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TONGE HALL, TONGE HALL CLOSE, WILLIAM STREET, MIDDLETON, ROCHDALE, LANCASHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

Research Report Series 43-2014

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SUMMARY

Dendrochronological analysis undertaken on 41 of the 45 samples obtained from timbers in different parts of Tonge Hall produced a single dated site chronology comprising 38 samples with an overall length of 239 rings. These rings were dated as spanning the years AD 1449–1687. Interpretation of the sapwood on the dated samples indicates that the roof, first-floor frame, and structural timbers of the hall range, as well as the roof and stair timbers of the cross-wing, were all cut as part of a single programme between AD 1589–1614. A ground-floor fire place bressumer of the hall range has an estimated felling date of AD 1609–34, while the timbers of a first-floor partition wall have an estimated felling date in the range AD 1640–65. The latest dated timbers are the floorboards of the cross-wing attic, which have an estimated felling date in the range of AD 1697–1722.

CONTRIBUTORS

Alison Arnold and Robert Howard

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CONTENTS

INTRODUCTION

Tonge Hall is Grade II* listed and is described in the listing as dating to the AD 1580s with eighteenth- and nineteenth-century alterations. The following background information is from both the listing entry and Gardner (pers comm). Standing in a slightly isolated position off a gravelled trackway (Fig 1a/b), Tonge Hall is a substantial late sixteenth-century timber-framed house on a stone plinth, with a single cross-wing to the east and a hall range running westwards that appears always to have had two storeys, although this is not certain. At the rear, facing south and east, the frame has been encased in brick. The main front and the side wall of the cross-wing, however, retain elaborate exposed framing with decorative quatrefoil panels, coved jetties, and projecting gables both to the wing and to a narrow parallel projection in front of the hall.

Internally, there are substantial remains of historic timberwork. The hall and cross-wing ranges are both roofed by principal rafter with tiebeam and queen-strut trusses (one cross-wing truss having a collar), supporting double purlins to each pitch. Both hall and cross-wing have a number of wall posts (many encased in plaster), with possibe braces (again encased) to the tiebeams. There are also studs and cross-rails visible in some walls, along with a substantial amount of decorative woodwork.

There are also timbers to the ground- and first-floor ceilings, including dragon beams to the cross-wing and a bressumer to the hall fireplace. A solid oak spiral staircase remains in the cross-wing, although it is again not certain whether this is original, a replacement, or a totally new and later insertion. Unusually, the attic of the cross-wing is floored by a number of butt-edged oak boards. These are not particularly wide, and thus probably not part of the primary phase, but neither do they look particularly modern, and thus potentially represent eighteenth-century work to this part of the house. The cross-wing also has a parlour lined with bolection-moulded panelling, most of which is believed to date from *c* AD 1700.

In addition, the hall range contains timbers (main beams and common joists) of a first-floor frame. It is again uncertain if this is original or represents the flooring-in of an originally open hall. The first-floor rooms here have also been divided by a brick-filled stud and cross-rail partition wall. It is thought that this feature also represents a period of eighteenth-century alteration.

When built, its double-jettied form of timber-frame construction was used as an outward display of wealth, a display mirrored by the fine interior panelling. Tonge Hall was obviously a building of note and in this part of the country is a rare surviving example of this building-type. Whilst, over time, the building has suffered deterioration, it is currently in a state of major disrepair due to vandalism and damage caused by a fire that took hold of the building in 2007. The fire principally affected the roof structure, sweeping over the rooms below such that the roof is now incapable of protecting the interior space against damage associated with water ingress and gradual collapse.

SAMPLING

Sampling and analysis by dendrochronology of Tonge Hall was requested by Mair Hughes (English Heritage, Heritage at Risk Architect) in order to inform work to protect and stabilise this building which is on the Heritage at Risk register and in receipt of grant-aid for the repairs. The aim was to obtain independent dating evidence for the primary construction of the hall and its ensuing chronological development. Of particular interest, apart from the original construction date of the building, was whether or not the first-floor frame of the hall range and the stair of the cross-wing range were part of the original build or were later insertions.

Thus, having first assessed the timbers as to their suitability for tree-ring analysis, a total of 45 samples was obtained from the most appropriate timbers, the majority of these by coring. Each sample was given the code TNG-B (for Tonge, site 'B') and numbered 01–45 (Table 1). Five samples (TNG-B01–B05) were obtained from the roof timbers of the cross-wing, with a further nine samples (TNG-B06–B14) being obtained from the roof and associated structural timbers of the hall range. Ten samples (TNG-B15–B25) were taken from the first-floor frame of the hall range, with one sample (TNG-B25) being taken from the fireplace bressumer. Six samples (TNG-B26–B31) were taken from the treads of the spiral staircase of the cross-wing and eight samples (TNG-B32–B39) from the cross-wing attic floorboards (these last obtained by, and following agreement, removing 10mm slices from the end of those boards which were already lifted and loose). Finally, six samples (TNG-B40–B45) were taken from the first-floor partition wall of the hall range.

The locations of these samples were recorded at the time of sampling, either on sketch drawing, building plan drawings, or by photographic record (Figs 2 and 3a-k). Details of the samples are given in Table 1. The trusses have been numbered from north to south in the cross-wing and east to west in the hall, with individual timbers then being further identified as appropriate.

ANALYSIS AND RESULTS

Each of the 45 samples obtained from Tonge Hall was prepared by sanding and polishing. It was seen at this time that four samples from the hall range (one from a first-floor intermediate post to the north, and three from the first-floor partition wall) had too few rings for reliable dating and they were rejected from this programme of analysis. The annual growth ring widths of the remaining 41 samples were measured, the data of these measurements being given at the end of this report.

The data of the 41 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this resulting in the production of a single site chronology comprising 38 samples with each sampled element of the building being represented. The 38 samples, cross-matching with each other as shown in Figure 4, were combined at their indicated offset positions to form site chronology TNGBSQ01 with an overall length of 239 rings.

Site chronology TNGBSQ01 was then compared to an extensive corpus of reference material for oak, which indicated a consistent and repeated match with a number of these when the date of its first ring is AD 1449 and the date of its last measured ring is AD 1687 (Table 2).

Site chronology TNGBSQ01 was also compared to the three remaining measured but ungrouped samples, one from the cross-wing roof and two from the first-floor frame of the hall range, but there was no further satisfactory cross-matching. These three ungrouped samples were then compared individually to the full corpus of reference data, but again, there was no satisfactory cross-matching and they must, therefore, remain undated.

INTERPRETATION

Analysis by dendrochronology of the timbers of Tonge Hall has produced a single dated site chronology comprising 38 of the 41 samples measured, with its 239 rings dated as spanning the years AD 1449–1687.

None of the dated samples from Tonge Hall retains complete sapwood (the last growth ring produced by the tree before it was felled), and it is thus not possible to provide the precise felling date for any timber. The dated timbers from the different areas, do however, appear to be coeval and each group of timbers includes samples that do retain some sapwood or at least the heartwood/sapwood boundary (this last indicated by 'h/s' in Table 1 and the bar diagram). Allowing for the minimum and maximum numbers of sapwood rings the trees are likely to have had (the 95% confidence interval being 15–40 sapwood rings), it is possible to estimate a likely felling date range for the timbers and therefore the area of the building which they represent.

Cross-wing and hall range - primary construction

Twenty-six timbers have been dated that appear likely to represent the primary construction. These timbers are from the cross-wing roof, the cross-wing spiral stair, the hall range roof and structural timbers, and the hall range first-floor frame.

The average date of the heartwood/sapwood boundary on the samples from the cross-wing roof is AD 1575, whilst that of the samples from the spiral stair in the cross-wing is AD 1574. Thus the timbers of these two areas have estimated felling date ranges of AD 1590–1615 and AD 1589–1614 respectively.

The average date of the heartwood/sapwood boundary on the samples from the roof and structural timbers of the hall range is AD 1573, while on the floor-frame timbers to the hall the average heartwood/sapwood boundary is AD 1574. Thus the timbers of these two areas have estimated felling date ranges of AD 1588–1613 and AD 1589–1614 respectively.

It would thus appear that these timbers from the cross-wing and hall represent a single programme of felling, although in a moderately large building such as this, it is possible that timbers could perhaps have been felled a year or so apart. The likelihood of a single-felling programme is furthermore supported by the fact that the heartwood/sapwood boundary on the samples which retain it is at a similar relative position and date. Amongst these samples it varies by only 12 years from AD 1568 on sample TNG-B26 to AD 1580, on samples TNG-B01 and -B30, with the majority of samples having a heartwood/sapwood boundary dated to the AD 1570s. Such a similarity is indicative of timbers felled over a very short period of time.

Taken overall, the average date of the heartwood/sapwood boundary on the cross-wing roof and stair timbers, and the hall range roof, structure, and floor frame timbers, is AD 1574. Thus an estimated felling date in the range AD 1589–1614 is obtained.

Hall Range - later timbers

A sample from the bressumer to the ground-floor fire-place has a heartwood/sapwood boundary date of AD 1594. Thus this timber has an estimated felling date in the range AD 1610–34, which, it will be seen, overlaps with the estimated felling date range of the timbers associated with the primary construction of the cross-wing and hall range. It is therefore just possible that the bressumer was felled at the same time as the primary construction timbers, although this cannot be proven and it could clearly also simply have been felled a few years later.

The first-floor partition wall to the hall range, on the other hand, is certainly later, the average heartwood/sapwood boundary ring on the three dated samples here being AD 1625. Using the same sapwood estimate as above, 15–40 rings, would give these timbers an estimated felling date in the range AD 1640–65

Cross-wing - floorboards

The latest timbers detected in this programme of analysis are represented by the floorboards to the attic of the cross-wing. The average heartwood/sapwood boundary ring on these samples is dated AD 1682, which would give the timbers an estimated felling date in the range of AD 1697–1722.

CONCLUSION

Dendrochronological analysis has indicated that there appears to be no significant difference between the felling date of the timbers used in the cross-wing roof and spiral stair timbers, and the first-floor frame, roof, and structural timbers of the hall range. It would appear that all these timbers were felled as part of a single programme of work (though possibly not all at exactly the same time) between AD 1589–1614, and thus demonstrates that the first-floor of the hall and the spiral stair to the cross-wing were part of the original build.

The ground-floor fireplace bressumer of the hall range has an estimated felling date of AD 1610–34 and thus could be part of the primary construction phase or alternatively could be of a slightly later date.

The timbers of a first floor partition wall of the hall range are certainly later, these having an estimated felling date in the range AD 1640–65. The latest phase of felling identified is for the floorboards of the cross-wing attic which have an estimated felling date in the range AD 1697–1722.

The overall cross-matching between the 38 samples in the dated site chronology suggests that the timber was probably derived from a single woodland source. Indeed, the level of cross-matching between some samples, TNG-B41 and -B42, or TNG-B33, -B34, and -B35, for example, with values in excess of t=10.0, is sufficiently high as to suggest some timbers may in fact derive from the same tree. It is possible, though, that some individual trees were more widely dispersed within the source woodland.

In respect of the location of the source woodland, it may be noted from Table 2 that, although site chronology TNGBSQ01 has been compared to reference chronologies from all parts of England, the highest levels of similarity (as indicated by the '*t*'-values) are found with other sites in northern and north-west England. Two other nearby sites in Greater Manchester and Cheshire give particularly good cross-matches. This would suggest that the timbers used at Tonge Hall are from a relatively local woodland source.

Despite having sufficient rings for reliable dating, and showing no problems such as compressed or distorted rings, three measured samples remain ungrouped and undated. The presence of undated samples is, however, a frequent feature of tree-ring analysis. In this respect Tonge Hall is slightly unusual in having such a high percentage (92.6%) of measured samples successfully dated.

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TABLES

Table 1: Details of tree-ring samples from Tonge Hall, Middleton, Rochdale, Lancashire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Cross-wing roof					
TNG-B01	East principal rafter, truss 2	86	4	1499	1580	1584
TNG-B02	West principal rafter, truss 2	97	10	1488	1574	1584
TNG-B03	East principal rafter, truss 3	120	no h/s	1449	------	1568
TNG-B04	West principal rafter, truss 3	122	10	1461	1572	1582
TNG-B05	East upper purlin, truss 1–2	115	17	------	------	------
	Hall range					
TNG-B06	North principal rafter, truss 6	61	h/s	1509	1569	1569
TNG-B07	Ridge beam between truss 5 and cross-wing roof	79	no h/s	1486	------	1564
TNG-B08	Tiebeam truss 6	90	no h/s	1477	------	1566
TNG-B09	First-floor main wall post, truss 6	93	no h/s	1464	------	1556
TNG-B10	North lower purlin, truss 5–6	68	no h/s	1495	------	1562
TNG-B11	First-floor intermediate post to north wall	nm	---	------	------	------
TNG-B12	Ground-floor main post to north wall	82	6	1501	1576	1582
TNG-B13	Ground-floor intermediate post to north wall	99	no h/s	1469	------	1567
TNG-B14	Ground-floor main wall post, truss 6	59	no h/s	1487	------	1545
	Hall range first-floor frame					
TNG-B15	West, main ceiling beam	97	4	1478	1570	1574
TNG-B16	West, middle main ceiling beam	84	h/s	1495	1578	1578
TNG-B17	East, middle main ceiling beam	56	h/s	------	------	------
TNG-B18	East, main ceiling beam	110	h/s	1469	1578	1578
TNG-B19	Bay 1, common joist 4 (from north)	78	no h/s	------	------	------

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
	Hall range, first-floor frame, and fireplace					
TNG-B20	Bay 1, common joist 6	54	h/s	1522	1573	1575
TNG-B21	Bay 1, common joist 7	88	12	1500	1572	1587
TNG-B22	Bay 2, common joist 3	98	9	1487	1575	1584
TNG-B23	Bay 2, common joist 5	81	h/s	1491	1571	1571
TNG-B24	Bay 3, common joist 2	78	h/s	1494	1571	1571
	Hall range fireplace					
TNG-B25	Fireplace bresummer beam	69	h/s	1526	1594	1594
	Cross-wing spiral stair					
TNG-B26	Step 6 (from bottom)	110	15	1474	1568	1583
TNG-B27	Step 7	70	no h/s	1487	------	1556
TNG-B28	Step 8	77	no h/s	1490	------	1566
TNG-B29	Step 9	79	6	1506		1584
TNG-B30	Step 10	65	h/s	1516	1580	1580
TNG-B31	Step 11	70	h/s	1505	1574	1574
	Cross-wing attic floorboards					
TNG-B32	Floor board (slice)	160	h/s	1518	1677	1677
TNG-B33	Floor board (slice)	145	h/s	1543	1687	1687
TNG-B34	Floor board (slice)	150	h/s	1536	1685	1685
TNG-B35	Floor board (slice)	90	h/s + 5nm	1595	1684	1684
TNG-B36	Floor board (slice)	64	no h/s	1508	------	1571
TNG-B37	Floor board (slice)	141	no h/s	1513	------	1653
TNG-B38	Floor board (slice)	144	no h/s	1524	------	1667
TNG-B39	Floor board (slice)	139	h/s	1540	1678	1678

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
	Hall range, first-floor partition wall					
TNG-B40	North cross-rail	52	14	1588	1625	1639
TNG-B41	Central cross-rail	51	13	1589	1626	1639
TNG-B42	South cross-rail	41	10	1595	1625	1635
TNG-B43	North stud post	nm	---	------	------	------
TNG-B44	Central stud post	nm	---	------	------	------
TNG-B45	South stud post	nm	---	------	------	------

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 TNGBSQ01 and relevant reference chronologies when the first-ring date is AD 1449 and the last-ring date is AD 1687

Reference chronology	Span of chronology	t-value	Reference
Staircase House, Stockport, Greater Manchester	AD 1489–1656	13.5	(Howard *et al* 2003)
Bramall Hall, Stockport, Cheshire	AD 1359–1590	9.5	(Arnold and Howard 2013 unpubl)
Hall I Th Wood, Bolton, Greater Manchester	AD 1467–1687	8.4	(Groves *et al* 1999)
Manor House, Sutton in Ashfield, Nottinghamshire	AD 1441–1656	8.3	(Howard *et al* 1996)
Aukland Castle, West Aukland, Co Durham	AD 1370–1520	8.1	(Arnold and Howard forthcoming)
Howley Hall, Morley, West Yorkshire	AD 1415–1635	8.0	(Arnold and Howard 2014 unpubl)
Refectory/Librarian's roof, Durham Cathedral	AD 1431–1683	7.9	(Arnold *et al* 2007)
Riding House, Bolsover Castle, Derbyshire	AD 1494–1744	7.7	(Howard *et al* 2005)

FIGURES

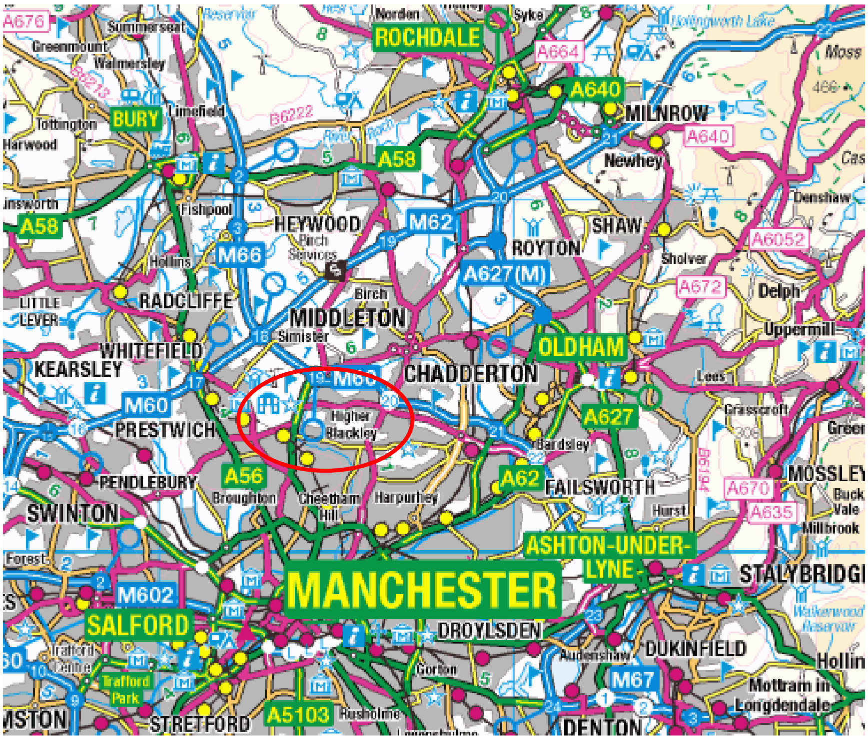


Figure 1a: Map to show the location of Middleton © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

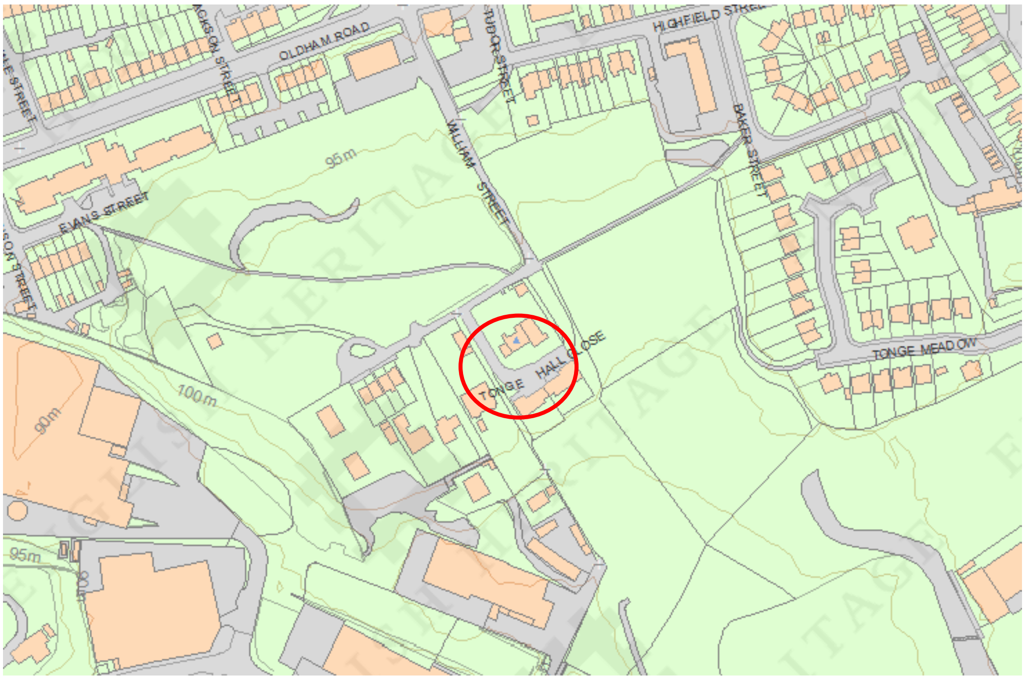


Figure 1b: Map to show the location of Tonge Hall © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900.

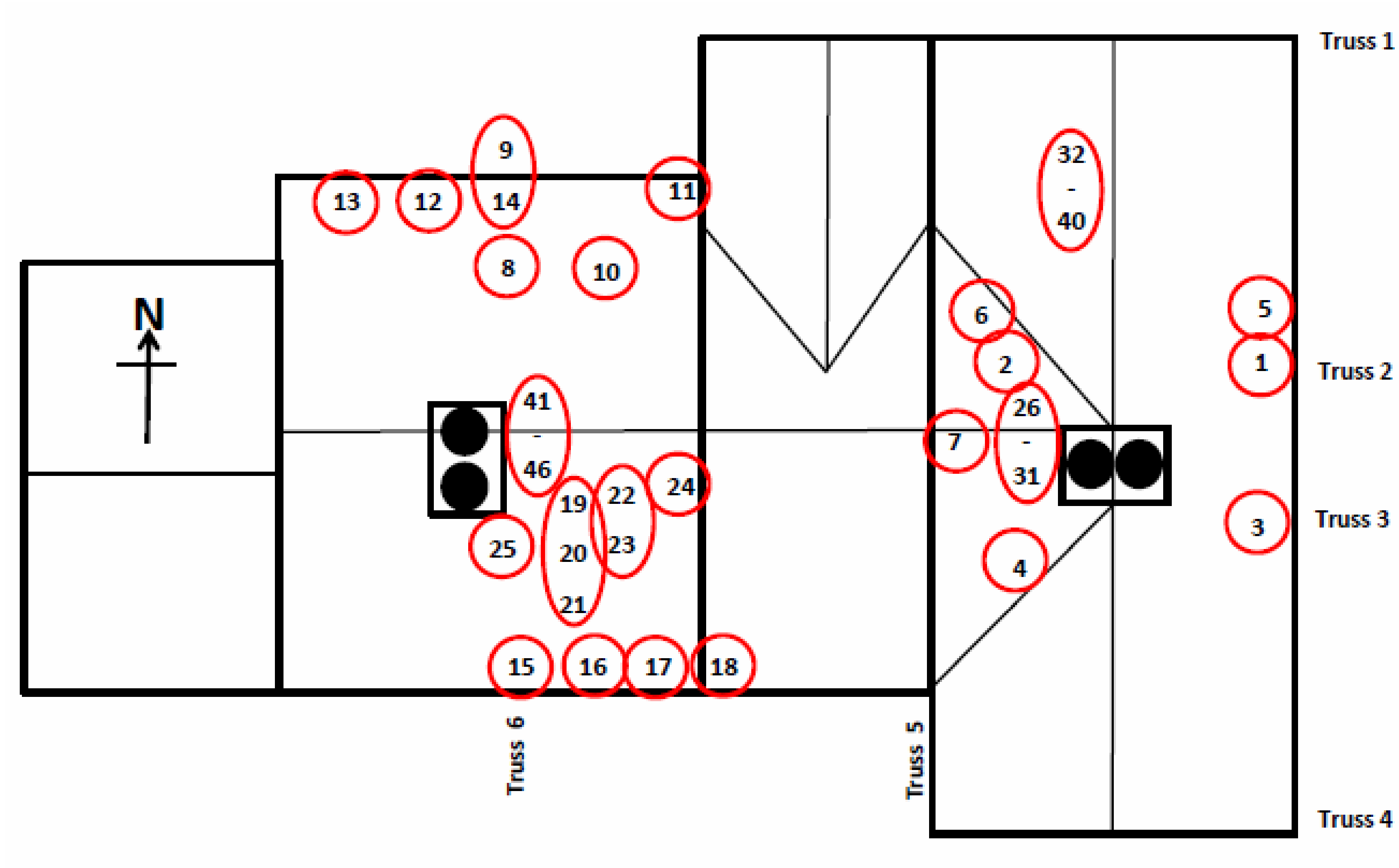


Figure 2: Simple schematic plan of Tonge Hall to show arrangement of the rooms and the general location of the sampled timbers

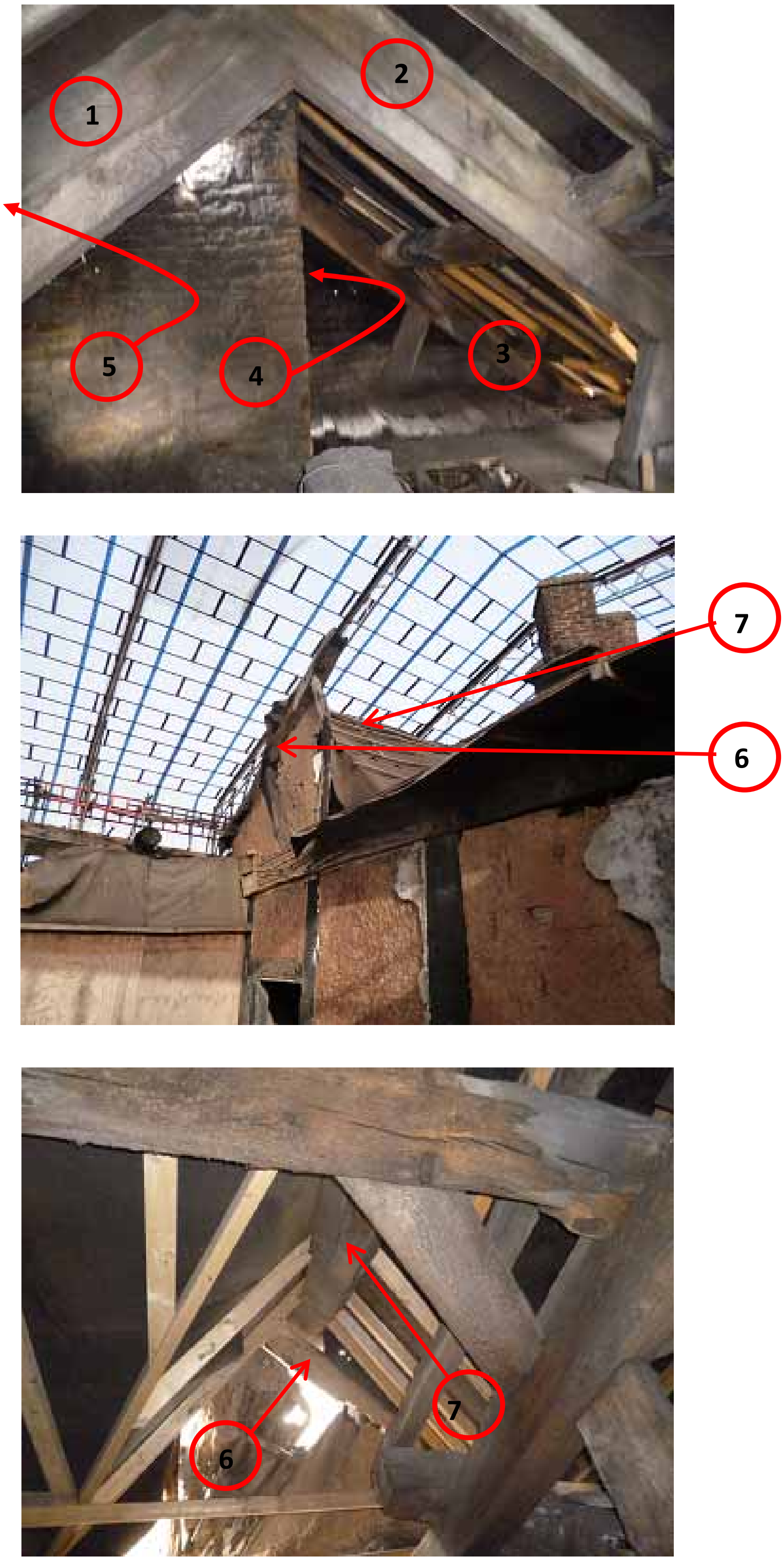


Figure 3a-c: Annotated photographs to locate sampled timbers

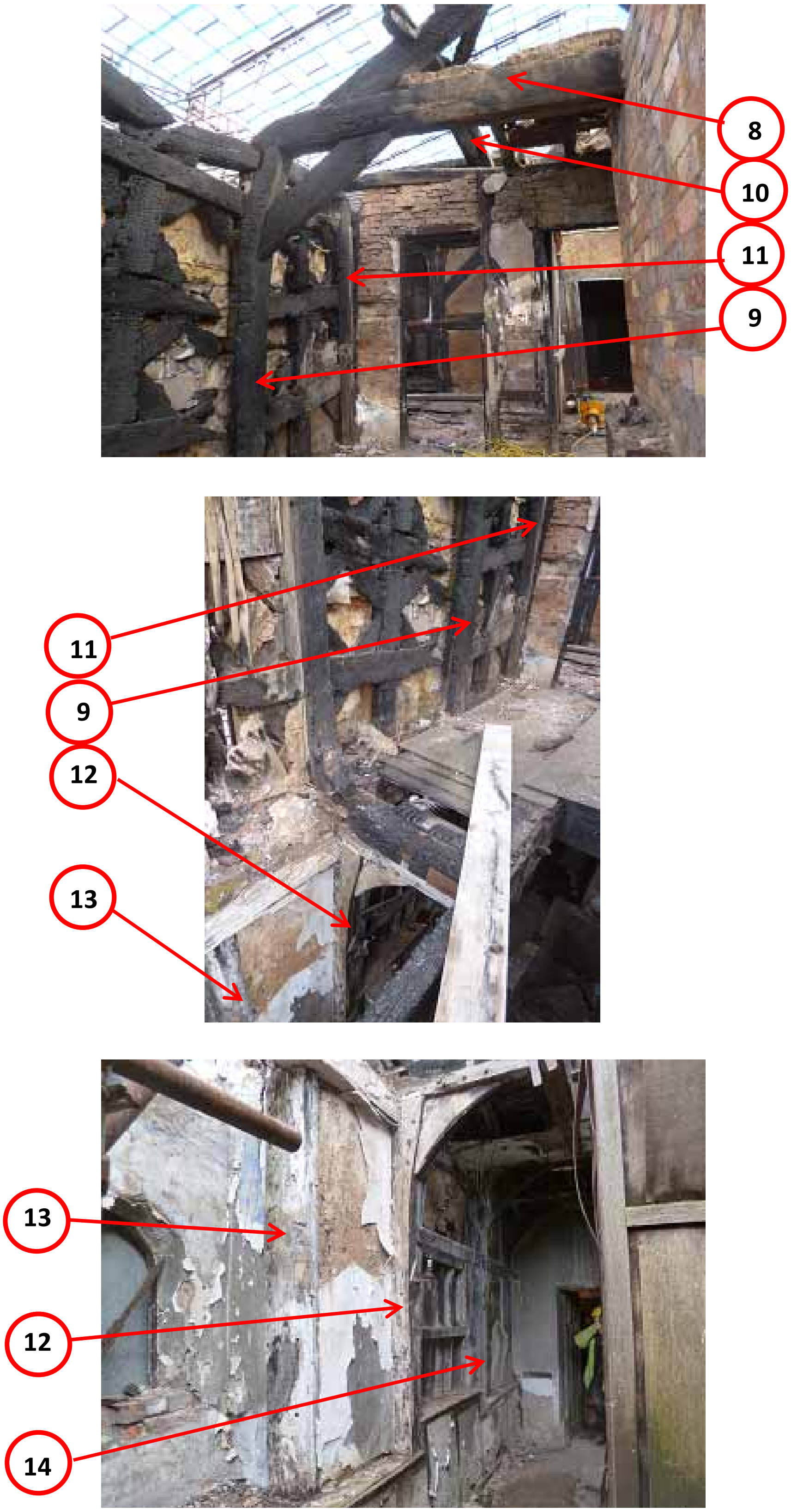


Figure 3d-f: Annotated photographs to locate sampled timbers

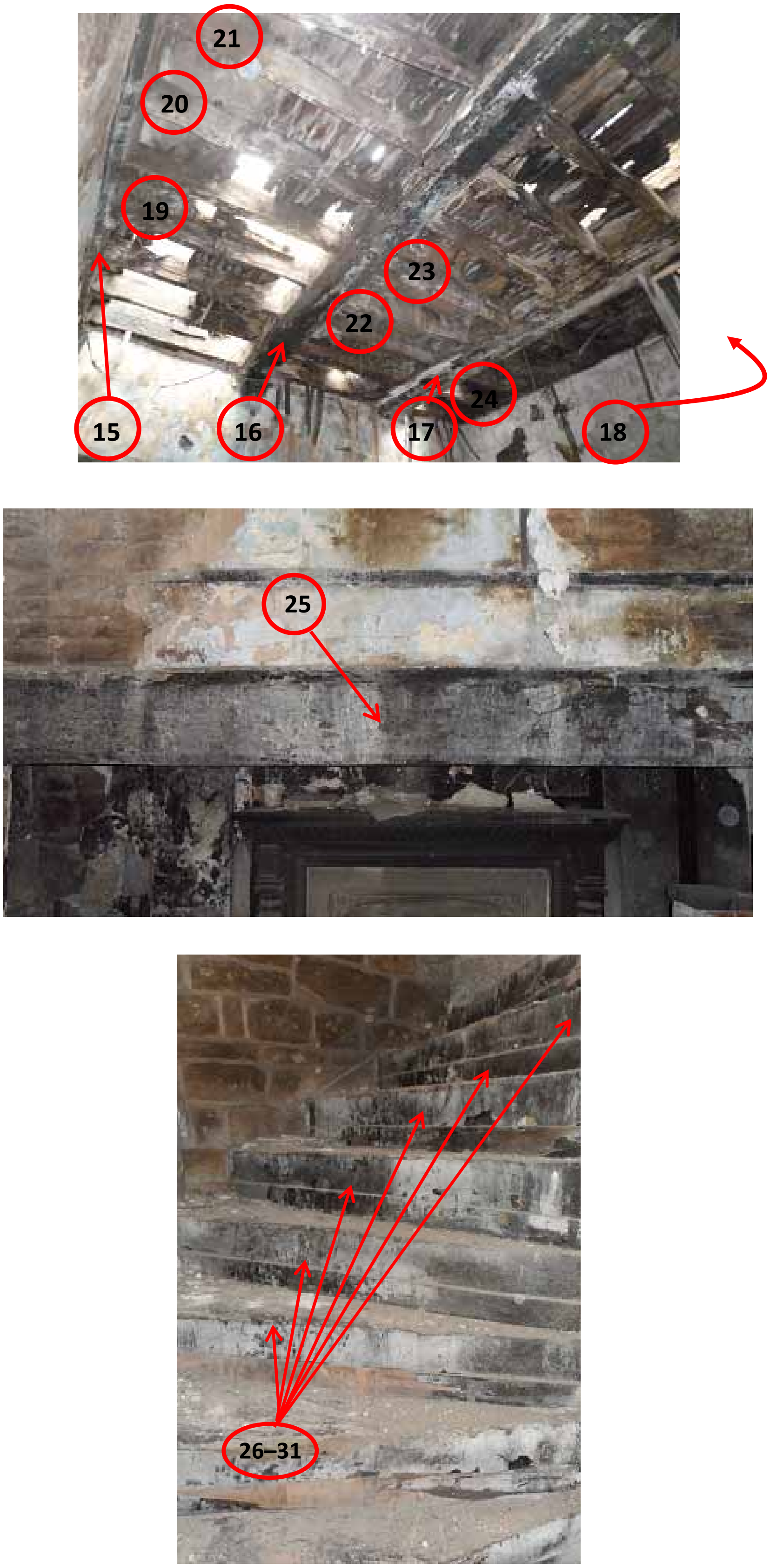


Figure 3g-i: Annotated photographs to locate sampled timbers

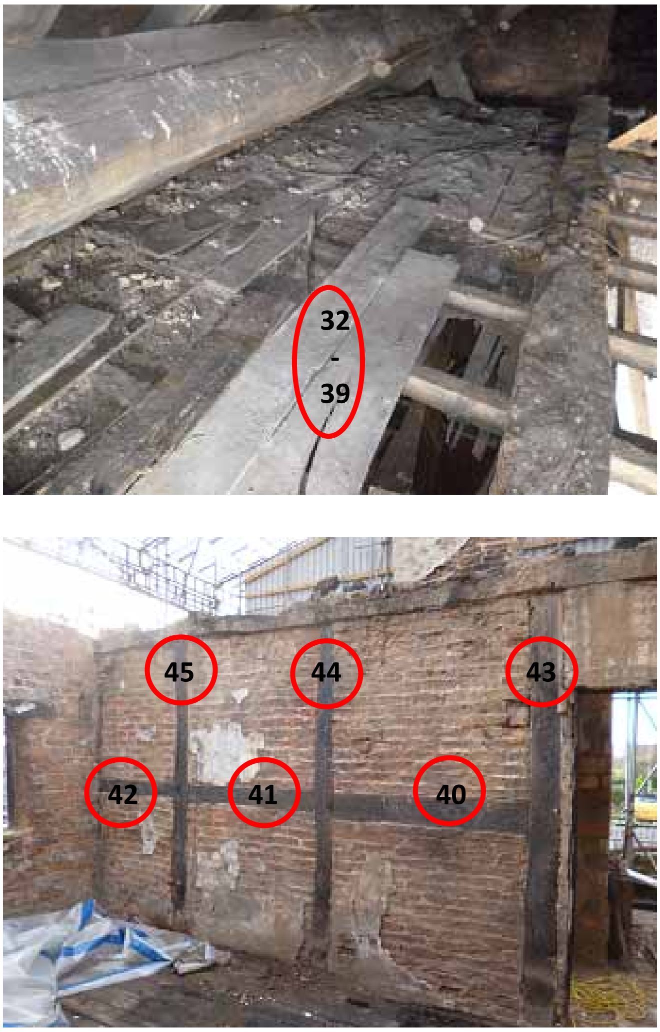
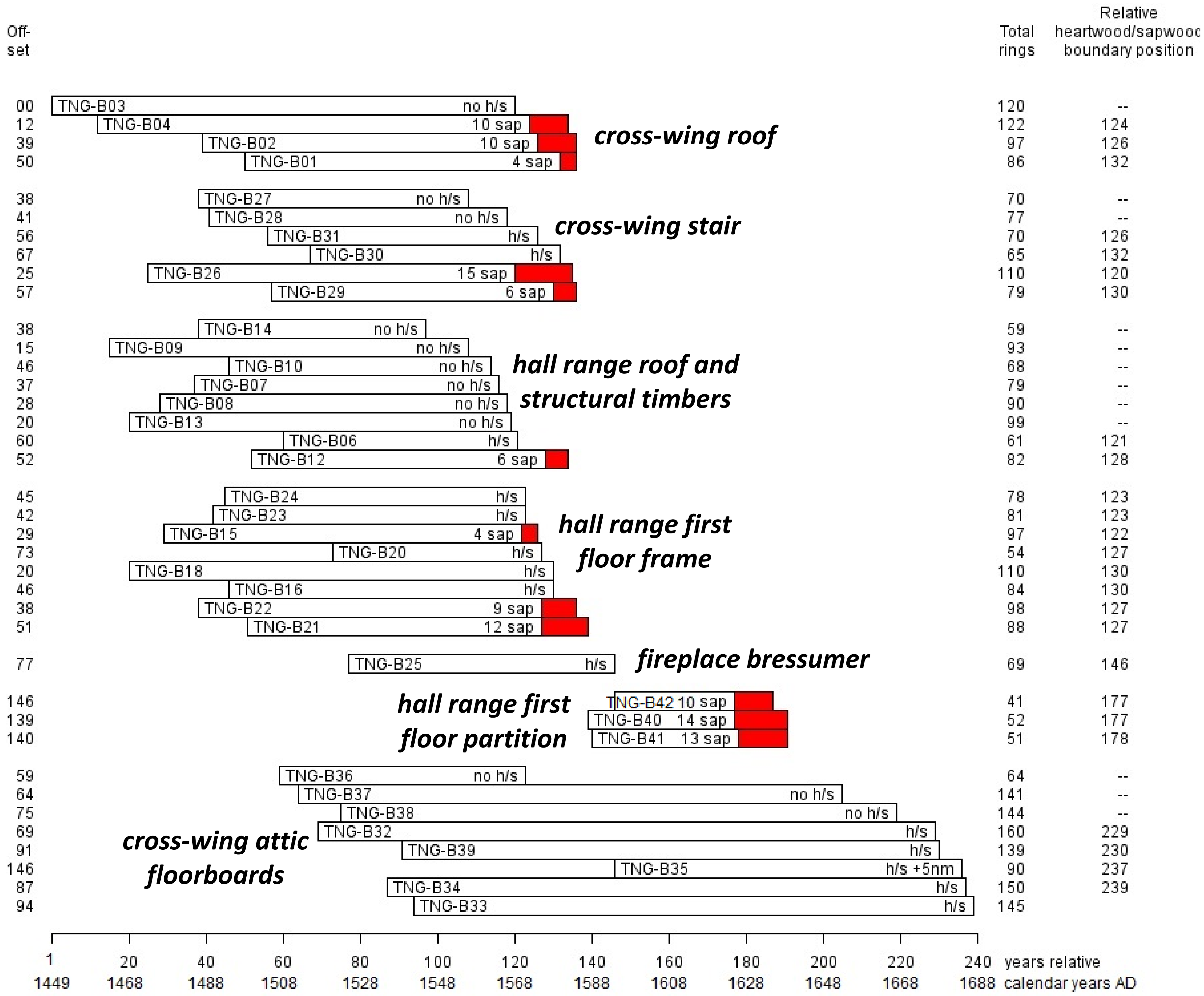


Figure 3j-k: Annotated photographs to locate sampled timbers



White bars = heartwood rings, shaded bars = sapwood rings;
h/s = heartwood/sapwood boundary; nm = rings not measured

Figure 4: Bar diagram of the samples in site chronology TNGBSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

TNG-B01A 86
249 162 168 103 112 163 180 122 128 125 161 104 151 123 126 137 112 139 116 97
113 105 153 175 207 169 180 162 171 165 149 117 137 132 110 134 186 160 186 175
228 244 218 192 168 181 231 214 231 235 292 250 251 190 246 200 159 75 95 148
168 195 212 185 179 198 162 46 56 76 173 184 201 187 173 193 132 103 135 164
210 334 225 159 208 181
TNG-B01B 86
174 165 168 105 112 156 194 125 129 134 156 116 153 128 124 134 116 135 121 98
116 105 157 175 214 175 185 170 162 155 150 120 136 132 110 137 191 153 192 178
238 225 220 185 165 178 232 220 223 232 289 246 246 192 240 193 171 72 99 139
182 181 225 175 170 195 159 43 59 75 187 189 217 185 163 192 117 110 134 163
230 314 221 182 211 162
TNG-B02A 97
270 283 230 192 250 279 316 289 293 209 211 253 151 158 107 115 107 158 185 131
110 147 99 192 95 101 130 133 121 100 105 84 75 178 153 145 153 125 176 179
159 125 90 131 110 96 109 119 130 151 145 193 275 239 226 303 265 300 293 269
262 276 287 259 176 253 176 134 73 89 142 228 168 240 203 190 276 108 54 62
57 138 134 198 172 222 202 123 96 103 117 156 175 107 103 102 123
TNG-B02B 97
252 322 303 179 201 284 312 298 260 187 206 251 166 139 110 114 92 163 190 132
131 146 110 183 100 113 134 131 125 103 100 87 83 164 157 137 157 128 182 171
156 129 95 128 109 100 107 120 126 151 156 195 264 227 232 296 275 296 284 282
261 267 293 275 178 271 160 156 71 87 132 234 166 227 193 184 287 104 56 58
63 130 134 187 163 228 212 118 107 96 117 160 168 124 97 109 115
TNG-B03A 120
222 109 241 303 132 163 312 284 221 262 199 229 217 219 152 207 210 223 229 178
96 93 74 60 66 96 125 125 94 104 116 139 117 153 189 164 177 142 175 64
39 62 78 65 54 81 107 112 100 95 112 143 129 89 88 85 114 156 150 100
121 115 106 103 100 117 90 85 92 108 68 53 70 71 54 84 84 107 108 121
98 128 96 89 64 67 87 49 57 57 79 73 72 46 40 45 57 67 59 73
64 62 82 59 71 62 71 60 78 91 148 119 137 124 125 109 77 40 69 53
TNG-B03B 120
174 88 217 275 156 267 310 287 282 303 201 209 200 199 165 222 216 204 214 177
105 102 89 64 59 99 115 125 82 117 114 139 124 156 185 169 183 140 171 62
44 56 79 64 54 78 116 110 89 96 114 146 130 83 87 84 110 159 154 107
108 117 104 103 104 110 88 87 89 109 72 51 68 73 57 82 82 107 109 123
104 126 92 85 62 70 86 54 64 66 81 78 70 47 40 42 62 65 56 76
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253 325 239 238 246 150 120 104 127 171 179 186 179 217 212 193 235 291 225 428
492 218 214 308 216 210 254 248 281 299 259
TNG-B42A 41
219 159 143 228 250 284 422 341 323 582 486 523 568 479 428 651 426 457 496 323
264 282 296 351 325 304 292 315 227 201 246 302 249 452 483 206 227 298 200 215
265
TNG-B42B 41
229 162 135 224 252 285 434 327 318 590 539 549 590 487 428 648 434 467 507 325
259 287 293 361 329 291 300 317 232 198 251 292 254 439 475 196 231 287 205 219
271

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

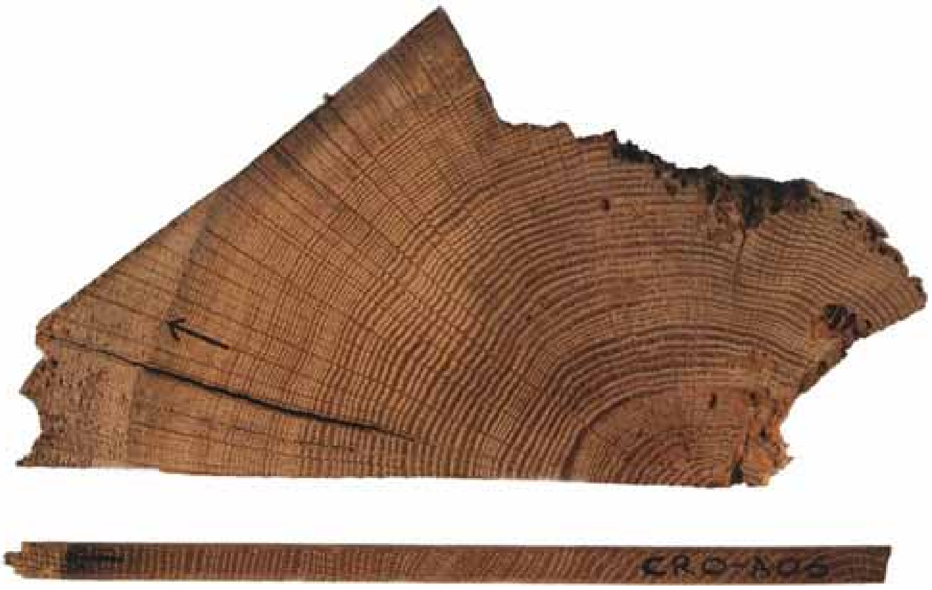


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

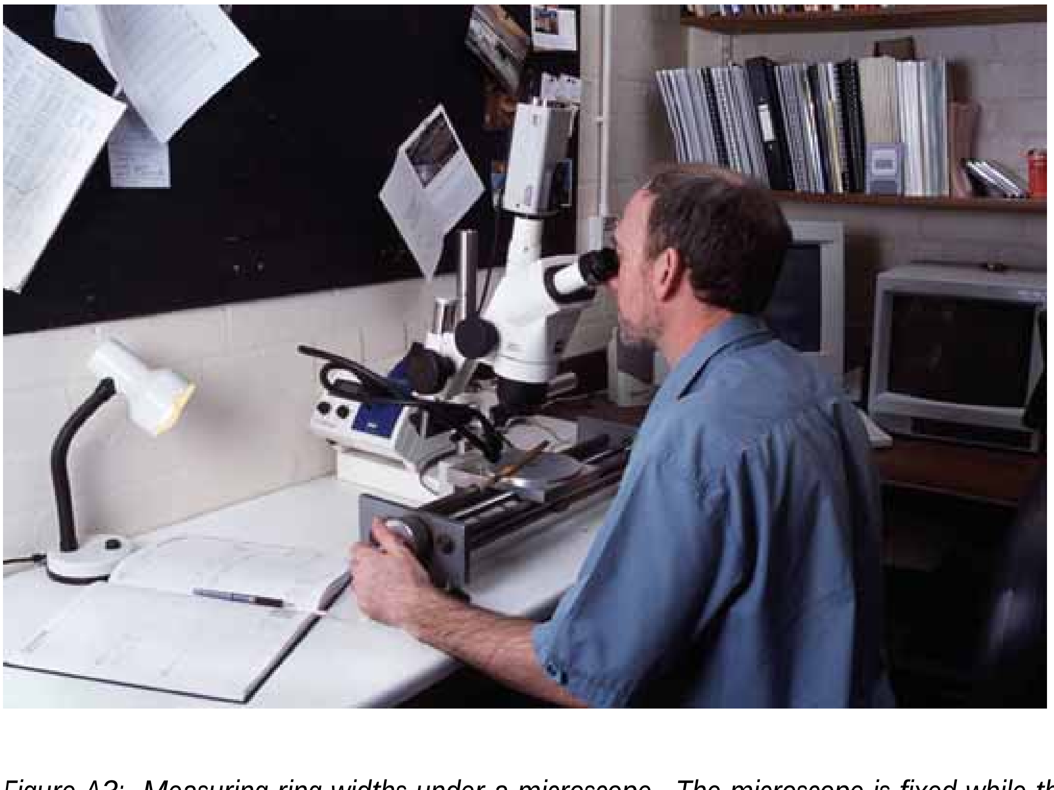


Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

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

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

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

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

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

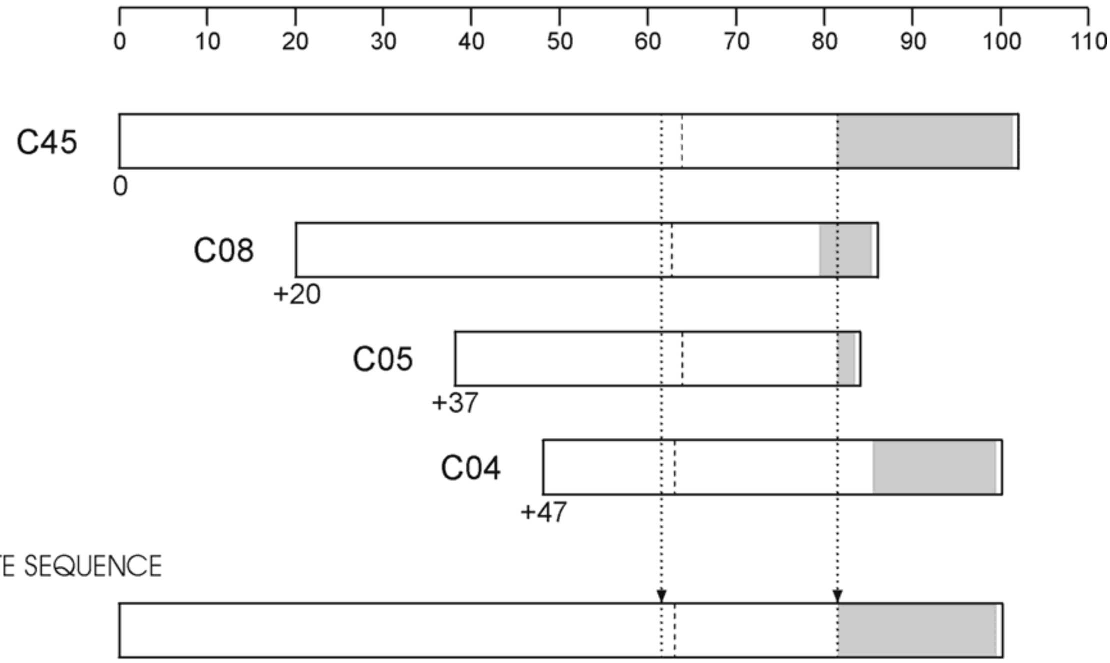


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

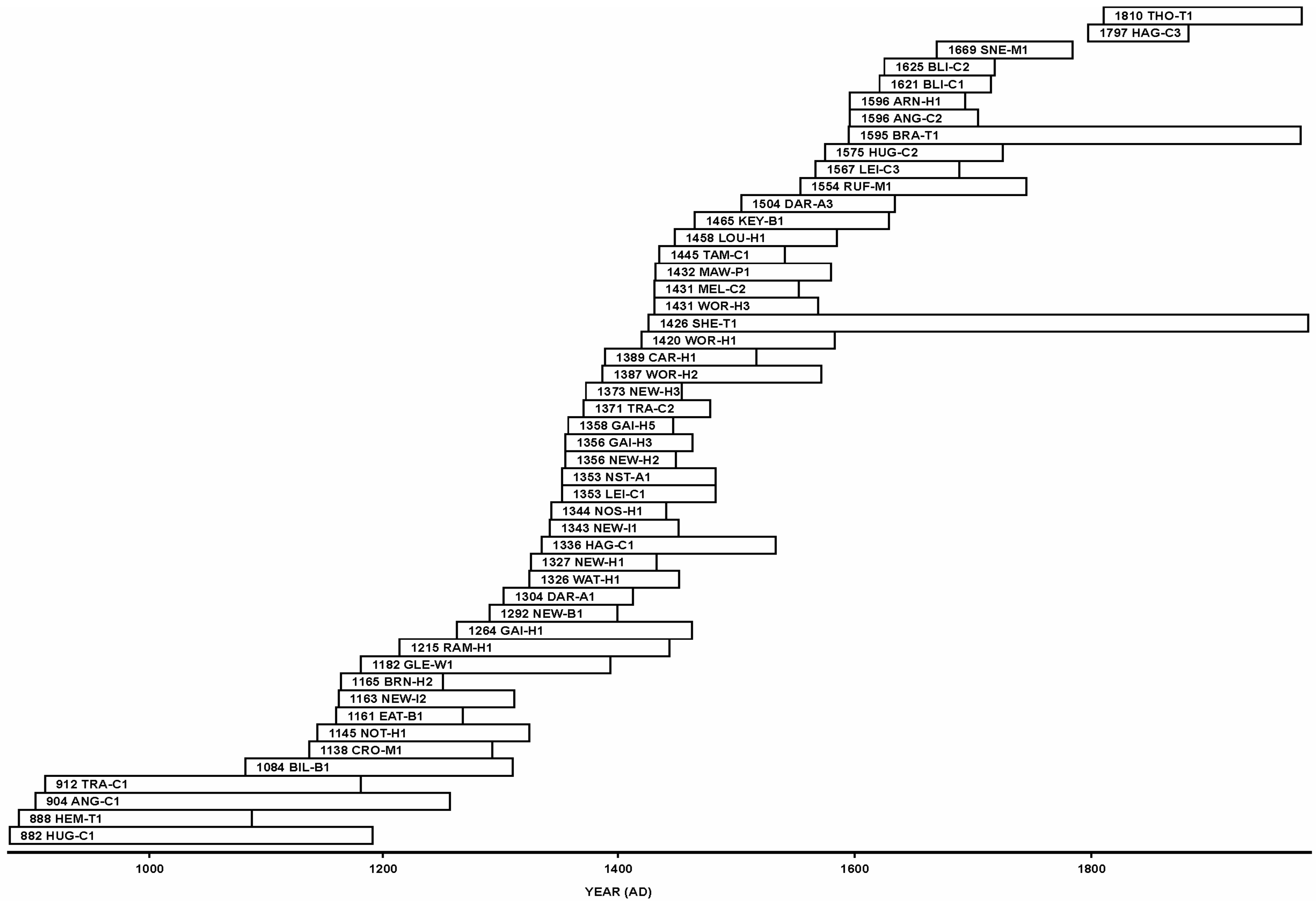
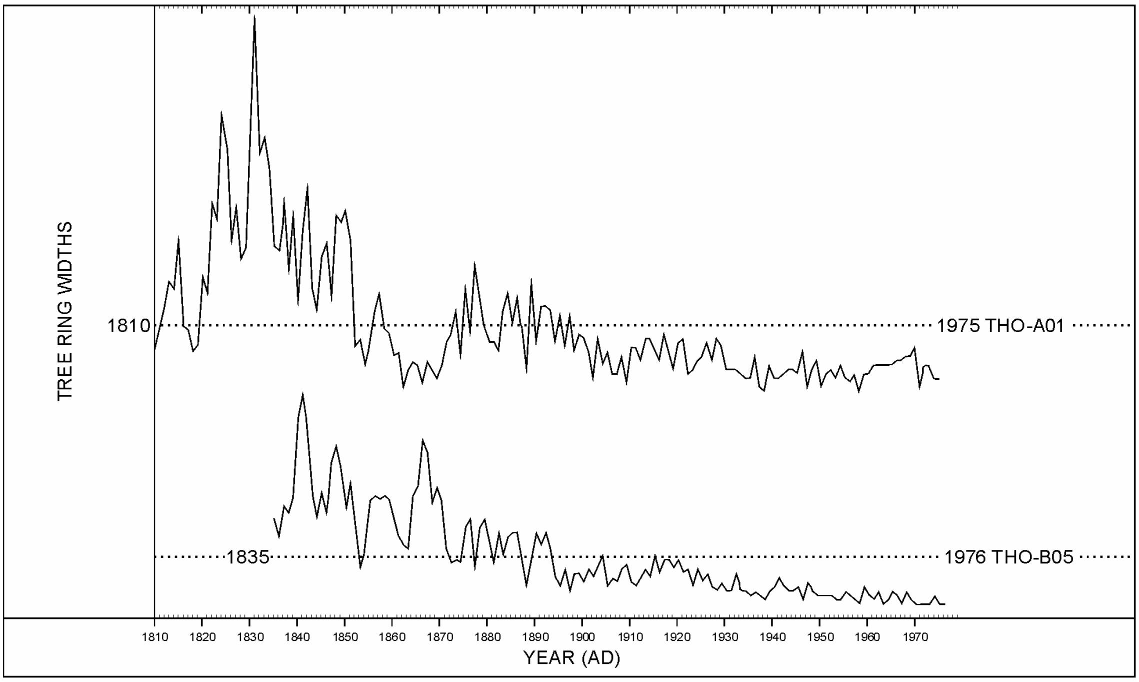


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

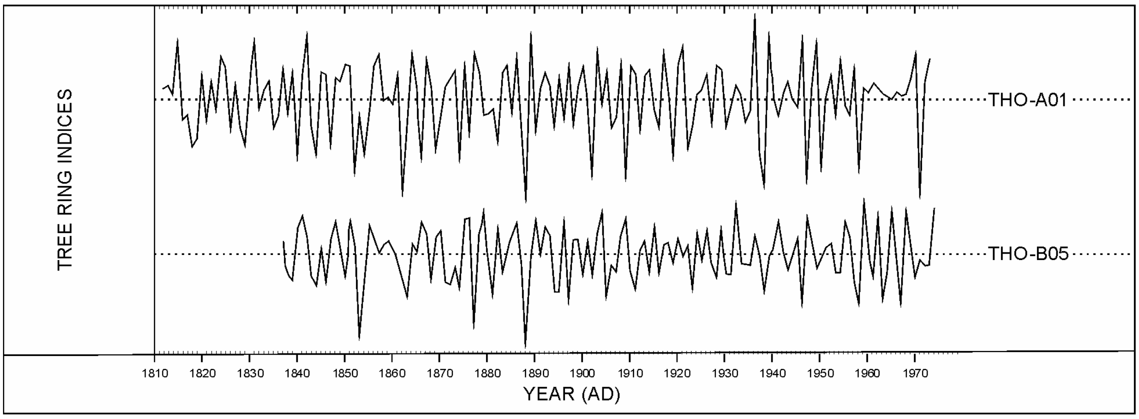


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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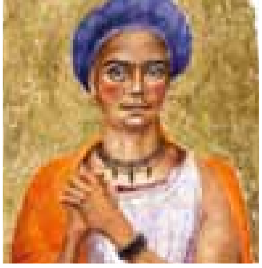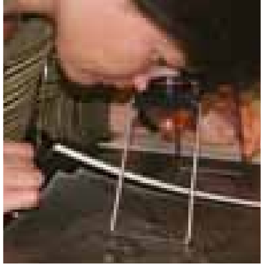

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