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46 HIGH STREET, EXETER, DEVON
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Dendrochronological analysis of 32 of the samples obtained predominantly from the roof and floor frames of 46 High Street, Exeter, has produced two site chronologies. The first site chronology comprises 25 samples, from the roof, floor frames, and a small number of other timbers, and has an overall length of 183 rings. These rings are dated as spanning the years AD 1309–1491. Interpretation of the sapwood on these samples indicates that all the timbers represented were probably cut as part of a single programme of felling, estimated to have taken place in AD 1492–1515.

The second site chronology comprises two samples with an overall length of 84 rings. This site chronology, and a further five ungrouped samples and one unmeasured sample, remain undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Laboratory would like to thank Thorntons, the owners of 46 High Street Exeter, and their shop staff, for their cooperation with this programme of tree-ring analysis and their help during sampling. We would also like to thank the staff of St Blaise, conservation builders, for their considerable cooperation, help, and interest during sampling as well. We must also thank John Allan of Exeter Archaeology for his help and advice in respect of the phasing of this building, Richard Parker, also of Exeter Archaeology, for the use of his drawings, and Andy Pye, Planning Archaeologist at Exeter City Council, for his assistance with this programme of analysis. Finally we would like to thank Dr Peter Marshall, Scientific Dating Coordinator, for commissioning this programme of tree-ring dating.

ARCHIVE LOCATION

Historic Environment Service
Matford Offices
County Hall
Exeter EX2 4QW

DATE OF INVESTIGATION

2009

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INTRODUCTION

According to the Exeter Urban Archaeological Database record (11183.00), from which this introduction is taken, the buildings now known as 46 and 47 High Street, Exeter (SX 92036 92650, Figs 1 and 2) represent an early, and now rare surviving, example of the construction of a pair of late/post-medieval, 'semi-detached', timber-framed houses as 'mirror images' of each other. The buildings are particularly unusual for Exeter in being entirely timber-framed, rather than the combination of stone side, or party walls, and timber transverse walls more common to the City, eg 41/42 High Street.

Superficially, the two now look very different to each other. While number 46, which is Grade II* listed, retains most of its original façade (Fig 3), number 47 was refaced with render in the eighteenth century. Also, the street-front gable of number 46 has been replaced by a hipped roof. Internally, although the ground floors of both buildings have been extensively fitted out as shops, and little actual framing survives here other than some in the south-west wall of number 47, the upper floors of both retain much of their original fabric.

In plan (Fig 4) the buildings consist of two rooms to the main block, centred on a central stack and stair turret, with a further block to the rear. The jettied timber-framed frontage of number 46 once continued across number 47; this has carved angel figures (renewed) on the brackets, and a coved jetty with curving shafts ornamented with barley-twist fillets and pellets. The side elevation of number 46 was originally open to a narrow street called Lamb Alley, running between High Street and what is now known as Cathedral Yard, this elevation also being ornamented. The ground floors originally consisted of a shop at the front of each property, and domestic accommodation behind.

The typical framing style is of close-studding, with massive studs stretching from floor to ceiling on ground, first, and second floors. The original roof comprised seven bays formed by eight principal-rafter trusses (Fig 5) with chamfered tiebeams, there being double through-purlins to each pitch as well as a ridge to the apex. The pair of buildings has been variously dated from as early as AD 1500–40 by some authorities, to as late as AD 1550 by others, and there is a similar example, at 41/42 High Street, believed to have been built in the AD 1560s, but not dated by dendrochronology.

SAMPLING

Sampling and analysis by dendrochronology of the timbers at number 46 High Street were requested by Francis Kelly, Historic Buildings Inspector at English Heritage's Bristol office. The primary purpose of this programme was to inform listed building consent as part of repairs and alterations to the structure. It was hoped that this analysis would establish the extent of the surviving primary phase elements and hence indicate with greater certainty the date of the initial construction of this house. This would place it, and by inference its partner, more securely in the typological sequence of post-medieval development of this part of Exeter.

Thus, from the timbers available a total of 33 oak samples was obtained by coring. Each sample was given the code EXT-H (for Exeter, site 'H') and numbered 01–33. Fifteen of these samples, EXT-H01–15, were taken from the roof of number 46. A further 14 samples, EXT-H16–23, and EXT-H24–29, respectively, were obtained from the small areas of second and first floor-framing exposed immediately behind the west, or street frontage, gable (Fig 6a/b). A final four samples, EXT-H30–33, were obtained from a small selection of other timbers.

Given that additional timbers were in theory available for sampling, particular to the front rooms of both the first and second floors, the samples obtained in this programme of analysis might appear a little restricted in both location and element type. Sampling was constrained, however, by the small areas of floor-boarding that could be lifted and by the thinness of the wall studs (despite being broad), and the fact that they formed the immediate party wall, without any intervening void, to the properties to either side. A very small number of other timbers to the rear first and second floor might also have been available, but, being set deeply in ceilings, and in food preparation, storage, and sales areas, it was deemed inappropriate to core these timbers.

The location of samples was noted at the time of coring and, where possible, the exception being EXT-H32 from the gable header beam, marked on the drawings made by Richard Parker of Exeter Archaeology and provided by English Heritage, or on photographs taken at the time of sampling. These are reproduced here as Figures 7a–d. Further details relating to the samples can be found in Table 1. In this Table the trusses have been located and numbered following the scheme on the drawings provided, ie, from site east to site west, with individual timbers being further located on a north–south basis as appropriate.

ANALYSIS

Each of the 33 samples obtained was prepared by sanding and polishing. It was seen at this time that one sample, EXT-H19, had less than the minimum of 54 rings necessary for reliable dating, and this sample was rejected from this programme of analysis. The annual growth-ring widths of the remaining 32 samples were, however, measured, the data of these measurements being given at the end of this report.

The data of the 32 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), and at a minimum value of t=4.9 two groups of cross-matching samples could be formed. The first group comprises 25 samples, cross-matching with each other as shown, sorted by sample location, in the bar diagram, Figure 8. These were combined at the indicated off-sets to form site chronology EXTHSQ01, this having an overall length of 183 rings. Site chronology EXTHSQ01 was then compared to an extensive series of reference chronologies for oak matching repeatedly and consistently with a number of these when the date of its first ring is AD 1309 and the date of its last measured ring is AD 1491. The evidence for this dating is given in Table 2.

The second group comprises two samples, cross-matching with each other as shown in the bar diagram, Figure 9. These two samples were combined at the indicated off-sets to form site chronology EXTHSQ02, this having an overall length of 84 rings. Site chronology EXTHSQ02 was also compared to an extensive series of reference chronologies for oak, but there was no cross-matching and the samples must remain undated for the moment.

The two site chronologies, EXTHSQ01 and EXTHSQ02 were compared to each other, and with the five remaining measured but ungrouped samples. There was however no further satisfactory intra-site cross-matching, although some tenuous cross-matching was noted which would clearly require additional statistical support. The five ungrouped samples were then compared individually with the full series of reference chronologies but, again, there was no satisfactory cross-matching and all such individuals must, therefore, remain undated.

INTERPRETATION

None of the dated samples in site chronology EXTHSQ01 retains complete sapwood, and it is thus not possible to indicate a precise felling date for any of the timbers represented. Fourteen of the 25 samples, however, do retain some sapwood, or at least the heartwood/sapwood boundary. It may be seen from Table 1 and the bar diagram, Figure 8, that this boundary varies by 18 years, from relative position 158, AD 1466, on sample EXT-H16, to relative position 176, AD 1484, on sample EXT-H26. Such consistency in the position of the heartwood/sapwood boundary is indicative of timbers representing a single programme of felling, with all the trees being cut at the same, or very similar, time.

The average date of the heartwood/sapwood boundary on these 14 dated samples is AD 1476. Using a 95% confidence interval of 15–40 years for the sapwood rings the trees might have had, and allowing that the latest dated ring on any sample, EXT-H02, is AD 1491, would give the timbers represented an estimated felling date in the range AD 1492–1516.

CONCLUSION

The evidence of tree-ring dating suggests, therefore, that all the timbers dated in this programme of analysis were cut as part of a single episode of felling which took place between AD 1492 and AD 1516. Such a date would support the view that numbers 46 and 47 represent late-medieval developments of this part of Exeter, and date to the late fifteenth or early sixteenth century, slightly earlier than had been inferred previously.

It may be noted that the level of cross-matching between two samples, EXT-H02 and H07, at a value of t=13.7, is sufficiently high to suggest the likelihood that the two timbers represented, the south principals of trusses 2 and 4 respectively, are derived from the same tree, an interpretation supported by the probability that both beams appear to be half trees. A similar interpretation might also be made in respect of the timbers represented by samples EXT-H24 and H33, a first-floor joist and a main post respectively which cross-match with each other with a value of t=12.4. In this case, however, while the joist might be a halved, or indeed, a quartered tree, it seems most likely that the post is a whole tree trimmed down. The remaining intra-site cross-matching is such that it suggests that these timbers were likely to have been derived from a single, though potentially extensive, woodland source.

Where this source woodland was cannot be identified precisely by dendrochronology (eg Bridge 2000). However, it would appear that the timbers analysed are likely to have been derived from nearby sources. As may be seen from Table 2, which lists a short selection of the reference chronologies used to date site sequence EXTHSQ01, some of the highest t-values are with reference chronologies from other sites in Exeter itself or elsewhere in Devon.

A second sequence, comprising two samples, and five further individual samples, or just fewer than 16% of those obtained and measured, remain ungrouped and undated. None of these samples show any obvious problems with their annual growth rings, such as distortion, compression, or erratic growth, which would make cross-matching and dating difficult, and only two samples, EXT-H06 and H10, have numbers of rings which, although above the minimum of 54, are towards the lower end of the required figure. All other single samples have sufficient rings and show no peculiarities.

BIBLIOGRAPHY

Boswijk, G, and Tyers, I, 1997 *Tree-ring analysis of Booth Hall and 16–18 High Town, Hereford*, Anc Mon Lab Rep, 101/1997

Bridge, M, 2000 Can dendrochronology be used to indicate the source of oak within Britain? *Vernacular Architect*, 31, 67–72

Exeter Urban Archaeological Database monument record 11183.00

Groves, C, and Hillam, J, 1993 Tree-ring analysis of oak timbers from the medieval barn, King's Pyon, near Leominster, Hereford and Worcester, 1992 - Interim report, Anc Mon Lab Rep, 24/1993

Groves, C, 2005 *Dendrochronological Research in Devon: Phase I*, Centre for Archaeol Rep, 56/2005

Miles, D, 2003 Dating buildings and dendrochronology in Hampshire, in *Hampshire Houses 1250–1700: Their Dating and Development* (E Roberts), 220–6

Nayling, N, 2001 *Tree-ring analysis of timbers from 21 The Mint, Exeter, Devon*, Centre for Archaeol Rep, 55/2001

Tyers, I, and Groves, C, 1999 Tree-ring dates from Sheffield University: List 104, *Vernacular Architect*, 30, 113–28

Tyers, I, and Wilson, R, 2000 *Tree-ring analysis of oak timbers from 66 and 68 Westgate Street, Gloucester*, Anc Mon Lab Rep, 19/2000

Tyers, I, 2004 *Tree-ring analysis of oak timbers from Roscarrock, near Port Isaac, Cornwall*, Centre for Archaeol Rep, 30/2004

TABLES

Table 1: Details of tree-ring samples from 46 High Street (Thornton's), 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)
Roof						
EXT-H01	Upper south purlin, truss 2–3	128	h/s	1347	1474	1474
EXT-H02	South principal rafter, truss 2	157	23	1335	1468	1491
EXT-H03	Tiebeam, truss 2	125	h/s	1352	1476	1476
EXT-H04	North principal rafter, truss 3	126	15	1362	1472	1487
EXT-H05	Tiebeam, truss 3	89	no h/s	1355	------	1443
EXT-H06	North principal rafter, truss 4	57	15	------	------	------
EXT-H07	South principal rafter, truss 4	106	no h/s	1331	------	1436
EXT-H08	Tiebeam, truss 4	123	h/s	1360	1482	1482
EXT-H09	North lower purlin, truss 3–4	108	h/s	1372	1479	1479
EXT-H10	North principal rafter, truss 5	58	no h/s	------	------	------
EXT-H11	South principal rafter, truss 5	85	no h/s	1355	------	1439
EXT-H12	North principal rafter, truss 6	117	4	1364	1476	1480
EXT-H13	South principal rafter, truss 6	126	h/s	1353	1478	1478
EXT-H14	North principal rafter, truss 7	119	no h/s	------	------	------
EXT-H15	North upper purlin, truss 6–7	73	2	1409	1479	1481

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Second floor frame						
EXT-H16	Joist 2 (from north)	101	h/s	1366	1466	1466
EXT-H17	Joist 3	58	no h/s	------	------	------
EXT-H18	Joist 4	86	no h/s	1379	------	1464
EXT-H19	Joist 5	nm	---	------	------	------
EXT-H20	Joist 6	88	4	1392	1475	1479
EXT-H21	Joist 7	84	no h/s	------	------	------
EXT-H22	Joist 8	84	no h/s	------	------	------
EXT-H23	Joist 9	81	no h/s	1384	------	1464
First floor frame						
EXT-H24	Joist 3	86	no h/s	1369	------	1454
EXT-H25	Joist 4	95	h/s	1384	1478	1478
EXT-H26	Joist 5	91	h/s	1394	1484	1484
EXT-H27	Joist 6	54	no h/s	1396	------	1449
EXT-H28	Joist 7	69	no h/s	1378	------	1446
EXT-H29	Joist 8	77	h/s	1407	1483	1483
Other timbers						
EXT-H30	South wall, stud post 1, first floor	126	no h/s	1309	------	1432
EXT-H31	South wall, stud post 2, first floor	63	no h/s	------	------	------
EXT-H32	West gable header beam, second floor	108	no h/s	1323	------	1430
EXT-H33	North-west corner post, first floor	99	no h/s	1370	------	1468

h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured

Table 2: Results of the cross-matching of site sequence EXTHSQ01 and relevant reference chronologies when the first-ring date is AD 1309 and the last-ring date is AD 1491

Reference chronology	Span of chronology	*t*-value	Reference
West Challacombe, Devon	AD 1319–1452	8.6	(Tyers and Groves 1999)
Kings Pyon barn, Herefordshire	AD 1346–1480	8.6	(Groves and Hillam 1993)
The Mint, Exeter	AD 1350–1429	8.6	(Nayling 2001)
Booth Hall/16–18 High Town, Hereford	AD 1302–1489	8.5	(Boswijk and Tyers 1997)
Hampshire Chronology	AD 443–1972	8.2	(Miles 2003)
Roscarrock, nr Port Isaac, Cornwall	AD 1373–1500	7.3	(Tyers 2004)
66/68 Westgate Street, Gloucester	AD 1209–1518	6.9	(Tyers and Wilson 2000)
Prowse barn, Sandford, Devon	AD 1380–1473	6.8	(Groves 2005)

FIGURES

Figure 1: Map to show the location of Exeter

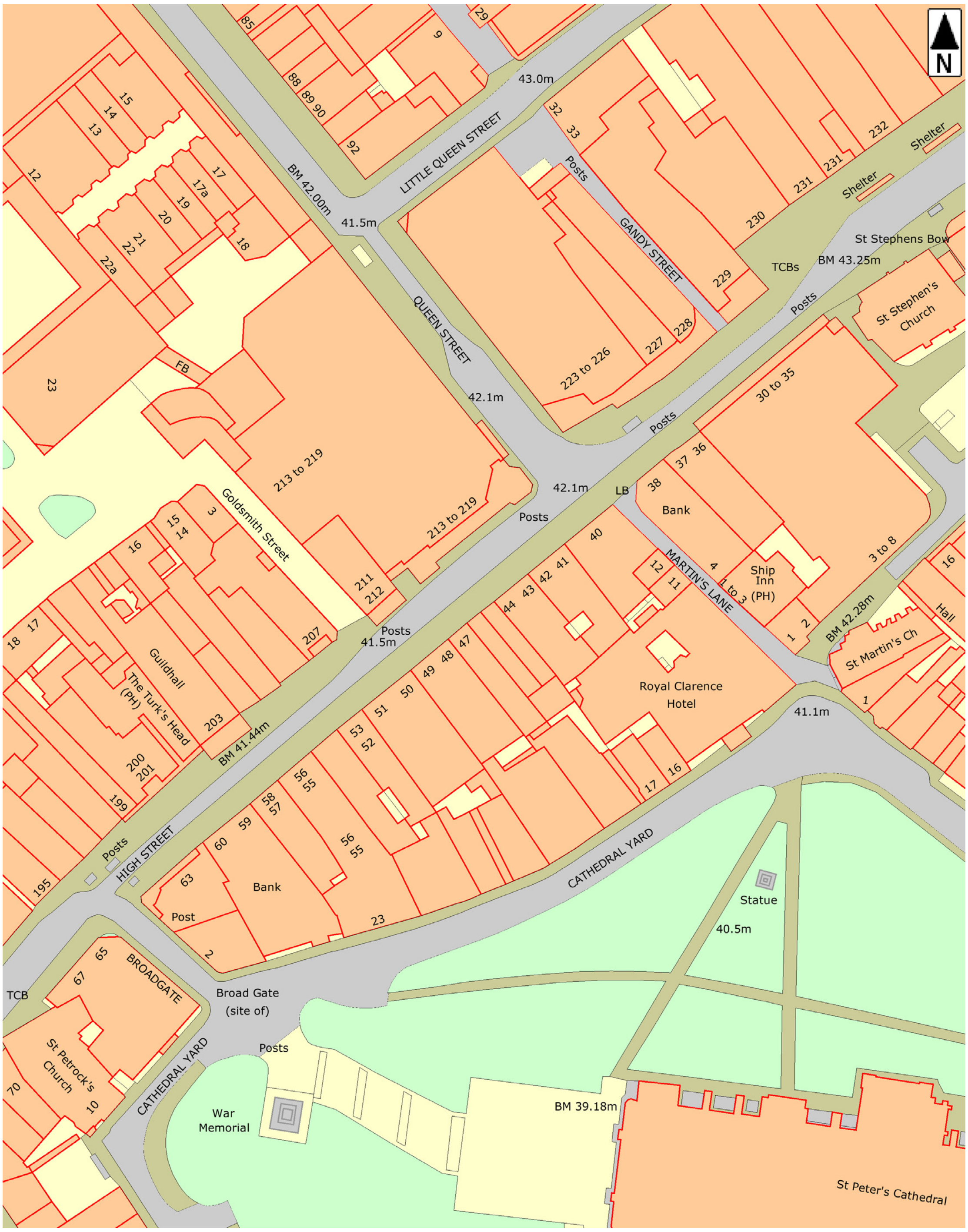


Figure 2: Map to show the location of 46 High Street, Exeter (

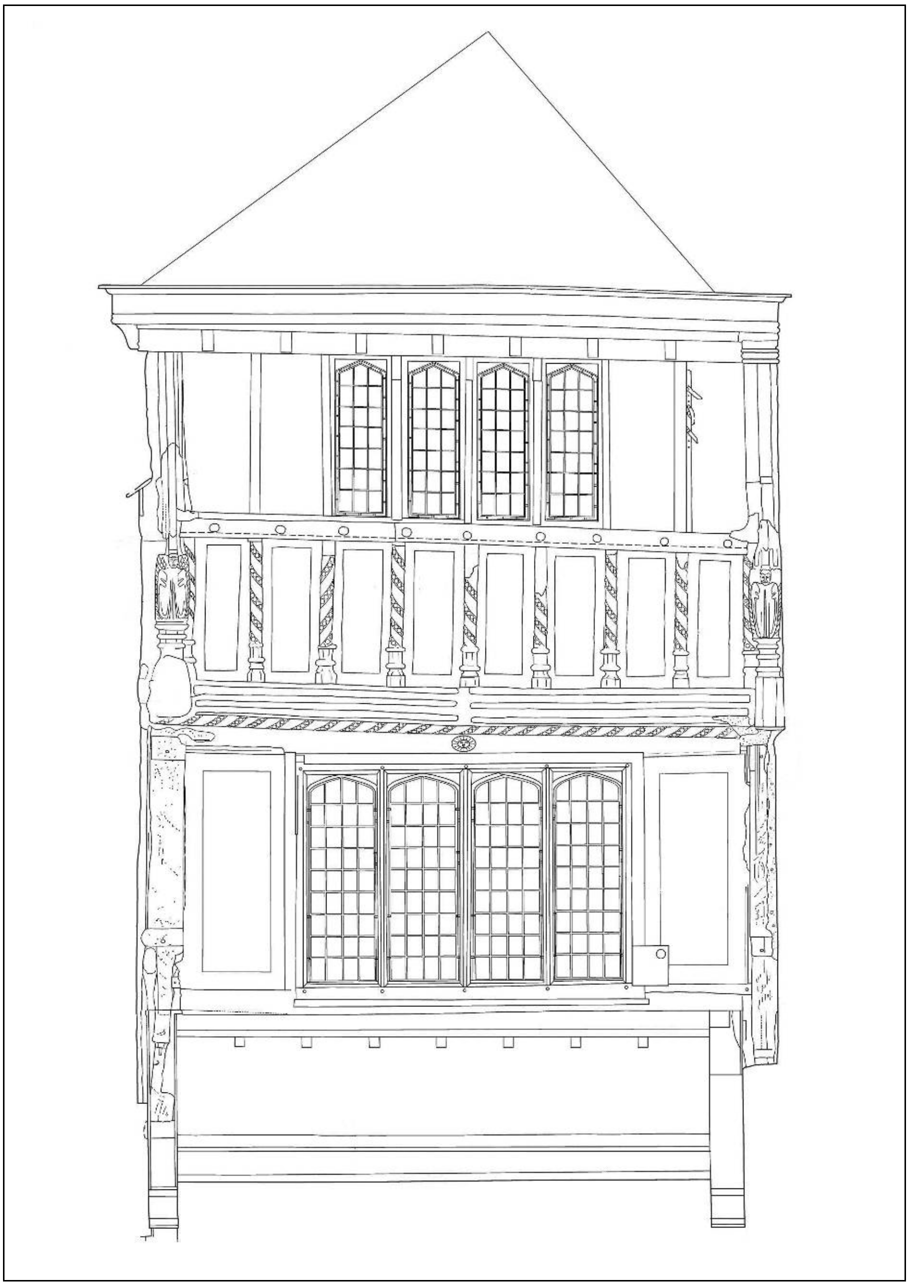


Figure 3: Elevation of the upper floors of 46 High Street (after Richard Parker, Exeter Archaeology)

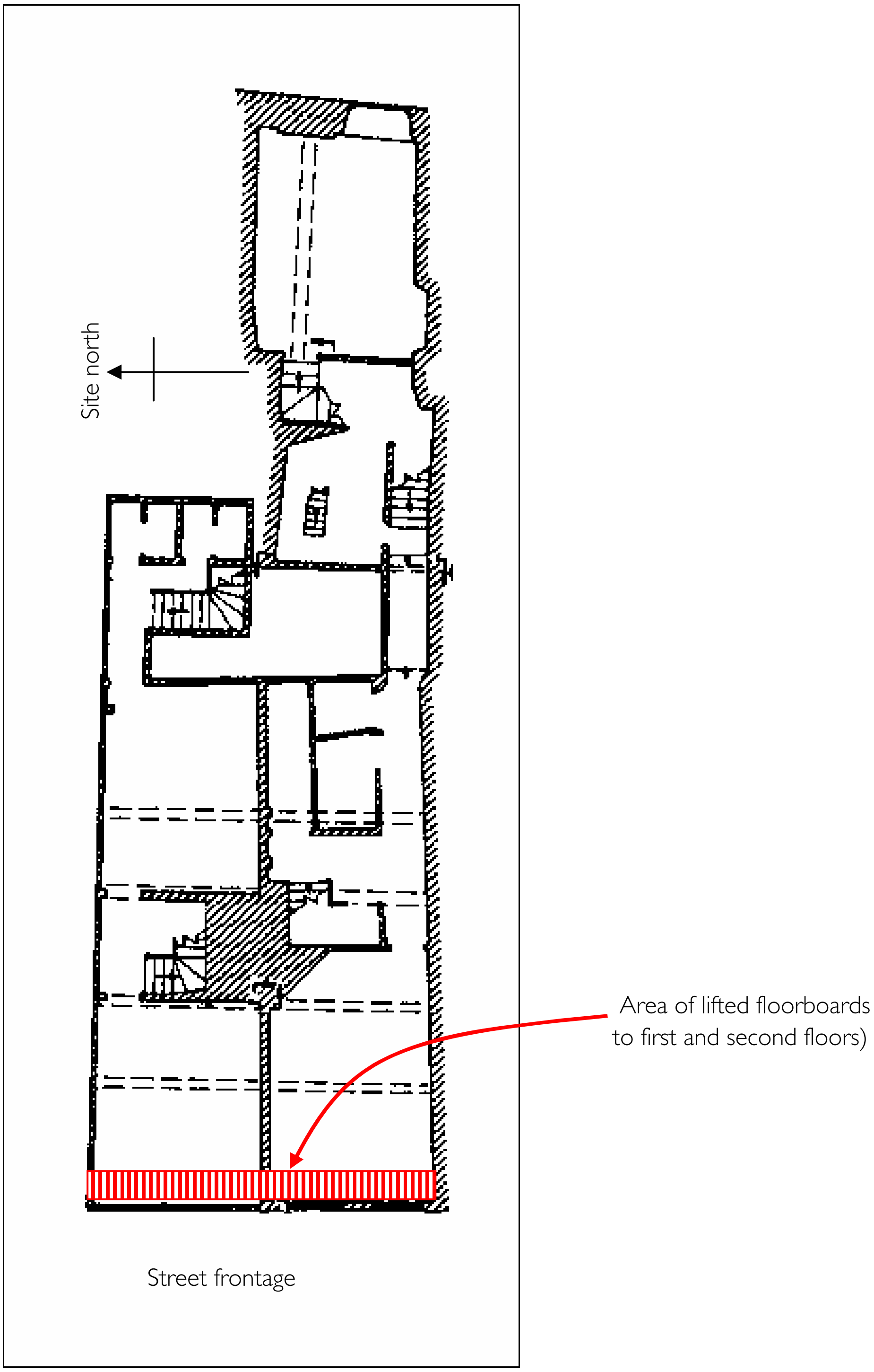


Figure 4: Plan of 46 High Street at first-floor level (after Richard Parker, Exeter Archaeology)

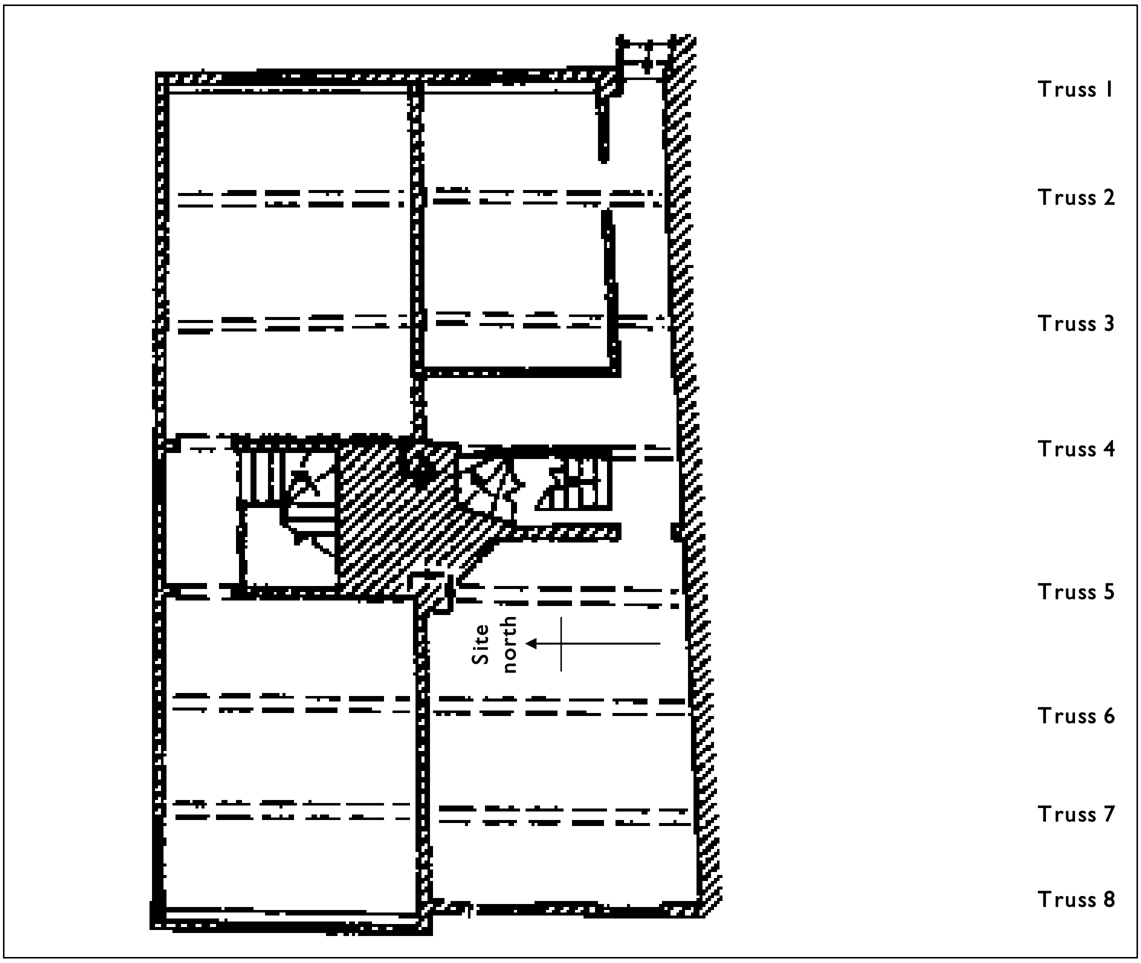


Figure 5: Plan to show location of the trusses (after Richard Parker, Exeter Archaeology)

Figure 6a/b: View of the exposed joists to second (top) and first-floor frames (bottom)(viewed looking east to west)

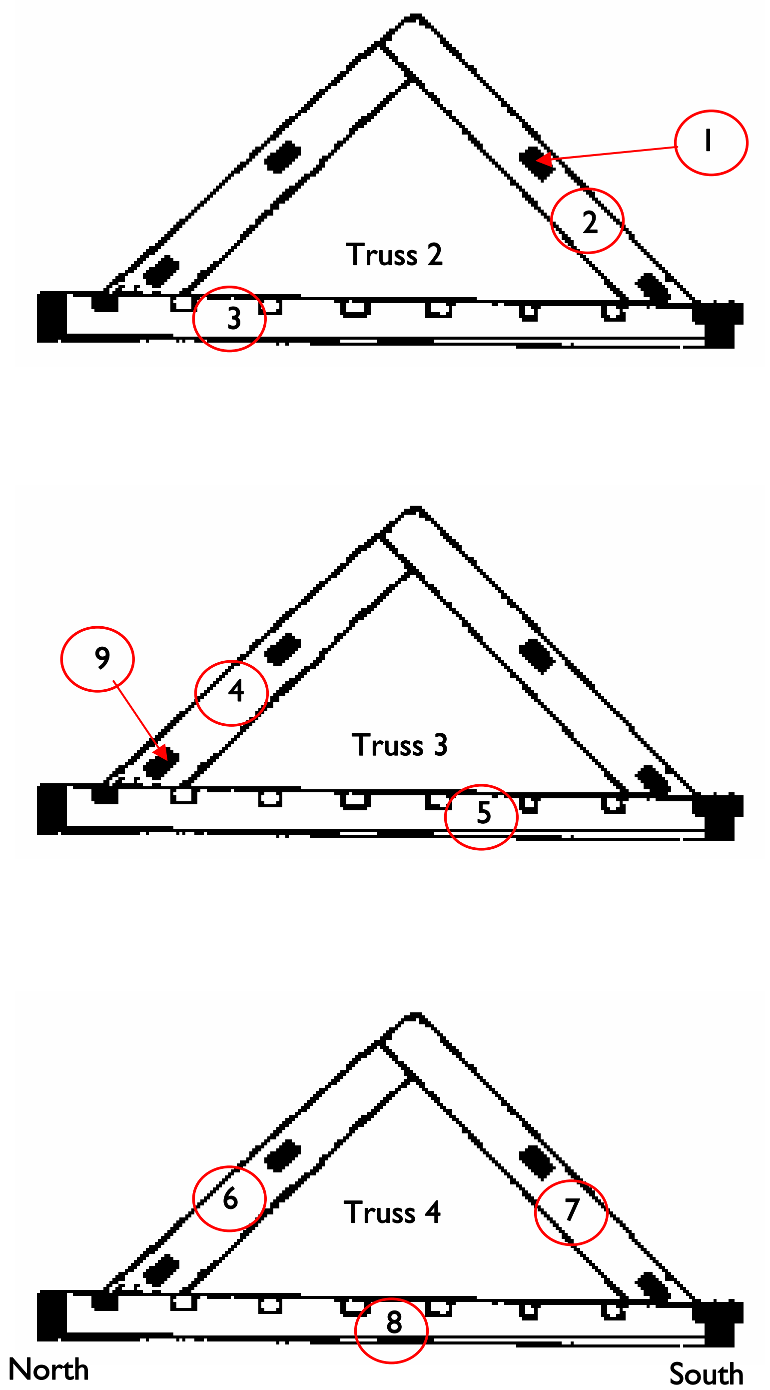


Figure 7a: Trusses 2–4 to show sampled timbers (after Richard Parker, Exeter Archaeology)

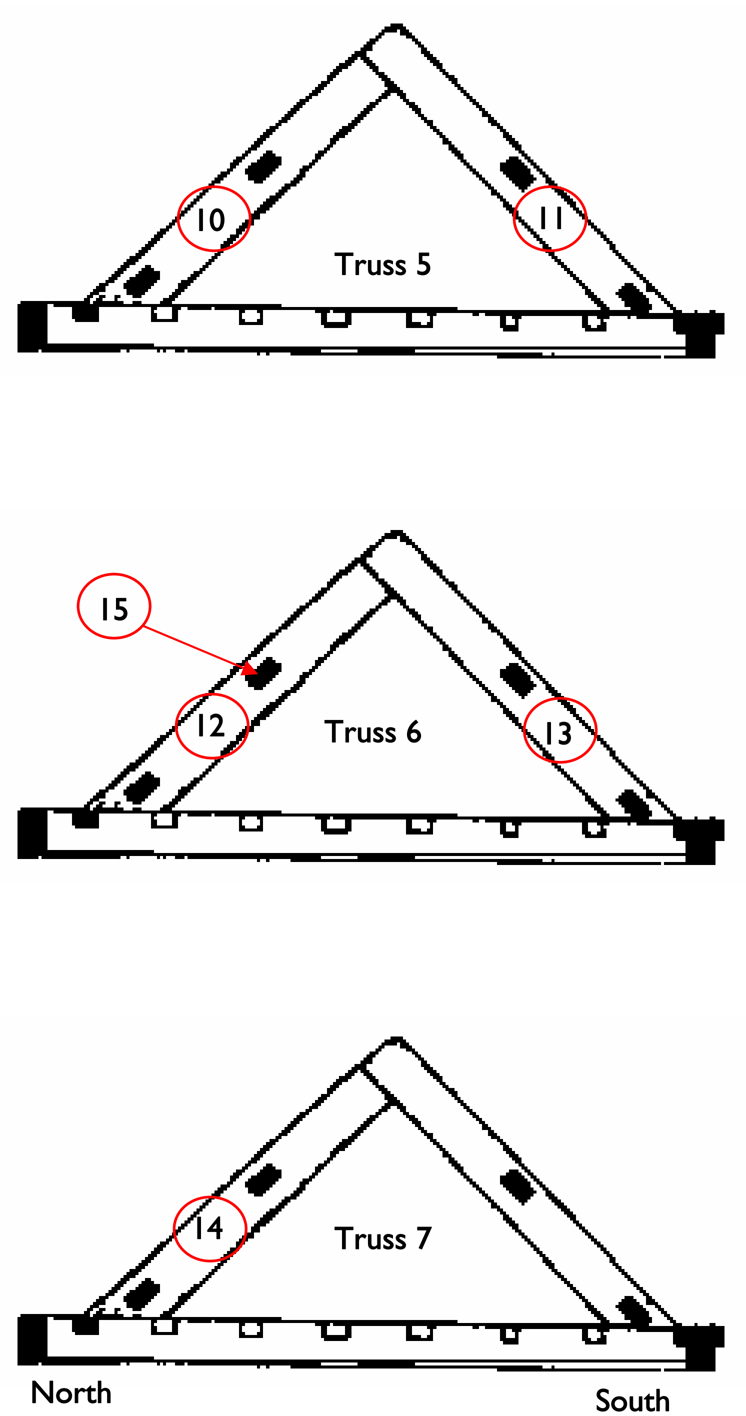


Figure 7b: Trusses 5–7 to show sampled timbers (after Richard Parker, Exeter Archaeology)

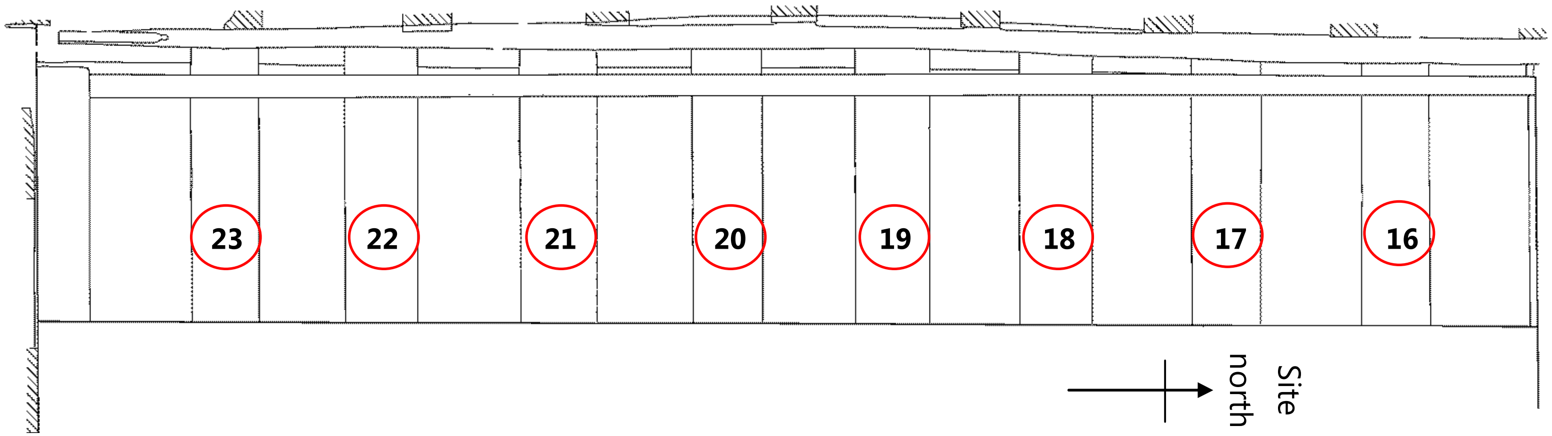


Figure 7c: Second-floor frame to show sampled timbers (after Richard Parker, Exeter Archaeology)

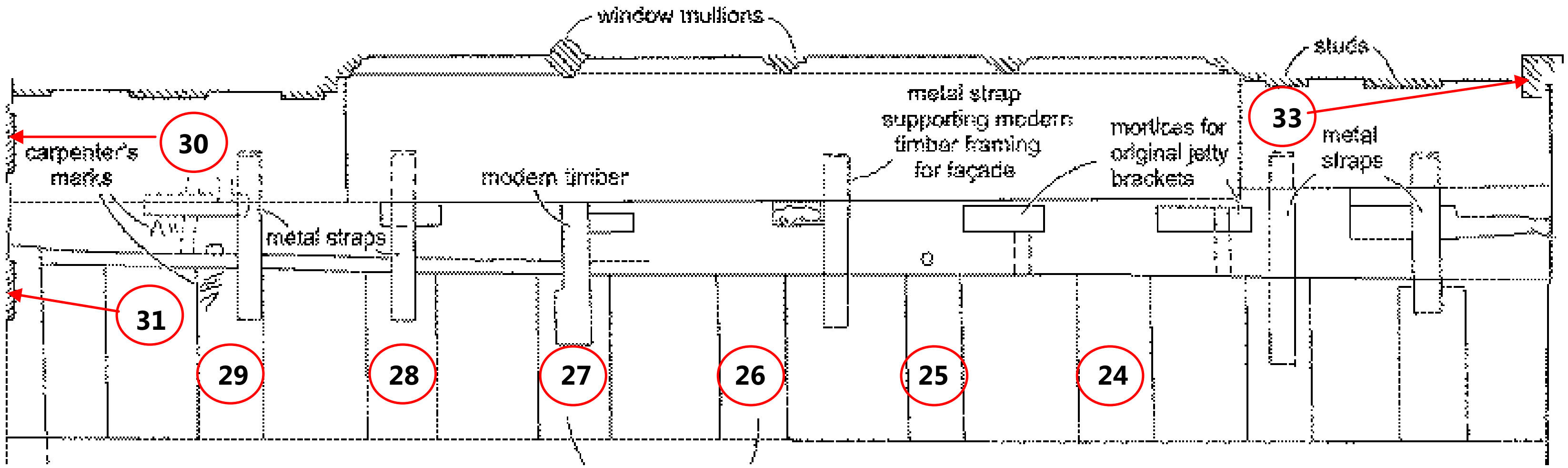
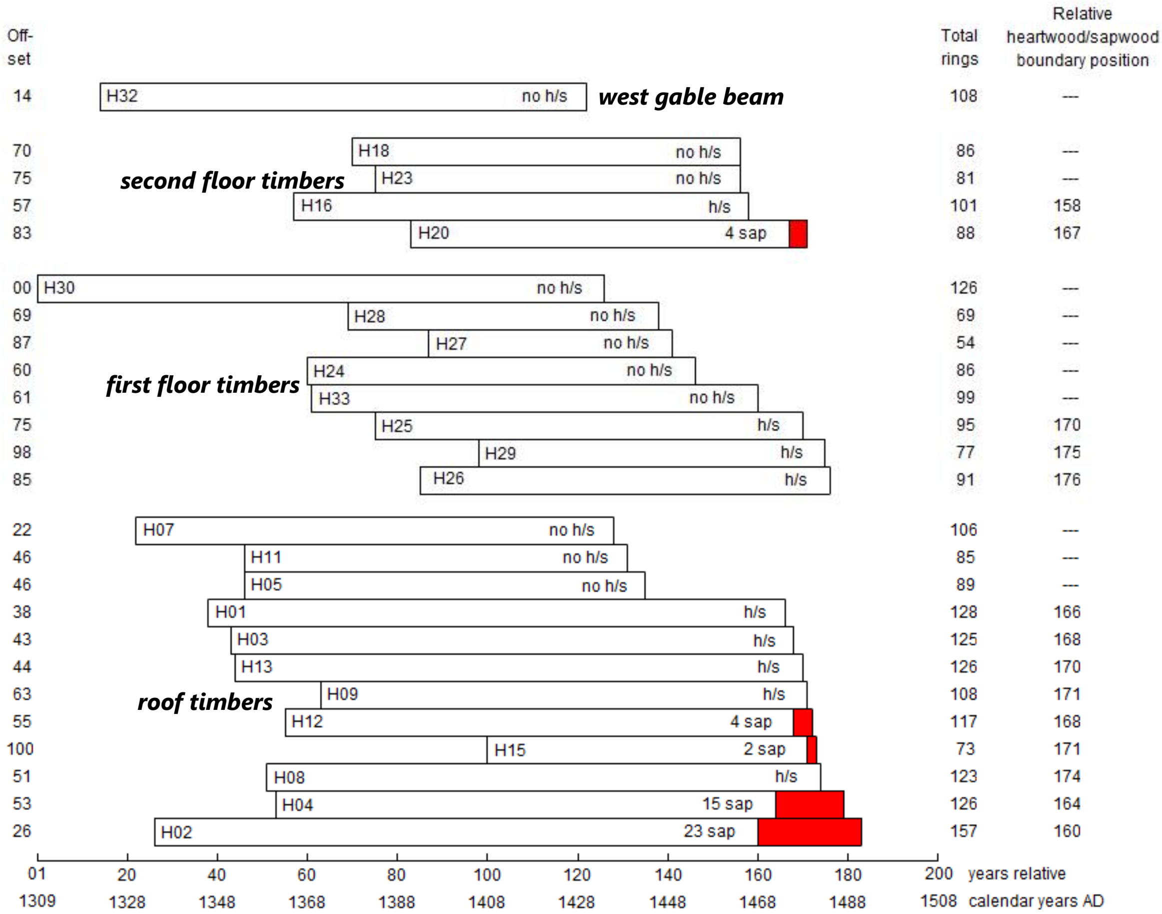
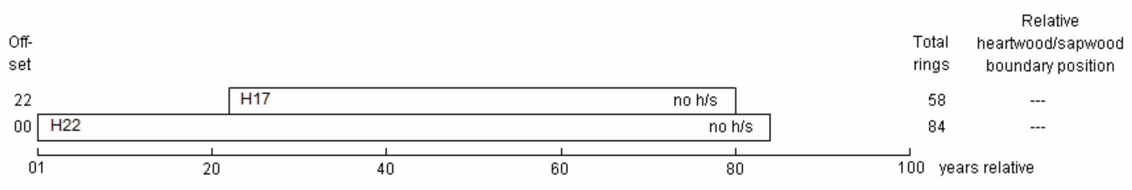


Figure 7d: First-floor frame to show sampled timbers (after Richard Parker, Exeter Archaeology)



White bars = heartwood rings, shaded area = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 8: Bar diagram of the samples in site chronology EXTHSQ01 sorted by sample location



White bars = heartwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary; only the sapwood rings are missing

Figure 9: Bar diagram of the samples in site chronology EXTHSQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

EXT-H01A 128
168 158 269 177 255 177 172 174 174 159 136 78 113 112 202 126 255 198 165 185
144 143 126 105 106 114 52 103 153 158 120 127 141 122 133 111 195 180 174 228
163 162 112 98 105 103 94 77 57 92 89 111 116 99 115 112 153 152 145 101
138 168 123 94 94 114 146 136 173 134 134 159 118 77 120 127 190 235 173 192
162 146 142 136 131 133 138 101 124 94 113 125 84 84 86 109 91 135 90 82
94 101 98 84 104 89 103 116 101 116 104 116 100 113 72 87 93 93 88 78
123 115 80 106 99 102 113 137
EXT-H01B 128
162 156 268 165 253 183 189 165 176 161 135 81 108 110 200 137 254 211 156 178
148 136 129 110 100 111 56 95 166 158 119 132 127 126 132 117 184 185 175 220
173 157 118 91 103 111 91 74 56 95 98 98 127 106 107 101 145 144 142 100
134 163 128 95 94 112 149 130 153 129 130 141 116 84 114 131 195 260 152 172
149 139 139 151 127 132 130 109 120 96 129 114 78 79 80 116 107 127 89 72
79 107 105 90 97 85 103 123 101 112 102 115 93 105 78 76 109 87 89 78
120 116 96 111 94 77 111 145
EXT-H02A 157
187 177 115 158 142 120 89 101 78 84 90 75 106 107 187 257 440 190 175 222
270 148 212 210 194 134 185 193 196 232 158 211 180 161 119 127 128 159 87 70
121 105 91 92 164 109 88 109 124 83 91 133 82 90 75 69 71 73 95 99
134 166 170 127 144 114 81 88 130 148 111 148 190 219 127 105 65 73 89 131
118 71 115 106 73 98 126 78 155 150 131 98 89 92 70 95 146 263 200 188
208 107 141 177 71 81 81 76 98 74 75 127 145 137 152 168 114 88 132 94
115 207 152 144 79 118 115 96 107 109 135 113 88 108 130 163 144 99 112 93
161 188 93 111 87 55 131 126 153 269 156 111 118 116 267 161 83
EXT-H02B 157
164 174 110 173 133 125 101 104 83 70 92 102 120 136 207 279 434 181 170 224
260 160 199 223 197 133 182 208 197 222 162 206 188 159 130 131 122 155 78 77
123 108 85 99 167 99 88 113 114 91 98 129 93 80 76 70 72 84 95 92
133 171 161 118 152 111 69 86 126 156 116 141 181 228 128 100 68 83 88 123
117 67 122 110 70 93 138 69 157 149 138 99 76 96 65 104 139 269 210 195
194 110 143 168 77 80 74 73 80 79 67 120 147 149 145 158 125 84 129 98
119 199 162 135 66 118 122 102 96 115 129 110 74 113 122 157 142 102 109 94
157 179 94 116 81 58 136 127 143 288 161 119 111 112 302 136 91
EXT-H03A 125
336 503 488 247 338 284 468 415 260 330 498 444 347 296 373 371 309 421 181 283
196 156 202 194 196 151 110 145 126 108 136 138 121 124 157 125 114 73 91 98
113 109 72 110 136 108 120 132 109 131 112 89 100 81 157 111 121 144 58 100
128 115 108 85 93 98 99 68 132 111 84 147 113 100 70 75 100 87 105 92
150 139 149 201 104 108 55 74 64 110 76 71 64 88 73 85 142 143 153 180
109 110 157 137 168 142 132 85 84 65 98 108 78 108 104 115 123 113 100 122
89 85 129 118 134
EXT-H03B 125
398 496 487 209 326 279 466 417 249 339 495 448 348 278 368 360 338 386 198 260
201 159 204 164 210 156 103 144 111 122 142 147 134 123 163 127 116 67 88 98
110 105 71 102 131 121 108 137 113 117 120 90 91 97 141 120 114 137 64 99
116 120 127 90 86 98 87 64 135 117 73 149 112 97 80 95 105 73 105 103
149 127 155 197 103 100 72 69 67 108 86 70 70 80 74 84 139 133 163 172

112 109 145 147 163 138 138 78 80 76 97 101 86 91 116 126 114 114 113 90
89 87 134 124 141
EXT-H04A 126
387 426 388 271 383 345 338 325 327 213 181 173 154 206 262 236 248 287 324 214
208 150 154 115 137 141 151 134 108 85 77 85 68 97 114 121 119 142 170 174
113 124 160 187 188 183 188 175 92 70 95 88 144 131 124 90 117 91 104 148
102 169 155 124 129 121 141 118 109 89 143 112 133 146 131 150 136 81 103 117
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98 116 114 100 72 83 97 95 121 100 104 95 104 104 135 108 80 97 102 115
171 172 208 179 223 265
EXT-H04B 126
386 453 390 273 376 347 332 318 302 210 178 176 163 174 244 250 231 278 312 199
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109 146 155 129 131 115 144 123 108 103 128 111 124 145 125 155 132 78 104 126
93 109 135 112 93 115 112 108 101 104 112 103 112 101 106 90 132 103 138 96
104 119 124 87 78 81 95 88 116 105 122 89 95 101 136 107 82 89 92 105
185 186 204 197 222 259
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174 96 150 88 104 59 124 105 141
EXT-H06A 57
195 133 132 164 254 350 246 308 218 198 191 216 251 428 320 228 147 427 189 221
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328 317 611 365 234 478 413 464 253 119 236 239 258 542 522 343 392
EXT-H06B 57
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EXT-H08A 123

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229 193 207 219 207 210 357 305 315 258 173 139 163 124 122 133 163 155 174 206
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170 161 148 175 174 162 117 119 156 140 141 133 181 148 129 156 135 130 93 81
89 123 136 102 102 91 93 125 139 118 112 109 117 84 76 115 107 125 132 104
147 156 109 137 124 117 124 171 130 147 130 126 119 111 122 139 104 90 73 87
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168 227 204 191 255 223 199 303 293 376 297 234 239 223 285 287 254 254 231 280
226 198 209 224 208 227 343 268 325 242 158 146 156 125 124 137 157 153 183 194
185 277 132 173 209 168 229 195 199 220 203 167 187 189 201 213 144 170 136 100
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93 107 136 104 100 95 92 121 133 120 120 110 118 86 80 107 114 135 127 109
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166 178 168 151 147 127 127 174 151 125 158 123 145 162 212 139 157 124 114 106
73 94 83 89 106 85 87 89 115 137 107 110 123 89 103 128 137 142 118 97
97 119 120 131 88 79 91 71 97 122 87 151 175 94 89 98 103 71 74 91
137 77 106 105 88 91 65 58 68 78 68 63 71 65 53 59 61 62 59 67
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81 121 101 87 87 86 110 148
EXT-H09B 108
193 155 160 153 150 115 131 174 172 125 156 135 145 159 201 157 153 129 108 116
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89 122 120 140 79 79 99 77 93 117 82 146 153 116 102 97 101 77 84 86
139 90 117 100 77 105 64 58 62 87 67 67 72 60 53 61 68 64 54 61
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94 105 98 100 79 98 97 151
EXT-H10A 58
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267 198 210 157 228 156 240 293 245 164 260 124 171 138 194 152 146 222 253 270
194 175 130 110 154 184 192 224 208 273 310 158 86 131 154 231 212 123
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136 146 137 118 169 158 118 139 112 127 95 113 171 136 122 109 126 155 103 135
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87 72 77 106 87 81 95 80 98 96 135 147 119 164 153 133 111 126 105 131
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78 72 80 111 91 84 99 90 91 104 149 151 148 174 151 108 138 141 114 112
90 76 86 67 65 58 66 61 61 79 60 90 101 90 111 98 122
EXT-H13A 126
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198 201 254 289 231 286 311 217 165 211 184 186 174 276 187 206 156 71 94 118
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319 361 332 227 280 379 318 279 279 253 257 283 297 262 214 212 173 241 199 77
92 150 197 176 172 153 142 165 153 172 177 164 124 118 74 79 77 79 88 134
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222 254 306 278 92 88 182 234 196 257 163 209 194 126 91 207 206 191 276 206
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EXT-H16B 101
293 255 166 189 183 138 158 99 116 143 103 99 116 226 440 466 290 341 413 347
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EXT-H17A 58
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239 176 176 132 219 148 114 160 210 119 128 153 192 166 153 191 200 172
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EXT-H21A 84
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EXT-H21B 84
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234 457 382 164 132 229
EXT-H25A 95
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EXT-H25B 95
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EXT-H26A 91
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EXT-H27A 54
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220 227 190 96 239 226 151 234 186 171 141 246 202 263
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201 227 236 101 243 213 154 201 187 163 141 244 216 257
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315 331 216 172 211 278 325 359 260 139 104 240 146 390 156 223 445 238 189 175
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EXT-H30A 126
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EXT-H30B 126
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110 130 104 257 203 250 236 277 292 202 249 491 495 540 260 334 320 289 358 377
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EXT-H31B 66
260 315 391 363 346 311 300 318 352 257 270 208 280 271 287 183 134 122 84 95
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243 160 157 115 186 177 208 307 231 329 207 186 253 165 220 223 306 236 299 247
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142 172 252 254 209 270 321 166 129 155 202 270
EXT-H32B 94
238 255 337 275 333 253 351 154 292 203 162 171 235 229 451 176 178 191 130 209
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EXT-H33A 99
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

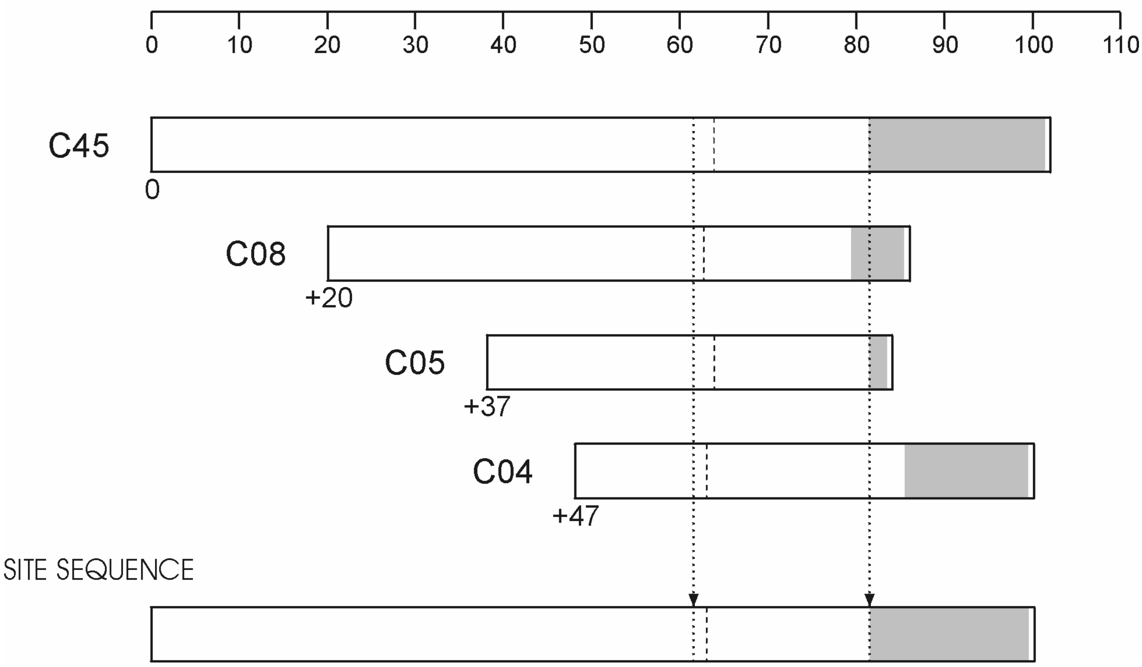


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

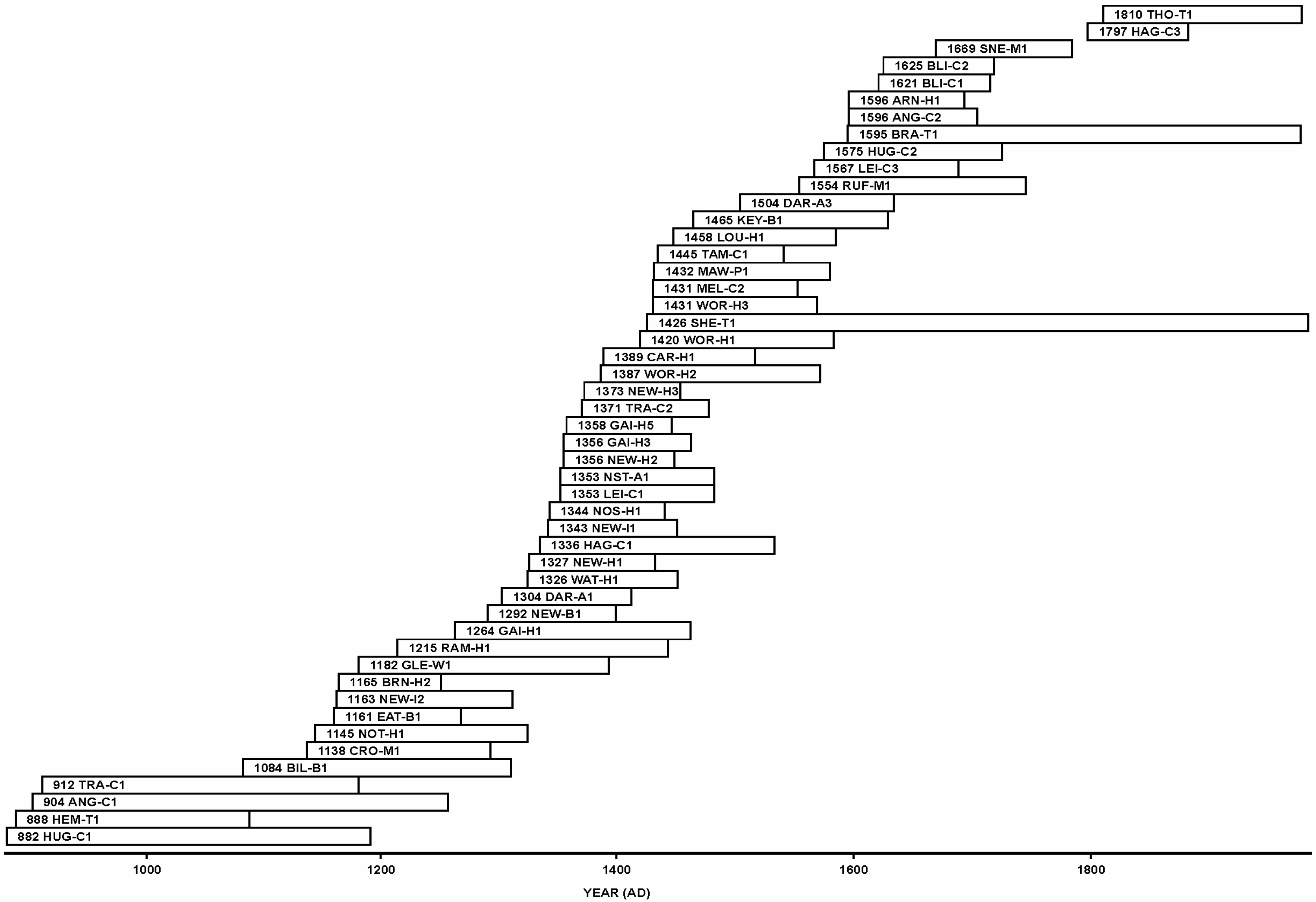
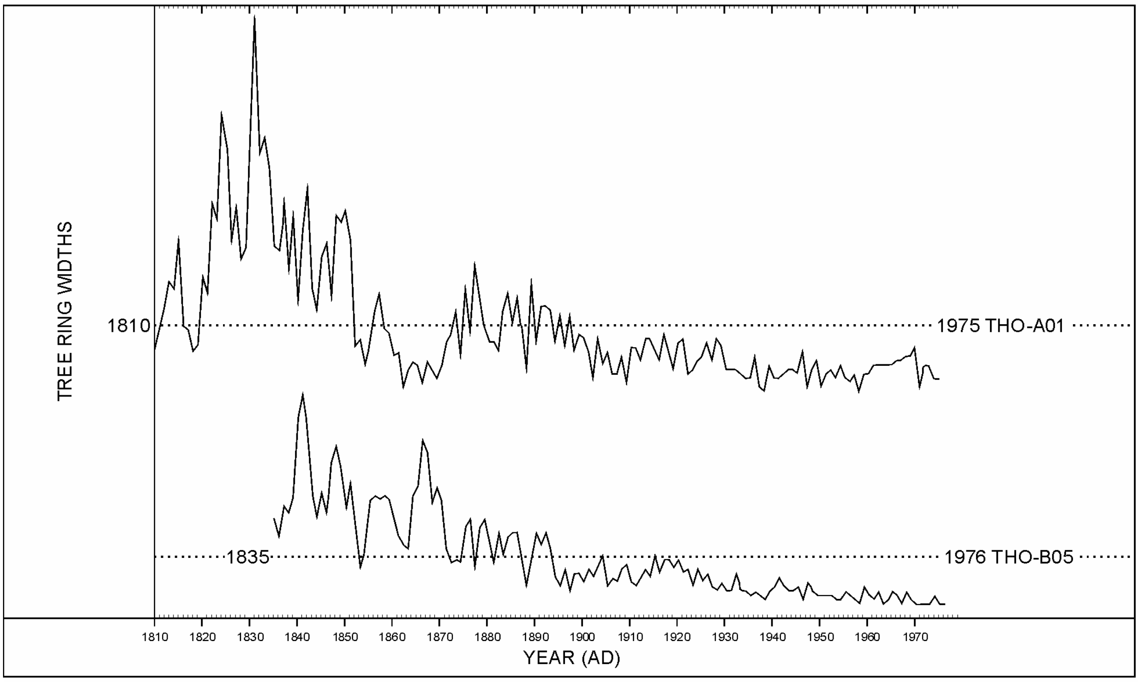


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

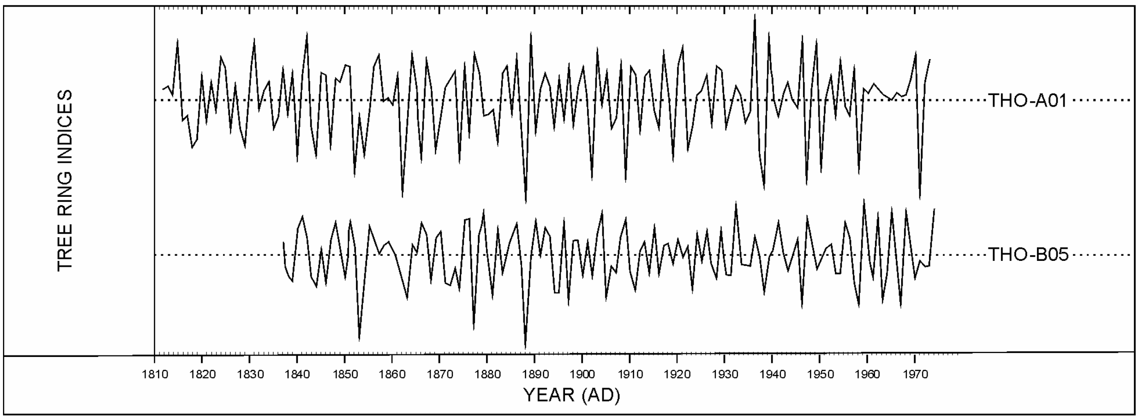


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

Hillam, J, Morgan, R A, and Tyers, I, 1987 Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, 3, 165–85

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

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, 8, 381–90

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