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CHURCH OF ST MARY, NEEN SAVAGE, SHROPSHIRE

TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY

Dendrochronological analysis was undertaken on 33 samples obtained from the nave and chancel roofs of St Mary's Church, Neen Savage, as well as from the porch. They produced two site chronologies. One site chronology, comprising 22 samples, can dated, its 306 rings spanning AD 1227–1532, while the second site chronology, comprising three samples, is undated. The remaining eight samples are ungrouped and undated. Interpretation of the sapwood on the dated samples indicates that the nave timbers have an estimated felling date of AD 1412–37, while the chancel timbers have an estimated felling date of AD 1424–49 and the two tiebeams were not felled before AD 1390. These timbers are likely to have been felled for a single programme of building works, although possibly not all at the same time as each other, with work on the chancel following on almost immediately from that on the nave roof. The dated timbers from the porch have an estimated felling date in the range AD 1547–72.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Nottingham Tree-ring Dating Laboratory would like to thank Barry Treves, Church Warden, for his considerable help and cooperation with this programme of analysis, and for the hospitality shown at the time of sampling. We would also like to thank John Tiernan, English Heritage, Heritage at Risk Architect/Surveyor for his helpful discussions on the possible phasing of the timbers. Finally we would like to thank Shahina Farid and Cathy Tyers (English Heritage Scientific Dating Team) for commissioning this programme of tree-ring dating and their assistance during the production of this report.

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Shrewsbury SY2 6ND

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

CONTENTS

INTRODUCTION

The Church of St Mary at Neen Savage in Shropshire, about seven miles west of Kidderminster (Figs 1a/b), is of Norman origin, dating to the twelfth century, with its nave, chancel, and west tower belonging to this period. It is listed Grade II* and the listing description indicates that the tower originally had a timber spire, but that this was destroyed by a fire in AD 1825, after which the upper levels and the battlements were renewed. Inside, the roof, which comprises a series of close-set rafter frames with ashlars and archbraced collars, runs uninterrupted through nave and chancel (Figs 2 and 3). In addition there are six decorated tiebeams. The church also has a timber-framed south porch with diagonal struts between the posts on the west side, and a gable with foiled circles.

Judging by the clean, well cut, and squared nature of some of the beams, it would appear that a substantial amount of timberwork to the roof is of relatively modern date, with almost all the archbraces, many rafters, and some ashlars, probably having been replaced as part of a programme of extensive restoration in AD 1882. It is likely that at least one, and possibly two, of the decorated tiebeams, were replaced at this time as well. The porch too may have undergone some renovations, but these are less clear and it certainly appears to retain some original timber.

SAMPLING

Sampling and analysis by dendrochronology of timbers within St Mary's Church were requested by John Tiernan, English Heritage, Heritage at Risk Architect to inform grant-aided repairs to the two roofs. Although it is believed that both the nave and chancel roofs are of fifteenth-century date, this is uncertain and not very specific, and it is thought that the church underwent some restoration in the sixteenth century. It was hoped that tree-ring analysis would establish the date of the roofs with greater precision and certainty and determine, if possible, whether both roofs, including the 'tiebeams', were of the same date or were substantially different. The brief also requested that samples be obtained from the porch, the date of this again being uncertain.

Although at the time of the initial assessment of the timbers for suitability for tree-ring analysis it was seen that some of them appeared to have relatively low numbers of rings, or to have been replaced in recent times, it was also seen that, within each roof, and amongst the tiebeams, and porch timbers, there appeared to be a sufficient number of timbers with sufficient numbers of rings, to make sampling worthwhile, particularly given the number of timbers potentially available. Thus from these timbers a total of 33 samples was obtained by coring. Each sample was given the code NSV-A (for Neen Savage, site 'A') and numbered 01–33. Twelve samples, NSV-A01–A12, were obtained from the timbers of the chancel roof, with a further 10 samples, NSV-A13–A22, being obtained from the nave roof. Three of the six 'tiebeams' of the chancel and nave were also sampled as NSV-A23–A25. Finally, eight samples, NSV-A26–A33, were obtained from the timbers of the porch.

The locations of these samples were recorded at the time of sampling, the positions of these being shown in Figures 4a–h, with details of the samples being given in Table 1. In this table, as in the drawings and plans, the frames of the two roofs have been numbered consecutively from east to west (frames 1–16 being in the chancel, frames 17–45 being in the nave), with individual timbers then being further identified on a north–south basis as appropriate. The tiebeams have also been numbered from east to west. The porch is described as having two trusses numbered from north (or inner truss) to south (or outer truss), with individual timbers being further identified as being to either east or west.

ANALYSIS

Each of the 33 samples obtained was prepared by sanding and polishing and their annual growth ring widths were measured. The data of these measurements are given at the end of this report. The data of the 33 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing two separate groups, accounting for 25 samples, to be formed, the samples within the two groups cross-match with each other as shown in Figures 5 and 6. The cross-matching samples of each group were combined at their indicated offset positions to form site chronologies NSVASQ01, this having an overall length of 306 rings, and NSVASQ02, with an overall length of 81 rings.

The two site chronologies were then compared to an extensive corpus of reference chronologies for oak, this process indicating a consistent and repeated match with a series of these for site chronology NSVASQ01 when the date of its first ring is AD 1227 and the date of its last measured ring is AD 1532 (Table 2). There was, however, no conclusive cross-matching for site chronology NSVASQ02, and it must, therefore, remain undated.

The two site chronologies were then compared with the eight remaining ungrouped single samples but there was no further conclusive matching. The single remaining ungrouped samples were than compared individually with the full range of reference chronologies for the oak, but again there was no conclusive cross-matching and all eight samples must remain undated. This analysis may be summarised as follows:

Site chronology/samples	Number of samples	Number of rings	Date span AD (where dated)
NSVASQ01	22	306	1227–1532
NSVASQ02	3	81	undated
Ungrouped	8	---	undated

INTERPRETATION

Analysis of 33 samples from the timbers within St Mary's Church has produced two site chronologies, one of which can be dated. Interpretation of the sapwood on the dated samples indicates that timbers of different phases of felling are present.

Site chronology NSVASQ01

None of the 22 constituent samples of site chronology NSVASQ01 retains complete sapwood (the last growth ring produced by the tree before it was felled), and it is thus not possible to determine a precise felling date for any of the timbers represented (Fig 5). A number of samples do, however, retain the heartwood/sapwood boundary, meaning that only the sapwood rings have been lost, and it is thus possible to reliably estimate a likely felling date range for some of the timbers. Estimated felling dates are calculated using a 95% confidence interval of 15–40 sapwood rings.

Nave roof

Seven timbers have been dated from the nave roof. The heartwood/sapwood boundary on the four samples that retain it ranges from AD 1391 on NSV-A16 and NSV-A17, to AD 1407 on NSV-A20, which suggests that these timbers are probably all part of a single programme of felling. The average date of this boundary is AD 1397 which gives the timbers represented an estimated felling date of AD 1412–37.

The felling date range of the timbers represented by the three other dated samples cannot be determined because they do not have the heartwood/sapwood boundary and are thus missing not only all their sapwood rings, but an unknown number of heartwood rings as well. However, they are clearly broadly coeval and there is no reason to suspect they are reused older timbers, thus it is likely that they were also felled in the period AD 1412–37 as well.

Chancel roof

Six timbers have been dated from the chancel roof. The heartwood/sapwood boundary on the three samples that retain it is very slightly later those from the nave roof, ranging from AD 1407 on sample NSV-A09 to AD 1410 on sample NSV-A06, which again suggests that these timbers are all probably part of a single programme of felling. The average date of the boundary on these three samples is AD 1409 which gives the timbers represented an estimated felling date of AD 1424–49.

The felling date range of the timbers represented by the three other dated samples again cannot be determined because they do not have the heartwood/sapwood boundary.

However, they are clearly broadly coeval and there is no reason to suspect that they are reused older timbers, thus it is likely that they were also felled in the period AD 1424–49.

Tiebeams

The two dated samples from tiebeams do not retain the heartwood/sapwood boundary, and it is thus not possible to produce an estimated felling date range. However, with last heartwood ring dates of AD 1345 and AD 1375, and allowing for a minimum of 15 sapwood rings, they are unlikely to have been cut before AD 1360 and AD 1390 respectively. It is thus possible that they were felled at about the same time as the timbers used for the nave and chancel roofs.

Porch

Of the seven samples from the porch which have dated, only one, NSV-A33, retains the heartwood/sapwood boundary, this being dated to AD 1532. Thus the timber represented has an estimated felling date in the range AD 1547–72. The other dated timbers from the porch are clearly broadly coeval and may well also have been felled at the same time in the mid-sixteenth century but in the absence of any trace of sapwood it is not possible to prove this.

Site chronology NSVASQ02

Site chronology NSVASQ02 comprises three samples, two from the chancel and one from the nave (Fig 6). Although none of these three samples can be dated, the fact that they cross-match with each other would suggest that the trees they represent are coeval with each other, and emphasises the similarity in date of the nave and chancel roofs.

CONCLUSION

The results obtained in this programme of analysis appear to suggest the possibility that the dated timbers from the nave roof, with an estimated felling date range of AD 1412–37, were felled slightly earlier than those from the chancel roof, which have an estimated felling date range of AD 1424–49.

These estimated date ranges clearly overlap suggesting the probability of a common or extended period of felling. It should be noted, furthermore, that the structural evidence strongly suggests that these two roof areas represent a single phase of construction. This structural evidence, combined with the overall variation in heartwood/sapwood boundary dates being only 19 years, would suggest the likelihood that while the timbers used for the two roofs were probably cut as part of a single programme of building works, it is unlikely, given the nature of the undertaking, that they were all felled at exactly the same time as each other. It is more likely that the timbers were cut over a short period of time as the roof was constructed and in reality it is therefore likely that work on the chancel roof followed on almost continuously from that of the nave roof. It is possible that the dated tiebeams were felled as part of this same programme of work, but the lack of traces of sapwood means that this is not proven. Tree-ring analysis has, however, clearly established that the porch is over a century later, dating to the third-quarter of the sixteenth century.

As may be seen from Table 2, although the dated material from St Mary's Church has been compared to reference chronologies from all parts of Britain, there is a tendency for the best matches, or the highest degree of similarity, to be found with those comprising data from other west midland sites. This suggests that the oak timbers used at St Mary's Church are from relatively local regional woodland sources. The overall cross-matching of the samples analysed here is variable. This might suggest that the trees used have not all come from a single, close-set, woodland, but were possibly widely distributed throughout the wood, or may even have come from different woods. It is likely, however, that two timbers, the east and west posts of truss two to the porch, represented by samples NSV-A30 and NSV-A31, have been derived from the same tree, these samples cross-matching with a value of t=14.3.

Eight of the 33 samples obtained remain ungrouped and undated. None of these samples show any apparent problems with their annual growth rings, such as distortion or compression, which would make cross-matching and dating problematic, and all have sufficient rings for analysis. It is possible that the timbers have been sourced from some niche location which is as yet not represented in the available corpus of reference data, or that some timbers have been sourced from different locations. This has the effect of making them 'singletons' which are often more difficult to date than groups of well replicated samples. It is, however, a common feature of tree-ring analysis for some samples not to combine with the main group or to date individually.

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TABLES

Table 1: Details of tree-ring samples from St Mary's Church, Neen Savage, Shropshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Chancel roof					
NSV-A01	South ashlar, frame 1 (from east)	91	no h/s	1300	------	1390
NSV-A02	North ashlar, frame 2	77	h/s	------	------	------
NSV-A03	South rafter, frame 2	60	h/s	------	------	------
NSV-A04	South ashlar, frame 2	68	h/s	------	------	------
NSV-A05	North rafter, frame 3	69	h/s	1341	1409	1409
NSV-A06	South rafter, frame 4	70	h/s	1341	1410	1410
NSV-A07	South ashlar, frame 5	111	no h/s	1293	------	1403
NSV-A08	South rafter, frame 5	55	no h/s	1343	------	1397
NSV-A09	South rafter, frame 8	127	h/s	1281	1407	1407
NSV-A10	South rafter, frame 10	64	h/s	------	------	------
NSV-A11	South ashlar, frame 14	71	no h/s	------	------	------
NSV-A12	North rafter, frame 15	55	no h/s	------	------	------
	Nave roof					
NSV-A13	South ashlar, frame 22	73	h/s	------	------	------
NSV-A14	North ashlar, frame 25	70	no h/s	1276	------	1345
NSV-A15	South rafter, frame 26	63	h/s	1337	1399	1399
NSV-A16	North ashlar, frame 27	78	h/s	1314	1391	1391
NSV-A17	South ashlar, frame 28	78	h/s	1314	1391	1391
NSV-A18	North ashlar, frame 29	70	no h/s	1320	------	1389
NSV-A19	North rafter, frame 33	58	h/s	------	------	------
NSV-A20	South ashlar, frame 34	65	h/s	1343	1407	1407
NSV-A21	North rafter, frame 36	82	no h/s	------	------	------
NSV-A22	North ashlar, frame 36	116	no h/s	1271	------	1386

Table 1: continued

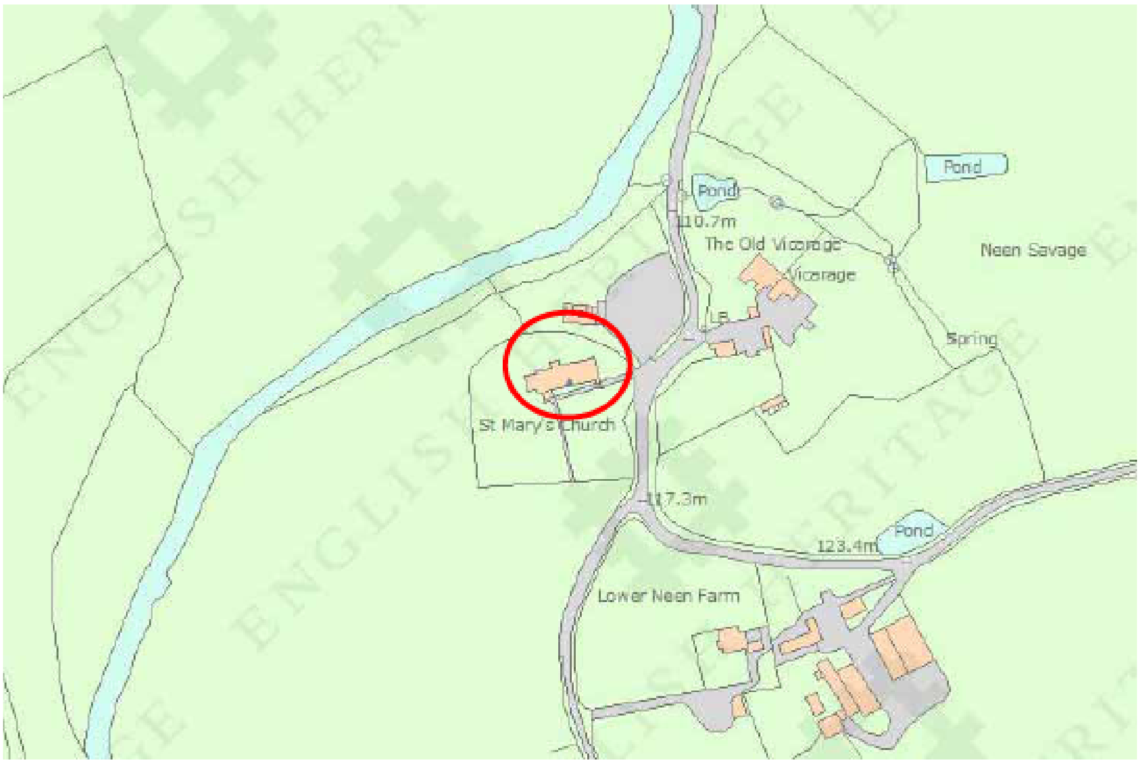
Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Tiebeams					
NSV-A23	Tiebeam 3 (from east)	119	no h/s	1227	------	1345
NSV-A24	Tiebeam 4	129	no h/s	1247	------	1375
NSV-A25	Tiebeam 5	123	h/s	------	------	------
	Porch					
NSV-A26	East archbrace, truss1 (inner/north truss)	145	no h/s	1325	------	1469
NSV-A27	East principal, truss 1	43	no h/s	1449	------	1491
NSV-A28	Tiebeam, truss 1	71	h/s	------	------	------
NSV-A29	West principal rafter, truss 1	50	no h/s	1453	------	1502
NSV-A30	East post, truss 2 (outer/south truss)	82	no h/s	1414	------	1495
NSV-A31	West post, truss 2	72	no h/s	1421	------	1492
NSV-A32	East wallplate	75	no h/s	1435	------	1509
NSV-A33	West wallplate	78	h/s	1455	1532	1532

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

Table 2: Results of the cross-matching of site sequence NSVASQ01 and relevant reference chronologies when the first-ring date is AD 1227 and the last-ring date is AD 1532

Reference chronology	Span of chronology	*t*-value	Reference
66/68 Westgate Street, Gloucester	AD 1209–1518	12.2	(Tyers and Wilson 2000)
Wigmore Abbey, Herefordshire	AD 1055–1729	9.8	(Tyers 2002)
Mercer's Hall, Westgate Street, Gloucester	AD 1289–1541	9.3	(Howard *et al* 1996)
Gatehouse, Kingswood Abbey, Kingswood, Gloucestershire	AD 1307–1428	9.0	(Arnold *et al* 2003)
Halesowen Abbey, Dudley, West Midlands	AD 1310–1535	8.8	(Arnold and Howard 2008b)
Pedagogues' House, Stratford upon Avon, Warwickshire	AD 1305–1403	8.5	(Arnold *et al* 2006)
Worcester Cathedral, Worcestershire	AD 1286–1424	8.1	(Arnold *et al* 2003 unpubl)
Primrose Hill, Kings Norton, Birmingham	AD 1354–1593	8.0	(Arnold and Howard 2008a)

FIGURES



Figures 1a/b: Map to show the location of Neen Savage (top) and St Mary's Church (bottom) © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: View of the chancel roof of St Mary's Church (photograph Robert Howard)

Figure 3: View of the nave roof looking west to east (photograph Robert Howard)

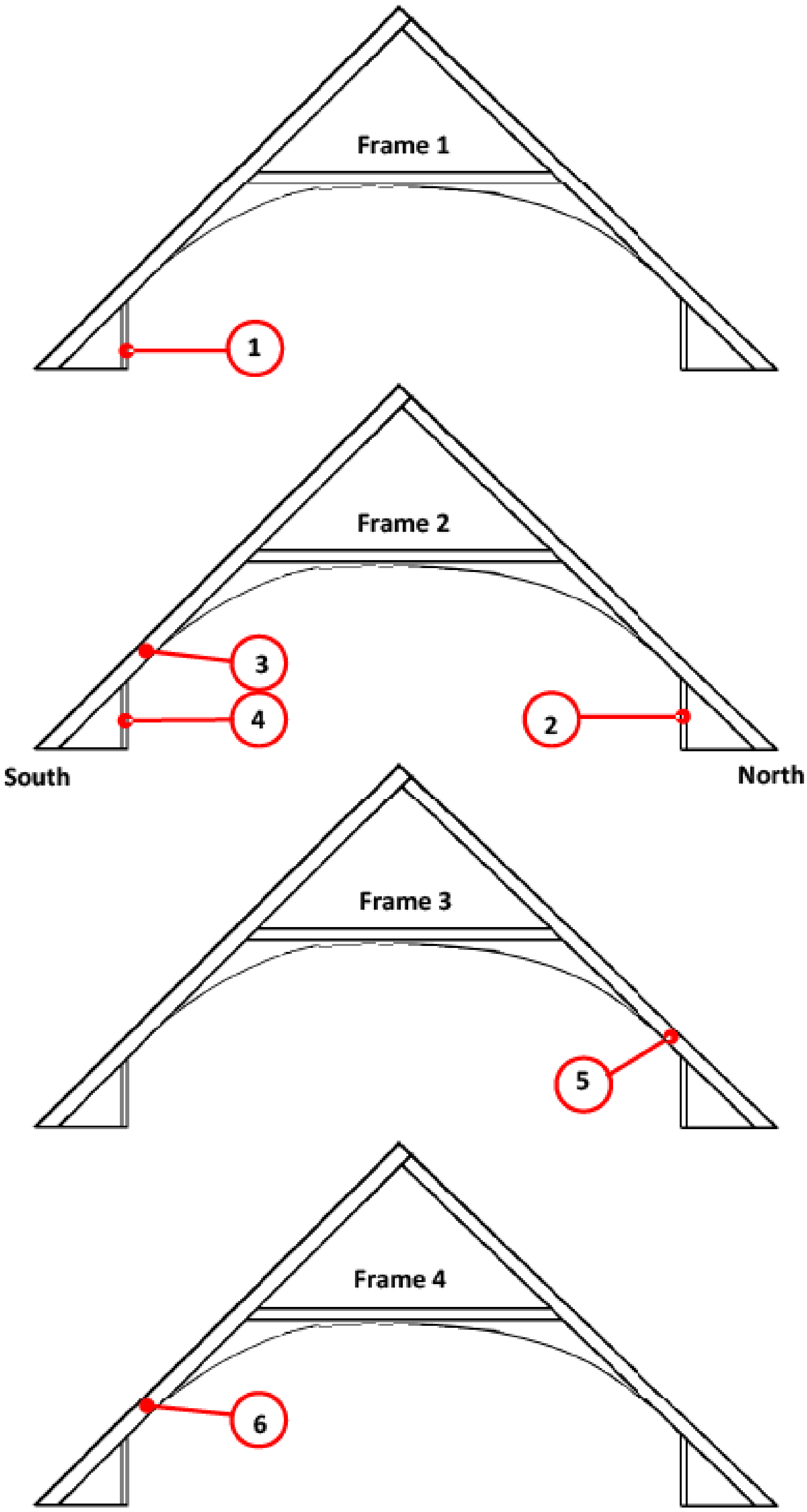


Figure 4a: Drawings of the roof frames to show sampled timbers

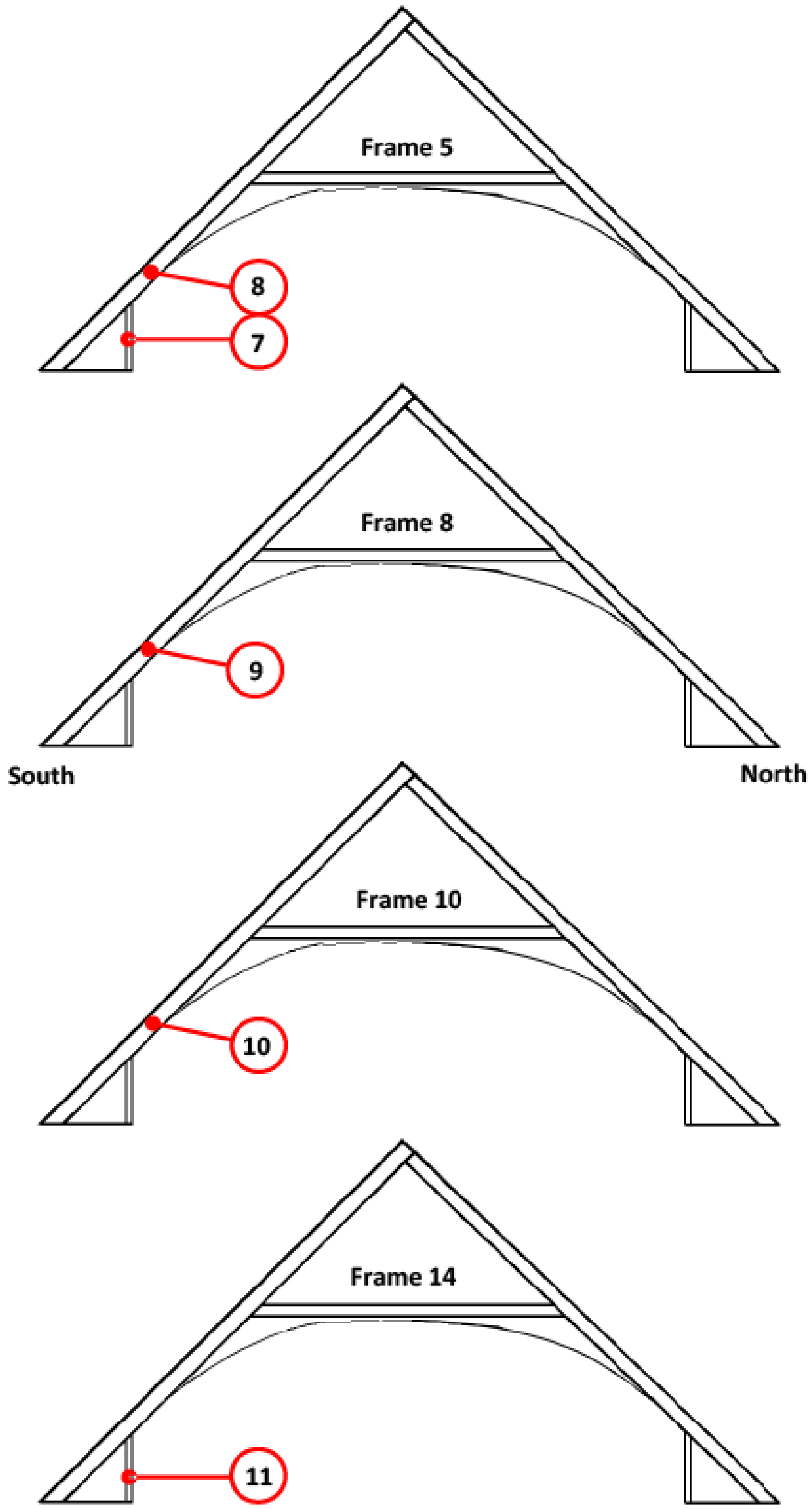


Figure 4b: Drawings of the roof frames to show sampled timbers

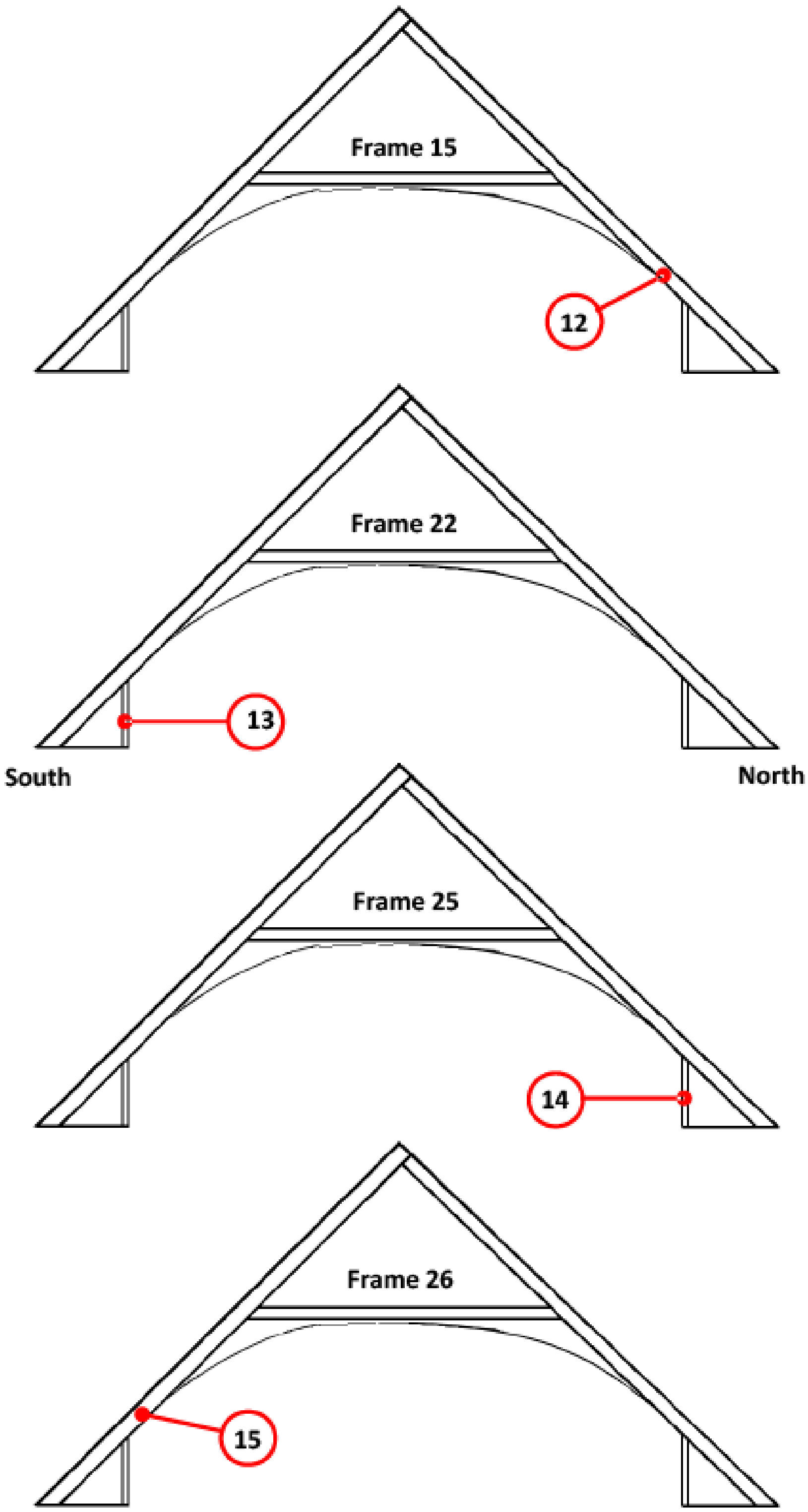


Figure 4c: Drawings of the roof frames to show sampled timbers

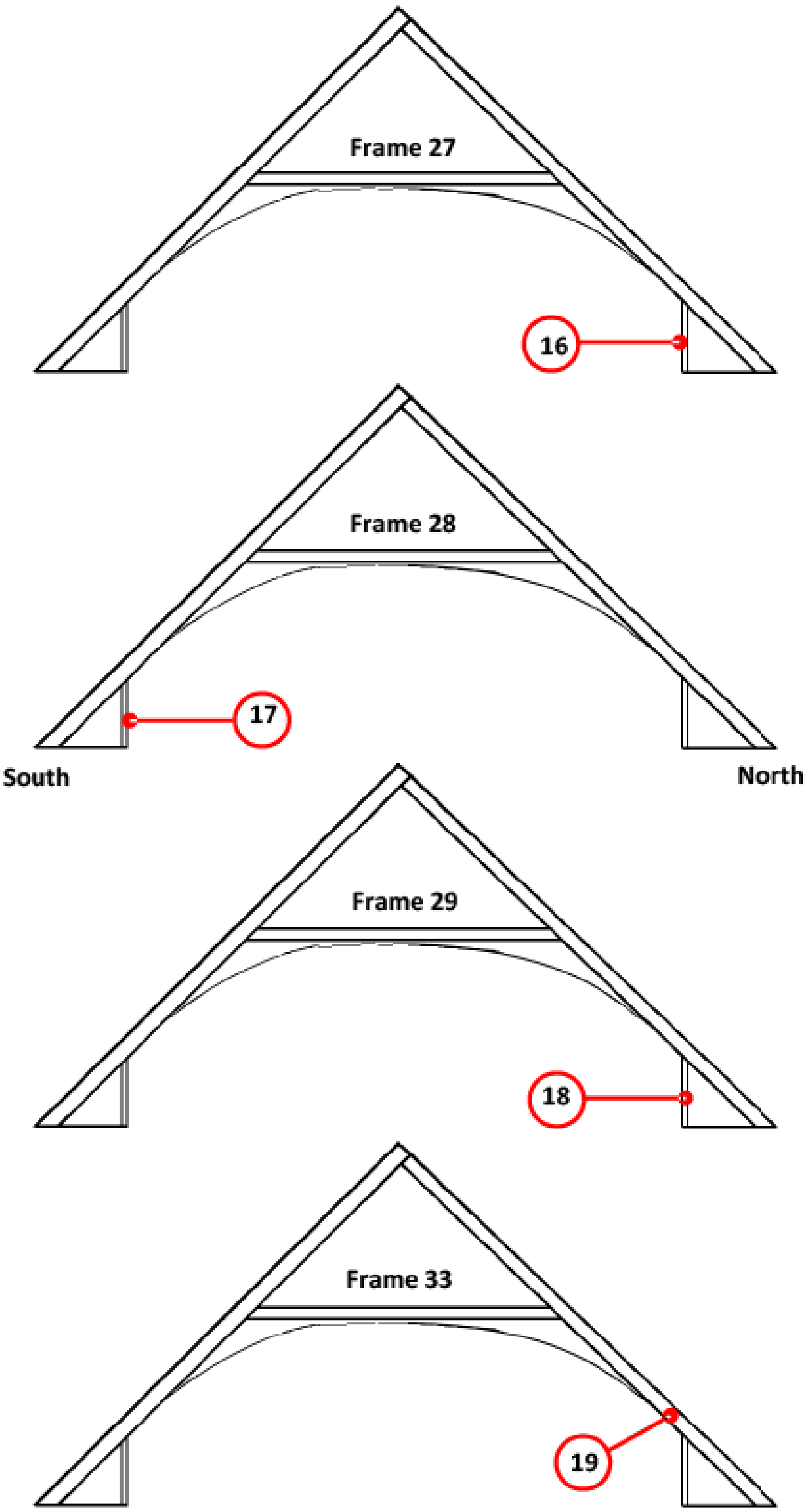


Figure 4d: Drawings of the roof frames to show sampled timbers

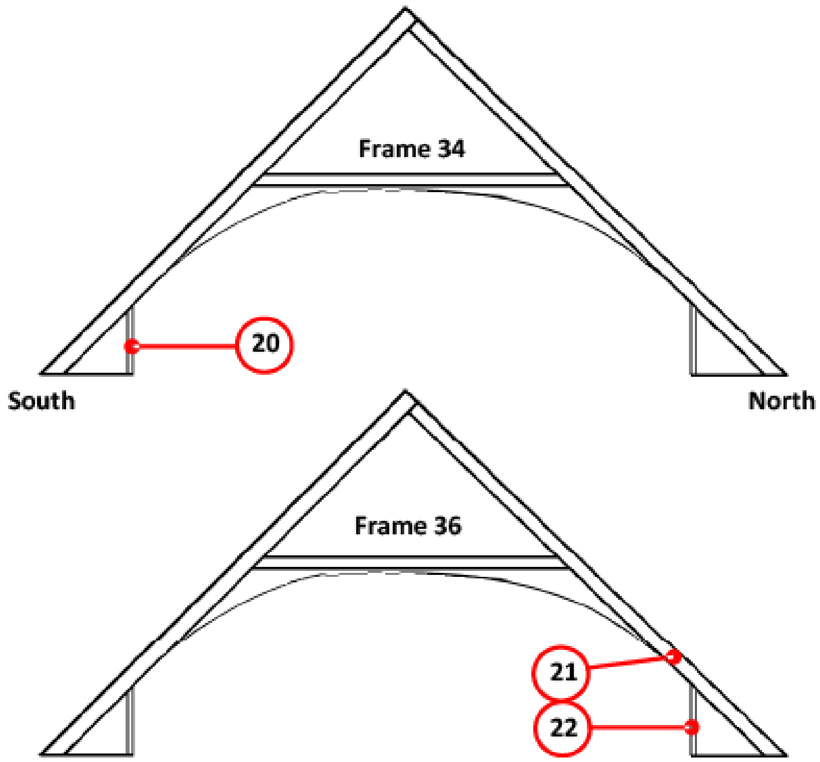


Figure 4e: Drawings of the roof frames to show sampled timbers

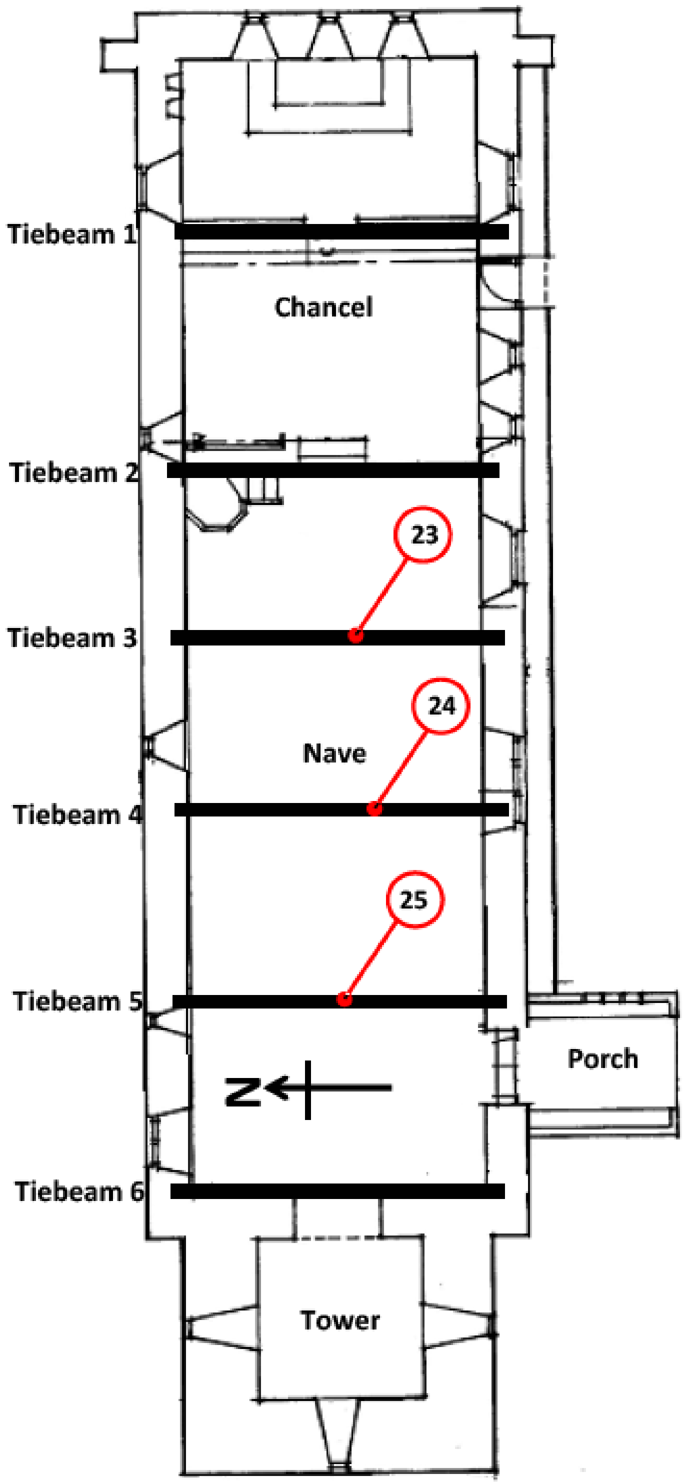


Figure 4f: Plan to show sampled timbers

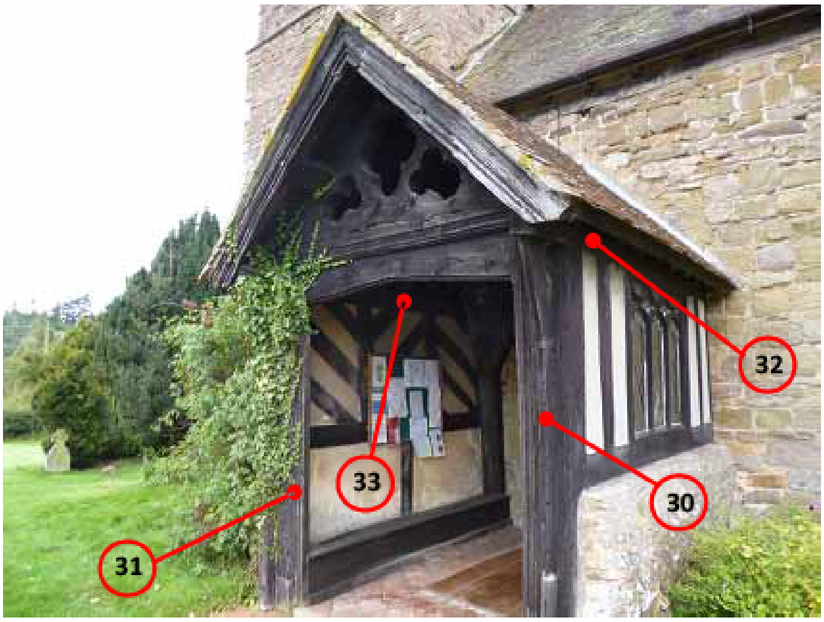
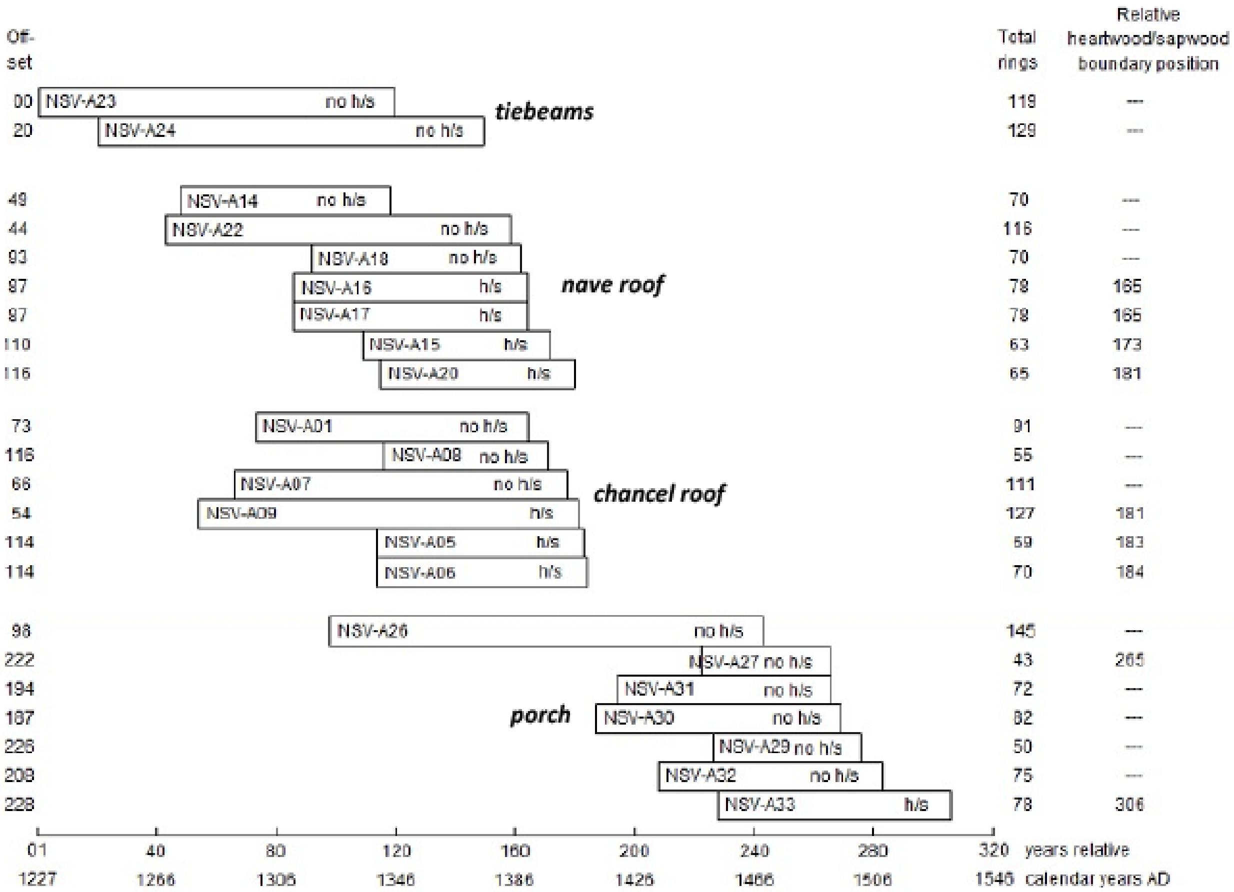
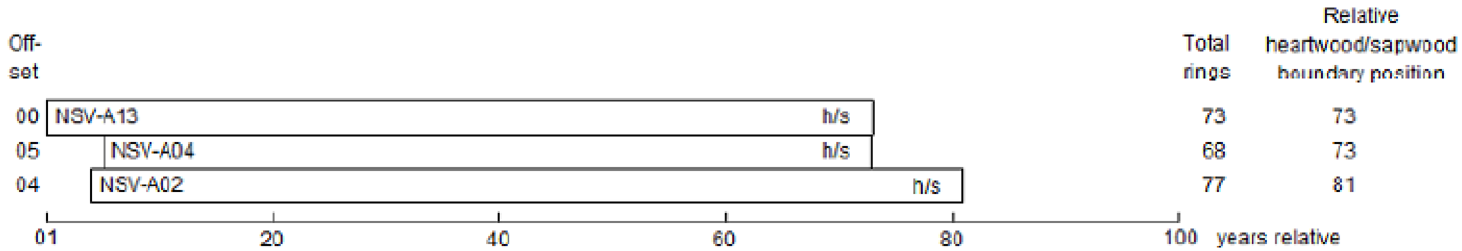


Figure 4g/h: Photograph to show sampled porch timbers (photographs Robert Howard)



white bars = heartwood rings; h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the samples in site chronology NSVASQ01



white bars = heartwood rings; h/s = heartwood/sapwood boundary

Figure 6: Bar diagram of the samples in site chronologies NSVASQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

NSV-A01A 91
168 219 190 194 306 286 273 298 246 203 194 162 216 181 185 162 182 162 100 127
97 91 85 96 89 75 71 76 63 57 53 45 46 40 34 51 59 75 75 84
76 103 98 88 105 94 117 138 150 182 139 157 131 164 149 140 100 106 111 96
68 82 87 89 96 68 71 71 54 79 89 76 87 89 81 68 62 54 63 78
62 49 62 67 76 81 93 75 75 68 87
NSV-A01A 91
169 215 199 182 324 282 266 292 252 203 200 162 221 173 185 172 181 150 111 124
96 92 88 104 75 80 72 78 63 60 46 46 48 41 35 53 57 71 80 79
79 102 103 78 124 78 119 138 151 178 135 154 137 175 154 139 109 103 112 104
75 85 83 92 76 68 81 65 67 82 67 70 95 82 80 66 67 54 65 71
68 50 59 76 64 79 85 81 68 58 90
NSV-A02A 77
229 240 204 136 205 159 110 125 114 118 112 92 123 114 135 121 127 195 182 244
197 225 132 203 107 108 60 119 96 104 53 53 85 107 75 100 67 87 57 82
96 100 117 121 103 110 95 94 110 132 109 135 98 107 81 90 42 77 71 98
68 68 54 75 92 65 73 67 70 65 74 67 39 36 51 34 46
NSV-A02B 77
227 206 180 152 195 162 115 122 123 113 117 98 120 117 132 116 130 148 140 155
194 217 139 207 109 107 75 110 90 96 56 53 85 107 76 103 62 91 60 82
104 111 117 119 92 112 100 107 110 138 127 117 100 112 81 85 43 79 68 103
65 62 57 79 76 75 68 78 64 68 50 87 37 38 50 63 71
NSV-A03A 60
447 412 388 372 293 301 326 285 244 285 257 292 257 200 200 209 240 226 168 202
225 214 243 185 193 215 163 217 159 162 150 121 140 159 168 142 154 162 147 121
142 120 143 108 104 106 148 123 108 151 117 110 107 110 110 125 125 171 151 159
NSV-A03B 60
495 427 393 381 300 325 328 278 243 296 284 283 281 203 204 227 229 226 184 202
240 227 245 195 203 217 173 203 166 144 138 128 151 170 163 132 164 160 151 118
143 119 151 104 107 112 143 120 110 153 121 112 109 108 99 112 140 160 171 164
NSV-A04A 68
215 223 137 108 100 98 104 125 111 117 102 117 157 146 121 114 116 82 76 85
108 83 105 78 95 53 96 80 108 67 87 96 107 75 153 125 110 107 117 151
156 166 187 148 157 161 103 96 142 106 135 115 118 62 73 65 104 46 156 109
118 87 104 120 90 89 88 70
NSV-A04B 68
202 198 136 158 129 108 101 123 117 117 104 131 150 150 131 107 121 82 74 91
110 87 112 83 97 55 97 88 114 71 79 85 117 88 151 128 114 99 134 136
153 167 185 169 153 156 108 103 132 114 125 117 100 64 68 53 112 45 153 118
115 92 117 121 85 92 89 80
NSV-A05A 69
225 192 232 225 122 104 125 130 165 139 91 112 104 114 130 126 130 134 133 98
121 153 174 203 205 207 203 190 169 142 135 122 134 150 146 150 124 128 130 122
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170 85 159 125 104 138 95 151 221
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239 195 232 236 124 105 125 133 163 141 116 110 110 134 130 121 117 127 132 106
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107 102 109 121 81 137 132 90 83 107 111 115 84 96 81 104 118 123 139 140
129 95 159 125 92 98 110 112 123 147
NSV-A06B 70
397 442 433 401 409 272 343 368 381 382 343 332 384 307 282 271 260 250 239 173
217 207 221 211 179 198 170 164 150 101 125 115 110 121 142 139 117 81 109 112
110 95 107 125 86 148 125 99 76 96 118 114 84 100 80 100 112 131 137 142
135 96 151 132 92 103 87 112 142 118
NSV-A07A 111
140 103 85 88 123 71 191 194 145 146 125 117 131 148 101 125 105 73 86 112
103 180 232 191 148 128 89 73 97 90 72 71 64 57 53 58 66 58 43 67
71 60 71 78 88 96 67 64 77 75 66 72 91 73 55 71 77 81 104 88
88 85 71 78 98 91 93 65 71 50 107 102 74 65 81 56 90 73 58 88
78 85 84 65 77 87 59 59 58 59 73 86 74 76 68 65 73 64 64 56
48 56 45 53 45 67 57 60 60 47 86
NSV-A07B 111
135 94 84 95 106 76 175 192 159 150 124 124 128 142 100 124 107 86 79 105
101 192 227 192 149 116 104 91 107 94 75 75 67 52 53 60 66 53 56 67
64 63 77 80 75 92 66 63 78 75 65 67 91 78 50 85 65 90 104 93
92 82 73 83 98 85 92 59 73 53 103 95 79 64 85 67 87 68 59 86
81 84 78 70 74 86 65 59 66 57 82 95 67 89 60 65 67 58 61 64
39 57 47 46 46 62 62 53 60 53 89
NSV-A08A 55
193 180 150 104 88 139 138 160 88 106 167 152 118 129 150 150 134 110 180 219
216 186 191 218 196 162 207 147 167 184 189 166 196 151 185 171 189 176 146 161
167 192 126 217 150 137 182 146 190 151 137 165 117 162 134
NSV-A08B 55
131 219 157 104 99 136 143 119 83 105 198 144 119 132 146 148 126 117 194 216
222 178 195 217 201 160 230 135 160 192 185 164 187 164 213 164 194 173 147 164
165 203 128 215 153 143 185 145 193 126 132 170 117 167 152
NSV-A09A 127
161 141 76 69 73 91 58 65 86 107 36 102 152 67 75 77 88 112 100 127
135 135 158 139 182 180 228 205 179 129 136 132 157 221 242 286 278 273 204 157
192 163 160 195 124 108 105 128 115 106 99 108 100 101 100 106 98 107 100 110
94 86 92 95 117 100 84 98 123 107 137 90 108 120 96 105 130 108 139 69
83 43 100 112 100 110 119 82 124 125 71 109 101 92 107 95 98 104 98 96
85 70 92 79 70 98 89 103 105 75 65 77 59 71 59 46 63 85 73 80
78 45 85 69 63 95 112
NSV-A09B 127
138 139 73 71 80 84 56 62 94 106 47 104 148 67 83 85 92 111 95 122
128 132 160 139 182 188 219 212 181 130 110 124 135 210 261 300 279 283 209 170
195 169 171 170 104 90 94 116 95 107 103 106 104 98 95 105 94 110 94 109
90 90 78 101 112 96 75 87 123 111 131 91 103 125 100 109 131 107 135 81
75 48 96 114 101 117 118 79 120 126 78 106 95 87 95 104 115 125 101 92
79 56 95 90 68 103 84 101 105 70 80 68 60 84 59 52 72 78 77 72
71 57 85 81 66 87 98
NSV-A10A 64
187 330 359 234 286 259 230 160 188 212 232 180 190 174 207 155 132 121 178 163
155 175 201 208 173 193 193 130 125 148 128 134 137 146 107 110 109 104 120 143
113 95 96 82 86 92 84 107 90 115 110 112 107 112 103 103 104 135 93 99
104 120 124 121
NSV-A10B 64
145 347 362 269 240 270 252 179 180 209 210 175 192 176 214 166 123 118 179 168
167 164 200 206 174 196 203 132 135 146 138 136 125 136 114 115 100 103 117 127
121 100 92 74 87 84 88 95 98 121 103 104 109 107 117 107 106 136 91 93
103 128 117 140
NSV-A11A 71
85 102 150 135 121 79 103 93 87 82 80 63 65 82 48 61 67 67 68 83
71 103 83 78 73 78 87 92 96 91 73 121 151 151 194 168 135 110 99 107

105 104 122 107 150 171 128 96 90 115 85 86 87 76 76 103 87 123 116 97
96 107 97 72 70 67 73 78 75 100 73
NSV-A11B 71
84 97 150 139 123 76 104 92 81 82 77 68 71 73 47 59 69 61 75 76
74 107 72 80 75 85 92 81 94 89 82 131 153 146 201 164 143 113 93 117
110 96 124 114 150 172 128 99 89 111 89 83 84 85 85 101 89 116 113 94
102 104 96 72 73 60 79 79 75 96 85
NSV-A12A 55
128 151 213 114 122 155 138 133 168 204 134 148 115 132 106 100 103 100 78 78
93 67 98 86 87 103 107 136 121 125 104 128 121 134 125 156 110 102 115 117
114 126 100 122 110 100 113 119 124 115 85 110 128 140 170
NSV-A12B 55
122 167 215 107 116 160 145 134 179 199 145 143 119 125 106 98 94 116 80 74
92 64 101 83 88 106 103 142 122 121 101 125 124 139 118 160 103 108 101 122
118 119 114 118 101 104 95 111 129 117 87 114 128 153 143
NSV-A13A 73
191 164 187 167 159 136 168 130 139 116 87 110 103 97 89 85 92 98 122 101
75 94 85 75 74 100 73 124 68 114 57 174 78 103 67 71 68 110 103 114
107 100 81 118 131 139 160 145 140 207 121 96 101 148 130 139 89 107 100 82
54 75 52 189 70 123 100 118 89 80 68 70 104
NSV-A13B 73
180 157 182 167 154 131 174 125 138 105 83 101 101 100 80 92 94 110 107 100
79 83 79 75 71 110 78 126 80 114 56 153 102 89 54 60 82 95 85 103
100 96 81 118 121 121 160 152 141 195 118 94 104 140 129 135 86 96 103 79
59 71 62 181 67 110 79 125 89 81 67 82 90
NSV-A14A 70
148 110 73 77 149 142 202 207 206 268 248 128 202 253 221 276 282 315 268 230
237 274 239 214 239 227 243 159 221 197 238 253 223 201 203 265 260 223 297 422
250 230 217 259 242 240 226 253 207 140 109 145 149 139 126 114 158 167 73 100
81 68 90 123 95 65 84 77 87 100
NSV-A14B 70
151 96 80 85 135 110 204 211 205 254 261 120 195 223 241 271 284 315 273 228
239 275 228 214 255 215 259 154 199 194 222 242 210 201 204 258 279 231 293 446
240 243 228 275 234 267 248 266 215 146 113 138 148 137 137 112 159 153 76 116
76 68 93 119 100 69 80 81 86 103
NSV-A15A 63
200 208 187 157 212 171 202 209 183 180 166 196 257 157 164 153 192 172 147 169
157 176 185 119 184 164 167 164 167 158 159 161 273 142 151 167 143 146 164 166
164 132 156 114 126 108 107 146 120 143 117 126 81 83 108 68 89 106 95 109
114 89 130
NSV-A15B 63
179 202 187 159 226 181 194 222 185 174 167 196 232 160 168 165 209 170 150 191
151 175 190 130 190 148 177 171 159 160 175 159 261 144 146 166 150 142 165 187
162 131 150 124 117 104 112 126 109 126 110 119 89 75 101 76 84 98 93 95
100 97 107
NSV-A16A 78
301 343 208 259 210 246 215 216 167 159 116 124 103 151 139 204 117 86 104 123
115 132 108 107 126 125 111 157 134 189 191 154 166 125 121 151 131 167 119 128
104 123 132 135 131 173 117 148 201 207 176 110 140 134 93 121 115 123 117 129
131 118 110 112 122 121 90 90 92 129 104 79 85 79 75 60 62 65
NSV-A16B 78
313 342 206 258 211 247 214 214 166 189 120 130 104 150 128 192 116 91 111 119
113 154 125 98 131 125 119 153 143 183 195 153 173 126 145 151 137 171 118 131
115 121 110 150 110 183 131 137 207 207 165 98 148 136 100 113 121 107 139 123
125 121 118 107 115 121 89 89 96 131 104 79 78 87 76 57 65 60
NSV-A17A 78
453 313 175 255 184 184 190 172 157 171 167 142 148 214 187 151 140 94 144 151
125 163 152 150 164 171 124 144 147 160 197 168 156 121 118 169 111 203 106 126

121 110 114 145 150 187 110 131 160 203 173 92 118 162 81 140 91 103 152 121
115 162 157 101 165 166 95 92 82 84 106 78 97 78 89 65 47 75
NSV-A17B 78
451 313 188 254 185 190 190 183 155 183 167 130 158 198 186 159 164 113 131 150
121 146 139 148 152 171 132 129 151 155 189 159 142 116 110 163 112 192 104 127
118 96 106 167 131 162 107 153 156 203 170 93 126 153 74 136 98 107 137 139
137 153 148 151 139 162 100 81 82 95 92 75 101 78 92 68 56 76
NSV-A18A 70
240 251 190 181 142 116 107 149 124 160 133 125 119 130 85 123 126 110 169 146
104 152 138 144 181 157 142 140 151 172 171 194 141 174 119 95 94 120 152 205
144 153 154 159 139 95 145 146 160 131 123 146 150 162 145 160 135 134 110 112
112 95 120 112 95 99 114 98 107 106
NSV-A18B 70
220 249 204 183 121 98 106 144 125 159 135 120 123 126 94 119 128 110 162 157
98 159 134 135 200 160 135 142 146 181 160 192 143 172 118 97 90 128 164 203
146 159 150 161 144 100 131 135 155 131 118 132 155 159 140 156 136 133 104 111
110 96 129 107 94 99 112 101 101 106
NSV-A19A 58
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182 178 142 182 203 204 184 195 171 174 146 113 109 146 121 107 108 115 118 109
112 172 173 146 131 128 126 154 156 144 130 128 104 93 92 90 84 99
NSV-A19B 58
288 378 395 267 215 198 170 223 212 182 137 128 142 129 125 144 144 150 155 148
200 171 164 190 203 194 179 178 185 165 141 103 112 144 121 111 106 120 124 114
120 182 181 132 128 128 123 153 160 143 128 128 112 104 76 101 90 99
NSV-A20A 65
129 114 111 95 86 94 110 107 127 114 125 92 100 98 94 87 67 41 59 79
91 79 100 92 92 101 112 146 115 126 148 150 180 163 103 146 133 112 70 95
63 77 70 70 61 81 76 92 112 111 135 156 226 255 232 234 190 298 225 135
146 130 90 135 143
NSV-A20B 65
114 117 123 87 67 125 108 103 119 108 133 100 97 104 91 87 84 45 59 80
85 88 99 85 100 101 110 137 109 140 151 169 171 164 98 139 107 88 64 76
60 73 61 89 59 64 85 85 104 110 139 128 203 274 225 225 215 303 220 143
164 134 78 140 147
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105 101 118 166 288 347 242 194 120 121 108 97 69 130 100 108 89 83 90 103
91 75 81 103 91 98 97 125 89 95 100 91 92 111 141 148 147 103 126 123
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63 78 64 68 87 78 92 86 66 83 113 71 104 85 90 77 81 78 82 70
95 103
NSV-A21B 82
100 104 123 164 276 376 284 199 126 119 108 96 71 137 91 120 76 92 92 100
94 78 80 102 96 89 96 134 83 97 99 87 91 102 131 141 135 124 128 128
93 75 67 62 80 61 48 44 52 58 64 62 42 60 54 53 57 67 68 72
66 69 70 75 73 76 85 80 67 76 106 75 88 78 83 70 74 84 79 65
81 84
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319 261 404 304 250 184 264 226 244 171 134 119 148 142 142 132 96 106 100 114
73 117 143 107 67 92 89 78 107 124 138 139 119 166 150 203 206 162 132 205
147 177 157 176 263 198 223 187 167 195 188 164 221 137 120 106 110 104 106 128
94 119 140 106 130 179 137 210 210 164 179 189 215 240 262 206 159 160 271 187
200 156 175 168 212 146 166 147 190 123 125 142 174 187 125 146 153 94 134 125
115 124 113 134 115 108 114 130 119 117 112 125 134 147 117 156
NSV-A22B 116
292 265 395 304 242 189 282 205 248 176 126 135 134 147 136 151 95 91 99 104
75 107 128 96 73 89 96 79 101 114 131 148 126 158 156 208 200 152 143 194
150 185 164 160 276 201 217 196 159 212 185 162 220 140 116 98 114 103 101 114

94 119 129 107 135 187 146 229 200 173 178 182 215 242 248 212 165 161 257 184
201 151 181 168 203 140 164 129 168 125 125 140 175 166 121 156 134 91 128 118
124 126 112 146 112 115 115 130 112 112 111 138 136 143 107 155
NSV-A23A 119
114 94 114 119 82 51 40 107 135 107 156 126 135 112 96 99 159 153 114 181
123 95 81 98 137 97 132 143 129 131 140 128 107 113 150 158 139 148 154 153
96 196 175 142 169 156 180 216 128 174 185 126 144 192 145 160 157 181 179 231
148 146 140 161 90 150 136 167 146 137 151 130 117 121 170 206 156 157 131 157
126 131 131 168 151 171 165 181 210 142 118 115 162 227 192 121 170 140 139 137
146 115 107 131 100 153 143 121 190 156 153 131 137 115 121 133 134 126 167
NSV-A23B 119
90 94 113 123 78 51 45 100 138 105 133 111 136 112 99 97 155 155 139 148
110 87 83 115 145 108 131 136 126 134 121 135 103 104 149 157 139 159 151 152
108 183 166 142 160 156 178 215 144 167 178 117 153 190 134 157 161 174 193 220
159 143 139 156 90 157 139 164 145 143 152 131 117 126 179 181 164 154 131 154
121 139 129 165 140 171 168 184 229 131 114 111 187 215 188 146 171 140 122 143
146 121 125 135 92 148 148 118 190 164 143 123 143 117 113 112 133 139 155
NSV-A24A 129
89 98 140 93 161 109 130 136 142 138 117 141 65 114 82 67 88 73 92 114
100 116 97 116 126 110 151 150 139 112 92 52 89 182 109 142 167 153 114 143
117 125 154 164 110 196 192 196 199 171 133 120 101 112 159 160 139 164 140 142
168 156 155 169 131 177 156 159 207 198 161 141 185 186 178 185 166 180 111 107
154 128 110 140 93 115 137 118 184 145 134 142 131 133 129 128 111 113 139 135
123 137 129 112 132 103 110 115 138 119 129 146 120 118 95 156 181 152 129 146
148 114 142 146 112 134 143 140 120
NSV-A24B 129
101 113 143 95 171 100 133 148 143 141 118 140 67 112 85 66 90 75 85 112
101 109 103 121 125 111 148 153 135 112 110 50 92 181 105 140 165 149 114 148
114 118 153 166 110 200 189 195 203 171 126 121 107 120 151 167 139 159 137 139
179 171 157 162 138 172 164 162 209 189 157 162 193 170 177 179 170 163 126 121
153 118 120 134 96 112 128 124 175 129 140 129 146 134 134 121 112 110 151 134
123 129 128 121 132 99 106 125 130 123 146 119 127 106 106 157 179 165 122 150
149 122 133 152 115 123 133 141 130
NSV-A25A 123
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149 140 146 146 146 132 158 142 149 163 167 190 192 145 121 89 91 50 55 55
57 117 157 160 217 171 119 143 118 96 179 139 177 183 217 229 207 131 101 131
132 109 110 128 94 101 85 64 54 51 62 71 69 81 75 98 90 107 103 140
130 101 82 66 64 80 96 110 93 78 98 83 84 103 120 96 78 74 62 54
53 51 50 90 71 68 59 53 46 53 65 53 58 48 49 83 91 78 70 85
74 78 75
NSV-A25B 123
229 238 191 154 204 166 171 150 130 183 118 138 126 177 153 110 108 101 116 113
153 143 148 135 154 134 167 150 139 168 167 199 189 135 140 110 85 64 50 53
78 108 154 159 220 165 133 129 120 100 171 142 162 193 209 231 193 121 114 140
128 115 106 125 99 89 89 65 65 48 67 64 74 80 73 106 90 103 101 146
120 102 75 61 65 78 98 109 89 84 90 88 78 107 115 92 78 72 67 53
45 60 47 92 70 67 56 59 37 45 65 59 53 53 50 91 80 80 62 93
91 78 79
NSV-A26A 145
83 104 156 94 128 151 134 214 205 155 251 209 246 278 280 261 449 414 464 414
321 225 189 220 347 298 332 195 188 214 205 188 220 185 166 131 170 206 212 232
164 211 223 210 185 98 73 87 90 96 136 166 192 204 285 228 179 211 182 195
204 206 206 222 234 147 249 183 222 149 112 141 140 193 259 364 235 197 260 225
255 209 220 253 334 240 111 133 186 180 187 206 163 168 106 171 233 260 336 240
268 196 200 198 205 259 214 257 181 180 160 207 205 296 178 178 181 173 189 241
232 203 182 207 171 163 183 135 198 212 168 246 174 177 143 168 154 125 168 146
106 118 175 186 219

NSV-A26B 145
108 98 154 85 142 146 137 218 217 143 242 212 242 278 282 264 428 418 482 432
328 231 185 221 295 294 337 215 210 214 206 184 212 179 176 120 168 214 214 228
185 225 234 204 179 94 76 85 84 105 139 176 179 203 281 228 189 209 182 208
198 205 210 224 227 135 267 190 237 154 115 140 137 196 246 368 230 240 226 192
228 219 228 233 344 233 120 134 200 190 210 212 165 171 90 157 212 240 292 228
249 187 193 209 219 243 206 284 180 179 175 220 206 300 175 180 171 200 158 253
209 210 194 194 176 171 188 147 193 201 180 231 176 173 133 160 141 118 176 137
133 108 169 193 199
NSV-A27A 43
438 371 375 485 407 349 310 321 320 319 353 491 403 400 439 376 298 250 267 320
368 390 367 339 276 241 292 290 172 207 260 320 391 409 323 329 282 298 369 321
324 309 324
NSV-A27B 43
439 369 398 477 408 343 324 318 310 323 368 490 366 390 434 375 310 243 276 267
360 395 350 357 263 272 289 299 225 199 257 330 397 414 318 316 299 290 367 312
322 307 325
NSV-A28A 71
635 482 502 548 505 680 675 630 453 433 557 640 501 429 406 548 401 278 595 584
565 476 343 476 549 425 396 422 393 481 348 409 343 314 287 351 329 287 350 261
303 403 368 346 362 293 187 51 46 35 40 46 47 84 68 68 76 75 87 105
79 84 100 193 196 219 150 174 306 474 356
NSV-A28B 71
688 483 500 586 509 692 700 588 479 433 582 645 471 426 408 563 418 301 576 595
551 434 339 481 541 487 416 412 389 468 370 383 337 318 276 352 339 306 353 271
309 377 363 352 346 321 147 71 33 34 40 43 56 54 93 65 76 73 93 99
103 106 96 168 206 219 131 190 271 491 355
NSV-A29A 50
352 240 223 350 284 305 271 387 389 370 404 297 196 303 278 263 271 271 260 200
289 289 494 472 237 215 222 221 345 300 307 320 292 323 317 282 251 268 193 259
325 384 370 511 295 263 305 290 247 337
NSV-A29B 50
382 243 202 347 291 309 278 374 387 373 387 295 197 305 283 258 278 313 250 225
325 317 517 413 246 189 240 259 346 295 334 323 289 287 329 273 254 268 198 275
351 380 367 537 281 265 321 293 244 345
NSV-A30A 82
256 261 286 295 243 149 159 163 113 191 187 143 166 232 187 201 178 211 335 160
194 243 165 154 164 155 171 213 168 185 244 210 216 195 232 235 208 215 223 226
226 209 340 243 231 201 276 248 204 248 198 228 250 273 256 283 353 318 232 282
291 509 497 271 212 290 297 493 308 303 371 315 324 351 293 256 227 178 160 206
264 256
NSV-A30B 82
247 285 279 293 259 153 176 166 123 210 169 153 169 246 212 215 223 261 303 160
182 224 178 147 188 139 167 214 160 186 249 244 220 198 227 253 208 218 210 235
218 206 323 235 229 206 270 234 210 226 182 228 243 281 257 262 323 285 245 275
286 500 503 281 212 295 296 493 330 313 356 321 332 349 293 260 212 196 152 203
279 286
NSV-A31A 72
577 334 519 401 330 332 398 376 378 428 355 565 337 383 360 316 226 337 242 289
418 286 325 447 334 342 307 464 403 409 376 376 356 320 237 332 278 244 222 367
266 252 325 225 234 290 350 361 369 434 350 259 317 278 534 447 267 243 300 271

453 281 284 280 237 259 315 256 230 231 175 274
NSV-A31B 72
610 461 493 448 347 318 385 378 346 398 366 554 342 425 365 299 218 321 240 290
418 274 329 454 328 348 309 439 414 382 370 368 342 290 256 318 271 235 234 371
267 257 300 234 220 288 361 369 365 459 339 268 303 279 539 431 261 240 312 287
447 297 261 285 232 275 288 270 241 208 191 208

NSV-A32A 75
249 166 138 175 226 279 289 165 244 426 321 303 252 273 253 214 346 235 266 344
262 301 257 330 322 365 284 223 345 194 300 516 347 360 442 339 295 204 215 234
307 231 276 271 207 217 275 204 197 241 168 231 217 190 155 179 187 181 209 175
169 217 174 164 275 196 151 140 131 206 190 206 131 127 220
NSV-A32B 75
262 168 140 166 227 270 303 147 261 426 319 298 234 267 250 214 340 225 267 360
253 305 270 366 316 351 267 231 312 195 292 567 329 331 434 354 291 214 239 216
316 244 271 250 216 212 281 199 207 231 174 225 237 175 168 190 182 164 209 181
165 219 171 154 288 196 159 132 125 212 190 209 124 129 212
NSV-A33A 78
282 282 223 313 332 368 314 357 455 263 429 525 517 466 401 409 334 311 276 292
464 321 321 335 368 296 342 301 320 210 172 179 222 201 138 141 159 150 129 169
193 284 220 140 227 260 212 214 187 243 279 284 195 201 306 264 284 327 332 239
239 205 240 244 332 200 313 265 202 318 147 40 57 50 41 33 28 39
NSV-A33B 78
254 276 234 301 333 374 305 350 459 272 425 516 523 410 402 418 321 293 267 312
470 311 320 343 378 301 340 309 304 207 176 181 220 189 143 134 162 134 129 171
192 281 223 137 234 267 200 218 190 237 297 305 185 199 285 270 269 334 321 240
250 199 246 240 321 224 297 259 193 313 148 37 56 47 40 35 30 40

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

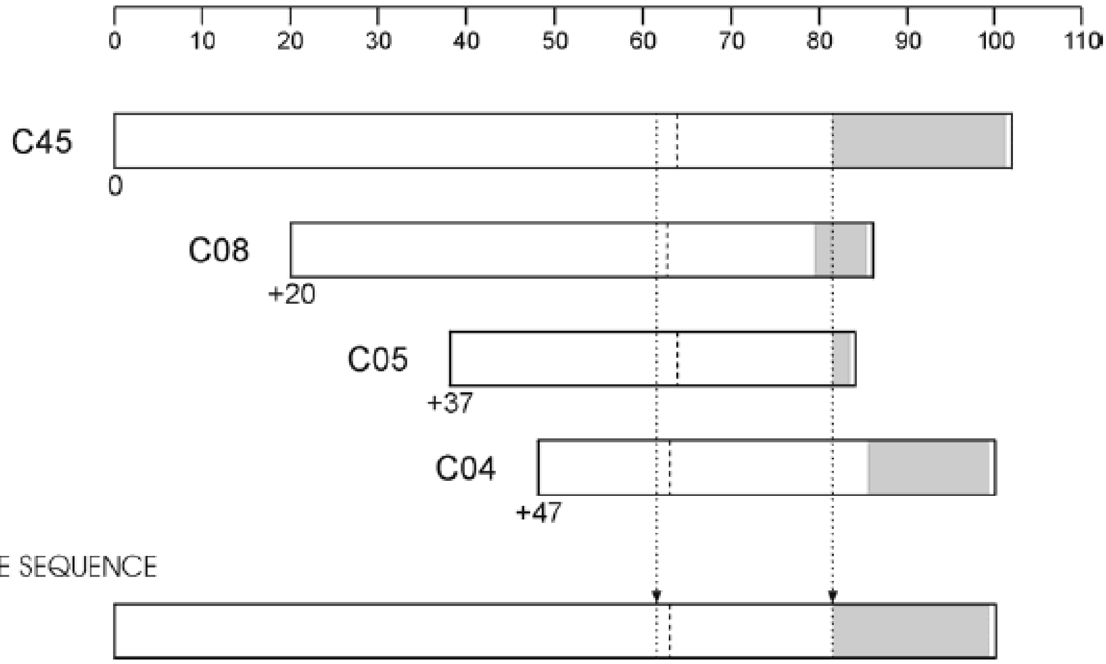


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

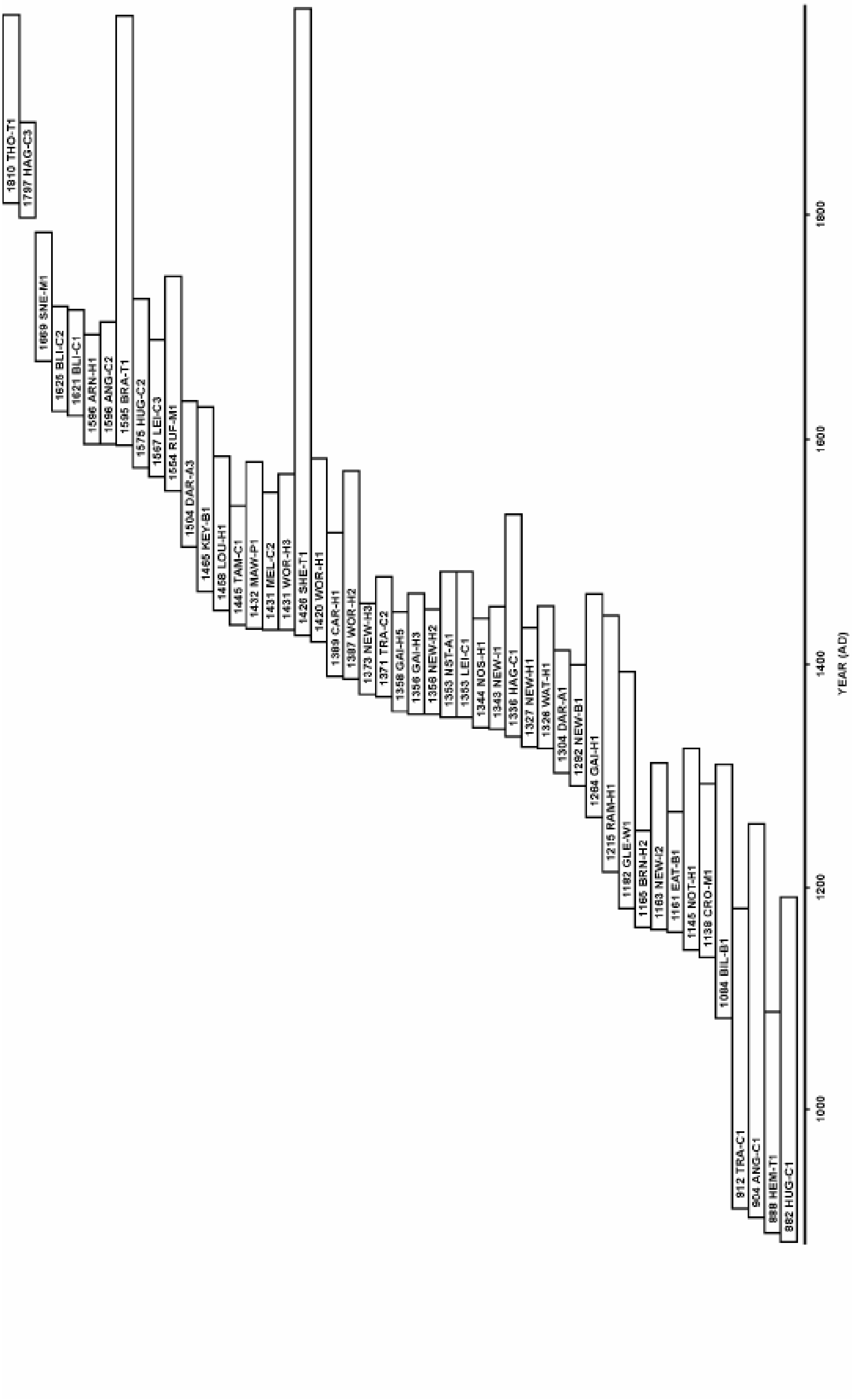
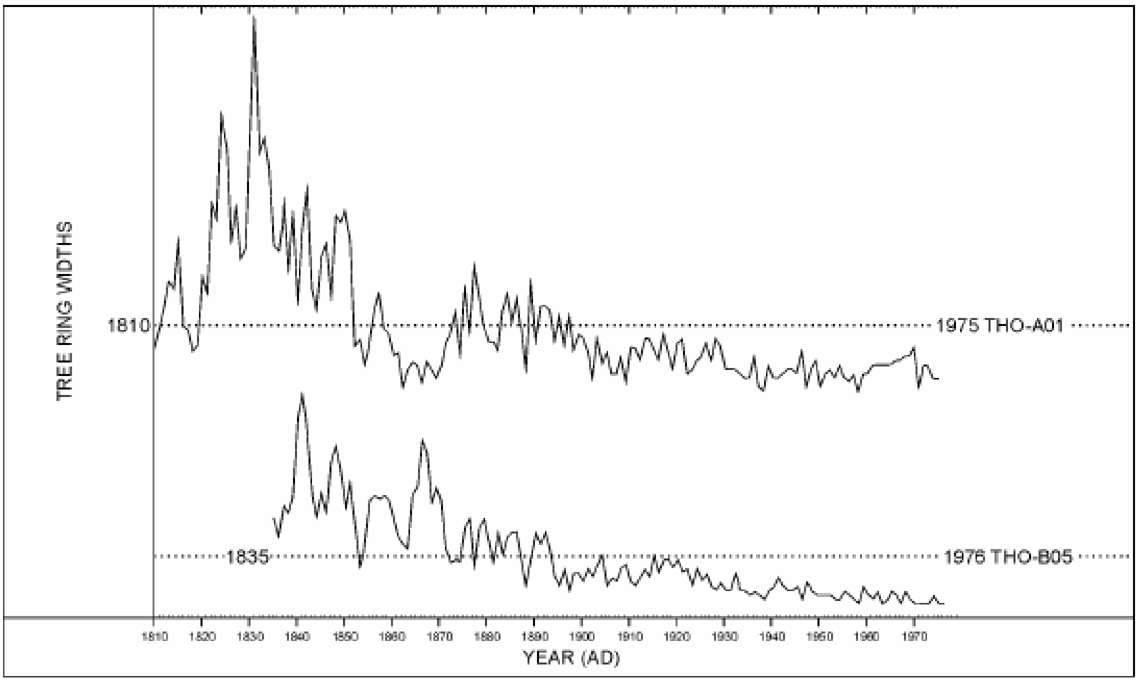


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

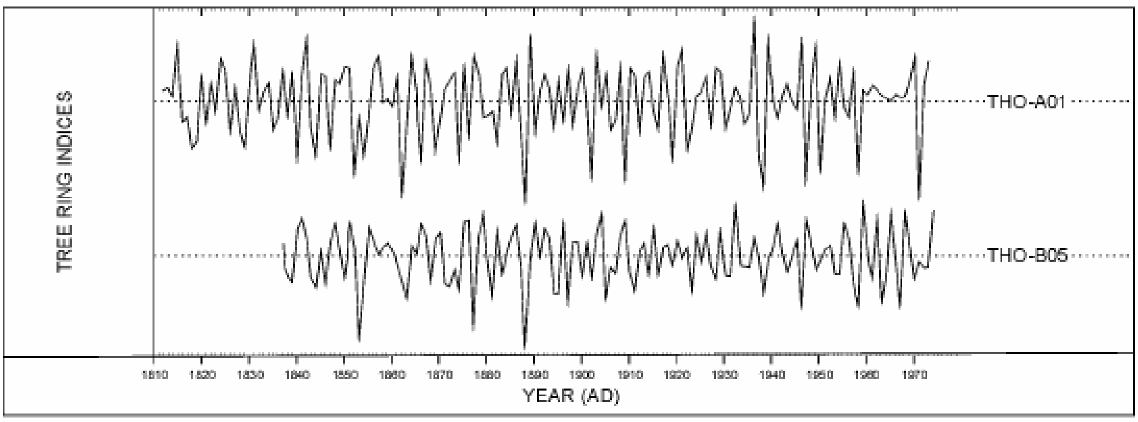


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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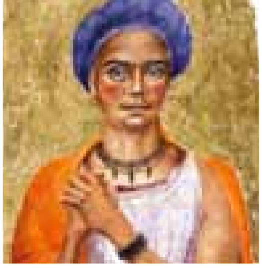


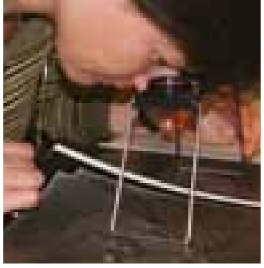


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