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The Great Tythe Barn, Bolton Abbey, North Yorkshire

Tree-ring Analysis of Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

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Research Report Series no. 48-2015

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SUMMARY

Dendrochronological analysis was undertaken on 42 of the 43 samples obtained from the northern and southern parts of the Great Tythe Barn at Bolton Abbey. This analysis produced a single site chronology comprising 37 samples, being 169 rings long, and dated as spanning AD 1350–1518. Interpretation of the sapwood on the dated samples indicates that the entire barn is the product of a single programme of felling starting in the spring of AD 1518 and finishing in the dormant period during the winter of AD 1518/19. As such, it is clear that the two parts of the barn, in spite of showing some differences in construction, are coeval. Five measured samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold, Robert Howard, and Cathy Tyers.

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DATE OF INVESTIGATION

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CONTENTS

INTRODUCTION

The Great Tythe Barn, a Grade II* listed building, is part of the Scheduled Monument of Bolton Priory, the remains of which lie some 350 metres to the north-north-east of the barn (Figs 1a/b/c). The barn has been the subject of preliminary survey and recording undertaken by the Yorkshire Vernacular Buildings Study Group (YVBSG 2004) and is currently the subject of further research. The barn is a substantial, approximately north-south, double-aisled structure, just over 47 metres long (Figs 2 and 3), formed of king-post trusses, and is hipped at either end. The trusses support double purlins to each pitch of the roof. The upper principal rafters, above the tiebeams, tend to have a noticeable 'knee' in them near their bases, and there are slightly curved braces between arcade posts and tiebeams, between arcade posts and arcade plates, and between wall posts and aisle ties. There are also wind braces springing from the upper parts of the principal rafters to the ridge beam. Along the length of the barn, mid-way between each king-post truss, the roof is supported by intermediate trusses which consist of pairs of principal rafters linked at their upper ends by a saddle on which stands a stubby upper king-post supporting the ridge. These principals are carried by the arcade plates, with further principals supporting the aisle roof (Figs 4a/b).

The six trusses of the northern end of the barn have been numbered following the original carpenters marks I–VI, from north to south, while the four trusses of the southern end are numbered I–IIII, again from north to south. Although all of the trusses are of the same overall design and construction, there are noticeable differences between the northern six trusses and the four trusses to the southern end of the barn. The four southern trusses tend to utilise timber of larger scantling, with the posts widening towards the top from a cross-section of approximately 458mm x 305mm near ground level, to 660mm x 305mm near the top. In the northern part of the barn the posts widen less markedly, with the maximum cross-section being 610mm x 305mm. The braces are up to 400mm broad on the southern trusses, but only 280mm broad on the northern trusses. In addition, the joints in the wider or larger timbers of the southern end all appear to require three pegs to secure them, while the joints in the northern timbers only require two pegs.

Whilst it had been generally accepted that the barn was of sixteenth-century origin, these differences had previously led to speculation as to whether the barn comprised two completely separate phases of construction of different date or whether the two ends were basically coeval but perhaps constructed by two different teams of carpenters.

SAMPLING

An initial programme of dendrochronological analysis, instigated by Arnold Pacey of the YVBSG, was undertaken on the Great Tythe Barn in 2005 (Howard 2007) with the aim of ascertaining the date of construction of the northern and southern sections of the barn. It was hoped that this earlier analysis would resolve the chronological relationship between the two sections of the barn and establish whether either section was of pre- or post-Dissolution date.

This first programme of analysis produced a total of 17 samples, nine from the northern end and eight from the southern. However, due to limited access at that time, sampling was less than optimal for such a large structure and, whilst the results hinted at a possible break of construction, albeit by only a single year, between the two halves of the barn, the issue was not adequately resolved. In 2014 English Heritage commissioned a programme of additional sampling to inform decisions relating to the future use of the barn. It was hoped that it would be possible to enhance the previous findings and provide further information relating to the extent of the survival of timber associated with the primary construction. Access issues to individual timbers had significantly improved and it was intended that this new programme would target previously inaccessible timbers, particularly those with surviving bark edge. In addition, it was hoped to ascertain when the internal partition wall (on the line of truss 1 south) was inserted.

Thus, having first reassessed the timbers throughout the barn as to their suitability for tree-ring analysis, and in compliance with the limits set by the Scheduled Monument Consent, an additional 26 samples were obtained from the most appropriate timbers by coring, this giving an overall total for the site of 43 samples. Each sample was given the code BLT-A (for Bolton Abbey, site 'A') and numbered 01–43 (Table 1), those from the earlier programme of analysis being renumbered as appropriate. Nineteen samples (BLT-A01–A19) have been obtained from the six trusses of the northern end of the barn (trusses 1–6 north), 22 samples (BLT-A20–A37 and BLT-A40–43) from the timbers of the four trusses of the southern end (trusses 1–4 south), and two samples (BLT-A38 and A39) from the only extant timbers of the internal partition wall. It should be noted that a number of timbers selected for sampling had complete sapwood present but that it was in a highly friable state and, unfortunately, could not be kept intact on the core during sampling. In respect of the sampling, it might be noted that while there were many other timbers which could potentially have been sampled (to the intermediate trusses for example), these were often less suitable in either having lower ring numbers, or perhaps not having sapwood or the heartwood/sapwood boundary

Where possible (samples BLT-A38 and BLT-A39 not being shown), the locations of the cores were recorded at the time of sampling on drawings taken from the YVBSG survey, these being shown here as Figure 5a-k. The samples have been located following the schema of these drawings, with individual timbers being then further identified on a north-south or east-west basis as appropriate.

ANALYSIS AND RESULTS

Each of the 43 samples obtained from the Great Tythe Barn was prepared by sanding and polishing. It was seen at this time that one sample, BLT-A38, had less than the 40 rings deemed necessary for possible dating here and it was rejected from this programme of analysis. The annual growth ring widths of the remaining 42 samples were measured, the data of these measurements being given at the end of this report.

The data of the 42 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of a single group comprising 37 samples being formed, the samples cross-matching with each other as shown in Figure 6. The 37 samples were combined at their indicated offset positions to form site chronology BLTASQ01, this having an overall length of 169 rings.

Site chronology BLTASQ01 was then compared to an extensive corpus of reference material for oak, this indicating a consistent and repeated match with a series of these when the date of its first ring is AD 1350 and the date of its last measured ring is AD 1518. The evidence for this dating is given in Table 2.

Site chronology BLTASQ01 was also compared to the five remaining measured but ungrouped samples, but there was no further satisfactory cross-matching. These five ungrouped samples were then compared individually to the full corpus of reference data, but again there was no satisfactory cross-matching and they must all, therefore, remain undated.

INTERPRETATION

Northern trusses 1–6

Of the 17 dated samples from the northern part of the barn, five retain complete sapwood, this meaning that they each have the last growth produced by the tree represented before it was felled. In each case this last growth ring is dated AD 1518. In one instance this outermost growth ring appears to be complete, comprising spring wood and summer wood (Fig 7a), and would thus appear to indicate that the timber represented was felled during the dormant period in the winter of AD 1518/19. The remaining four samples all have spring wood but very little, if any, summer wood (Figs 7b-f) suggesting that the timbers represented were felled during the summer of AD 1518 before the dormant season set in. It should, however, be noted that the outermost rings on sample BLT-A08 are all very narrow and thus it is possible that its outermost ring is complete and hence it could also have been felled during the dormant period in winter AD 1518/19,

The amount of sapwood, including the known sapwood amounts lost during coring, and the relative position the heartwood/sapwood boundary on the other nine samples from the northern end of the barn, makes it very likely that the trees they represent were felled in, or around, AD 1518 as well. As, may be seen, on Table 1 and Figure 6, the heartwood/sapwood boundary of this entire group of dated timbers from the northern section varies by only 12 years, from relative position 133 (AD 1482) on sample BLT-

A03, to relative position 145 (AD 1494) on samples BLT-A07, BLT-A10, and BLT-A11. Such a small variation is indicative of a group of timbers representing a single felling programme. The remaining three samples have no trace of sapwood but the level of cross-matching within this group of timbers from the northern end of the barn, as well as possible same-tree matches between BLT-A02 and BLT-A19 (t = 10.3) and BLT-A17 and BLT-A18 (t = 12.2), strongly suggests that they are coeval and hence part of the same programme of felling.

Southern trusses 1–4

Of the 20 dated samples from the southern part of the barn, three also retain complete sapwood. In two instances, the outermost complete and measured ring dates to AD 1517 but partial spring wood is present for the following year (Figs 7f and 7g) indicating that the timbers represented were felled during the spring of AD 1518. The outermost growth ring of the remaining sample appears to be complete (Fig 7h) and dates to AD 1518 and would thus appear to indicate that the timber represented was felled during the dormant period in winter AD 1518/19.

The amount of sapwood, including the known sapwood amounts lost during coring, and the relative position of the heartwood/sapwood boundary of the other 17 samples from the southern section, again, makes it likely that the timbers they represent were also part of the same felling programme. As may again be seen on Table 1 and Figure 6, the heartwood/sapwood boundary on this entire group of dated timbers from the southern section varies, with one exception, by 17 years from relative position 139 (AD 1488) on sample BLT-A36, to relative position 156 (AD 1505) on sample BLT-A33. Such a variation is again indicative of a group of timbers representing a single programme of felling. The exception is BLT-A41 which has a slightly earlier heartwood/sapwood boundary dating to AD 1481, but this is one of the three dated timbers with bark edge.

DISCUSSION

The timbers from the northern and southern section of the barn are clearly coeval and represent a single programme of felling but there are differences between the timbers in each section which suggests that they were derived from different, albeit relatively local, woodland sources.

The 17 dated samples from the northern section cross-match with each other very well, with a number of values in excess of t=5.0, t=6.0, and t=7.0 being seen. Such values would suggest that the source trees were growing close to each other in a discrete area of woodland. Indeed the cross-matching between some samples, as indicated above, would suggest that some pairs of timbers may be derived from single trees. The 20 dated samples from the southern section, on the other hand, appear more disparate and cross-match with each other slightly less well, with fewer values in excess of t=5.0 being seen and no potential same-tree matches. The cross-matching between the dated samples from each section is generally relatively lower suggesting different sources were being used for timbers from either end of the barn. In respect of the location of the source woodlands, it may be noted from Table 2 that, although site chronology BLTASQ01and its two sub-sequences, representing the two sections of the barn, have been compared to reference chronologies from all parts of England, the highest levels of similarity are found with other sites in northern England, particularly those elsewhere in Yorkshire. This suggests that the dated timbers used throughout the Great Tythe Barn are from relatively local woodland sources.

The rate of growth and ages of the trees used in the two sections of the barn show some overall differences (Fig 8). Although the number of rings present in the cores is under-representative of the age of the tree at felling it can be seen that the trees used in the southern section tend to be younger and faster grown when compared to the more variable ages and growth rates of the trees used in the northern section. This again points to the use of different woodland sources.

Also notable is the difference in date of the average heartwood/sapwood boundary for the two sections of the barn with timbers in the northern section tending to have earlier heartwood/sapwood boundary dates than those from the southern section (Fig 9; Table 1). The average heartwood/sapwood boundary ring of the northern samples is dated AD 1489, while on the southern samples the average heartwood/sapwood boundary is dated to AD 1497. In the absence of any complete sapwood this could have led to the suggestion that the northern section potentially pre-dated the southern section by a few years which is clearly not the case as the timbers used in both sections appear to represent a single programme of felling.

CONCLUSION

Tree-ring analysis of 42 measured samples from the Great Tythe Barn at Bolton Abbey has produced a single site chronology, BLTASQ01, comprising 37 samples and being 169 rings long. These rings are dated as spanning the years AD 1350–1518. The dated samples all represent timbers associated with the main primary construction of the barn; unfortunately it was not possible to date the only measured sample from the internal partition.

The analysis undertaken shows that those dated timbers with complete sapwood were felled over a period spanning a maximum of just under a year but potentially a minimum of around six months. The earliest definite felling identified is in spring AD 1518 with the latest felling identified being in the winter of AD 1518/19. The southern section of the barn has timbers felled in spring AD 1518 and winter AD 1518/19, whereas the northern section of the barn has timbers felled during summer AD 1518 and winter AD 1518/19. As such, it is clear is that the two parts of the barn are coeval. The results also indicate that all of the timbers were derived from local woodlands but that the source of timber for the two sections of the barn appears to be different.

The presence of undated samples is, however, a frequent feature of tree-ring analysis, and in this respect the Great Tythe Barn is slightly unusual in having such a high number of its measured samples, 88%, successfully dated, particularly when considering that some parts of North Yorkshire are problematic. Despite having sufficient rings for reliable dating, five measured samples, BLT-A09, BLT-A15, BLT-A34, BLT-A35, and BLT-A39, remain ungrouped and undated, although none of them show any distortion or disturbance to their growth which might make cross-matching and dating difficult.

BIBLIOGRAPHY

Arnold, A J, and Howard, R E, 2013 unpubl Tree-ring analysis of timbers from Red Gables Cottage, Boyne Hill, Chapelthorpe, Crigglestone, West Yorkshire, Nottingham Tree-ring Dating Laboratory unpubl computer file *CRGASQ01*

Arnold, A J, and Howard, R E, 2015 *Whalley Abbey, Whalley, Lancashire; Tree-ring analysis of timbers from the Great Hall and North Range,* English Heritage Res Rep Ser, 3/2015

Hillam, J, 1984 *Tree-ring analysis of timbers from Elland Old Hall, West Yorkshire,* Anc Mon Lab Rep, 4165

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1991 List 39 nos 2a, 10, Nottingham University Tree-Ring Dating Laboratory, general list, *Vernacular Architect*, **22**, 40–3

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 23, Nottingham University Tree-Ring Dating Laboratory, results, *Vernacular Architect*, **23**, 51–6

Howard, R E, Laxton, R R, Litton, C D, Morrison A, Sewell, J, and Hook, R, 1993 List 49 no 9a, Nottingham University Tree-Ring Dating Laboratory, Derbyshire, Peak Park and RCHME dendrochronological Survey 199–92, *Vernacular Architect*, **24**, 43–4

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1994 List 57 no 4a, Nottingham University Tree-Ring Dating Laboratory, results, *Vernacular Architect*, **25**, 36–40

Howard, R, 2007 (unpublished), *Tree-Ring Analysis of Timbers from the Great Tythe Barn, Bolton Abbey, North Yorkshire*,

Tyers, I, 2001 *Dendrochronological analysis of timbers from Headlands Hall, Liversedge, West Yorkshire,* ARCUS Rep, 574c

Yorkshire Vernacular Buildings Study Group (YVBSG) 2004,The Great Tythe Barn, Bolton Abbey, North Yorkshire

TABLES

Table 1: Details of tree-ring samples from the Great Tythe Barn, Bolton Abbey, North Yorkshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	North barn, trusses 1–6					
BLT-A01	Brace to tiebeam from east arcade post, truss 1	107	no h/s	1378	------	1484
BLT-A02	Brace to tiebeam from west arcade post, truss 1	99	no h/s	1371	------	1469
BLT-A03	East arcade post, truss 2	124	36C	1395	1482	1518
BLT-A04	Brace to tiebeam from east arcade post, truss 2	87	h/s	1403	1489	1489
BLT-A05	Brace to tiebeam from west arcade post, truss 2	105	25C	1414	1493	1518
BLT-A06	East arcade post, truss 3	68	h/s	1420	1487	1487
BLT-A07	Brace to tiebeam from west arcade post, truss 3	115	24C	1404	1494	1518
BLT-A08	Tiebeam, truss 4	136	30C	1383	1488	1518
BLT-A09	West arcade post, truss 5	88	h/s	------	------	------
BLT-A10	Tiebeam, truss 3	112	24C	1407	1494	1518
BLT-A11	West principal rafter, truss 3	90	3	1408	1494	1497
BLT-A12	East arcade post, truss 4	136	21+5mm ?c	1374	1488	1509
BLT-A13	East principal rafter, truss 4	67	h/s+30mm c	1418	1484	1484
BLT-A14	West arcade post, truss 4	113	9	1383	1486	1495
BLT-A15	Brace to tiebeam from east arcade post, truss 4	73	h/s	------	------	------
BLT-A16	Brace to tiebeam from east arcade post, truss 5	58	h/s	1433	1490	1490
BLT-A17	Brace to tiebeam from west arcade post, truss 5	60	no h/s	1413	------	1472
BLT-A18	Brace to tiebeam from west arcade post, truss 6	89	h/s	1397	1485	1485
BLT-A19	South brace to west arcade plate from truss 6	91	h/s	1397	1487	1487

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
	South barn trusses 1–4					
BLT-A20	South brace to east arcade plate, truss 1	82	h/s	1421	1502	1502
BLT-A21	King post, truss 2	97	2	1408	1502	1504
BLT-A22	Tiebeam, truss 2	69	h/s	1436	1504	1504
BLT-A23	East aisle tie, truss 3	127	h/s	1364	1490	1490
BLT-A24	West lower purlin, truss 3–4	62	17	1445	1489	1506
BLT-A25	North brace, to east arcade plate, truss 4	83	19C	1435	1498	1517
BLT-A26	East arcade post, truss 4	91	h/s	1403	1493	1493
BLT-A27	West arcade post, truss 4	83	h/s	1415	1497	1497
BLT-A28	West arcade post, truss 1	69	8	1439	1499	1507
BLT-A29	East arcade post, truss 2	82	h/s	1422	1503	1503
BLT-A30	West arcade post, truss 2	96	12+10mm	1417	1500	1512
BLT-A31	East arcade post, truss 3	86	20+2mm	1431	1496	1516
BLT-A32	West arcade post, truss 3	86	4+20mm	1420	1501	1505
BLT-A33	Brace to tiebeam from west arcade post, truss 3	77	2	1431	1505	1507
BLT-A34	South brace to west arcade plate, truss 3	48	7+10mm	------	------	------
BLT-A35	East rafter, intermediate truss 3A	72	h/s	------	------	------
BLT-A36	East lower purlin, truss 3–4	53	4	1440	1488	1492
BLT-A37	South hip purlin	53	h/s+20mm	1437	1489	1489
BLT-A40	East principal rafter, truss 2	93	17C	1425	1500	1517
BLT-A41	King post, truss 3	168	36C	1350	1481	1517
BLT-A42	Tiebeam, truss 3	89	h/s+15mm c	1416	1504	1504
BLT-A43	West plate, aisle post truss 4 to south wall	84	h/s+20mm c	1420	1503	1503
	Partition wall timbers					
BLT-A38	Cross wall, units 5–7	nm	---	------	------	------
BLT-A39	Aisle wall, units 3–5	83	9	------	------	------

h/s = the heartwood/sapwood ring is the last ring on the sample; C = complete sapwood is retained on the sample; c = complete sapwood on timber, but all or part lost from sample in coring; nm = rings not measured: mm = millimetres of core lost during sampling

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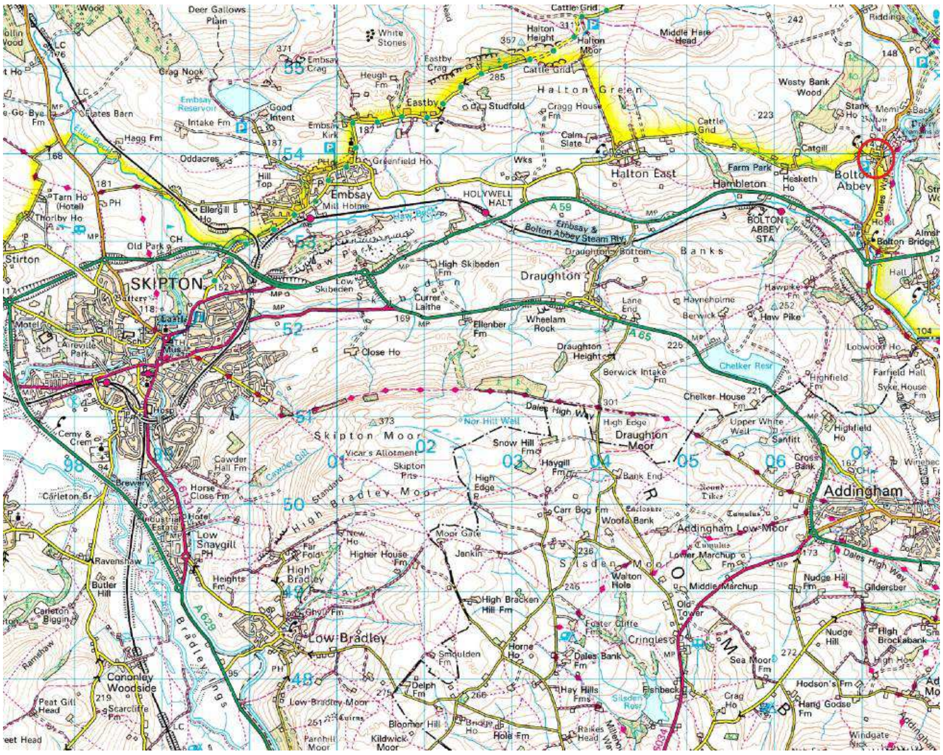
Table 2: Results of the cross-matching of site sequence BLTASQ01 and relevant reference chronologies when the first-ring date is AD 1350 and the last-ring date is AD 1518

Reference chronology	Span of chronology				Reference
		BLTASQ01	BLTA-N	BLTA-S	
Headlands Hall, Liversedge, West Yorkshire	AD 1388–1487	11.4	8.7	11.4	(Tyers 2001)
Elland Old Hall, West Yorkshire	AD 1372–1574	10.0	9.7	7.8	(Hillam 1984)
Nether Levens Hall, Kendal, Cumbria	AD 1395–1541	9.8	8.5	8.1	(Howard *et al* 1991)
Red Gables Cottage, Crigglestone, West Yorkshire	AD 1384–1590	9.8	8.5	7.3	(Arnold and Howard 2013 unpubl)
Horbury Hall, Wakefield, West Yorkshire	AD 1368–1473	9.2	8.2	7.5	(Howard *et al* 1992)
Whalley Abbey, Whalley, Lancashire	AD 1362–1559	9.0	6.2	8.1	(Arnold and Howard 2015)
Ordsall Hall, Salford, Greater Manchester	AD 1385–1512	8.7	7.3	7.4	(Howard *et al* 1994)
Hall Broom Farm, Dungworth, Derbyshire	AD 1382–1495	8.7	7.5	7.8	(Howard *et al* 1993)

FIGURES



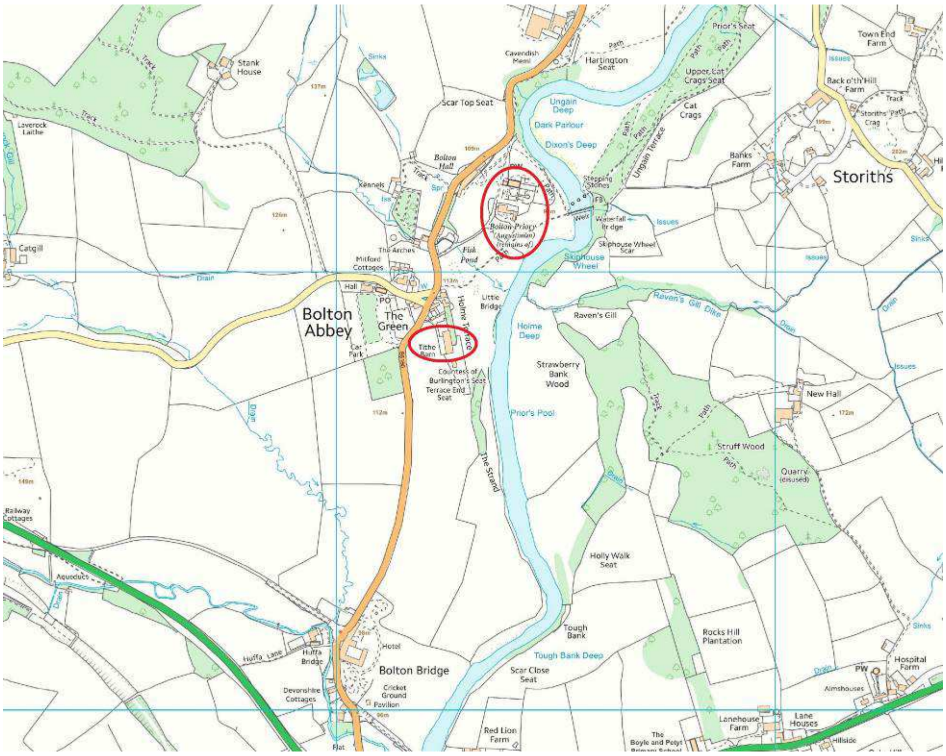


Figure 1a/b: Maps to show the location of Bolton Abbey (top) and the Barn and Priory (bottom). © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

Figure 1c: Map to show the detailed location of the Barn. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

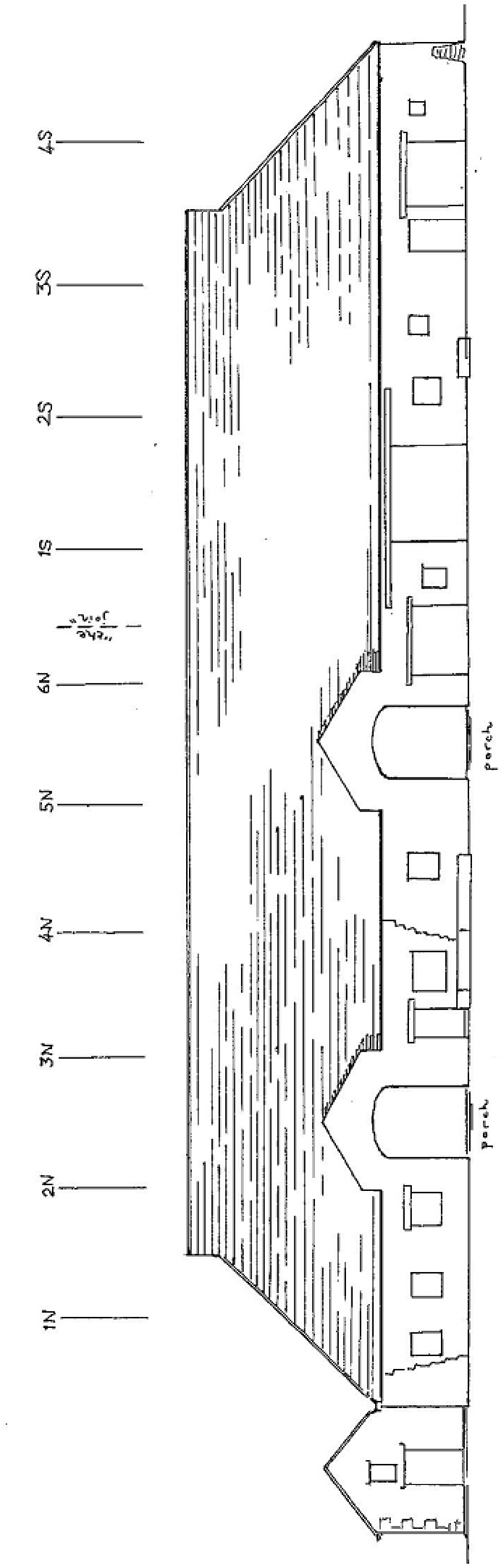


Figure 2: Exterior elevation of the Great Tythe Barn from the front or west (after Yorkshire Vernacular Buildings Study Group)

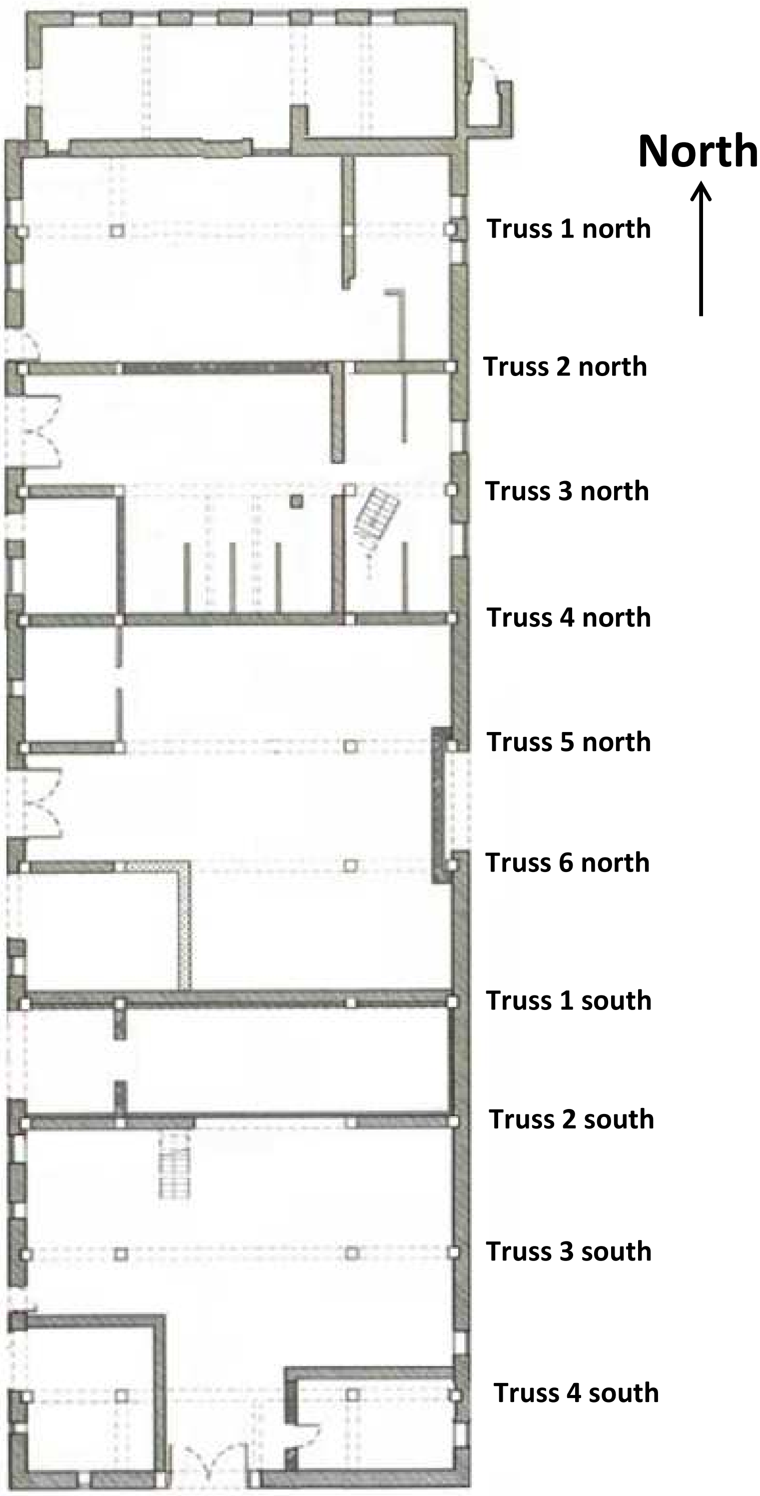


Figure 3: Plan of the Great Tythe Barn (after Yorkshire Vernacular Buildings Study Group)

Figure 4a/b: Views of the trusses (photographs Robert Howard)

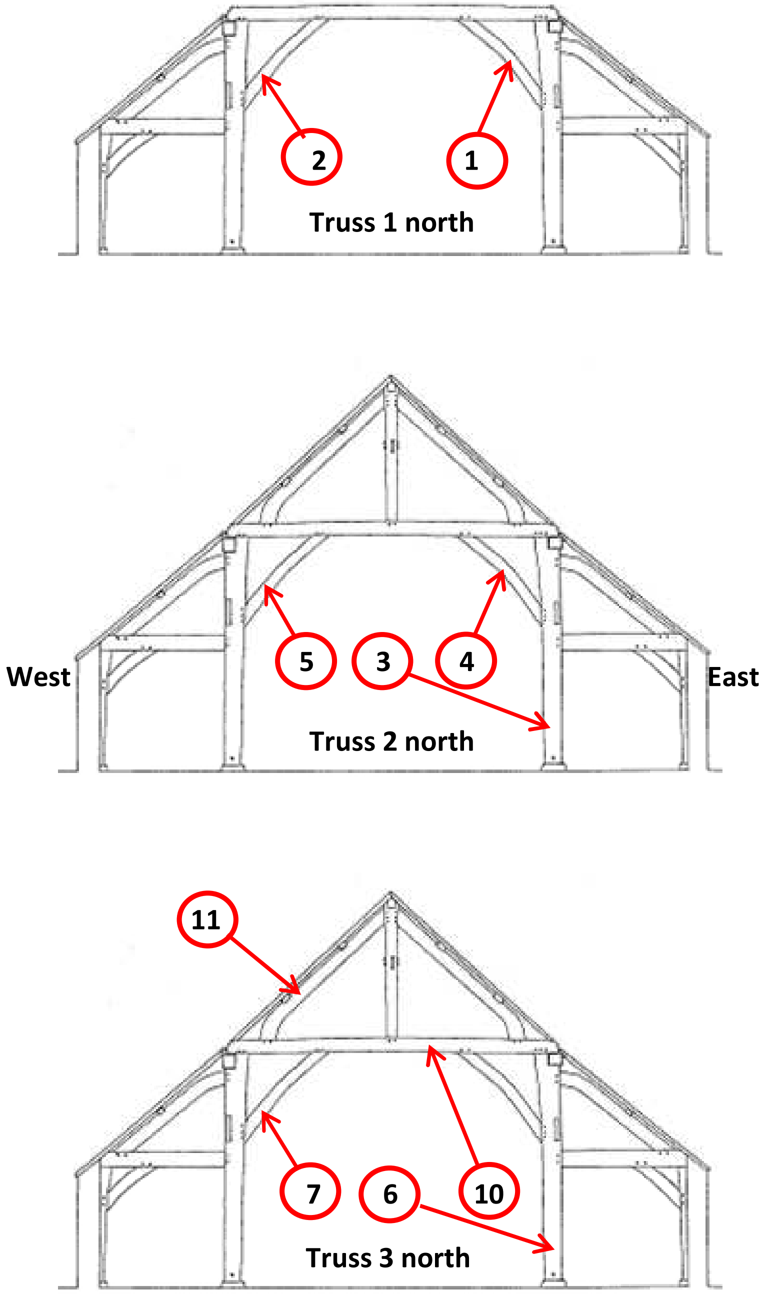


Figure 5a-c: Sections through the trusses to help locate sampled timbers (after Yorkshire Vernacular Buildings Study Group)

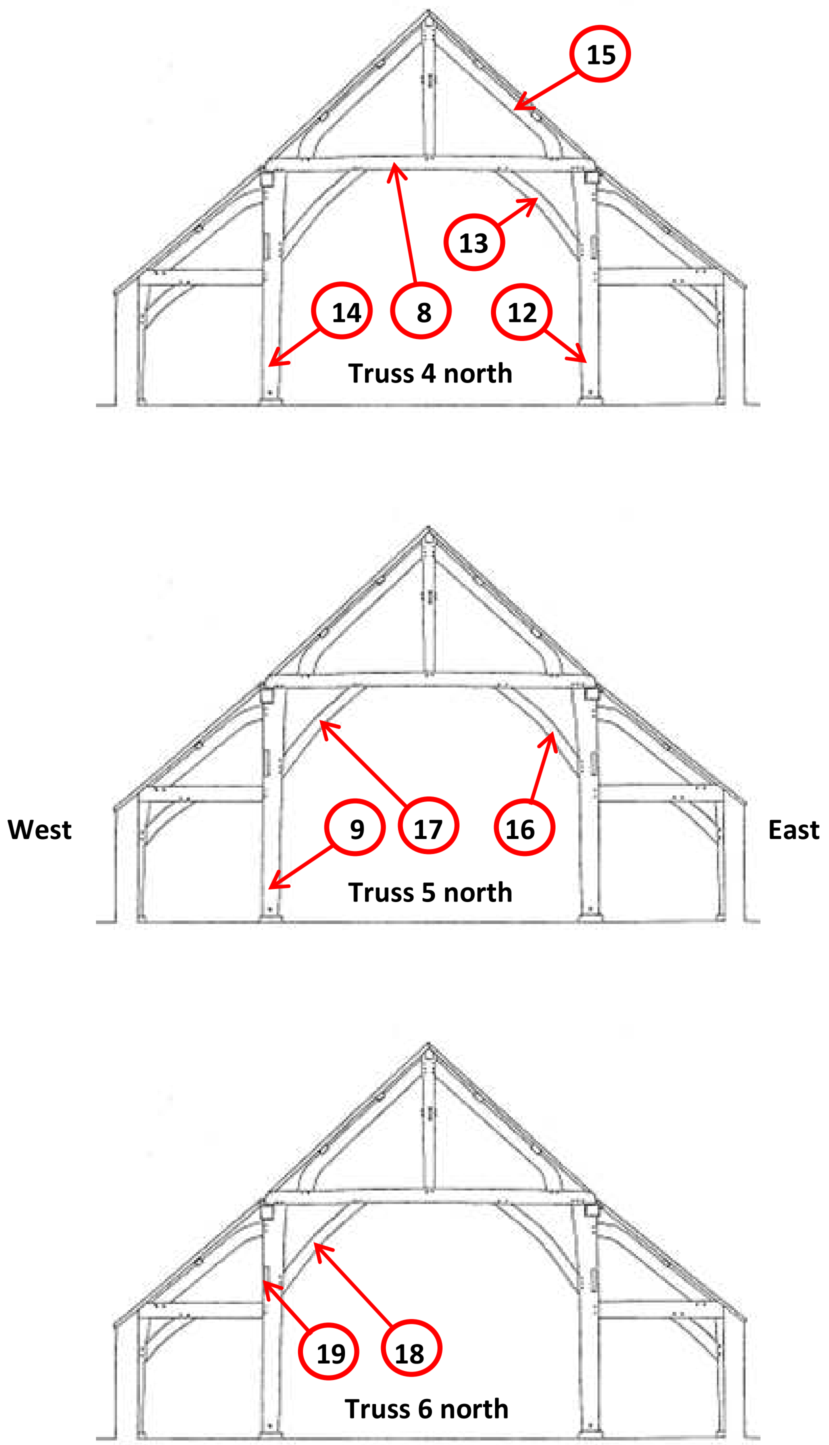


Figure 5d-f: Sections through the trusses to help locate sampled timbers (after Yorkshire Vernacular Buildings Study Group)

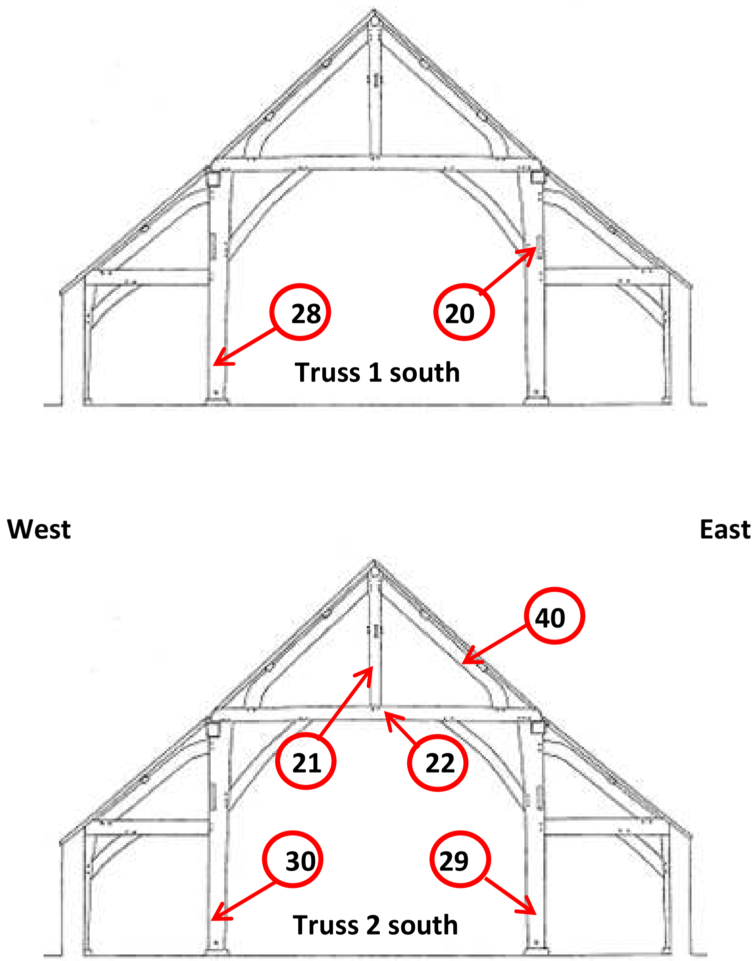
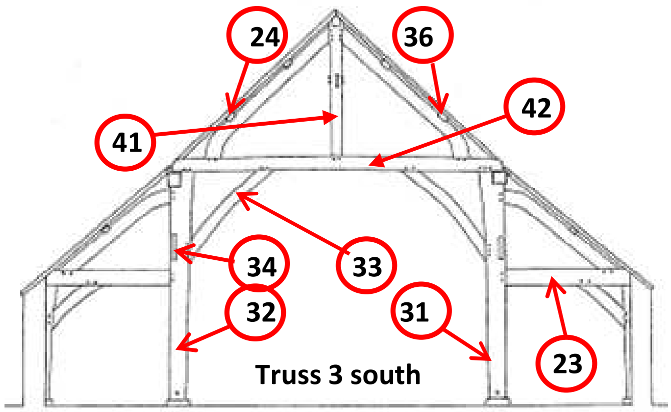
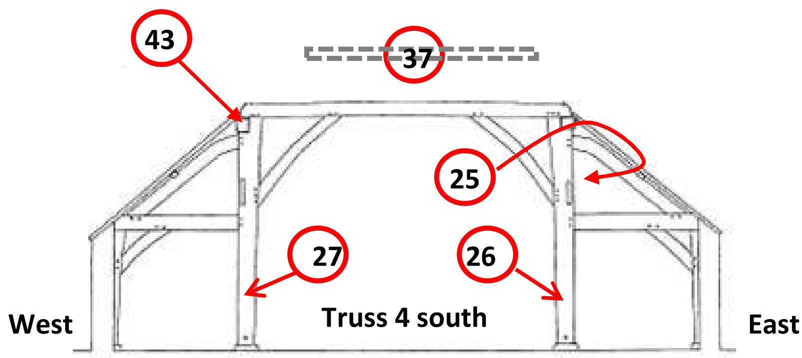


Figure 5g/h: Sections through the trusses to help locate sampled timbers (after Yorkshire Vernacular Buildings Study Group)





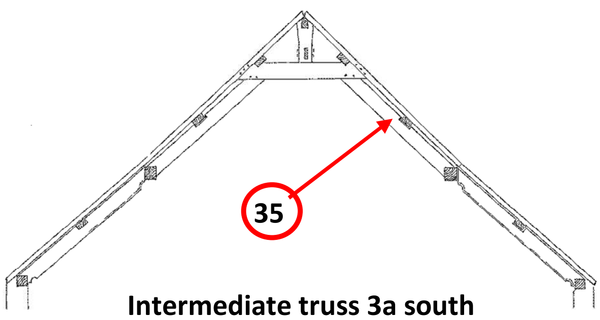
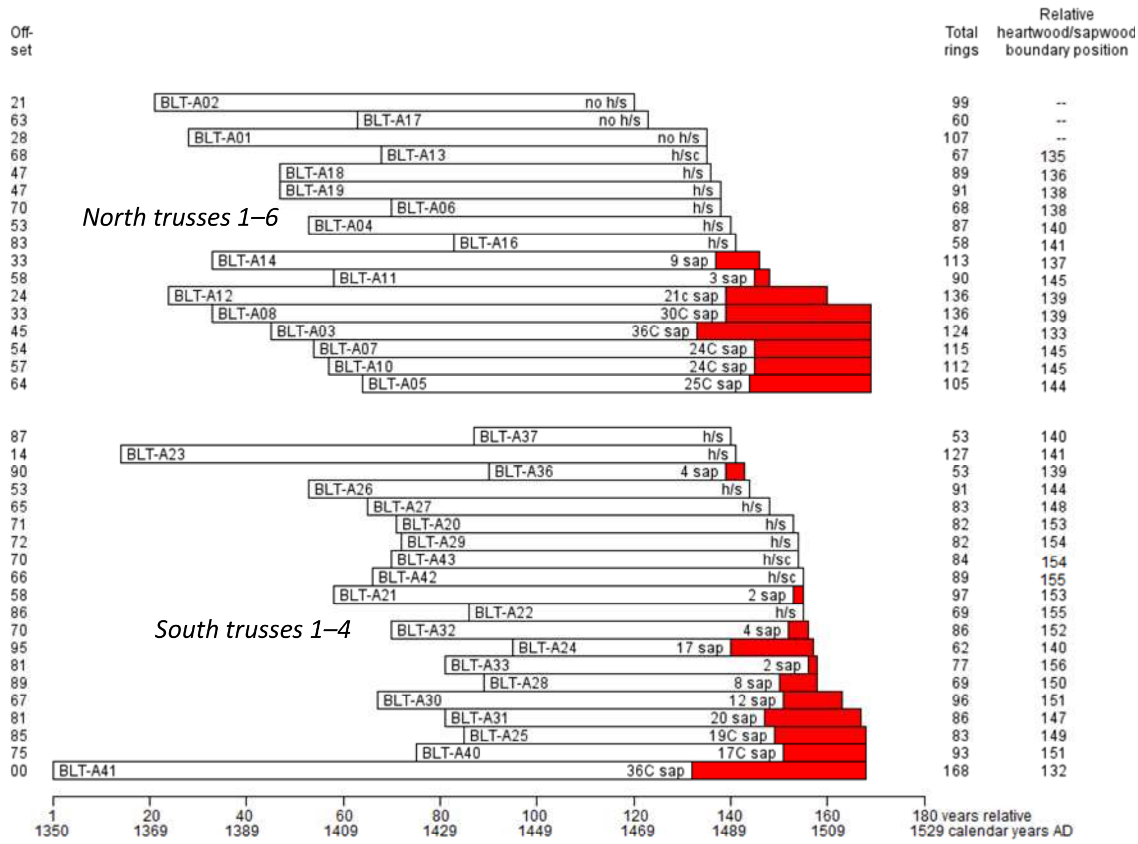
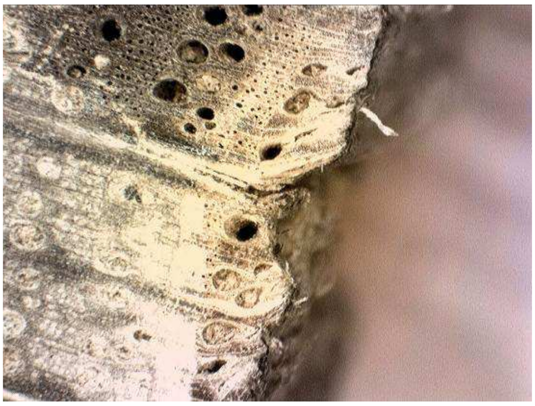


Figure 5i-k: Sections through the trusses to help locate sampled timbers (after Yorkshire Vernacular Buildings Study Group)

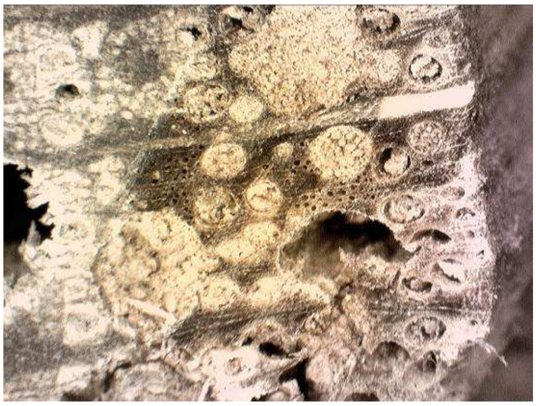


White bars = heartwood rings; shaded bars = measured sapwood rings
c= complete sapwood is retained on the timber, but all or part has been lost from the sample in coring
+ mm = estimated length, in millimetres, of lost sapwood
C = complete sapwood is retained on the sample
h/s = heartwood/sapwood boundary

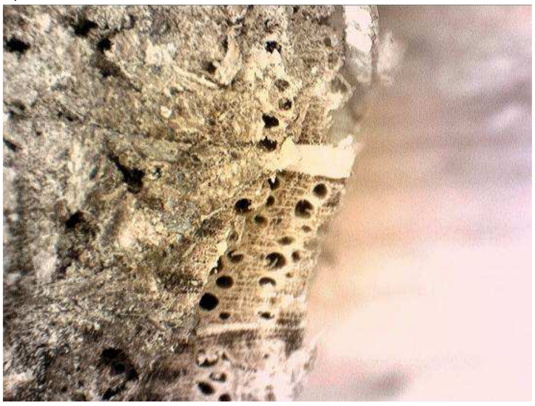
Figure 6: Bar diagram of the samples in site chronology BLTASQ01 sorted by sample location



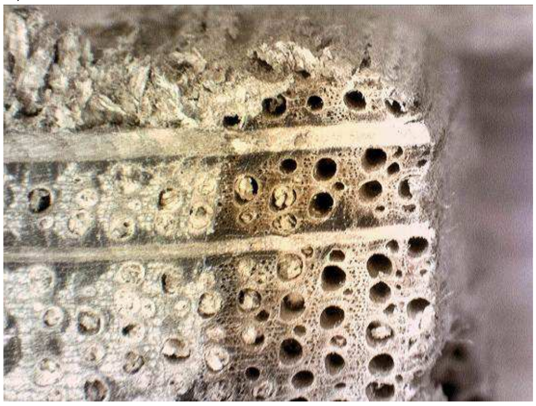
a) BLT-A03



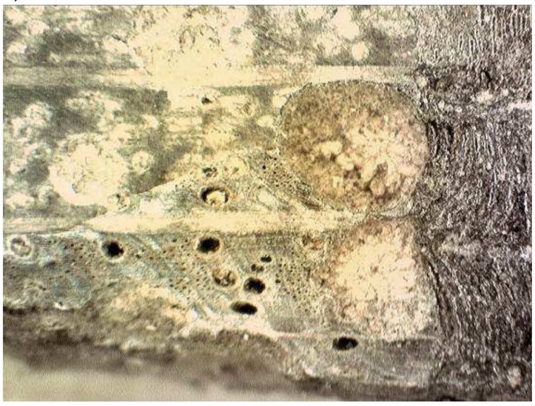
b) BLT-A05



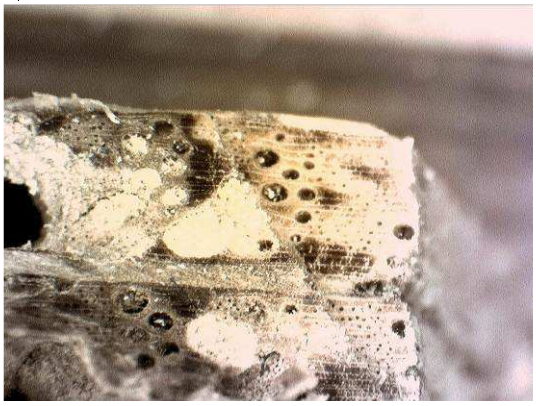
c) BLT-A07



d) BLT-A08

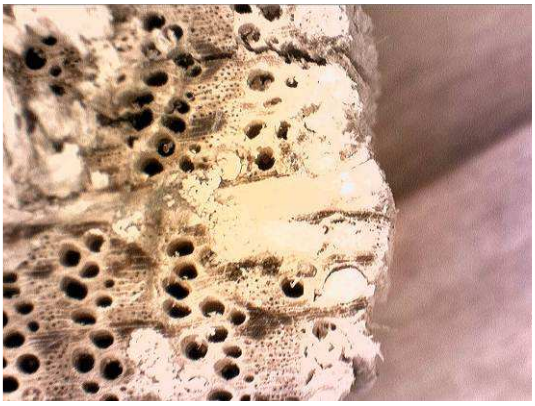


e) BLT-A10



f) BLT-A25

Figure 7a-f: Cores with sapwood complete to bark edge (photographs Ian Tyers)


g) BLT-A40

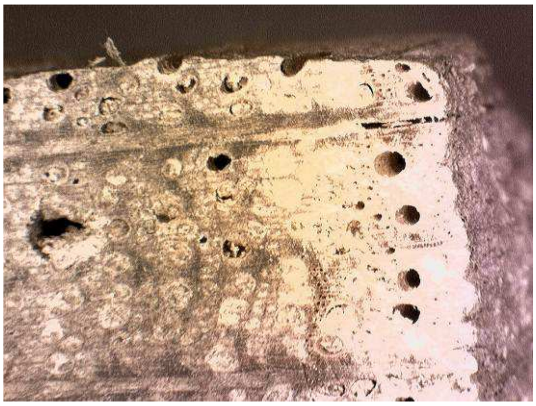

h) BLT-A41

Figure 7g-h: Cores with sapwood complete to bark edge (photographs Ian Tyers)

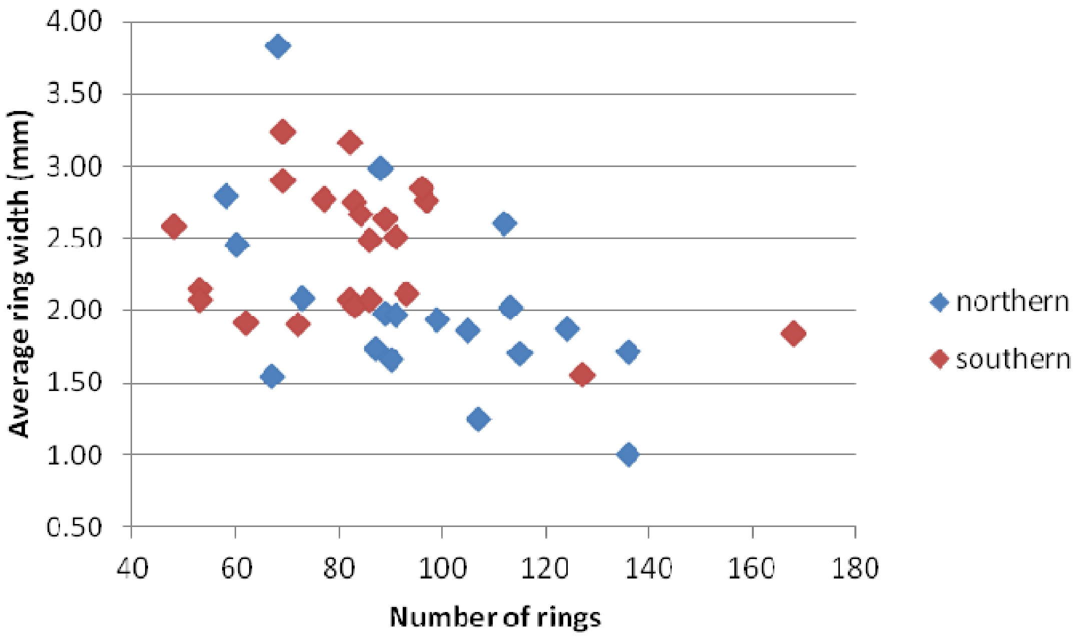


Figure 8: Diagram illustrating the differences in average ring width and ring sequence length between the northern and southern sections of the barn

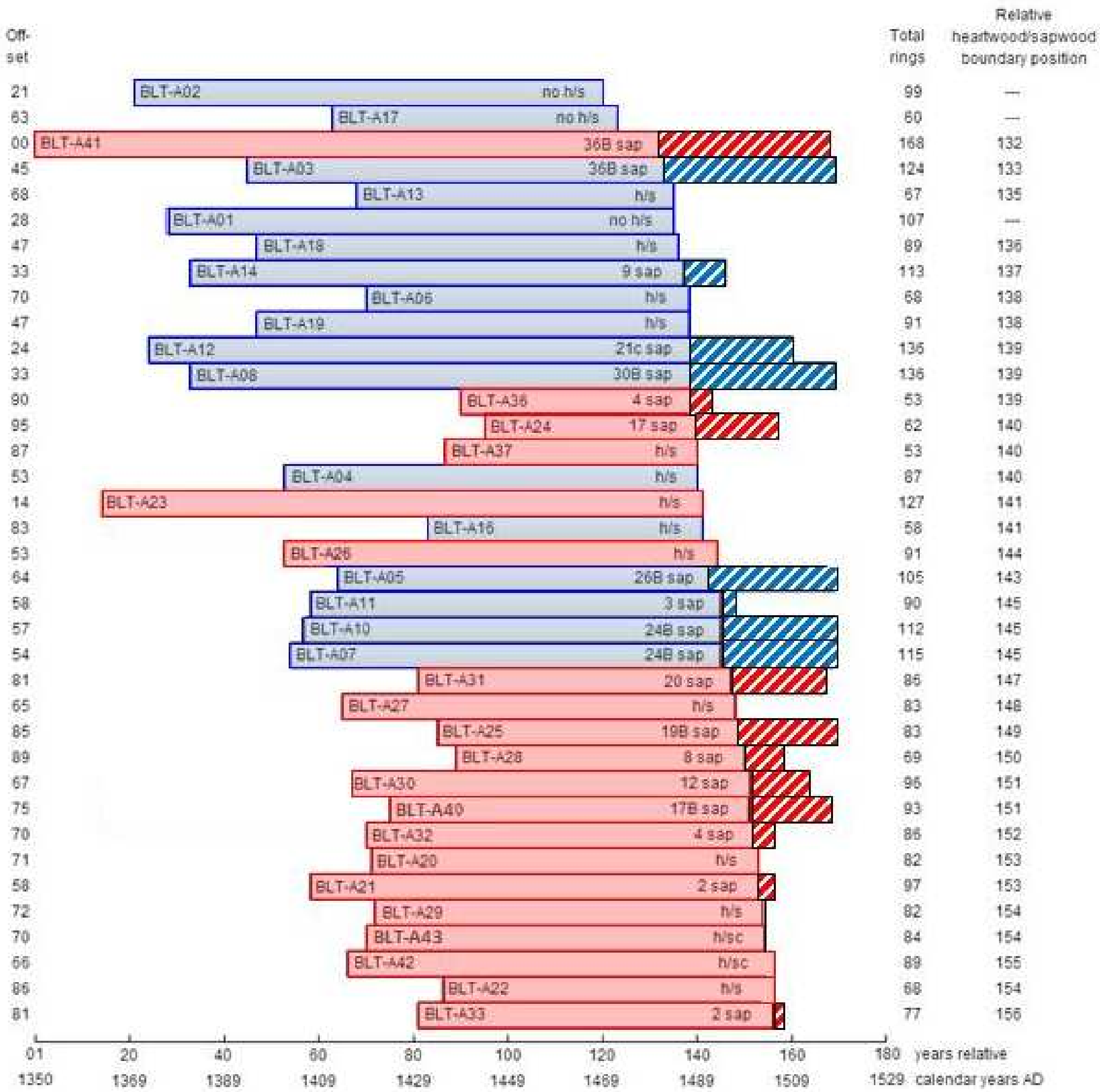


Figure 9: Bar diagram of the samples in site chronology BLTASQ01 sorted by heartwood/sapwood boundary date with the northern section samples in blue and the southern section samples in red

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BLT-A01A 107
117 191 176 169 193 170 165 113 174 156 197 218 180 172 216 175 156 166 157 130
119 143 183 147 127 153 179 174 177 131 162 146 144 153 182 141 134 131 92 108
163 92 183 146 79 117 134 119 104 88 86 111 94 92 111 88 82 124 74 86
71 65 77 74 64 69 78 76 73 100 88 73 96 92 123 97 115 112 137 126
114 129 129 99 119 106 95 88 107 119 114 133 135 135 135 123 115 142 132 113
94 95 101 111 118 112 111
BLT-A01B 107
115 180 163 170 178 185 155 146 159 169 198 210 175 181 182 185 162 173 169 135
125 130 191 144 116 153 167 177 175 121 153 149 138 150 187 146 146 125 110 120
164 85 177 140 100 137 127 128 101 81 92 114 103 87 108 95 84 120 62 87
75 57 70 78 64 89 82 70 73 110 86 81 93 93 116 107 109 109 127 134
110 129 125 106 118 103 145 91 102 119 107 129 138 137 134 125 106 134 141 107
98 96 99 114 117 112 110
BLT-A02A 99
378 347 185 237 217 210 177 291 271 187 174 164 180 267 186 217 253 220 254 183
212 260 226 171 194 227 179 182 178 233 178 116 185 171 202 270 142 163 249 219
212 224 195 200 168 130 177 214 133 218 189 138 127 182 141 135 170 201 195 226
188 331 165 217 238 245 210 186 154 150 155 106 132 226 213 148 192 173 173 181
189 214 133 181 169 211 228 167 180 202 147 140 116 102 100 160 194 211 221
BLT-A02B 99
407 351 200 227 206 215 205 260 276 175 184 223 182 265 189 217 235 237 255 206
189 278 225 169 190 225 174 185 170 246 183 143 181 179 193 273 138 168 254 218
217 212 207 190 181 146 196 195 137 204 196 139 132 170 146 131 173 198 201 234
181 347 159 200 232 254 209 193 137 168 152 125 128 228 218 160 181 190 170 175
173 203 146 178 171 194 224 172 196 210 145 140 121 90 106 159 206 183 226
BLT-A03A 124
401 466 335 379 316 367 346 322 334 355 306 425 252 382 400 298 294 376 309 249
300 178 273 244 154 460 226 220 228 228 267 253 244 268 300 199 222 319 136 243
192 181 172 188 205 143 173 124 178 180 213 142 189 154 175 145 138 198 127 113
134 178 162 112 162 145 150 171 194 149 135 215 201 205 197 182 203 96 128 81
183 171 128 119 150 133 145 89 137 103 129 140 178 78 74 59 64 61 53 79
82 137 89 128 102 103 82 119 144 164 101 118 124 98 100 134 106 90 95 100
68 97 115 105
BLT-A03B 124
399 476 326 367 317 366 332 325 330 371 283 430 272 364 375 302 293 388 282 242
250 188 268 220 161 450 248 246 218 260 265 243 253 253 315 209 223 323 140 231
200 177 164 196 206 140 172 120 181 178 213 139 190 151 176 150 132 203 118 99
135 175 158 115 165 132 151 154 207 146 137 230 209 218 177 197 211 81 134 87
187 159 139 117 135 146 156 71 140 128 125 134 175 81 78 59 53 62 59 86
79 127 106 110 112 110 74 115 166 147 105 131 124 102 95 118 113 82 102 93
75 95 116 108
BLT-A04A 87
247 297 220 231 164 206 295 220 200 238 194 257 162 195 239 252 133 269 208 161
206 155 249 225 202 155 219 192 267 265 178 176 150 226 169 122 148 164 141 65
177 158 141 76 104 113 160 152 184 224 134 151 174 169 167 120 193 150 89 155
120 105 91 115 155 163 189 178 127 138 118 149 172 154 152 129 139 165 178 160
133 164 222 148 192 163 141

BLT-A04B 87
222 291 235 223 151 199 282 207 192 244 196 258 173 189 242 272 125 271 207 162
212 147 244 227 192 153 226 203 258 281 171 171 153 240 179 129 158 163 142 68
175 143 143 79 100 146 151 167 209 207 103 167 159 178 177 128 192 164 95 139
125 118 79 110 173 150 190 181 120 136 121 143 175 143 163 115 140 153 159 165
135 167 219 158 190 157 146
BLT-A05A 105
275 318 276 305 278 221 359 350 252 321 292 355 344 370 306 324 300 265 319 283
271 281 235 178 206 198 206 193 159 173 188 154 159 198 133 164 150 165 153 151
127 150 157 160 135 151 147 131 165 161 114 103 72 73 140 131 161 154 124 146
162 214 223 180 153 217 170 224 108 155 132 205 191 226 163 155 163 155 120 165
126 113 111 121 137 142 118 109 128 108 129 134 158 156 142 161 187 215 160 197
179 149 145 148 155
BLT-A05B 105
300 310 267 302 295 218 360 346 255 317 299 376 333 376 305 319 307 275 329 268
285 279 239 184 215 189 203 200 135 179 164 124 121 206 128 164 160 162 160 150
135 145 145 164 118 164 118 142 169 140 120 86 79 77 139 143 149 164 120 152
162 212 224 165 183 186 177 213 127 156 134 179 193 240 162 153 156 161 131 162
131 109 100 129 153 143 100 127 116 117 125 134 158 144 141 208 191 206 128 196
171 143 145 147 150
BLT-A06A 68
709 522 575 560 500 593 446 399 464 538 581 548 598 457 458 517 606 446 452 414
448 476 325 447 472 445 452 526 484 490 468 363 462 312 421 433 367 388 382 301
362 360 381 339 320 281 353 314 458 260 220 219 155 163 164 234 216 148 205 158
182 234 142 156 286 253 257 336
BLT-A06B 68
704 519 576 544 514 569 427 434 444 586 536 567 565 434 492 536 589 454 462 406
429 503 312 454 486 453 459 542 466 489 459 379 466 325 378 434 381 404 380 301
372 356 371 340 328 277 377 303 466 293 212 231 165 156 168 218 231 136 178 184
180 231 150 174 281 251 257 328
BLT-A07A 115
339 324 283 218 175 148 146 142 207 215 180 201 168 223 182 155 299 165 125 186
182 223 194 193 174 159 167 268 225 155 147 200 159 222 163 154 103 209 138 208
180 168 129 188 187 219 210 199 217 164 173 194 181 160 160 200 208 133 210 171
95 131 154 132 175 153 233 192 137 151 141 228 183 126 156 149 169 186 103 96
83 174 164 294 222 191 214 125 97 122 155 154 209 133 147 141 199 139 158 127
144 110 159 178 137 113 133 136 75 82 137 97 128 94 75
BLT-A07B 115
345 320 288 221 177 153 158 153 210 217 176 202 179 220 183 169 306 167 133 189
182 220 182 181 162 156 163 279 234 166 156 212 152 237 154 159 89 206 139 212
168 173 117 192 162 235 204 209 223 160 173 196 177 168 167 199 204 137 205 175
100 132 142 127 188 156 231 201 123 153 129 234 188 132 154 142 169 195 87 106
70 185 162 300 205 209 214 112 103 128 158 157 217 131 153 146 212 122 156 150
131 101 168 181 144 114 112 151 68 105 134 99 130 93 70
BLT-A08A 136
208 268 209 260 251 229 202 181 199 217 237 228 186 237 184 158 166 243 235 156
181 129 154 154 135 163 191 173 165 125 146 96 115 114 118 116 99 129 139 108
96 113 107 107 91 80 105 118 94 120 79 119 86 74 69 94 73 72 79 72
85 83 96 73 83 52 82 63 61 71 51 52 56 63 67 59 57 59 70 60
51 47 58 51 75 59 54 58 62 49 51 64 63 65 57 54 58 53 53 57
80 63 64 63 89 69 58 86 41 57 76 52 72 71 56 72 59 48 65 45
57 68 58 58 64 72 71 57 57 55 58 42 56 63 49 67

BLT-A08B 136
206 269 217 283 252 229 200 176 192 226 234 233 191 239 178 159 161 239 234 157
180 140 151 159 130 169 197 191 148 117 157 110 103 122 118 111 105 126 142 105
100 104 115 107 93 79 98 139 92 109 87 121 79 73 76 87 77 77 72 73
98 84 93 71 81 60 82 59 67 56 56 56 54 62 67 62 53 55 69 68
53 42 57 50 75 54 51 65 59 46 57 56 70 59 59 56 53 65 51 62
67 62 64 70 78 71 65 76 54 53 75 60 64 61 57 75 51 62 62 56
57 62 61 56 68 75 68 62 55 57 49 44 58 65 50 69
BLT-A09A 88
480 265 459 329 477 450 462 388 377 515 382 455 421 332 389 357 414 424 372 458
429 389 280 207 211 198 310 348 219 398 212 197 273 226 344 320 213 195 261 370
386 319 263 349 382 356 357 224 125 176 365 251 252 211 212 229 279 227 339 323
245 338 383 443 241 229 309 280 182 198 130 177 129 151 166 215 169 164 145 231
314 282 218 174 241 303 265 252
BLT-A09B 88
509 384 492 344 525 476 483 374 432 500 362 465 422 369 384 378 403 435 381 434
406 387 290 204 223 214 293 333 235 406 208 213 279 245 360 269 236 200 259 365
393 324 250 359 369 364 353 225 112 192 364 265 250 203 225 251 282 246 334 317
225 377 366 394 245 235 320 278 183 238 131 187 132 163 160 231 179 184 137 228
308 278 215 188 243 312 256 249
BLT-A10A 112
409 409 529 545 517 491 527 478 453 393 447 397 313 513 531 434 503 481 460 379
459 435 412 350 348 459 267 321 375 389 352 395 234 310 271 265 243 296 369 259
358 253 297 259 271 250 196 223 208 197 242 173 196 208 186 208 227 159 162 180
191 197 190 221 198 178 171 149 174 191 185 168 175 118 167 132 132 133 181 130
157 178 142 171 146 178 160 143 182 185 159 178 172 194 103 73 53 99 142 192
220 91 156 184 195 168 172 138 137 140 120 142
BLT-A10B 112
391 424 526 554 512 519 534 475 460 400 446 397 333 538 562 412 507 489 460 379
476 416 425 357 365 473 282 310 367 357 377 388 236 310 265 268 268 293 376 258
344 253 295 241 299 253 189 229 186 209 246 182 192 212 187 222 225 165 168 211
212 199 181 215 218 156 166 157 170 191 177 161 159 129 169 133 126 126 162 167
172 181 128 163 149 156 180 128 185 193 187 137 160 153 196 121 143 191 143 213
223 97 148 179 187 171 169 145 142 131 118 139
BLT-A11A 90
227 223 250 222 282 211 182 192 147 190 196 150 282 171 170 119 147 103 64 85
155 186 157 142 164 113 135 169 210 138 202 90 144 127 139 147 167 150 160 185
146 160 168 137 234 135 132 143 171 139 124 131 194 235 200 203 112 134 192 159
223 165 256 181 129 198 167 216 225 174 165 112 180 188 103 176 167 162 190 271
218 172 117 143 99 161 118 137 125 146
BLT-A11B 90
223 218 263 232 260 218 175 192 150 190 184 137 276 176 171 117 139 101 62 85
150 188 147 139 157 107 137 164 219 132 205 89 154 107 138 139 171 151 164 182
153 150 164 148 242 142 116 131 162 135 120 164 203 225 195 204 123 142 178 142
243 168 245 171 125 192 157 225 226 176 146 117 195 185 101 184 151 165 187 292
210 183 116 139 100 161 112 159 127 147

BLT-A12A 136
620 357 285 342 436 409 382 293 266 467 210 240 191 324 304 128 141 146 232 207
272 112 255 176 167 276 289 165 195 193 287 271 285 128 181 196 206 196 260 200
124 162 115 118 134 82 109 112 140 131 148 132 64 78 101 210 165 147 160 75
178 90 103 119 170 84 115 37 90 54 70 84 76 90 81 80 84 106 109 84
81 130 183 157 96 125 146 213 275 240 160 119 100 192 282 212 171 199 150 109
117 135 184 133 162 181 138 136 128 144 121 178 110 287 160 155 129 87 74 97
107 167 209 145 193 125 112 140 109 131 159 166 159 196 174 150
BLT-A12B 136
597 355 292 332 463 403 409 308 280 456 225 251 211 278 328 144 142 142 247 209
265 118 222 151 165 264 300 143 199 214 261 275 265 148 154 217 191 193 260 214
114 161 119 111 138 83 113 125 164 124 154 134 59 82 91 213 164 143 153 93
179 87 112 120 175 78 115 50 85 59 72 84 72 87 78 71 84 109 106 78
81 134 174 171 93 134 156 199 296 216 162 115 96 181 262 193 171 194 150 131
115 119 195 134 162 177 144 137 131 128 135 174 120 283 168 162 128 90 81 78
110 166 215 147 172 148 103 146 106 130 152 157 149 200 168 131
BLT-A13A 67
252 116 253 171 159 167 174 199 184 187 182 198 205 194 219 123 149 151 136 170
150 118 112 119 96 128 148 107 112 174 128 164 128 153 170 97 135 103 118 146
117 118 121 143 178 155 142 163 187 160 176 171 161 168 134 153 120 198 200 170
151 127 117 146 126 148 197
BLT-A13B 67
247 117 246 199 145 162 166 204 178 194 170 185 199 195 230 134 146 151 141 163
146 124 110 124 93 139 143 114 114 177 135 164 125 152 173 110 135 106 121 151
121 119 125 142 189 146 132 147 184 159 193 165 162 169 137 151 124 179 208 155
154 118 135 148 125 145 194
BLT-A14A 113
777 461 431 413 429 501 282 232 286 200 336 196 79 139 146 192 307 416 176 385
418 390 295 437 256 306 565 270 284 450 278 170 231 156 164 148 98 176 147 187
193 180 215 68 96 95 175 240 208 215 93 102 65 135 95 147 66 124 68 97
69 94 90 93 120 70 84 100 129 156 104 94 203 327 328 96 192 181 185 214
203 166 132 164 176 243 268 221 272 149 154 136 175 191 137 157 196 139 108 134
142 110 181 131 278 167 143 137 83 92 81 112 164
BLT-A14B 113
770 456 462 437 426 493 285 248 283 196 361 212 71 142 149 186 300 425 174 361
410 387 290 446 273 281 584 276 277 437 285 164 240 148 165 159 106 157 150 198
204 185 210 78 101 101 165 224 223 208 103 107 68 143 90 150 75 109 71 103
65 92 96 93 112 71 88 98 111 162 110 96 201 324 331 94 196 196 175 218
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158 100 181 132 279 156 165 147 84 85 84 123 168
BLT-A15A 73
244 263 179 247 253 306 262 273 284 285 250 221 253 250 199 194 187 173 204 244
174 104 135 155 185 180 207 216 196 221 257 177 251 210 189 259 282 206 210 250
160 244 185 143 123 109 157 164 165 175 179 148 151 156 192 178 187 185 225 220
271 167 201 219 296 247 268 221 218 224 197 178 252
BLT-A15B 73
238 265 185 230 241 308 268 276 289 291 253 239 240 235 190 200 185 178 210 249
177 110 138 157 171 179 227 211 192 212 240 190 250 194 191 264 278 209 189 256
170 228 178 154 120 118 150 154 157 193 182 155 134 154 190 192 188 186 218 223
265 164 215 228 283 256 256 240 190 223 196 182 242

BLT-A16A 58
312 351 327 385 381 404 252 289 217 167 261 424 365 222 426 346 281 269 348 332
220 356 281 328 459 281 357 278 238 275 267 204 218 355 325 250 277 231 221 137
196 192 375 307 243 171 165 106 168 153 246 234 281 243 374 234 287 303
BLT-A16B 58
322 350 306 381 373 413 248 285 207 176 298 410 364 228 407 332 296 289 339 291
215 375 304 300 454 259 357 330 242 258 301 210 195 306 331 276 281 224 217 131
214 185 376 295 253 198 185 116 133 170 233 230 261 243 379 232 280 297
BLT-A17A 60
401 377 320 215 446 401 159 448 337 217 235 306 293 215 232 220 264 255 219 419
242 412 303 309 224 362 156 138 134 112 175 225 240 165 225 171 196 189 284 253
173 202 164 185 245 196 179 204 200 389 185 193 162 245 268 275 213 175 170 278
BLT-A17B 60
401 385 310 224 432 387 151 457 314 207 242 310 282 214 228 217 258 258 223 395
235 400 307 304 233 355 145 137 127 105 168 223 254 165 222 179 190 195 276 254
178 192 175 182 265 175 189 200 195 399 189 197 156 256 257 288 212 168 166 271
BLT-A18A 89
273 290 311 358 347 198 385 348 337 357 163 225 264 252 259 259 227 184 164 128
184 257 94 220 167 116 163 176 195 160 139 153 164 228 253 276 176 231 225 220
195 198 121 117 100 108 136 202 216 139 225 162 160 148 204 182 148 210 182 187
269 198 176 195 156 255 185 145 148 213 271 231 193 148 189 131 140 109 162 156
189 173 152 109 159 117 198 203 236
BLT-A18B 89
281 282 315 360 345 200 378 360 337 347 171 226 257 239 275 264 220 182 164 128
188 258 92 217 182 123 148 170 198 148 145 168 166 220 262 275 176 231 229 206
200 203 132 110 107 106 145 189 224 142 226 146 159 153 199 190 145 210 178 182
271 194 200 183 166 240 190 146 143 214 278 237 184 152 188 128 134 110 175 146
181 168 146 104 160 118 199 218 253
BLT-A19A 91
267 234 240 458 285 199 277 282 265 360 205 194 239 239 243 275 249 273 234 203
246 260 150 303 224 131 218 203 287 217 263 276 298 263 278 299 187 226 301 250
258 218 153 167 181 129 143 184 146 110 184 125 120 129 131 119 105 164 122 149
162 137 190 194 153 158 151 109 108 150 137 123 170 139 155 119 137 125 174 177
110 140 152 156 215 155 175 135 165 160 236
BLT-A19B 91
250 228 242 464 286 209 282 278 268 344 198 207 252 246 260 271 269 217 220 204
249 265 140 316 212 141 209 207 295 226 259 271 306 262 272 310 193 223 293 242
271 209 162 172 182 131 143 170 155 111 156 142 121 125 117 126 106 164 123 140
178 135 184 209 162 165 150 117 114 162 126 121 171 148 150 110 149 112 181 168
126 138 159 159 205 162 166 140 153 159 236
BLT-A20A 82
281 216 291 277 250 244 225 264 338 285 325 298 202 289 210 193 201 304 197 166
143 154 196 320 401 241 375 347 361 329 380 363 281 340 198 244 196 200 184 188
188 173 227 181 168 150 175 181 157 150 170 158 162 84 94 121 114 122 188 159
145 136 157 145 157 159 184 144 146 160 130 165 134 163 156 187 142 136 146 142
129 182
BLT-A20B 82
250 234 284 276 242 234 198 262 353 291 309 307 220 304 197 208 190 314 198 172
142 153 207 324 438 203 388 346 364 317 407 331 274 336 195 242 209 192 190 195
196 175 232 168 182 143 172 192 151 156 182 153 170 93 106 94 103 121 182 181
162 151 146 139 142 156 172 140 159 173 128 159 143 171 165 165 165 137 118 141
132 180

BLT-A21A 97
120 262 156 238 309 340 340 359 436 413 329 269 322 269 206 277 242 291 240 296
271 304 267 333 379 260 295 341 362 328 428 308 375 393 302 335 346 306 249 341
323 368 335 286 352 270 255 248 280 317 263 250 275 233 319 263 245 264 287 262
244 204 196 245 199 223 270 362 308 308 218 241 212 194 219 236 231 200 295 341
218 218 262 189 215 325 232 294 219 269 192 196 189 197 265 169 238
BLT-A21B 97
121 246 165 234 336 361 400 393 455 452 328 253 359 286 219 269 281 264 250 294
254 308 287 326 381 284 284 343 370 329 434 295 369 356 287 347 345 301 230 340
325 370 312 290 356 265 262 250 279 316 266 253 259 246 312 267 248 275 282 280
237 181 217 254 221 203 266 344 300 309 246 199 215 181 184 222 234 242 247 284
231 243 247 189 221 270 271 270 209 257 182 205 185 193 269 162 240
BLT-A22A 69
433 360 403 332 366 322 352 536 568 416 280 367 378 390 224 296 332 330 376 371
424 381 255 275 382 326 363 339 282 310 293 303 268 276 346 334 226 289 266 181
165 150 157 192 157 140 141 156 184 198 175 265 180 233 186 288 278 238 312 286
354 260 204 261 194 160 281 237 317
BLT-A22B 69
446 374 414 347 377 344 373 544 572 425 285 378 385 407 240 270 347 316 360 406
429 389 271 373 304 326 382 350 273 293 308 300 290 281 348 328 233 304 260 172
162 139 171 196 165 134 157 157 185 186 185 290 163 243 171 300 276 233 325 283
352 276 193 235 200 132 275 256 327
BLT-A23A 127
104 103 114 155 123 113 119 145 174 122 170 173 121 152 156 188 138 124 129 142
144 155 110 136 136 158 171 133 126 134 134 115 133 82 129 135 198 187 221 244
200 187 192 185 258 271 218 201 304 271 189 193 156 121 132 124 218 219 195 174
222 152 82 75 142 182 166 168 260 254 247 185 177 120 106 117 121 87 100 82
129 135 118 151 121 143 139 164 219 174 174 148 167 111 186 114 115 148 147 159
167 109 101 133 160 174 200 194 124 192 161 223 239 201 160 180 160 152 69 100
141 130 95 155 105 115 60
BLT-A23B 127
105 97 121 156 121 122 123 146 151 123 167 168 134 133 176 193 157 124 125 126
168 147 144 133 157 161 159 127 133 104 136 107 125 85 118 139 186 173 195 212
201 185 190 197 228 310 204 200 239 216 181 193 165 128 140 154 221 223 190 184
223 149 71 81 161 174 145 182 256 251 266 167 164 128 115 114 124 100 82 81
148 123 120 154 124 145 144 158 240 174 147 165 168 123 181 129 112 148 141 157
174 101 113 140 156 171 190 205 133 205 155 223 249 203 162 198 153 153 65 117
135 131 96 170 107 115 61
BLT-A24A 62
265 199 323 240 388 239 297 280 234 305 218 261 336 290 228 254 229 237 153 159
162 228 248 234 233 200 172 166 209 191 231 281 177 143 176 149 219 153 191 133
155 144 162 127 114 142 83 86 124 148 95 171 136 166 123 155 103 131 129 113
84 145
BLT-A24B 62
264 187 314 246 376 250 315 270 234 310 215 261 323 301 242 244 235 229 151 157
175 235 245 243 239 202 165 164 210 202 246 263 186 135 184 145 198 168 190 133
142 137 171 126 115 131 92 96 114 147 105 181 128 160 124 144 108 130 123 114
86 141

BLT-A25A 83
390 417 331 452 223 213 179 144 207 264 483 248 341 457 467 418 334 498 265 291
235 310 320 178 208 252 282 217 283 159 187 179 254 238 218 185 219 170 201 152
165 157 100 86 135 134 110 119 162 121 137 152 214 117 130 128 110 139 108 160
147 174 102 159 127 142 121 128 119 155 158 125 171 117 154 80 87 87 136 138
153 154 169
BLT-A25B 83
400 422 313 461 229 232 167 150 213 261 455 265 357 467 474 410 325 507 271 288
245 312 318 181 215 245 284 226 282 168 192 171 251 230 210 192 218 164 198 155
167 148 100 87 143 136 115 118 161 119 137 168 207 119 133 126 110 140 118 156
151 186 105 153 131 137 127 134 121 157 160 125 166 116 153 83 94 93 127 129
152 156 172
BLT-A26A 91
463 432 402 346 247 349 336 297 317 332 318 233 253 250 261 293 222 356 221 187
234 235 286 203 147 167 191 222 331 301 226 404 314 303 278 270 282 318 277 236
446 308 397 179 207 244 253 245 253 271 250 280 313 257 263 232 286 305 275 161
176 159 179 264 284 341 370 252 229 184 187 139 168 174 138 174 202 186 172 219
204 149 176 181 164 164 131 128 108 124 150
BLT-A26B 91
469 440 407 364 278 326 355 296 318 320 407 210 261 241 284 299 209 353 186 164
286 264 293 200 164 179 195 209 361 328 212 379 342 334 270 279 320 315 339 246
443 351 415 165 234 246 237 272 293 246 259 280 310 256 240 244 293 321 274 150
178 153 183 256 302 346 367 240 200 186 171 134 146 190 144 166 229 145 166 237
203 153 174 190 161 160 136 125 104 129 150
BLT-A27A 83
561 593 603 525 285 463 212 147 240 196 158 86 68 90 106 105 365 310 376 365
295 366 358 295 374 481 445 270 453 435 536 308 429 439 494 320 268 299 281 250
273 272 291 239 193 218 236 215 194 197 262 260 330 197 172 251 307 291 299 206
237 296 250 179 219 248 265 274 291 227 244 200 285 156 162 131 124 158 123 164
139 188 118
BLT-A27B 83
554 594 606 443 243 521 219 150 232 181 140 85 81 94 120 106 360 353 373 371
309 370 364 301 417 506 435 247 455 473 514 307 426 434 423 325 275 300 306 234
253 271 290 249 206 208 235 200 220 199 272 259 297 201 162 244 315 293 297 195
239 289 266 186 216 246 268 268 296 243 238 212 296 153 165 114 115 162 103 186
135 203 121
BLT-A28A 69
305 185 138 163 409 281 264 201 384 514 526 290 214 503 401 372 377 491 444 335
395 473 573 508 563 396 464 479 723 590 539 501 565 375 427 426 303 262 264 237
265 257 237 190 240 270 301 215 371 246 166 168 140 195 140 224 242 240 225 220
162 148 128 183 218 241 326 334 296
BLT-A28B 69
299 171 134 171 398 287 240 216 382 529 547 303 228 464 364 384 375 471 420 341
404 442 544 517 570 404 454 469 744 554 567 486 510 400 457 390 292 278 265 250
284 252 229 193 248 278 237 259 353 228 163 162 146 194 125 237 243 250 236 219
175 140 121 164 238 246 320 337 296
BLT-A29A 82
463 733 558 697 634 626 606 493 454 568 568 415 536 454 479 424 500 304 299 292
228 404 433 384 267 369 312 333 278 268 280 191 215 231 273 259 222 209 221 205
212 265 263 262 290 426 296 300 299 315 137 107 92 142 203 275 281 350 299 378
353 356 287 277 283 296 209 259 203 218 259 233 300 207 195 175 218 162 148 136
148 160

BLT-A29B 82
458 716 556 718 629 606 584 502 439 524 558 420 529 454 500 449 517 338 280 301
254 413 436 379 268 376 364 328 270 264 272 215 220 236 277 259 243 172 228 193
217 262 244 257 294 427 293 293 306 301 131 123 87 150 216 279 284 340 272 368
365 349 284 287 266 301 225 256 188 221 255 225 307 192 197 159 206 168 133 145
170 170
BLT-A30A 96
660 655 445 875 600 490 708 589 778 712 653 560 553 526 578 629 414 468 409 450
403 365 276 302 290 197 285 300 325 224 339 338 302 271 276 266 175 257 227 249
293 290 303 290 253 246 268 271 100 160 194 211 225 145 203 133 193 192 198 201
177 158 155 134 169 181 159 160 171 150 171 115 147 173 153 155 183 177 144 182
153 143 118 112 126 175 167 171 165 144 176 139 145 143 106 151
BLT-A30B 96
661 652 444 885 623 475 765 573 771 718 658 575 576 529 562 626 409 487 450 425
400 362 264 285 297 197 268 311 319 212 347 334 315 275 286 275 178 259 216 257
290 278 312 298 257 251 265 284 106 159 206 183 245 138 204 138 194 188 197 200
175 159 153 142 168 179 160 159 169 151 164 120 146 171 150 153 187 169 133 185
131 142 110 129 138 157 141 172 142 157 163 142 157 139 102 154
BLT-A31A 86
409 417 355 439 382 368 251 315 278 285 286 231 337 387 303 212 314 360 360 306
353 304 293 367 296 281 339 314 204 317 351 132 105 89 138 197 360 285 292 208
242 120 109 111 124 207 130 151 171 125 144 137 217 107 72 82 165 96 115 112
124 106 101 99 107 131 111 170 187 121 135 112 98 137 143 149 110 103 156 167
128 104 95 103 116 158
BLT-A31B 86
354 430 332 431 393 362 282 276 284 282 287 243 314 376 314 223 312 360 371 309
355 317 290 381 298 298 346 300 211 324 346 117 104 79 144 196 352 270 301 218
284 129 112 111 146 183 144 153 160 132 144 124 225 114 66 94 162 103 109 115
121 94 120 94 103 124 77 157 122 117 118 125 107 134 153 140 121 109 143 163
121 109 103 102 116 159
BLT-A32A 86
727 388 299 498 388 593 209 307 313 355 367 482 579 321 325 334 367 398 341 328
242 212 173 302 208 187 148 160 186 238 198 173 273 185 237 226 251 299 189 299
275 271 250 250 186 250 293 300 237 221 205 200 159 167 210 257 207 196 197 208
165 162 131 143 131 180 143 222 134 168 156 146 153 171 175 188 255 200 172 209
246 156 192 173 248 142
BLT-A32B 86
737 397 293 498 378 596 207 300 309 350 375 489 578 315 318 339 354 406 341 328
232 214 170 304 215 192 167 167 185 246 182 164 268 210 226 223 260 298 199 306
286 271 254 251 184 238 303 286 234 209 193 195 163 165 215 250 193 200 209 212
183 161 136 159 126 195 154 209 127 165 159 146 143 172 181 183 264 170 207 180
240 157 200 174 243 148
BLT-A33A 77
307 223 177 239 269 235 259 214 187 262 252 266 358 378 314 210 282 364 350 268
310 362 282 373 298 357 310 348 328 335 281 314 333 268 285 273 340 328 371 364
267 290 270 316 226 274 237 235 278 234 203 268 267 260 228 207 319 230 247 260
213 226 168 227 222 278 243 236 267 205 184 282 204 360 290 273 348
BLT-A33B 77
304 228 185 231 282 257 322 216 180 252 264 255 358 371 340 226 286 345 353 294
310 376 287 379 311 350 307 334 328 331 273 335 342 281 307 285 333 340 362 359
268 298 258 335 253 260 234 246 272 232 204 262 281 247 217 200 331 229 264 251
220 231 162 240 216 292 218 259 274 206 193 265 218 351 287 277 331

BLT-A34A 48
296 472 801 509 446 375 356 259 238 389 539 529 363 289 185 59 48 32 71 103
163 164 225 151 248 218 151 137 126 167 264 287 242 226 205 215 248 260 246 242
225 253 204 256 238 260 190 175
BLT-A34B 48
290 482 733 536 476 379 325 254 247 389 475 488 412 339 202 42 42 52 72 100
159 157 251 179 275 240 167 150 128 184 303 296 251 225 205 217 237 251 243 239
240 259 200 257 246 231 185 171
BLT-A35A 72
392 246 422 443 397 266 332 376 248 359 289 391 378 310 313 302 300 271 350 242
281 268 368 323 355 360 300 237 229 92 77 43 46 48 74 106 78 78 96 89
89 77 115 81 92 96 53 57 68 68 93 86 78 90 95 114 90 101 115 152
144 143 179 159 156 185 163 134 124 124 129 151
BLT-A35B 72
355 256 424 437 394 272 333 384 250 351 291 348 355 290 318 289 303 282 346 228
254 268 375 307 332 346 314 260 211 90 54 57 51 46 71 104 75 89 93 89
98 79 108 77 84 101 51 67 70 65 79 101 83 82 87 124 90 101 106 151
167 148 171 168 151 171 184 143 115 115 137 196
BLT-A36A 53
222 312 243 389 426 354 176 301 280 330 246 309 258 196 265 234 250 268 235 239
227 197 237 171 135 196 234 265 223 215 172 159 110 182 142 222 230 214 148 220
153 207 154 178 152 236 139 296 150 99 164 95 168
BLT-A36B 53
156 330 240 354 380 384 189 310 242 316 244 304 245 200 265 190 241 246 235 221
203 194 240 171 157 168 256 257 217 217 167 157 117 160 134 203 257 185 164 204
134 204 157 173 135 184 190 295 121 115 137 121 148
BLT-A37A 53
296 313 375 355 284 207 289 301 318 162 196 185 193 163 235 211 132 242 191 179
228 185 206 230 178 223 150 128 134 206 260 281 273 217 162 156 140 154 251 220
221 191 217 159 179 170 164 121 164 126 152 121 156
BLT-A37B 53
314 324 329 348 312 212 326 308 284 176 200 190 196 160 225 217 135 239 192 183
206 208 213 228 182 223 150 125 145 206 250 264 267 203 175 171 144 149 221 279
232 182 214 163 178 179 160 121 160 120 148 120 167
BLT-A39A 83
181 164 200 189 141 116 115 101 100 125 101 149 116 94 129 131 115 103 91 64
57 42 41 36 55 66 63 68 51 62 73 51 74 34 25 26 43 74 54 56
64 43 45 43 53 75 63 89 46 76 84 60 41 33 31 52 35 42 39 49
64 55 46 46 35 49 81 36 54 35 46 70 22 53 53 60 53 46 50 49
46 37 59
BLT-A39B 83
172 180 202 178 139 121 119 104 103 119 93 154 118 101 126 128 112 103 92 64
59 40 41 34 51 65 66 66 47 62 75 62 74 24 28 25 39 81 52 58
75 39 46 40 53 64 75 85 52 82 82 64 36 38 35 49 50 39 42 52
67 64 47 51 43 50 81 37 50 35 57 69 21 54 53 60 54 55 46 50
49 40 60
BLT-A40A 93
183 166 176 213 224 245 196 291 184 335 116 114 125 167 105 115 62 75 112 146
203 112 213 192 192 171 150 213 189 214 298 236 278 200 206 265 321 405 316 205
221 256 438 385 383 369 290 195 289 315 376 365 336 304 323 326 297 293 415 447
382 431 303 244 199 137 129 118 106 142 157 193 142 137 168 71 112 116 112 150
137 131 90 97 163 130 141 125 128 117 106 146 162

BLT-A40B 93
186 166 175 209 225 239 199 298 182 325 114 121 117 171 93 123 53 75 114 143
157 117 206 192 189 179 157 208 175 221 290 252 275 203 204 276 312 418 300 210
232 258 415 395 370 367 289 209 259 312 371 351 342 295 323 323 292 284 416 391
409 439 315 234 203 137 134 122 123 142 152 188 149 137 156 93 106 118 111 141
137 127 71 122 160 119 143 125 128 121 115 140 181
BLT-A41A 168
284 349 344 378 347 366 439 405 282 244 340 334 237 297 232 268 278 356 186 245
210 228 312 290 295 317 240 237 178 245 178 240 257 339 229 235 329 293 325 240
217 206 253 252 200 176 256 290 255 228 315 201 231 253 287 340 293 215 293 271
361 245 265 229 196 206 261 231 156 100 222 140 115 201 186 303 221 146 178 165
178 203 239 228 184 193 187 175 190 121 125 150 170 253 165 118 128 121 120 153
152 125 173 150 135 135 132 120 131 144 164 137 144 142 141 121 121 123 155 99
116 112 78 92 101 125 103 96 93 97 118 100 92 100 98 125 96 103 96 86
68 67 59 60 63 53 103 71 72 70 75 56 83 63 86 80 78 89 70 101
76 93 83 78 90 85 55 120
BLT-A41B 168
291 351 338 386 350 357 432 400 273 271 338 333 218 320 222 264 278 350 183 266
195 226 300 283 326 307 271 235 203 238 175 248 242 339 220 256 317 285 326 270
206 182 257 273 203 162 226 309 262 238 309 200 237 245 304 335 296 240 290 259
350 244 261 234 190 206 265 218 173 93 230 134 115 201 180 298 232 139 177 170
179 209 221 202 185 212 180 181 190 118 131 148 176 263 162 111 123 142 106 153
155 128 175 161 127 138 130 111 122 150 171 126 166 134 144 129 124 114 150 108
102 108 86 98 103 117 103 100 84 99 115 100 107 89 107 119 110 104 91 89
65 61 62 64 57 58 106 67 78 60 69 46 92 67 82 80 85 91 77 92
85 87 90 71 89 83 61 115
BLT-A42A 89
181 269 318 221 419 332 228 352 246 244 238 191 260 256 250 435 511 332 288 192
225 253 249 244 293 276 242 429 435 312 250 314 301 406 255 278 306 198 196 209
311 392 292 234 293 249 345 348 309 406 409 379 307 401 347 449 322 344 138 63
59 80 68 103 141 143 138 188 175 242 219 240 166 189 159 209 223 286 258 281
315 209 196 249 250 143 203 189 328
BLT-A42B 89
181 278 304 204 513 311 240 318 257 275 212 226 271 289 253 418 478 370 293 185
242 239 259 221 273 268 296 423 437 348 254 314 297 413 256 257 292 190 212 209
314 392 282 238 307 235 377 312 311 380 417 353 322 374 363 457 333 319 163 66
63 67 61 102 147 137 140 196 168 255 212 268 169 187 158 234 238 284 262 273
312 200 190 258 247 154 221 164 313
BLT-A43A 84
381 518 400 556 467 723 586 423 432 457 439 551 607 381 454 365 478 443 484 158
103 140 120 242 240 212 137 205 193 195 197 185 228 189 272 274 270 281 222 174
221 259 253 265 217 254 295 346 290 244 225 321 165 228 180 153 116 130 142 228
185 134 112 252 306 250 291 320 262 222 165 121 134 184 176 169 180 194 165 175
152 115 121 190
BLT-A43B 84
409 521 395 571 459 719 584 422 435 451 492 532 590 382 454 350 473 437 481 159
104 139 117 234 248 187 148 209 184 195 205 189 215 184 284 276 269 270 219 198
233 260 246 261 229 250 286 346 301 237 237 308 171 219 184 149 122 127 141 231
190 139 113 247 298 265 274 322 252 212 178 113 140 180 182 143 184 181 165 192
146 96 118 216

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

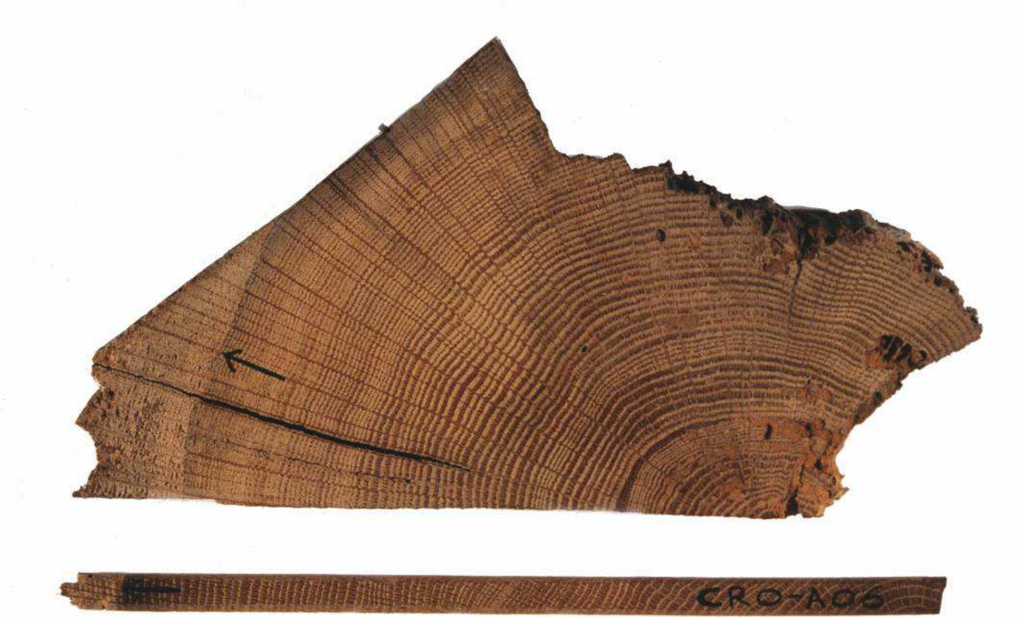


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

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

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

t-value/offset Matrix

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

Bar Diagram

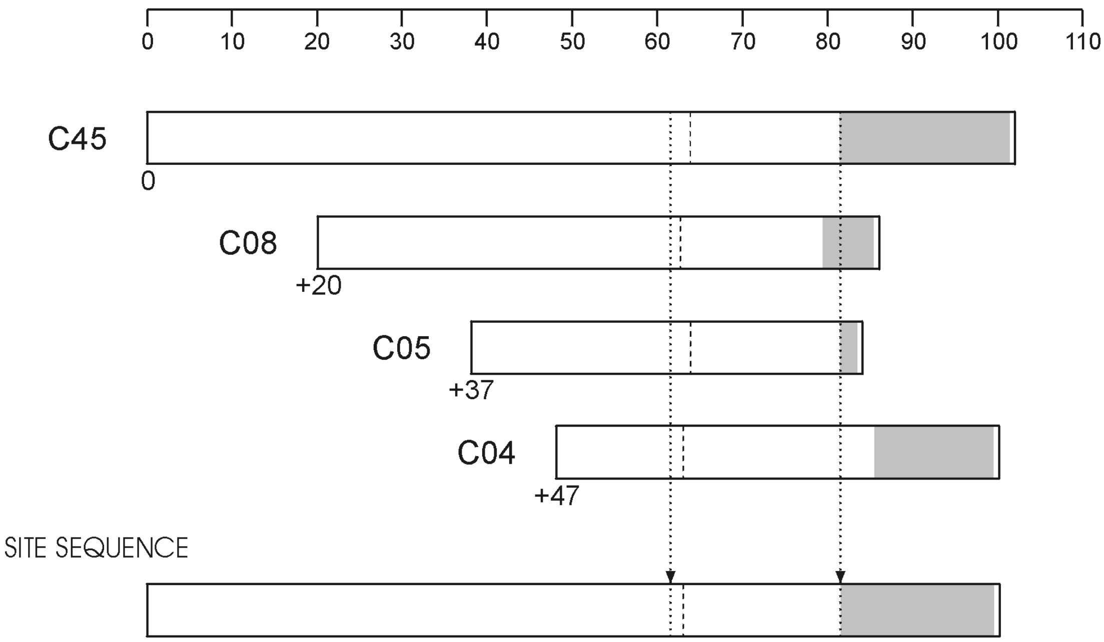


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

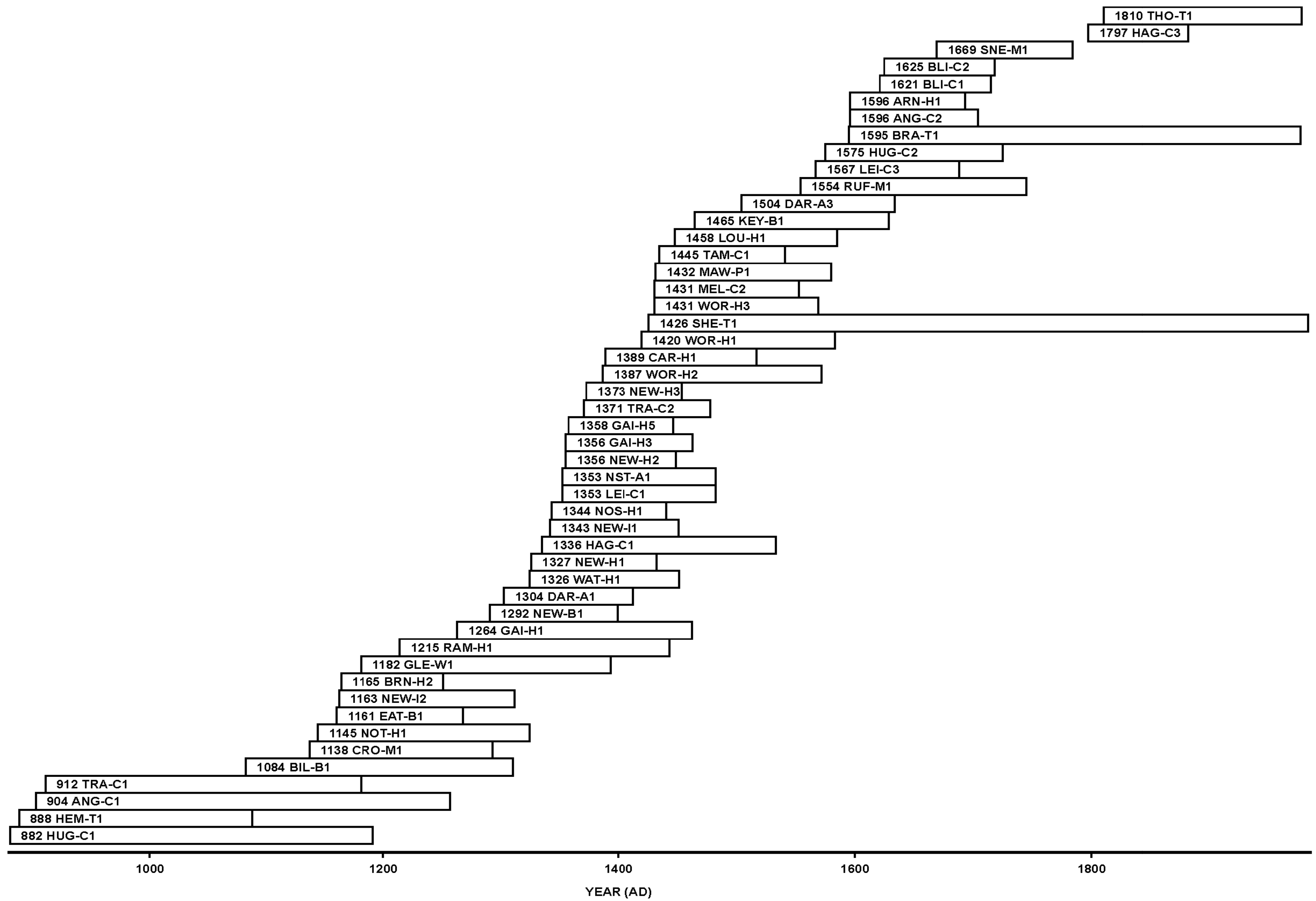
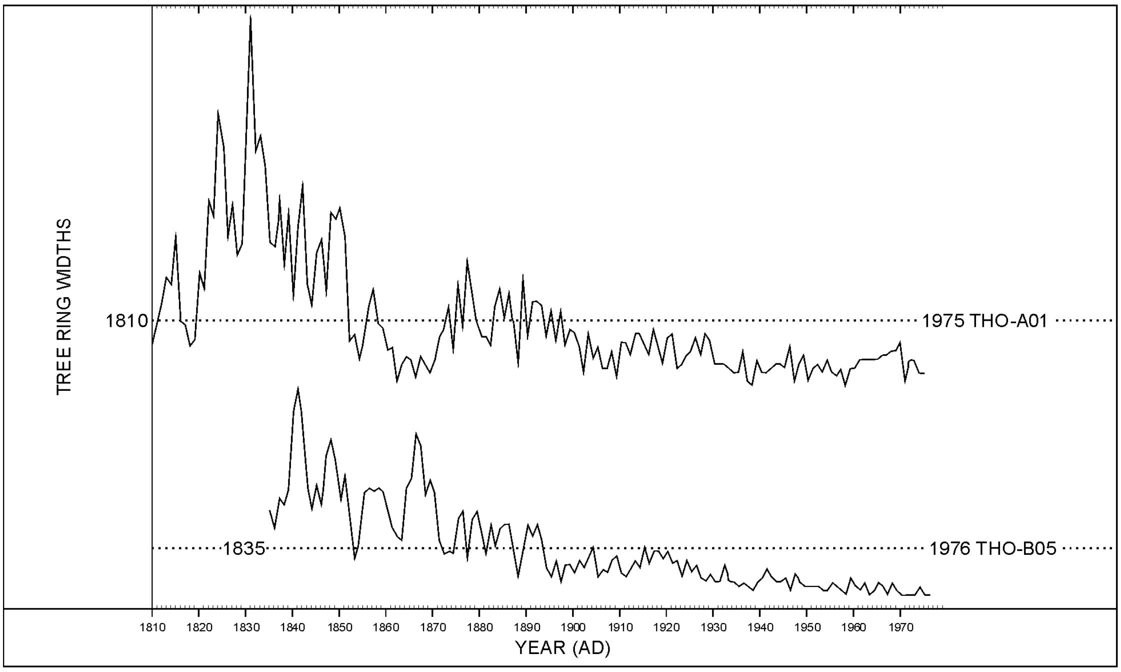


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

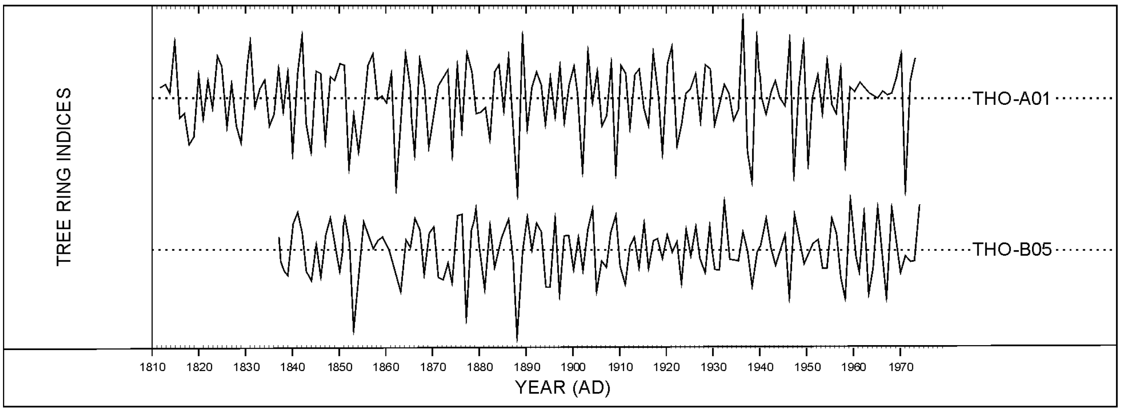


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

References

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

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

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

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

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

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

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

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

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

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

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

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

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