West Street, remain ungrouped and undated. It will be seen from Table 1 that these three have the lowest number of rings compared to all other samples obtained, these being close to the minimum required for reliable dating. Given that the source timbers for these three appeared to be typical of those to 7 West Street, but quite different in ring counts to those of 5 West Street/Stepcote Hill, this could perhaps be taken as evidence that they are from a different source, and thus possible of a different (although, given the stylistic similarity of the framing to both buildings, not very different) phase of construction.

REFERENCES

Arnold, A J, and Howard, R E, 2018 unpubl *3 High Street, Hinton Charterhouse, Somerset, Tree-ring Analysis of Timbers* – Nottingham Tree-ring Dating Laboratory unpubl computer file *HNTNSQ02*

Arnold, A, J, Howard, R E, and Litton C D, 2004 *Tree-ring Analysis of Timbers from New Inn House, 7 Wotton Road, Kingswood, Gloucestershire,* Centre for Archaeol Rep, 62/2004

Bridge, M C, 2002 *Tree-ring Analysis of Timbers from Muchelney Abbey, Muchelney, near Langport, Somerset,* Centre for Archaeol Rep, 114/2002

Bridge, M C, 2014 *Sherborne House, Newland, Sherborne, Dorset, Tree-ring Analysis of Timbers from the Tudor Wing*, English Heritage Res Rep Ser, 31/2014

Cartlidge, S, 2016 *5/7 West Street and 15/16 Stepcote Hill, Exeter, Heritage Statement*, Simon Cartlidge Architect, sch78/2016

Dunkley, J A, Henderson, C G, and Allan, J P, 1985 Survey of 5 West Street and 15 Stepcote Hill, in *Exeter Archaeology 1984/85* (C G Henderson), Exeter Museums Archaeological Field Unit, 36–38

Gray, T 2000 *Exeter Engraved, Volume I: The Secular City* Exeter (The Mint Press)

Howard, R E, 2000 unpubl, *Brockworth Court, Brockworth, Gloucestershire, Tree-ring Analysis of Timbers from the Hall and Cross-wings*, Nottingham Tree-ring Dating Laboratory unpubl computer file *BRKASQ02*

Howard, R E, Laxton, R R, and Litton C D, 1999 *Tree-ring analysis of timbers from Exeter Guildhall, High Street, Exeter, Devon,* Anc Mon Lab Rep, 56/1999

Hurford, M, and Tyers, C, 2014 *The Old Manor, West Lavington, Wiltshire, Tree-ring Analysis of Timbers,* English Heritage Res Rep Ser, 66/2014

Miles, D, 2007 *The Tree-ring Dating of the White Tower, HM Tower of London (TOL99 and TOL100), London Borough of Tower Hamlets*, English Heritage Res Dept Rep Ser, 35/2007

Miles, D and Bridge, M 2012 Tree-ring dates from the Oxford Dendrochronology Laboratory – List 246: General List, *Vernacular Architect,* 43, 97–100

Miles, D, Worthington, M, and Bridge, M, 2006 Tree-ring dates for buildings: List 177, *Vernacular Architect,* 37, 118–132

Parker, R and Allan, J, 2015 *The Transformation of the Building Stock of Exeter 1450-1700, in West Country Households 1500-1700* (eds J Allan, N Alcock, and D Dawson eds), Society for Post Medieval Archaeology Monograph Series, 35–68

Portman, D, 1966 *Exeter Houses, 1400–1700* (University of Exeter Press)

TABLES

Table 1: Details of tree-ring samples from 5/7 West Street and 15/16 Stepcote Hill, Exeter, Devon

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	5 West Street (ground floor)					
EXT-K01	Jetty joist 5 (from east)	146	15	1283	1413	1428
EXT-K02	Jetty joist 7	136	20	1293	1408	1428
EXT-K03	Jetty joist 8	94	h/s	1319	1412	1412
EXT-K04	Jetty joist 9	121	6	1298	1412	1418
EXT-K05	Jetty joist 10	130	15	1293	1407	1422
EXT-K06	Jetty joist 11	127	h/s	1286	1412	1412
EXT-K07	In-fill block 1 (east)	92	4	1330	1417	1421
EXT-K08	In-fill block 2 (west)	66	no h/s	1293	------	1358
EXT-K35	South main ceiling beam	116	h/s	1300	1415	1415
	15 Stepcote Hill (first floor)					
EXT-K09	Main north ceiling beam	126	3	1282	1404	1407
EXT-K10	Main south ceiling beam	129	8	1298	1418	1426
EXT-K11	Dragon beam	124	23	1311	1411	1434
EXT-K12	West frontage, centre post	133	h/s	1292	1424	1424
EXT-K13	West frontage, south door jamb	118	h/s	1290	1407	1407
EXT-K14	West frontage, jetty joist 9 (from north)	130	3	1282	1408	1411
EXT-K15	West frontage, jetty joist 10	139	28C	1301	1411	1439
EXT-K16	West frontage, jetty joist 11	129	27C	1311	1412	1439
EXT-K17	West frontage, bracket to joist 12	77	h/s	1339	1415	1415
EXT-K18	South frontage, jetty joist 3 (from east)	89	3	1338	1423	1426
EXT-K19	South frontage, jetty joist 8	89	no h/s	1293	------	1381
EXT-K20	South frontage, jetty joist 10	146	17	1283	1411	1428
EXT-K21	South frontage, bracket to joist 6	123	13	1301	1410	1423
	16 Stepcote Hill (roof timbers)					
EXT-K22	Tiebeam, truss 1	71	no h/s	1294	------	1364
EXT-K23	East principal rafter, truss 1	nm	---	------	------	------

Table 1: continued

EXT-K24	West principal rafter, truss 1	81	4	1348	1424	1428
Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
EXT-K25	Collar, truss 1	71	h/s	1336	1406	1406
EXT-K26	Tiebeam, truss 2	73	h/s	1341	1413	1413
EXT-K27	East principal rafter, truss 2	132	h/s	1295	1426	1426
EXT-K28	West principal rafter, truss 2	130	h/s	1293	1422	1422
EXT-K29	Collar, truss 2	60	h/s	1351	1410	1410
EXT-K30	East principal rafter, truss 3	131	h/s	1296	1426	1426
EXT-K31	West principal rafter, truss 3	90	2	1219	1406	1408
EXT-K32	Collar, truss 3	103	6	1311	1407	1413
EXT-K33	East upper purlin, bay 2	73	1	1340	1411	1412
EXT-K34	East brace, truss 2	111	h/s	1301	1411	1411
	7 West Street (ground floor)					
EXT-K36	Rear ceiling joist 2 (from east)	40	no h/s	------	------	------
EXT-K37	Rear ceiling joist 3	46	no h/s	------	------	------
EXT-K38	Rear ceiling joist 5	40	no h/s	------	------	------

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

Table 2: Results of the cross-matching of site sequence EXTKSQ01 and relevant reference chronologies when the first-ring date is AD 1282 and the last-ring date is AD 1439

Reference chronology	Span of chronology	t-value	Reference
Devizes Castle, Wiltshire	AD 1213–1407	9.3	(Miles *et al* 2006)
New Inn House, Kingswood, Gloucestershire	AD 1191–1519	9.2	(Arnold *et al* 2004)
Sherborne House, Sherborne, Dorset	AD 1318–1459	9.1	(Bridge 2014)
Brockworth Court, Brockworth, Gloucestershire	AD 1281–1447	8.9	(Howard 2000 unpubl)
White Tower, Tower of London, London	AD 1260–1489	8.5	(Miles 2007)
Muchelney Abbey, Somerset	AD 1148–1498	8.1	(Bridge 2002)
The Old Manor, West Lavington, Wiltshire	AD 1264–1497	8.0	(Hurford and Tyers 2014)
Holcombe Court, Holcombe Rogus, Devon	AD 1349–1536	7.7	(Miles and Bridge 2012)
Guildhall, High Street, Exeter, Devon	AD 1314–1456	7.5	(Howard *et al* 1999)
3 High Street, Hinton Charterhouse, Somerset	AD 1305–1517	7.4	(Arnold and Howard 2018 unpubl)

FIGURES

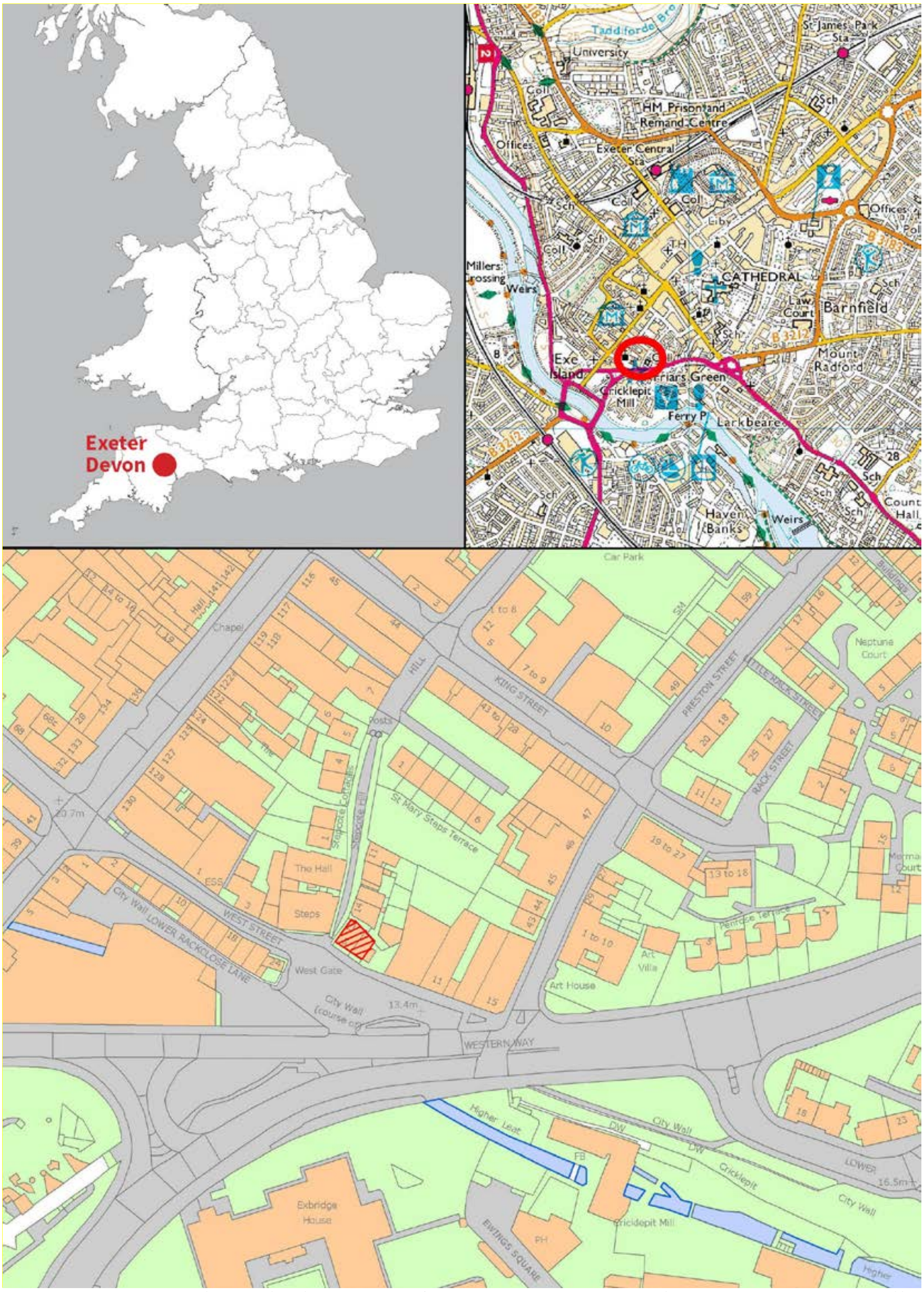
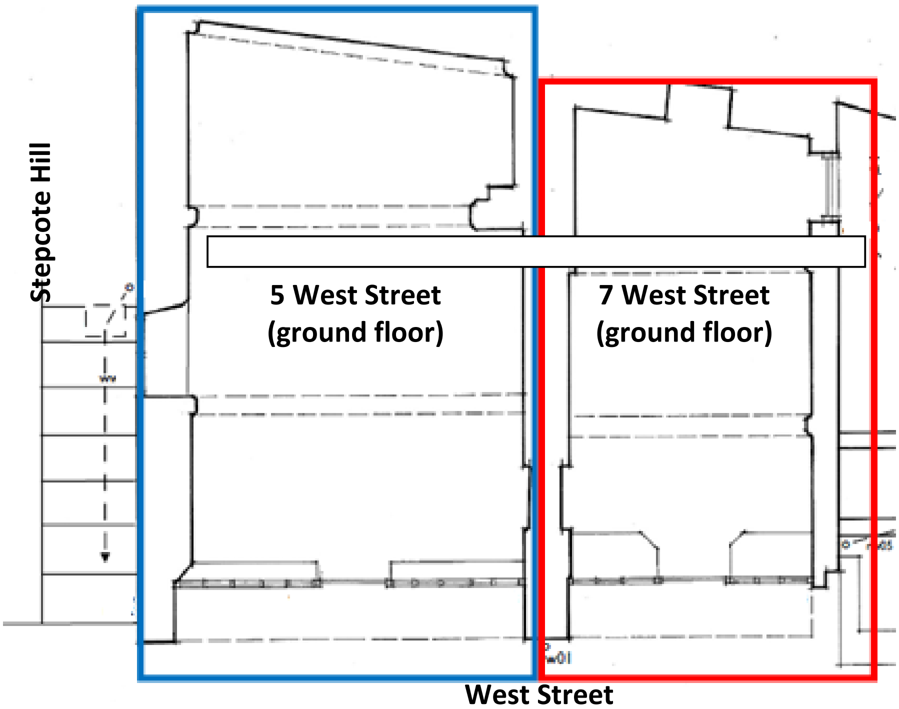


Figure 1: Maps to show the location of 5/7 West Street and 15/16 Stepcote Hill, Exeter, Devon, marked in red. Scale: top right 1:20000; bottom 1:1250.



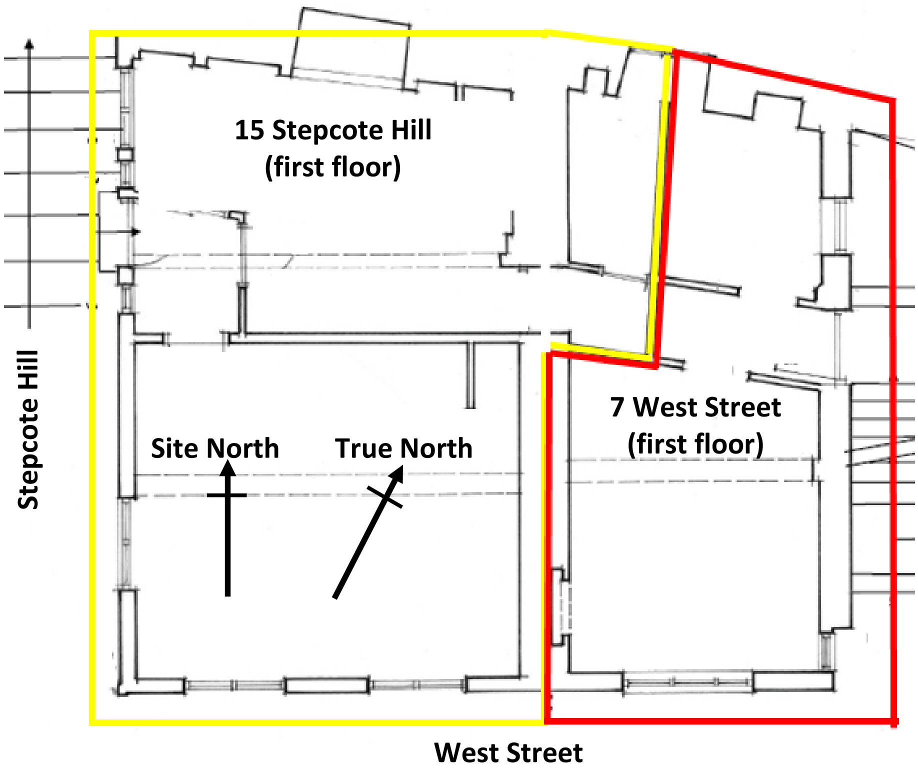


Figure 2a/b: Plans of the West Street/Stepcote Hill site to show layout and arrangement of the building (after Simon Cartlidge | Architect 2016)

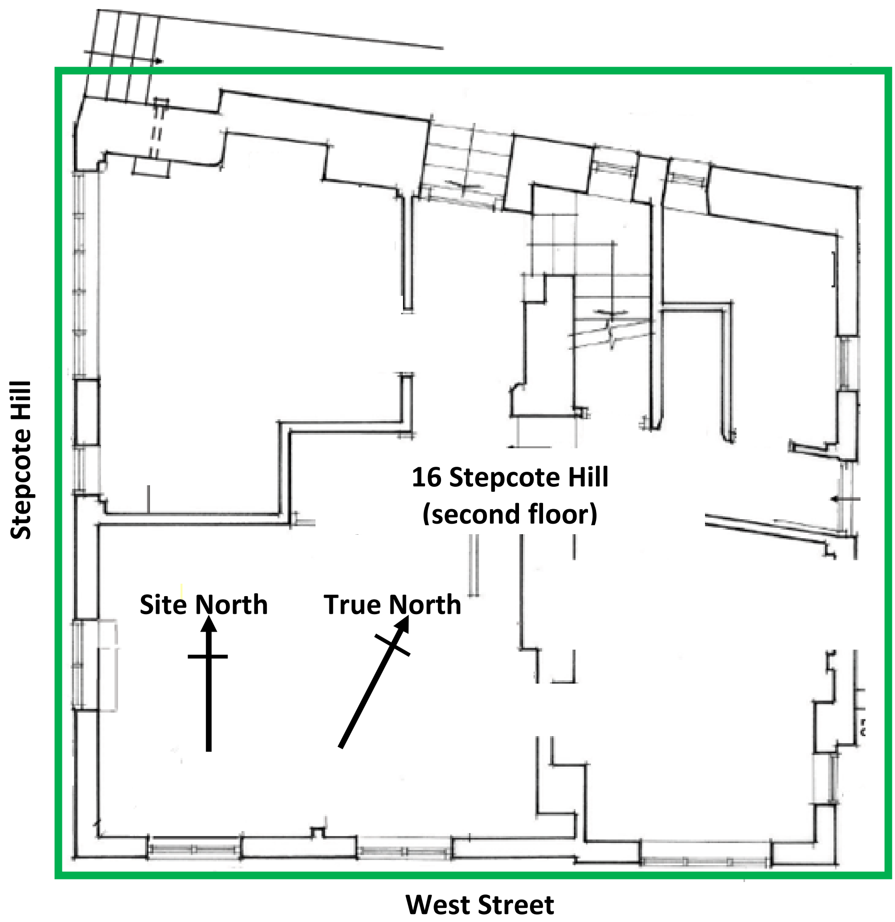


Figure 2c: Plan of the West Street/Stepcote Hill site to show layout and arrangement of the building (after Simon Cartlidge | Architect 2016)

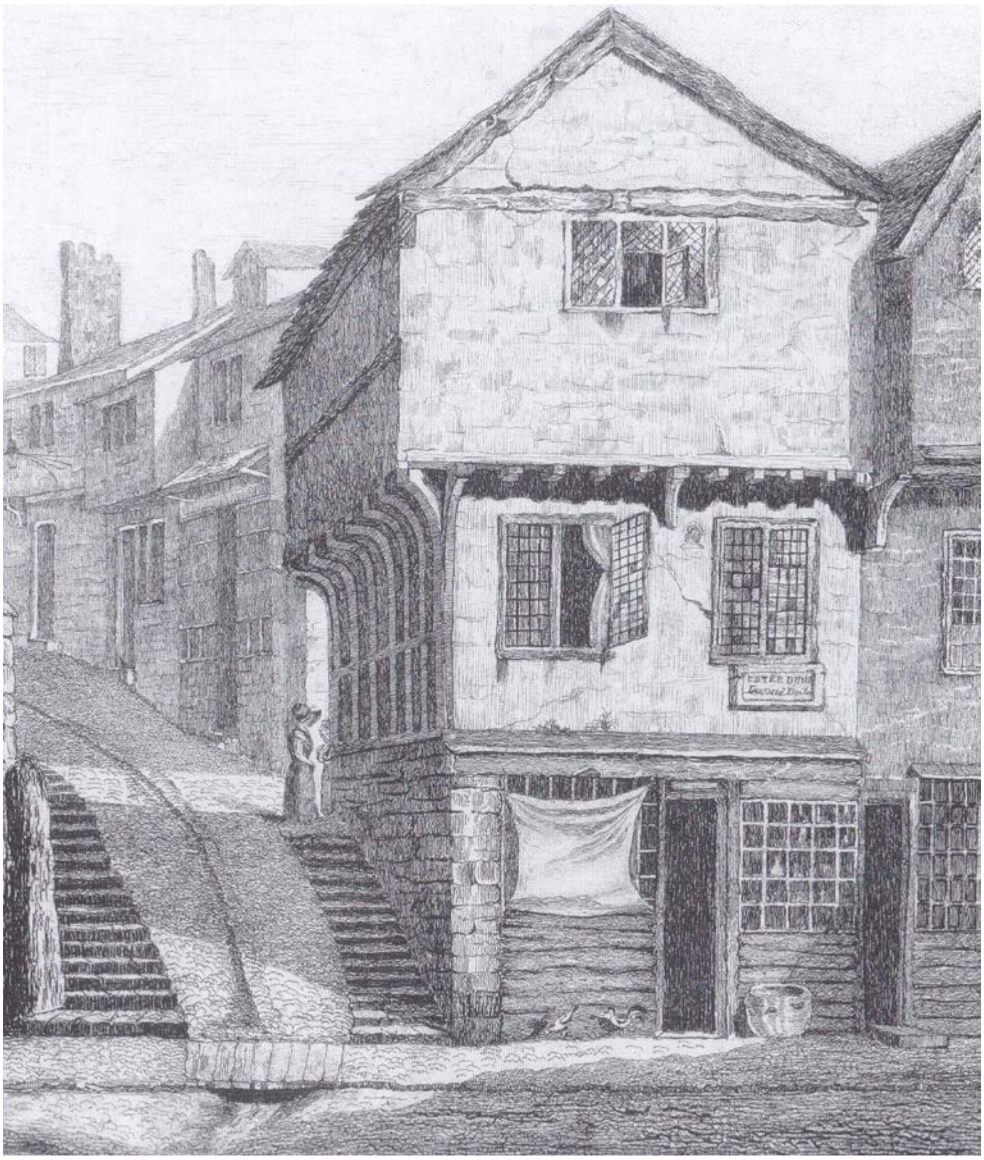


Figure 3: View of West Street/Stepcote Hill, an *etching, probably by the Exeter artist John Gendall, dated 1834 (after Gray 2000, no. 147)*

Figures 4a/b: Views of the ground floor ceiling in 5 West Street (top) and wall framing in 16 Stepcote Hill (bottom; photographs Robert Howard)

Figures 4c/d: Views of wall framing in 15 Stepcote Hill (top) and roof to 16 Stepcote Hill (bottom; photographs Robert Howard)

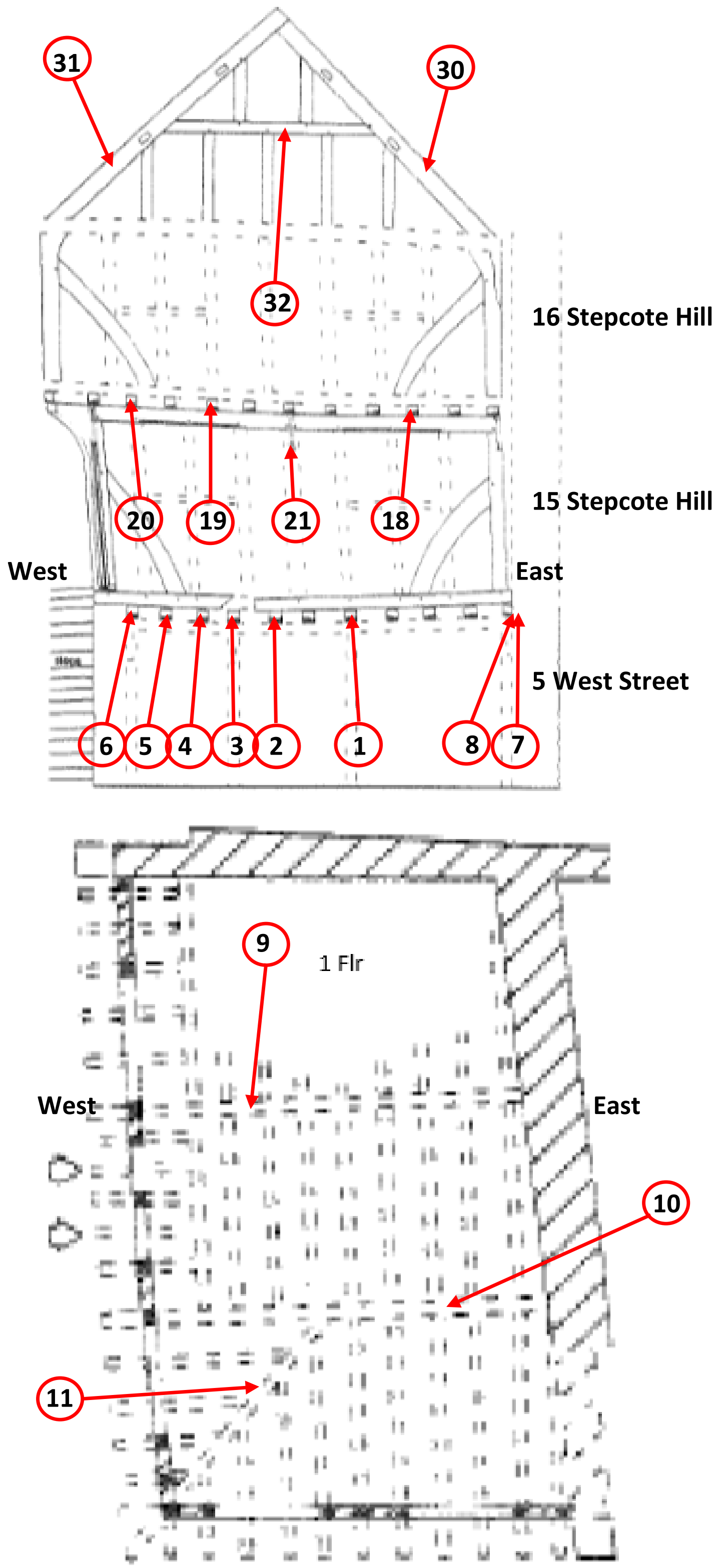
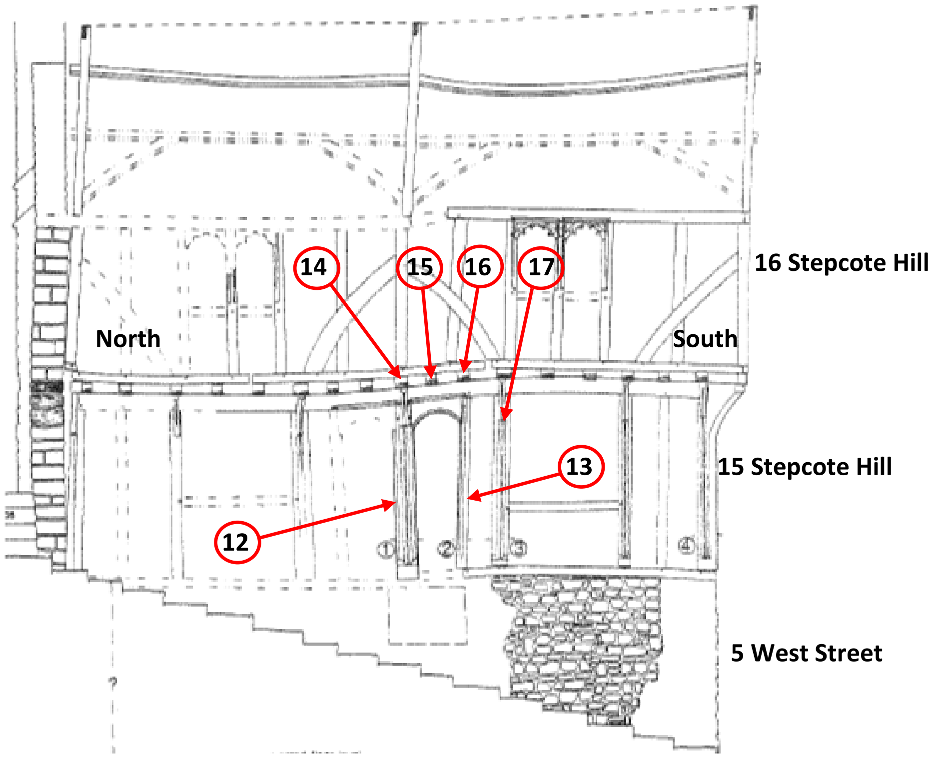


Figure 5a/b: Section through truss 3/West Street frontage of the western building (top) and ceiling plan of 15 Stepcote Hill (bottom) to show sampled timbers (after Dunkley and Templeton in Dunkley et al *1985)*



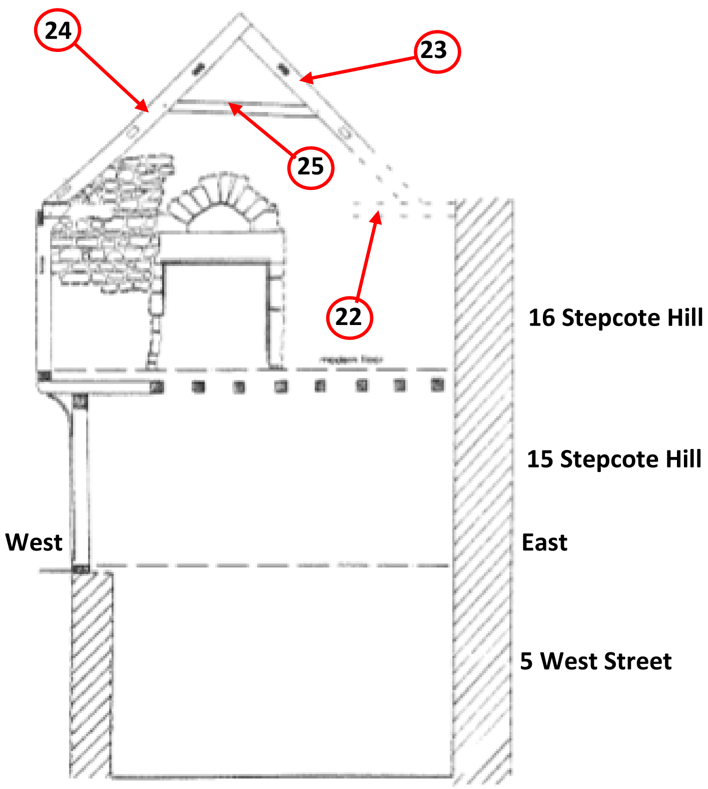
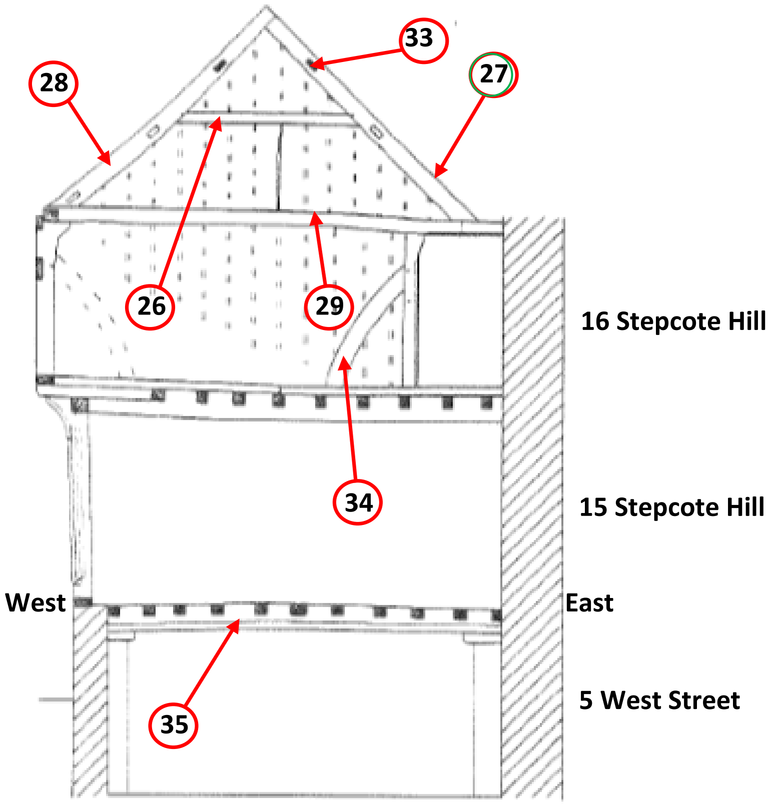


Figure 5c/d: Stepcote Hill elevation (top) and section through truss 1of the western building to show the sampled timbers (after Dunkley and Templeton in Dunkley et al *1985)*



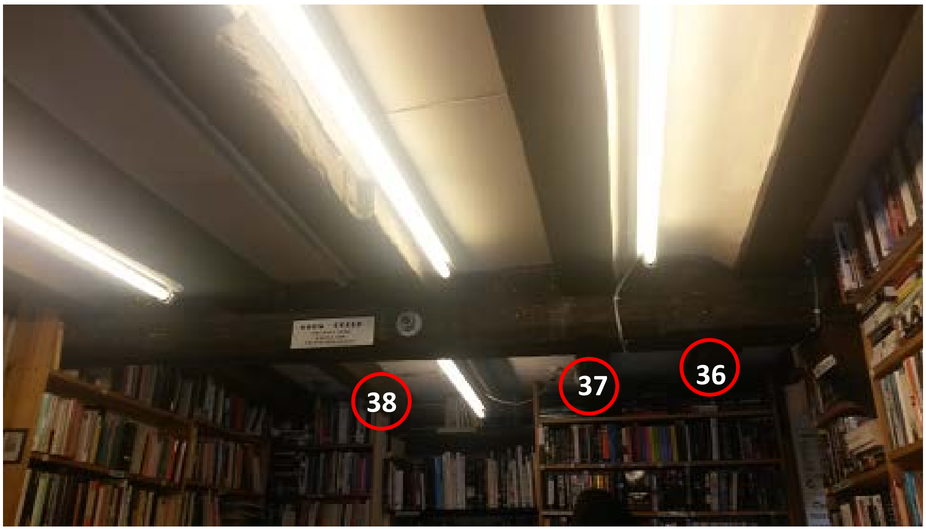
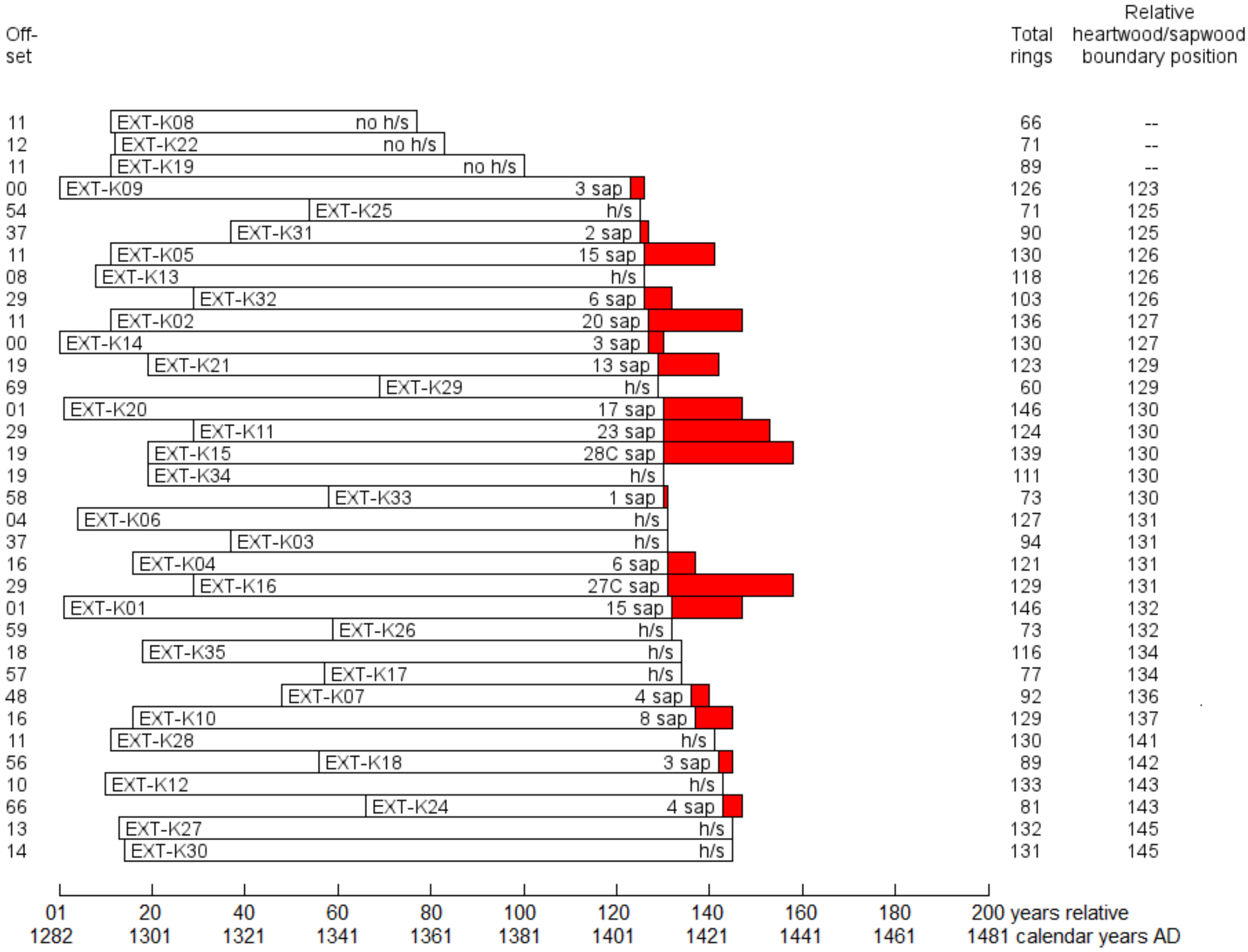
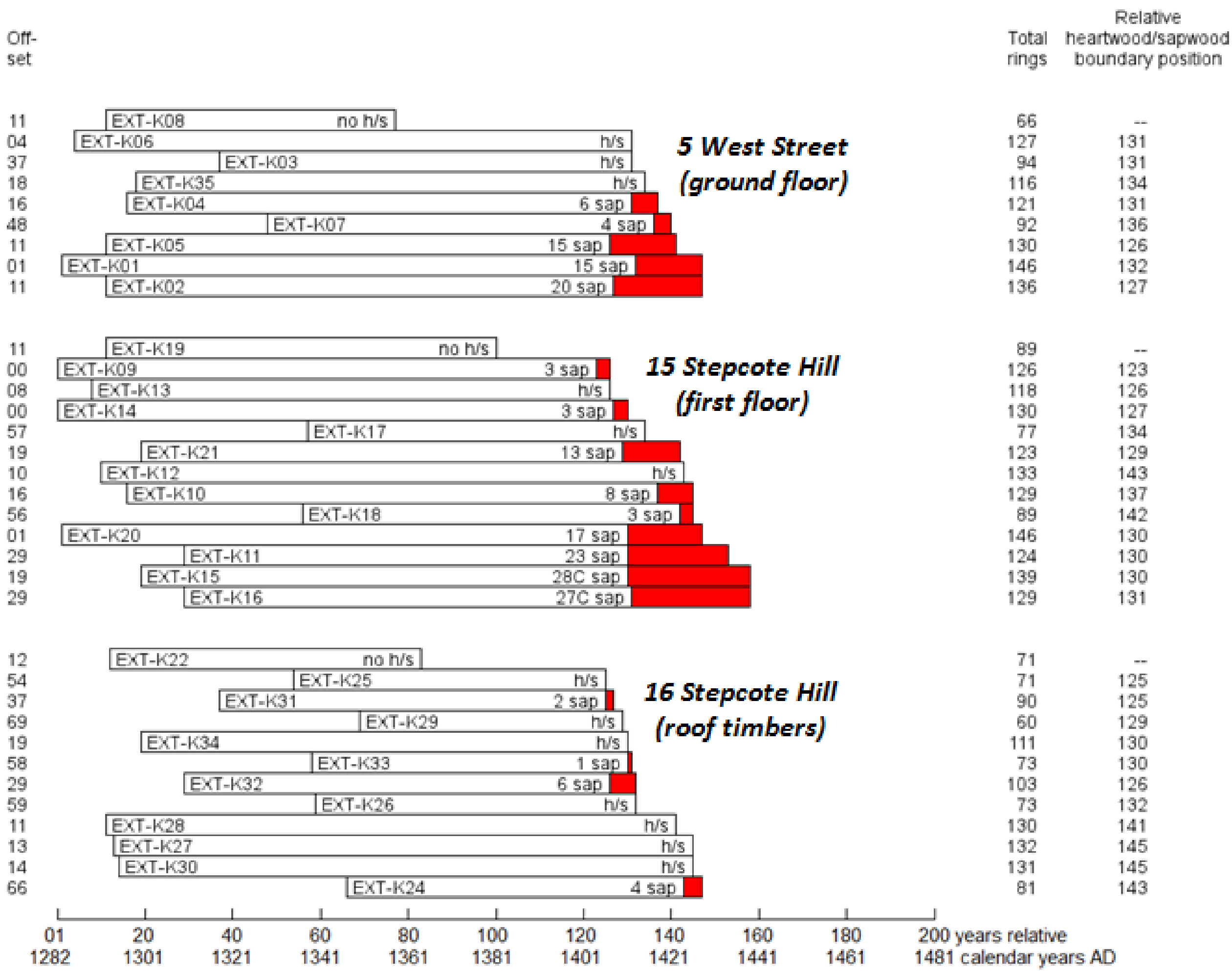


Figure 5e/f: Section through truss 2 of the western building (top, after Dunkley and Templeton in Dunkley et al *1985), and annotated photograph of ground floor ceiling timbers to 7 West Street (bottom) to show sampled timbers (photograph Robert Howard)*



white bars = heartwood rings; red bars = sapwood rings;
C = complete sapwood retained on the sample, the last measured ring date is the felling date of the tree represented; h/s = heartwood/sapwood boundary

Figure 6: Bar diagram of the dated samples in site chronology EXTKSQ01 sorted by h/s boundary date



white bars = heartwood rings; red bars = sapwood rings;
C = complete sapwood retained on the sample, the last measured ring date is the felling date of the tree represented; h/s = heartwood/sapwood boundary

Figure 7: Bar diagram of the dated samples in site chronology EXTKSQ01 sorted by sample location and in last measured ring date order

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

EXT-K01A 146
346 534 404 308 235 234 230 369 348 316 287 367 243 270 163 170 198 200 217 200
172 142 146 149 150 131 143 175 206 187 151 135 182 147 198 98 81 96 103 100
86 94 66 80 97 88 86 77 64 65 70 76 84 73 68 71 70 68 60 60
50 67 71 87 125 65 60 84 93 90 139 140 73 73 146 112 65 51 79 114
175 137 93 111 82 71 112 112 91 110 103 128 137 137 117 103 185 149 143 106
125 106 137 154 130 166 116 76 79 102 143 96 159 154 84 103 136 156 160 122
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217 182 190 117 134 219
EXT-K01B 146
347 528 420 309 271 254 228 353 345 317 286 370 235 276 178 191 207 207 213 183
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87 95 54 73 77 85 80 71 65 68 64 75 76 64 65 64 70 69 48 62
65 54 81 79 125 71 45 87 114 97 132 135 68 90 139 100 78 57 57 118
176 142 84 118 76 70 103 95 93 104 108 111 141 129 121 97 182 140 166 112
115 121 125 153 143 160 112 77 87 97 153 103 149 153 84 101 139 150 165 104
143 118 178 220 185 154 118 93 175 160 178 128 146 98 120 143 107 230 124 134
200 184 197 121 134 218
EXT-K02A 136
224 250 348 355 285 372 316 338 286 276 175 135 134 121 192 130 115 129 128 121
107 91 270 180 98 85 64 50 85 136 150 117 74 45 86 116 164 163 84 98
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51 51 56 59 73 56 53 64 48 57 43 56 49 79 48 63 65 54 40 46
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135 184 153 93 122 145 85 192 153 170 216 193 196 112 78 177
EXT-K02B 136
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56 49 54 60 70 50 60 68 45 55 51 50 51 70 51 60 71 42 35 59
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156 183 150 91 118 144 89 196 143 168 210 196 184 121 80 172
EXT-K03A 94
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EXT-K36B 40
386 312 330 336 274 314 236 237 201 253 196 235 320 280 231 246 250 240 238 236
306 274 209 126 169 164 138 161 202 185 139 132 153 124 150 133 138 206 208 193
EXT-K37A 46
389 376 346 378 324 257 225 293 266 301 510 432 367 314 264 393 376 389 343 164
93 84 153 162 173 145 168 157 151 271 174 181 285 115 89 110 105 82 87 185
207 263 305 414 515 548
EXT-K37B 46
378 382 381 410 310 209 249 298 282 280 513 431 337 364 261 391 390 368 329 152
95 83 142 168 158 131 160 157 148 250 192 182 279 107 84 118 129 70 81 164
218 252 307 398 504 573
EXT-K38A 40
220 216 115 132 181 125 111 181 282 245 229 323 340 387 168 225 350 485 570 775
633 393 399 310 461 297 432 911 928 990 885 353 548 481 551 596 506 522 417 523
EXT-K38B 40
199 235 115 132 189 135 119 180 276 214 247 334 344 387 168 246 362 480 595 788
610 407 363 312 440 320 432 907 933 993 886 385 525 481 542 654 459 536 412 509

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 Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of

the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

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

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

corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

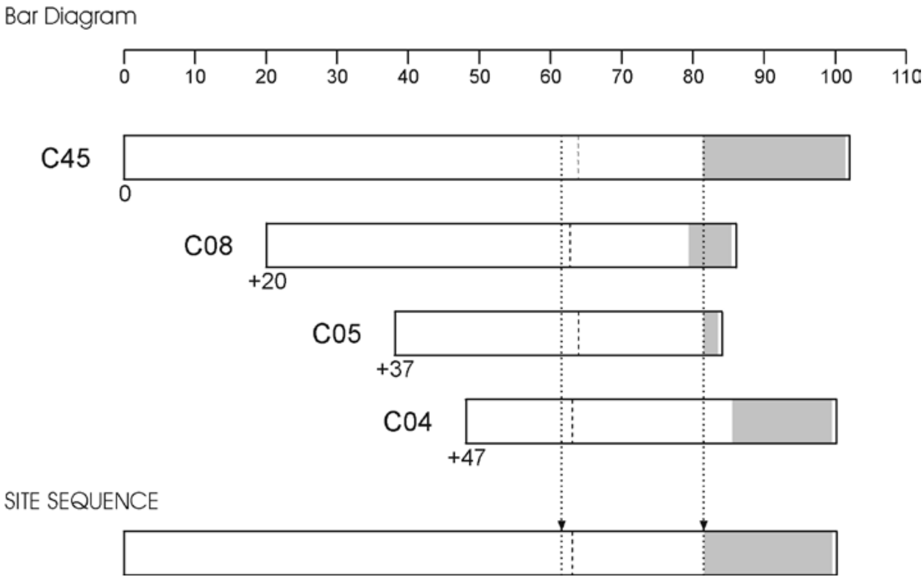


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

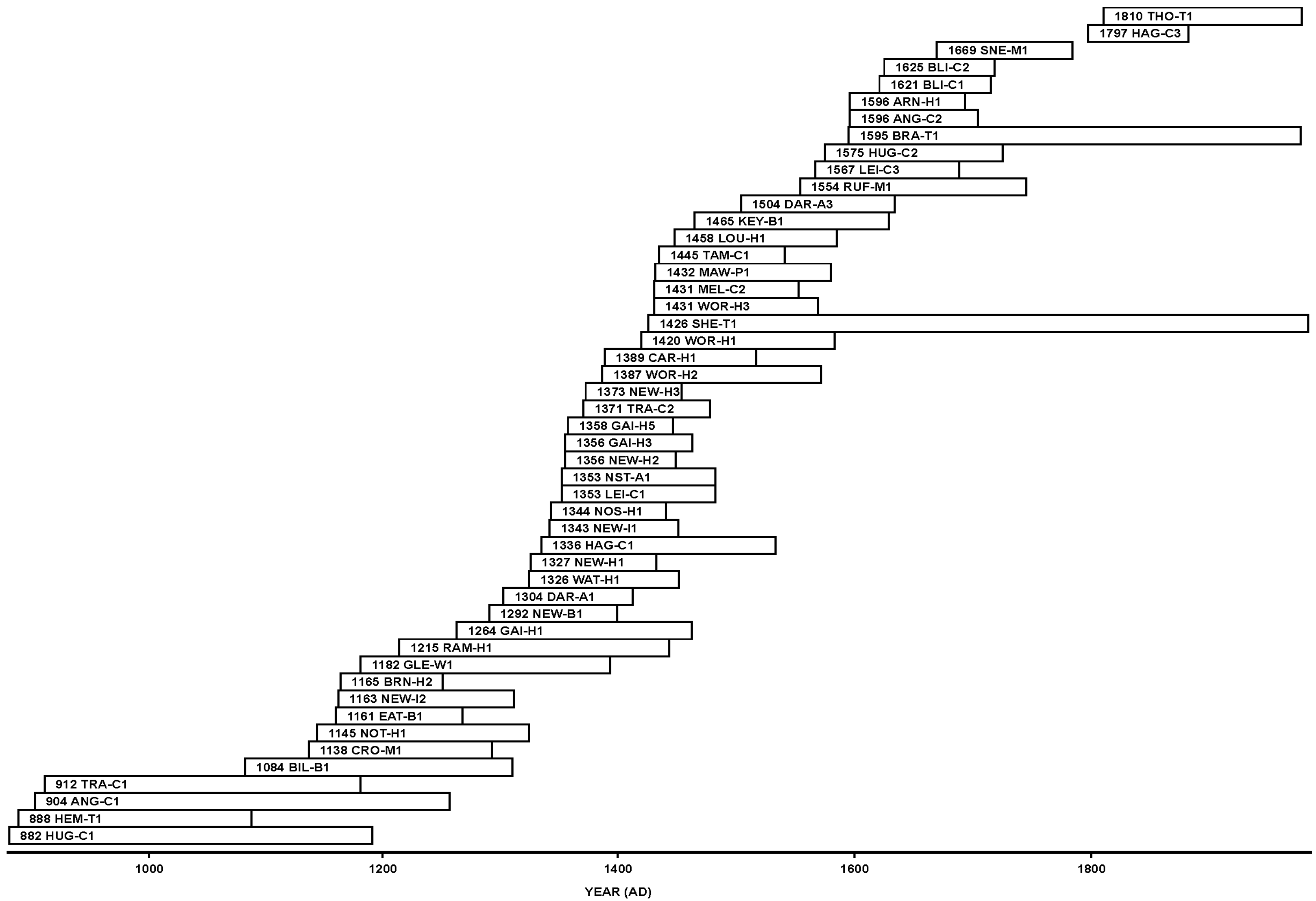
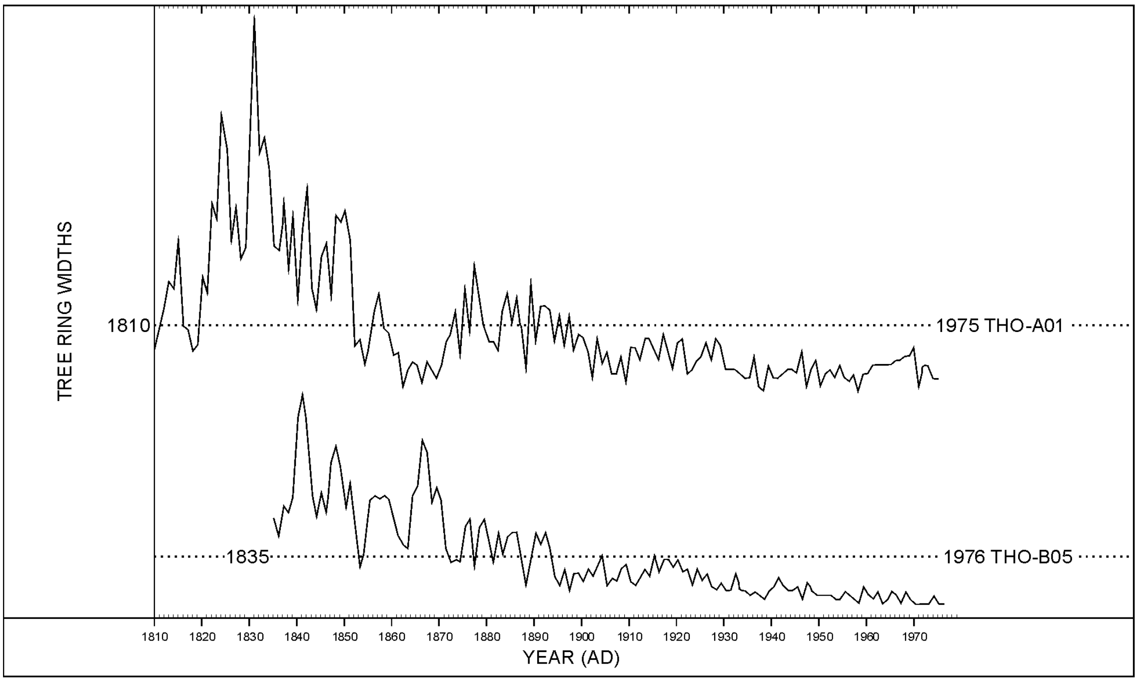


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

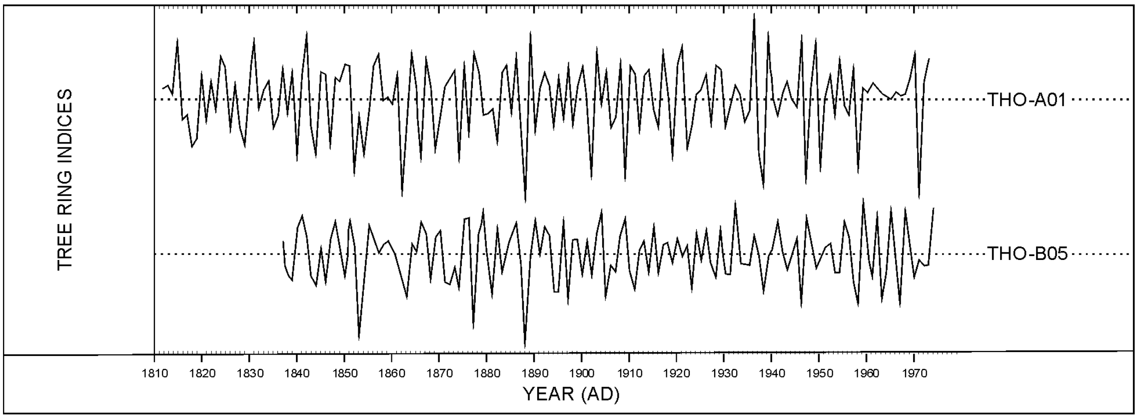


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

References

Baillie, M G L, and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-Ring Bull*, **33**, 7–14

English Heritage, 1998 *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*, London

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95 Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect*, **15–26**

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, **23**, 51–6.

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series **III**

Laxton, R R, and Litton, C D, 1989 Construction of a Kent master dendrochronological sequence for oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90–8

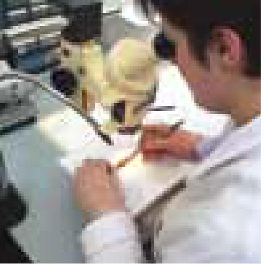
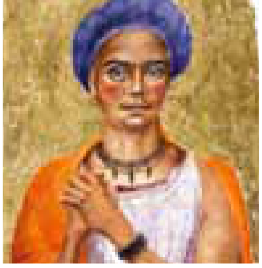
Laxton, R R, Litton, C D, and Howard, R E, 2001 *Timber: Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, **7**

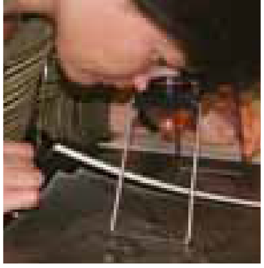
Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸ **18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architect*, **28**, 40–56

Pearson, S, 1995 *The Medieval Houses of Kent, an Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London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