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# 11 SILVER STREET, BRADFORD-ON-AVON, WILTSHIRE
# TREE-RING ANALYSIS OF TIMBERS

## SCIENTIFIC DATING REPORT

Matt Hurford, Martin Bridge and Cathy Tyers

ARCHAEOLOGICAL SCIENCE

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## SUMMARY

Dendrochronological analysis was undertaken on all eight samples taken from timbers associated with the medieval open hall at 11 Silver Street, Bradford-on-Avon. This resulted in the production of two site chronologies, BASSSQ01 and BASSSQ02, of 88 rings and 108 rings respectively, incorporating a total of seven samples. Unfortunately neither of these site chronologies nor the single ungrouped sample could be successfully dated. Hence no independent dating evidence was provided for the initial construction of this building.

## CONTRIBUTORS

Matt Hurford, Dr Martin Bridge, and Cathy Tyers

## ACKNOWLEDGEMENTS

The laboratories would like to thank Mrs R Jones for giving permission to undertake the work. Thanks are also due to the Wiltshire Buildings Record, most notably Avis Lloyd and Clive Carter, for arranging initial access, for supplying additional background information on the building, and for providing the drawings. The Wiltshire Buildings Record project work was supported by the English Heritage Historic Environment Enabling Programme. The dendrochronological work was funded by English Heritage and coordinated by Peter Marshall from the English Heritage Scientific Dating Team.

## ARCHIVE LOCATION

Wiltshire Archaeological Service
The Wiltshire and Swindon History Centre
Cocklebury Road
Chippenham SN15 3QN

## DATE OF INVESTIGATION

2009–10

## CONTACT DETAILS

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# CONTENTS

## INTRODUCTION

In 2009 the Wiltshire Building Records successfully obtained support through the English Heritage Historic Environment Enabling Programme for their project 'Wiltshire cruck buildings and other archaic roof types'. The detailed aims and objectives of the project are set out in the Project Design (Lloyd 2009). The overall aim is to establish a typological chronology of archaic roof types and hence elucidate the development of carpentry techniques in the county. This will then facilitate detailed comparison with other counties allowing Wiltshire to be placed in the regional context. Investigation of these late-medieval buildings (*c* AD 1200 – *c* AD 1550) will combine building survey, historical research, and dendrochronological analysis.

A series of buildings identified by the Wiltshire Buildings Record (WBR) as having the potential to contribute to the aims and objectives of the project was assessed for dendrochronological suitability during 2009. In order to maximise the potential, these detailed dendrochronological assessments and the WBR's assessments of the significance of the buildings within the project, informed the selection of the buildings subsequently subjected to detailed study.

A single final report produced by the Wiltshire Buildings Record (forthcoming a) will summarise the overall results from the project. However, each building included in the project will have an associated individual report produced by the WBR (forthcoming b), whilst the primary archive of the dendrochronological analysis is the English Heritage Research Department Report Series.

A brief introduction to dendrochronology can be found in the Appendix. Further details can be found in the guidelines published by English Heritage (1998), which are also available on the English Heritage website (http://www.english-heritage.org.uk/publications/dendrochronology-guidelines/).

### Silver Street

11 Silver Street, a grade II listed building, is located in the heart of Bradford-on-Avon (ST 8272 6104, Figs 1–2). It is aligned on a north-west to south-east axis but for ease of reference within this report the building has been described so that the elevation that fronts Silver Street is described as the south elevation.

The focus of this investigation is on the surviving elements of the open hall, which lie directly to the rear of the current shop frontage facing Silver Street (Fig 3). Details of the medieval remains are given below based on information provided in the Wiltshire Buildings Record report (forthcoming b).

The former open hall is believed to date to the mid-fourteenth to mid-fifteenth century, possibly around the beginning of the fifteenth century, on stylistic evidence. Three trusses and bays survive at roof level (Figs 3–5). The original elements are all heavily smoke-blackened. The presence of carpenters' marks, in the Roman form of II and III on trusses A and B respectively, suggests that the north end of bay 1 was marked by another, now-absent truss. There is a single row of clasped purlins, below which are curved windbraces. The diagonally set ridge piece is clasped below the apex and rests on a block on the two central trusses, trusses A and B. Trusses A and B are similar and comprise a cambered tiebeam with curved braces, a pair of principal rafters, and an arch-braced cambered collar. Truss C also comprises a tiebeam, a pair of principal rafters, and a collar, but neither the tiebeam nor the collar are braced.

## SAMPLING

Sampling and analysis by tree-ring dating of the timbers associated with the medieval open-hall roof at 11 Silver Street were commissioned by English Heritage. It was hoped to provide independent dating evidence for the construction of the original open hall and hence inform the overall objectives of the *Wiltshire Cruck Buildings and other roof types* project. The dendrochronological study also formed part of the English Heritage-funded training programme for the first author.

A total of eight oak (*Quercus* spp.) timbers associated with the open-hall roof were sampled by coring. Each sample was given the code BAS-S (for Bradford-on-Avon, Silver Street) and numbered 01–08. The location of the samples was noted at the time of coring and marked on the drawings provided by the Wiltshire Buildings Record, these being reproduced here as Figures 5–8. Further details relating to the samples can be found in Table 1. In this table the timbers have been located and numbered following the scheme on the drawings provided with the trusses and bays being numbered or labelled from north to south.

The sampling encompassed as wide a range of elements as possible, whilst focussing on those timbers with the greatest dendrochronological potential. Samples were not taken from the braces to the tiebeams, as it was noted that these are later elm (*Ulmus* spp.) replacements. Many of the windbraces were also later elm replacements. The few remaining original windbraces, the ridge piece, and all of the principal rafters were derived from fast-grown oak trees and were considered highly unlikely to provide samples with sufficient numbers of rings for reliable dendrochronological analysis.

## ANALYSIS AND RESULTS

Each of the eight cores obtained was prepared by sanding and polishing. The measurements and analysis was undertaken using a combination of software written by Tyers (2004) and the Litton/Zainodin grouping procedure (see Appendix). Tyers (2004) facilitates cross-matching and dating through a process of qualified statistical comparison and visual comparison. It uses a variant of the Belfast CROS programme (Baillie and Pilcher 1973).

The analysis resulted in two groups of timbers being identified, the samples of each group cross-matching with each other (Figs 9 and 10: Tables 2 and 3). The individual series in each group were then combined at the indicated offsets to form two site chronologies, BASSSQ01 and BASSSQ02. Both site chronologies were compared with an extensive range of reference chronologies for oak. However, no conclusive cross-matching was identified, so both chronologies remain undated.

The two site chronologies were compared to each other and with the remaining ungrouped sample, but there was no further satisfactory cross-matching. This individual sample was then compared with the reference chronologies, but again there was no satisfactory cross-matching, and so it also remains ungrouped and undated.

This analysis can be summarised as follows:

| Site chronology | Number of samples | Number of rings | Date span (where dated) |
|---|---|---|---|
| BASSSQ01 | 5 | 89 | undated |
| BASSSQ02 | 2 | 108 | undated |
| | 1 | | ungrouped and undated |

## INTERPRETATION

The heartwood/sapwood boundary is present on four of the five samples in site sequence BASSSQ01. Its relative date varies by only seven years, suggesting that these timbers are likely to represent a single felling programme. Sample BAS-S02 retains complete sapwood, with the unmeasured outermost sapwood ring immediately below the bark surface only being partially formed. The spring vessels and a very small amount of late (summer) wood are present, suggesting that this timber was derived from a tree felled during the summer of relative year 89. The remaining sample in this site chronology has no trace of sapwood on the core, but sapwood was present on the timber near to the site of the core. It is therefore likely that the outermost measured ring of BAS-S03 is relatively near to the heartwood/sapwood boundary, and thus also likely that this timber is part of the same felling programme as the other four timbers.

The heartwood/sapwood boundary is present on both samples in site sequence BASSSQ02. Its relative date varies by only two years, again suggesting that these timbers are likely to represent a single felling programme.

## DISCUSSION

Unfortunately the tree-ring analysis of the timbers from 11 Silver Street has been unable to provide any absolute dating evidence relating to the construction of the open-hall roof. However, the relative dating obtained between the individual samples does at least provide some information. BASSSQ01 indicates that two timbers from both trusses B and C and a purlin in bay 1 are likely to be coeval. The two timbers forming BASSSQ02, the tiebeams from trusses A and B, are also coeval.

The lack of similarity between the two site sequences and the ungrouped sample does not necessarily indicate that the timbers are of different dates. This lack of cross-matching could simply be due to them being derived from trees that have responded to different, potentially highly localised, growth conditions. This certainly seems a possibility as three of the five sequences in BASSSQ01 show a number of bands of narrow rings followed by a period of recovery (Fig 11), indicating that these trees have suffered a number of growth-retardation events, which will mask the more general climatic signal required for successful dating purposes. The cause of these events could be either natural environmental or anthropogenic influences, but these, combined with the relative shortness of site sequence BASSSQ01, may well explain the inability to obtain conclusive dating evidence. One of the samples in BASSSQ02 also has a clear disturbance in its growth pattern where the growth is suddenly retarded, with the tree never recovering to its former growth rate. Again, this will have reduced the chances of successful dating of this site sequence. The growth pattern of the ungrouped sample, BAS-S06, shows a clear overall decline in its rate of growth but no other apparent disturbances. The dating of individual samples, particularly relatively short series, is markedly more difficult than that of longer well-replicated site chronologies, in which the general climatic signal is enhanced at the expense of the background 'noise' resulting from the local growth conditions of individual trees.

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# TABLES

*Table 1: Details of tree-ring samples from 11 Silver Street, Bradford-on-Avon, Wiltshire*

| Sample number | Sample location | Total rings | Sapwood rings | Average ring width (mm) | Cross-section dimensions (mm) | First measured ring date (AD) | Last heartwood ring date (AD) | Last measured ring date (AD) |
|---|---|---|---|---|---|---|---|---|
| BAS-S01 | Truss C tiebeam | 70 | 22 | 1.34 | 130x190 | ---- | ---- | ---- |
| BAS-S02 | Truss C collar | 89 | 24C | 1.72 | 100x230 | ---- | ---- | ---- |
| BAS-S03 | Truss B collar | 57 | --* | 1.97 | 100x230 | ---- | ---- | ---- |
| BAS-S04 | Truss B west arch brace | 53 | 1 | 1.99 | 90x125 | ---- | ---- | ---- |
| BAS-S05 | Truss B tiebeam | 108 | h/s | 1.27 | 130x240 | ---- | ---- | ---- |
| BAS-S06 | Truss A collar | 61 | h/s | 1.37 | 120x230 | ---- | ---- | ---- |
| BAS-S07 | Truss A tiebeam | 68 | h/s | 0.89 | 130x210 | ---- | ---- | ---- |
| BAS-S08 | Bay 1 west purlin | 46 | 4 | 1.57 | 110x190 | ---- | ---- | ---- |

h/s = heartwood/sapwood boundary is present on the sample
C = complete sapwood is present on the sample; BAS-S02 was felled in the winter of relative year 89/90
* - some sapwood was present elsewhere on this timber but it could not be sampled, hence the outermost measured ring is within a few rings of the h/s boundary

*Table 2: Matrix showing the t-values obtained between the ring sequences in site chronology BASSSQ01; - indicates t-values less than 3.00;*

| | BAS-S02 | BAS-S03 | BAS-S04 | BAS-S08 |
|---|---|---|---|---|
| BAS-S01 | 6.04 | 3.48 | - | 3.25 |
| BAS-S02 | | 9.40 | 4.77 | 5.05 |
| BAS-S03 | | | 3.53 | - |
| BAS-S04 | | | | - |

*Table 3: Matrix showing the t-values obtained between the ring sequences in site chronology BASSSQ02*

| | BAS-S05 |
|---|---|
| BAS-S07 | 7.63 |

# FIGURES

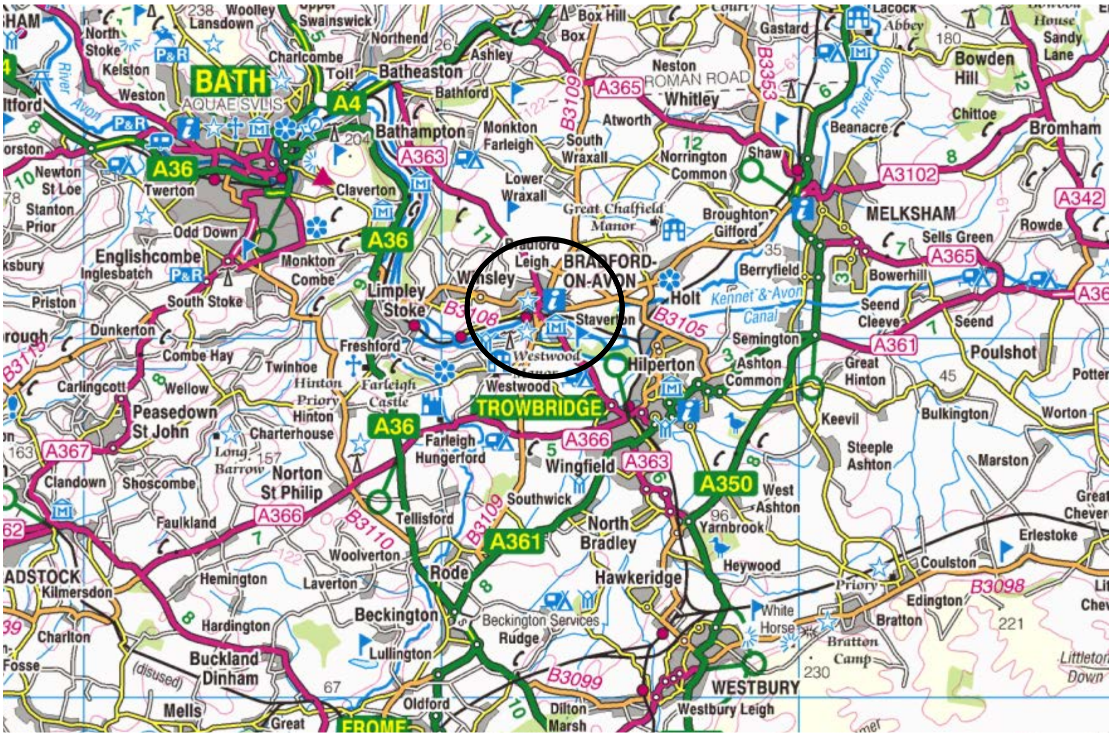



*Figure 1: Map to show the location of Bradford-on-Avon (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationary Office, © Crown Copyright)*


*Figure 2: Map to show the location of 11 Silver Street, Bradford-on-Avon (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationary Office, © Crown Copyright)*

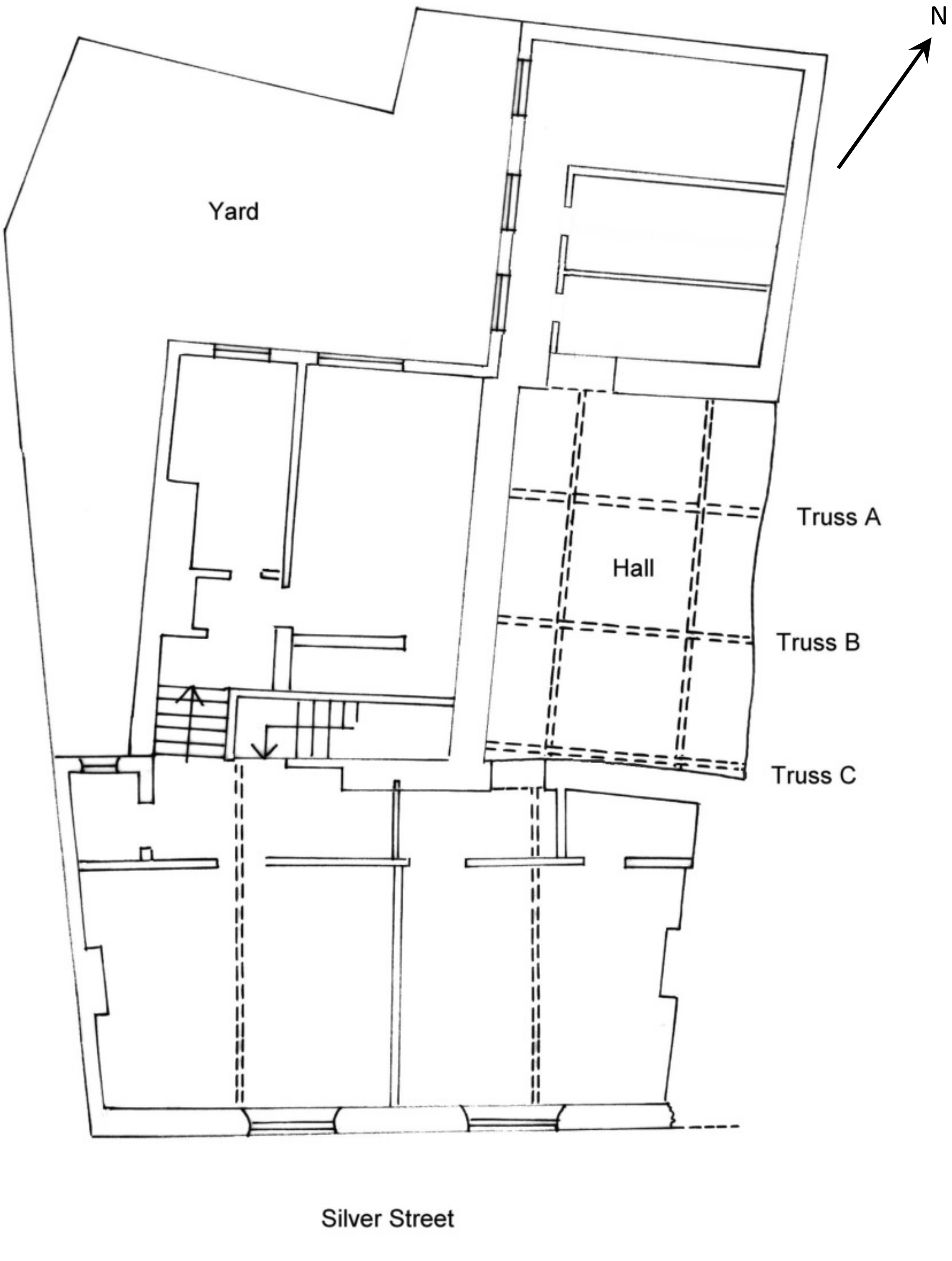



*Figure 3: The location of the medieval open hall within the current building at 11 Silver Street (based on a plan from the Wiltshire Buildings Record archive)*

*Figure 4: The interior of the open-hall roof in 11 Silver Street, viewed looking south*

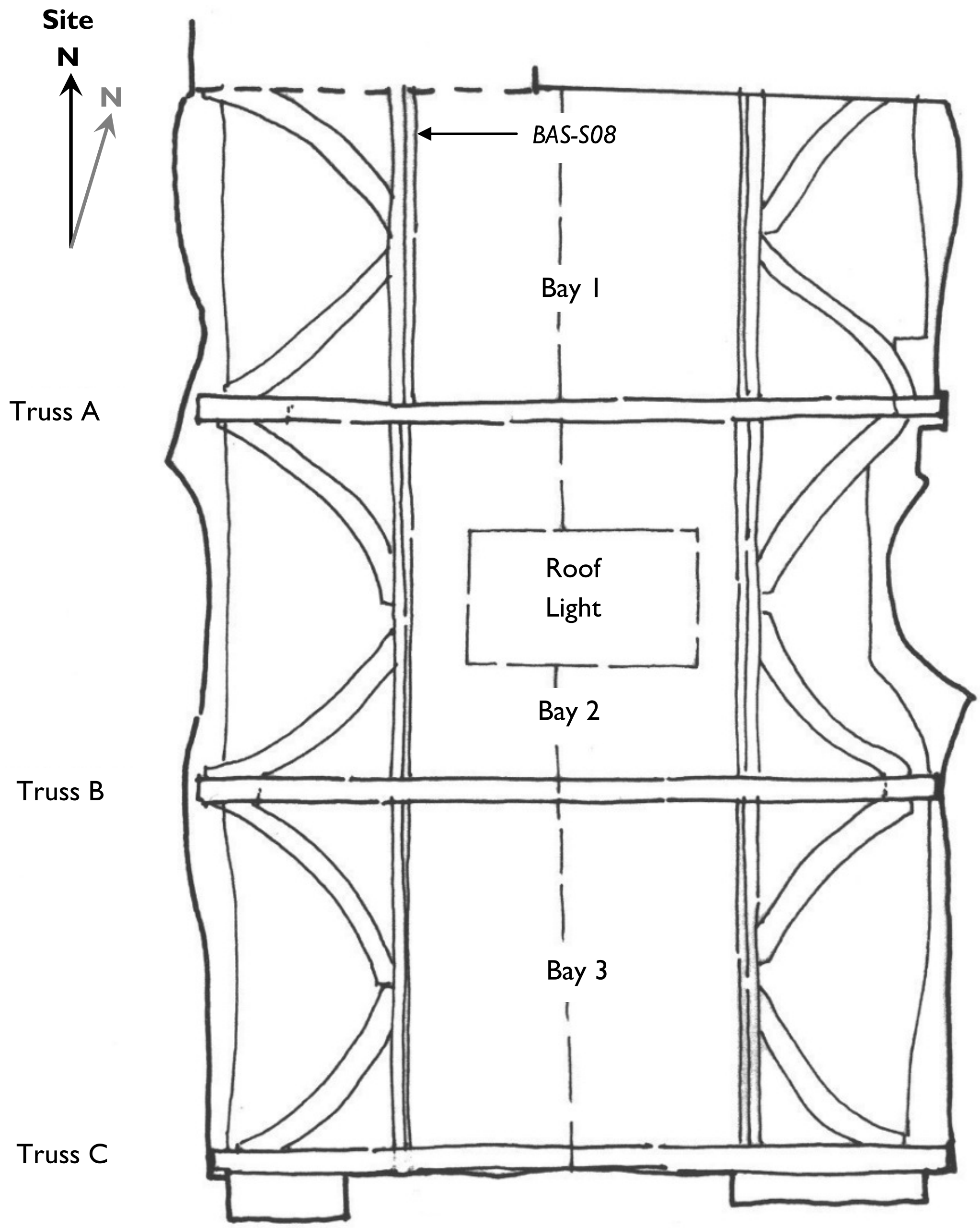



*Figure 5: Plan of the medieval open-hall roof in 11 Silver Street and the location of sample BAS-S08 (based on a drawing by Clive Carter of the Wiltshire Buildings Record)*

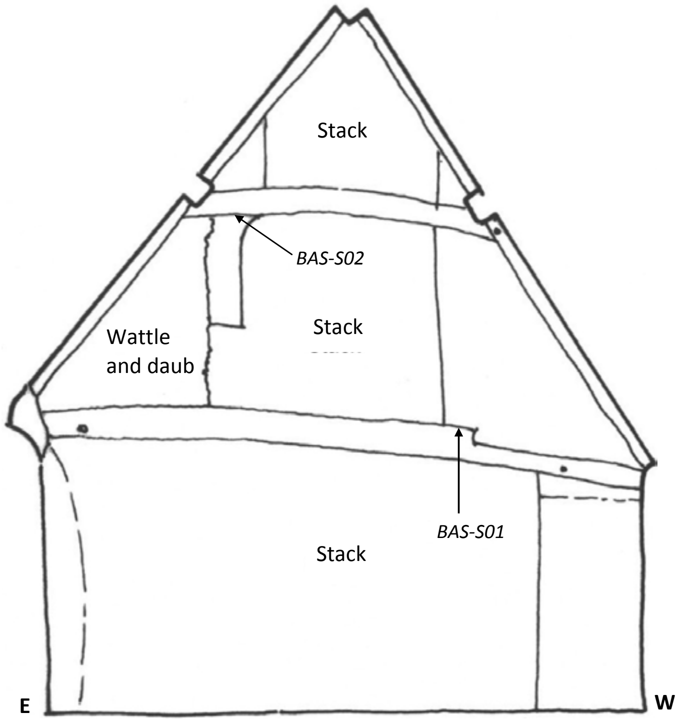



*Figure 6: The north face of truss C showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)*

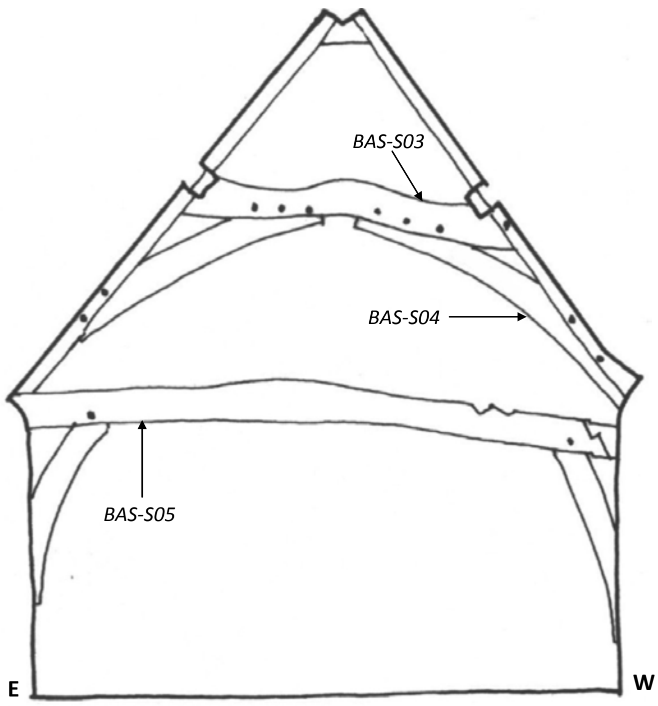



*Figure 7: The north face of truss B showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)*

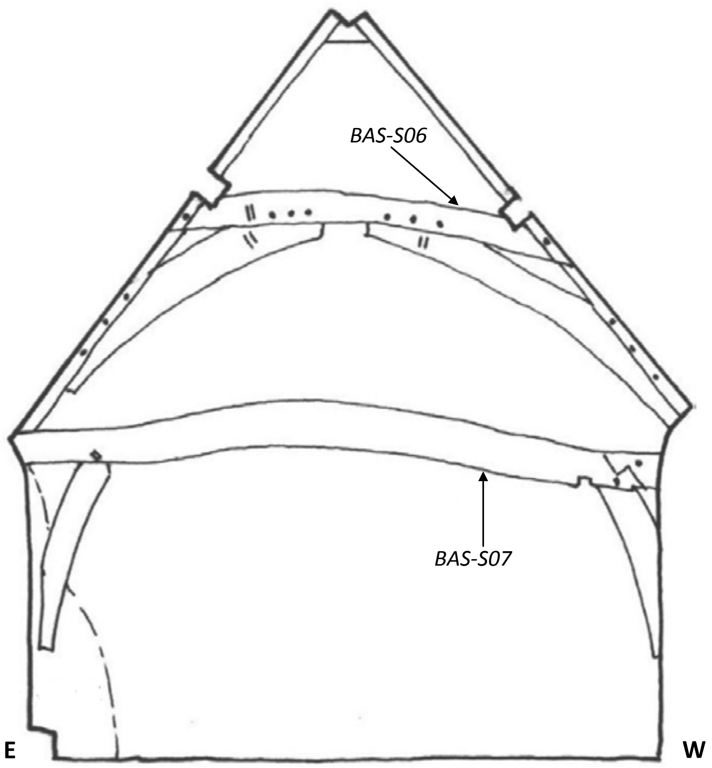
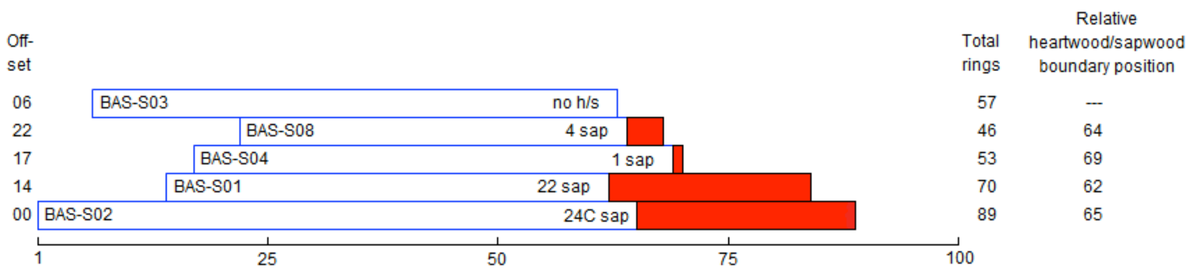
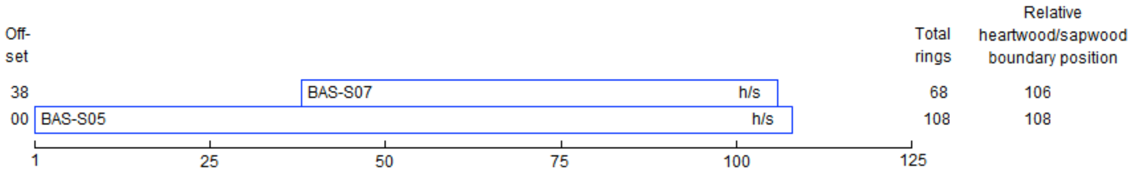



*Figure 8: The north face of truss A showing the sample locations (based on a drawing by Clive Carter of the Wiltshire Buildings Record)*




White bars = heartwood rings;
filled bars = sapwood rings
no h/s = the heartwood/sapwood boundary is not present on the sample
C= complete sapwood is retained on the timber

*Figure 9: Bar diagram of the samples in site chronology BASSSQ01*




White bars [ ] = heartwood rings;
h/s = the last ring of the sample is at the heartwood/sapwood boundary

*Figure 10: Bar diagram of the samples in site chronology BASSSQ02*

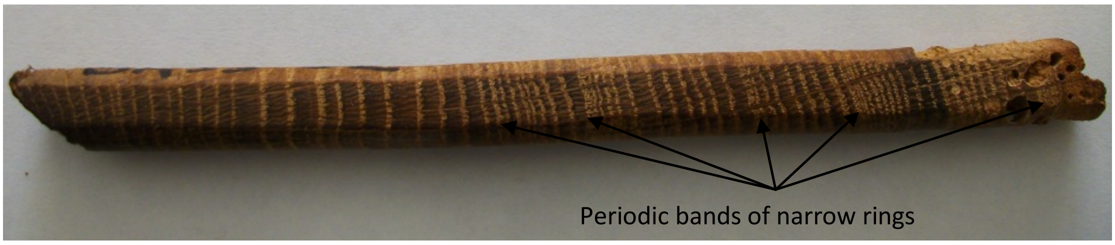



*Figure 11: Periodic narrow bands present of sample BAS-S02*

## DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BAS-S01A 70
232 249 320 257 196 189 185 361 326 444 238 239 272 215 321 284 180 182 269 271
135 94 76 56 72 73 85 121 80 73 137 152 73 99 51 78 86 94 97 112
68 51 60 81 63 55 76 100 102 102 120 103 92 62 65 82 107 107 127 67
51 48 65 78 88 74 59 45 42 72
BAS-S01B 70
235 224 315 271 183 177 184 423 310 395 213 240 273 218 320 290 190 186 268 274
137 96 74 53 66 71 87 128 73 81 134 142 82 89 56 88 123 81 92 106
69 68 61 78 74 52 85 93 112 116 120 97 100 58 68 82 104 109 132 62
45 50 63 80 85 64 59 58 45 71
BAS-S02A 89
167 149 155 167 199 214 176 96 206 256 272 160 260 256 242 416 378 434 262 305
367 443 323 296 281 166 137 127 134 79 115 141 227 246 128 82 98 119 189 313
225 210 166 167 240 267 124 128 138 230 180 176 234 181 109 43 77 106 99 87
111 118 189 213 174 174 147 133 131 151 170 242 248 94 52 71 60 75 119 56
46 47 49 62 84 98 49 60 68
BAS-S02B 89
164 158 154 180 212 206 173 97 205 262 266 162 262 251 237 426 388 433 282 314
364 448 317 291 276 163 138 130 138 86 112 148 228 263 131 81 102 120 195 307
229 216 169 163 248 270 125 133 143 230 178 174 234 182 107 49 76 107 94 92
107 124 188 191 182 175 140 137 135 163 179 233 248 95 61 60 61 75 123 60
40 54 46 64 86 100 50 63 68
BAS-S03A 57
174 96 205 153 254 140 202 184 186 320 344 421 245 345 372 458 287 343 245 130
75 46 46 58 138 175 211 231 119 108 103 102 149 283 207 247 227 217 394 379
101 182 176 232 188 178 203 175 99 52 76 138 110 119 125 152 268
BAS-S03B 57
181 95 212 242 248 138 195 179 192 310 349 446 245 355 380 455 293 342 226 131
74 38 38 75 136 170 211 240 123 101 105 103 144 278 206 248 230 209 395 373
107 182 179 224 192 180 207 164 102 47 86 145 101 106 123 151 277
BAS-S04A 53
419 193 490 320 332 197 237 171 175 149 135 95 55 110 161 337 331 226 172 124
144 259 333 402 374 318 331 326 280 127 160 62 78 80 118 180 234 139 94 107
110 122 81 101 109 128 149 143 183 150 222 115 172
BAS-S04B 53
397 474 496 319 318 220 236 178 172 143 125 94 52 116 165 357 325 216 184 127
136 272 331 407 407 358 336 328 281 125 156 63 77 86 111 184 236 136 90 107
99 117 90 100 106 128 147 136 188 166 222 125 180
BAS-S05A 108
331 200 267 334 281 230 134 190 231 190 258 258 227 275 199 212 335 309 236 191
189 244 176 174 156 205 258 250 291 201 144 179 151 103 74 56 103 96 95 67
85 86 89 64 77 107 88 68 113 96 68 90 162 149 105 132 98 108 71 60
88 123 90 105 101 80 57 100 84 57 52 86 66 125 93 80 81 84 94 90
81 111 90 81 60 71 81 91 111 95 36 79 78 78 89 60 62 41 52 56
46 55 48 45 34 31 36 43
BAS-S05B 108
348 332 284 336 278 226 136 188 232 193 253 259 245 267 199 219 341 314 238 189
190 243 182 169 153 205 275 254 302 204 154 192 147 101 86 58 85 95 90 73
89 86 88 68 78 104 91 69 119 91 74 84 165 151 103 130 100 106 72 64
86 120 95 97 106 76 61 110 86 56 52 85 58 144 90 90 75 88 86 84
83 106 86 79 64 61 84 89 103 98 46 75 84 74 92 58 59 49 48 60
47 52 41 46 33 32 30 41
BAS-S06A 61
219 248 372 356 165 250 220 260 180 294 195 191 193 280 255 197 220 243 217 161
177 113 100 119 109 100 124 52 52 71 56 51 90 80 75 81 104 124 138 122

84 138 197 89 135 59 62 97 71 95 65 61 47 44 51 55 54 58 61 81
86
BAS-S06B 61
192 246 426 418 173 245 217 259 179 290 188 194 182 276 262 196 218 241 222 156
179 115 101 114 110 103 122 51 58 68 57 49 90 81 73 95 102 111 147 122
86 141 189 104 122 70 70 98 68 89 63 63 47 44 52 54 59 56 56 80
90
BAS-S07A 68
95 175 138 134 142 122 122 113 110 97 146 98 77 101 141 140 86 101 77 68
56 53 59 90 109 86 99 64 73 120 106 82 68 87 71 129 104 76 74 176
88 87 66 96 73 87 79 73 117 102 98 67 53 85 91 74 103 69 74 47
43 54 48 43 58 59 34 47
BAS-S07B 68
83 163 135 126 146 122 121 115 110 97 141 103 71 99 138 135 86 99 81 65
53 51 61 91 109 87 94 66 67 125 100 89 70 83 73 122 104 83 68 174
90 79 71 90 78 87 75 69 125 99 95 69 48 91 77 83 94 74 69 47
40 51 43 49 58 63 42 50
BAS-S08A 46
215 314 265 249 220 217 247 161 155 141 183 163 180 188 222 182 265 228 209 203
128 103 141 193 107 81 79 149 128 90 112 116 65 66 56 122 49 81 62 91
157 224 181 167 129 109
BAS-S08B 46
227 325 261 252 218 219 255 154 154 142 188 158 188 200 226 196 257 246 204 198
133 103 149 191 113 74 81 154 116 84 127 114 75 58 51 101 55 85 55 91
156 228 180 176 133 115

# 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

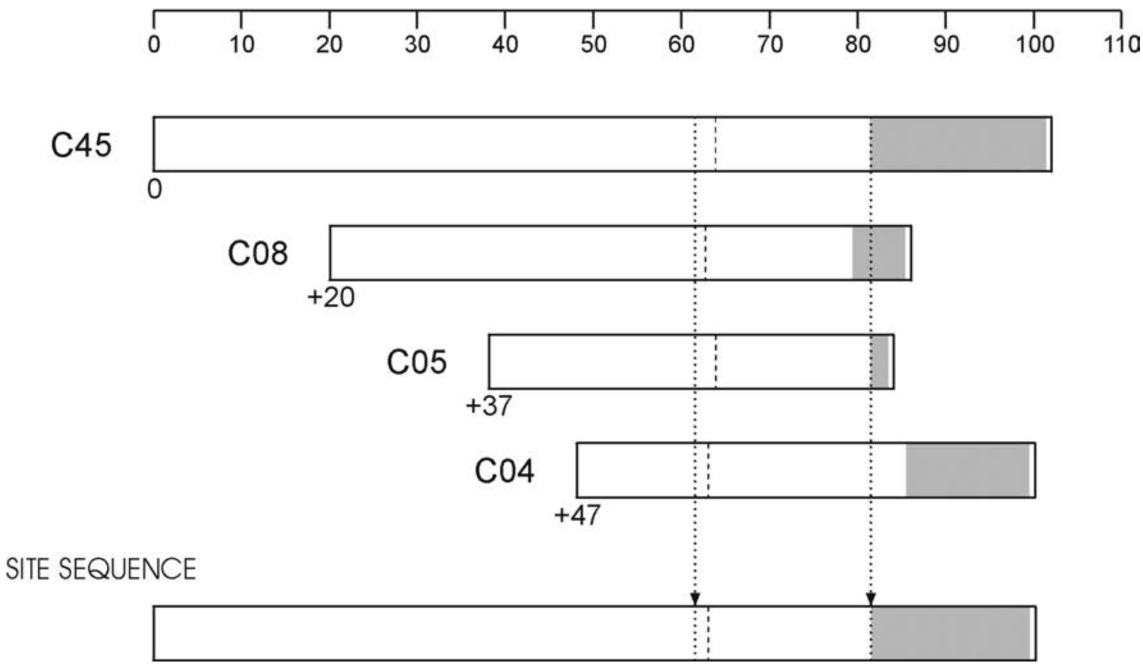



*Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

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

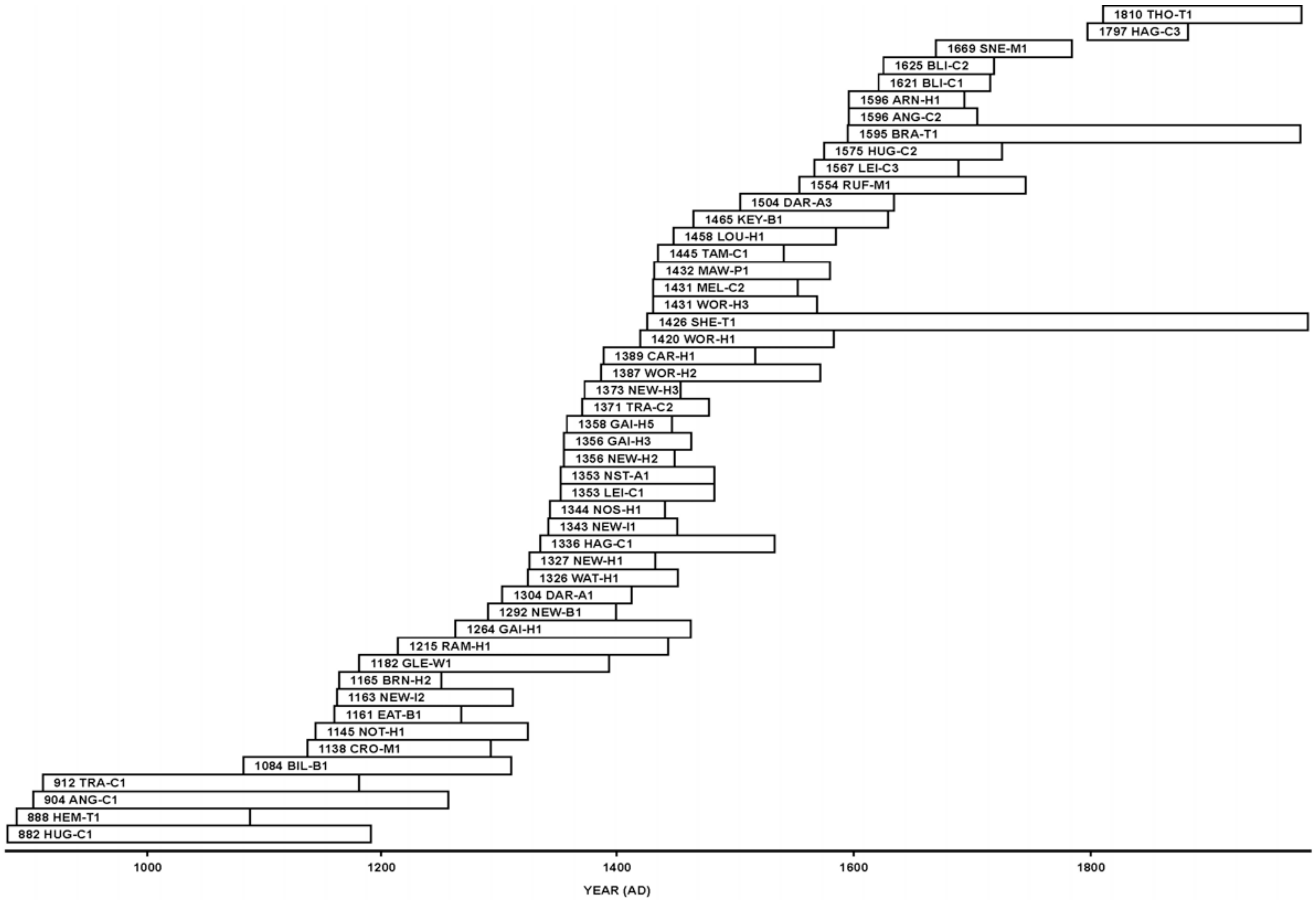
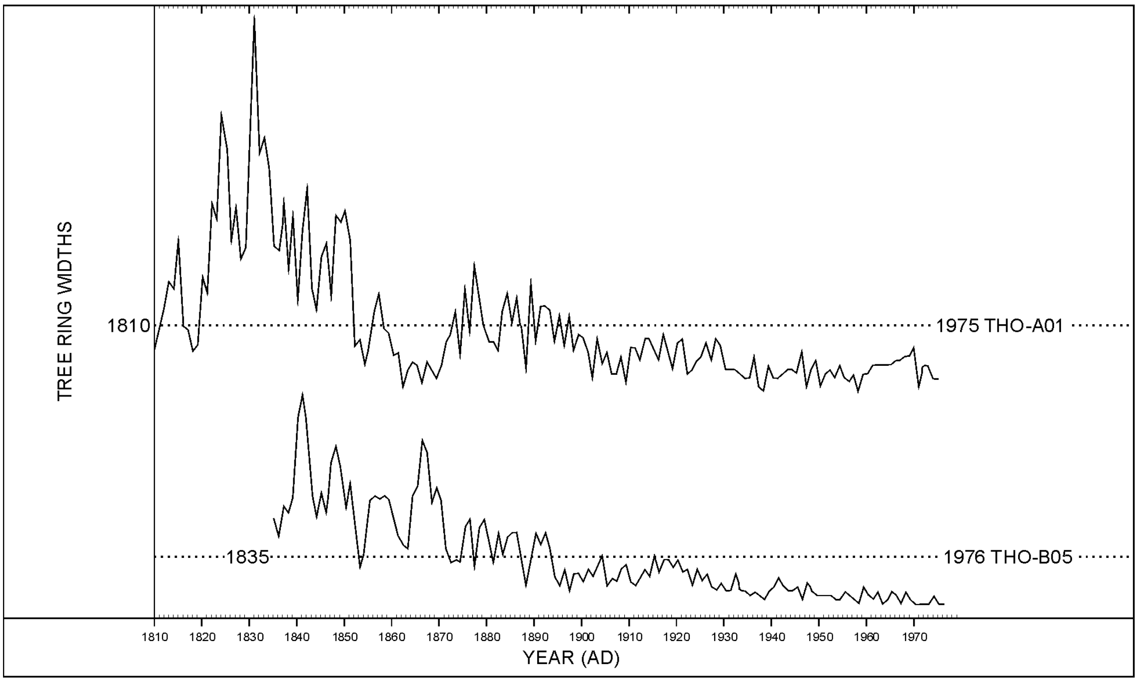



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

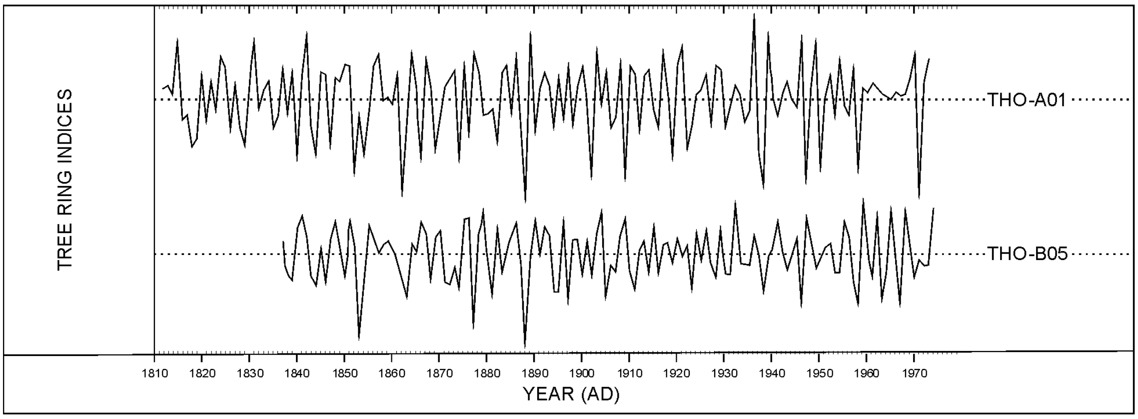



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

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

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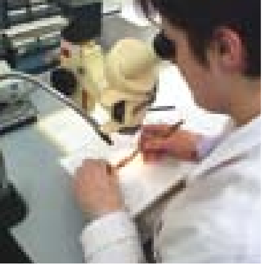
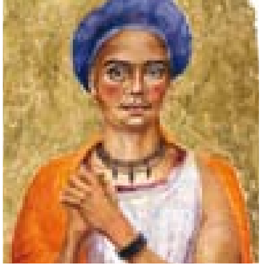



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