Historic England

Scientific Dating

Church of St Barnabas
Brampton Bryan
Herefordshire

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 44-2021

Front Cover: Church of St Barnabus, Brampton Bryan. Photograph Alison Arnold

Research Report Series 44-2021

CHURCH OF ST BARNABAS
BRAMPTON BRYAN
HEREFORDSHIRE

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

NGR: SO 37051 72513

ISSN 2059-4453 (Online)

SUMMARY
Analysis was undertaken on samples taken from timbers of the nave/chancel roof and cross frames resulting in the construction and dating of a single site sequence. This site sequence, BRMCSQ01, contains the ring series from all 35 sampled timbers and spans the period AD 1233–1644. Analysis of surviving sapwood suggests that the felling of the majority of timbers occurred in, or around, AD 1644. Two of the dated timbers, both braces, are felled earlier, one being felled *c* AD 1585 and the other having an estimated felling date in the range AD 1585–1615. Two other timbers may be felled slightly earlier, a tie having an estimated felling date in the range AD 1602–27 and a post having an estimated felling date in the range AD 1608–33, but it is also possible, bearing in mind the characteristics of the assemblage, that these are simply long-lived trees with more than the usual number of sapwood rings. The overall results suggest that construction of this roof occurred in the mid-seventeenth century and utilised some reused or stockpiled timber.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank Michael Sumner, Honorary Treasurer, for facilitating access for assessment and sampling. Mr Sumner also supplied the plan upon which some samples have been marked. Contractors on site were very helpful, enabling smooth access to the roof timbers in the void above the ceiling during the latest sampling visit. Fran Rhodes and Deborah Jarman of Forward St Barnabas Project are thanked for their support. Thanks, are also due to Shahina Farid of the Historic England Scientific Dating Team for her advice and assistance throughout the production of this report

ARCHIVE LOCATION
Historic England Archive
The Engine House
Firefly Avenue
Swindon SN2 2EH

HISTORIC ENVIRONMENT RECORD OFFICE
Herefordshire Historic Environment Record
Herefordshire Archive and Record Centre
Fir Tree Lane, Rotherwas
Hereford HR2 6LA

DATE OF INVESTIGATION
2017–21

CONTACT DETAILS

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

Cathy Tyers
Historic England
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA
cathy.tyers@historicengland.org.uk

CONTENTS

INTRODUCTION

The Grade I listed Church of St Barnabas (List Entry Number 1179943) now in the Parish of Wigmore Abbey but previously in the Parish of Brampton Bryan in Herefordshire (Fig 1). It is thought to have had its origins in the thirteenth century but was almost entirely rebuilt in AD 1656 for Sir Robert Harley, following substantial damage in AD 1643 during the Civil War. It is a rectangular, five-bay hall church, the eastern bay of which is used as a liturgical chancel. The church also has a west vestry, north vestry, and south porch (Fig 2). Further alterations and extensions were undertaken in the late-nineteenth century.

The roof over the nave and chancel is of triple hammerbeam type. The lower hammerbeams are supported on six pairs of part rectangular, part columnar wall posts on square plinths with dentilled cornices, supporting brackets with enriched pendants and moulded wall plates. The end pairs of posts and brackets carry no hammerbeams since they are adjacent to the east and west walls. The upper portion of the roof is concealed by a twentieth-century boarded ceiling (Fig 3). Access above this ceiling reveals the four central trusses with principal rafters, collar, queen posts, and ties (Fig 4). Stylistically this roof is thought to be seventeenth century in date. However, the timbers utilised may be earlier as it has been suggested that they were salvaged from the Castle Banqueting Hall, which was destroyed by fire in AD 1643 (Sidebotham 1990).

SAMPLING

Dendrochronology was requested by Sarah Lewis, Inspector of Historic Buildings and Areas for Historic England, as the church was identified as vulnerable and, therefore, a priority for repairs. Further input was provided by Nick Molyneux, also Principal Inspector of Historic Buildings and Areas. It was hoped that dendrochronology would provide independent dating evidence to better understand the historical development of the building and to shed light on the veracity regarding the reuse of the hammerbeam roof. This would help the parish understand the significance of the building in order to prioritise future repairs and grant applications.

Initially, in July 2017, core samples were taken from 12 of the oak (*Quercus* sp.) timbers that were accessible. Subsequently, in April 2018, a further 12 oak timbers were sampled from higher parts of the roof with the aid of a scaffold tower. In 2021 works undertaken on the roof covering allowed access to the roof void above ceiling level and a further 11 oak timbers were sampled. Each sample was given the code BRM-C and numbered 01–35 with duplicate core samples being taken from two of the timbers (samples BRM-C03 and BRM-C13) in order to maximise the measurable ring series. Further details relating to the samples can be found in Table 1. Trusses have been numbered from east to west; these and the location of samples have been marked on Figures 2 and 5–8.

ANALYSIS AND RESULTS

All samples were prepared by sanding and polishing, and their growth-ring widths measured; the data of these measurements are given at the end of the report. The duplicate cores taken from the north post of truss 3 were combined to produce a 201-year ring series. However, the initial core taken in 2018 from the north principal rafter of truss 3 represented only a small part of the overall ring sequence in the timber and had clearly distorted rings. The second core taken from this timber in 2021 was significantly better and hence the first core was excluded from further analysis. The measurements obtained for each timber sampled were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in all 35 ring-series matching at a minimum *t*-value of 5.3 to form a single group.

The 35 ring-series were combined at the relevant offset positions to form BRMCSQ01, a site sequence of 412 rings (Fig 9). This site sequence was compared against an extensive series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1233 and a last-measured ring date of AD 1644 (Table 2).

INTERPRETATION

Analysis has resulted in the successful dating of all 35 sampled timbers (Table 1; Fig 9). In the absence of sapwood complete to the bark edge, the estimate that 95% of mature oak trees from this area have between 15 and 40 sapwood rings is used to calculate felling date ranges or *terminus post quem* dates for felling (felled after dates). The heartwood/sapwood boundary is present on seventeen of the dated ring series, the interpretation of which indicates that more than one period of felling is represented.

Sample BRM-C32 retains complete sapwood and the last-measured ring date of AD 1644, the felling date of the timber represented. Two further samples, BRM-C02 and BRM-C05, were also taken from timbers with complete sapwood but in both cases all these friable outer rings were lost during the sampling process. By noting the amount of sapwood lost, it was possible to estimate that the samples had lost *c* 20 and *c* 22 sapwood rings, respectively. With last-measured ring dates of AD 1565 (BRM-C02) and AD 1622 (BRM-C05) these are estimated to have been felled in *c* AD 1585 and *c* AD 1644 respectively.

A further 14 samples have the heartwood/sapwood boundary ring, the dates of which, as above, suggest more than one felling is represented. The earliest heartwood/sapwood boundary ring amongst these samples is that of BRM-C19; this is AD 1570, which gives an estimated felling date for the timber of AD 1585–1610. Samples BRM-C33 and BRM-C03 have slightly later heartwood/sapwood boundary ring dates of AD 1587 and AD 1593, respectively and the estimated felling date ranges of AD 1602–27 and AD 1608–33. The other 11 samples have a similar heartwood/sapwood boundary ring date, ranging from AD 1601 (BRM-C30) to AD 1615 (BRM-C27), suggestive of a single felling. The average of these dates is AD 1610, allowing an estimated felling date to be calculated for the 11 timbers represented to within the range AD 1638–50; this allows for sample BRM-C34 having a last-measured ring date of AD 1637, with incomplete sapwood. The last measured heartwood ring dates of the remaining 18 dated timbers vary from AD 1358 (BRM-C25) to AD 1596 (BRM-C31), giving a series of *terminus post quem* dates for felling ranging from AD 1373 to AD 1611. These timbers, with the exception of BRM-C07, BRM-C11, and BRM-C31, could be felled in either *c* AD 1585 or AD 1644, or alternatively represent a completely different felling phase, or phases. However, when taking into account the overall level of matching within these dated timbers, which includes a number of *t*-values indicative of possible same-tree derivation for some timbers, it appears most likely that the majority of timbers were felled in, or around, AD 1644 (see below).

DISCUSSION

Prior to tree-ring dating being undertaken the roof had been dated stylistically to the seventeenth century and hence considered most likely to be associated with the extensive rebuilding for Sir Robert Harley in AD 1656, which followed the fire damage of AD 1643. However, it had been suggested that the timbers used in its construction were reused from an earlier structure.

The majority of the dated timbers were felled at some point within the range AD 1638–1650, with at least two timbers having been felled in, or about, AD 1644. It is thought likely that most of the timbers utilised were felled at this time, in the mid-AD 1640s. It can be seen (Fig 10) that this is the case regardless of timber type, with examples of braces, collars, hammerbeams, posts, and principal rafters all being represented within this AD 1638–50/AD 1644 felling phase. This supports the mid seventeenth-century construction date previously postulated (the AD 1656 rebuilding) and also suggests preparations, in the form of felling of timber, began almost immediately following the damage to the church occurring (AD 1643) even if construction did not begin for some time afterwards.

There is some evidence for the use of reused or stockpiled timbers in the identification of two braces, one felled in *c* AD 1585 and a second in AD 1585–1610. Additionally, a tie was dated to AD 1602–27 and a post to AD 1608–33, which would also suggest reuse or stockpiling. Alternatively, it may be that the trees represented by the tie and the post fall within the 5% of trees whose number of sapwood rings lie outside the usual 95% interval of 15–40, in this instance potentially having more than 40 sapwood rings (see below) which would allow these latter two beams to be felled with the majority of the timber.

It is unfortunate that 18 of the 35 dated timbers do not have the heartwood/sapwood boundary ring and so estimated felling date ranges cannot be given for these timbers. With *terminus post quem* dates for felling (felled after dates) ranging from AD 1373 to AD 1611 it is possible that construction of the roof utilises a disparate set of timbers representing several felling events. However, this appears unlikely. Firstly, there are a number of pairs of timbers that, based on the level of similarity of their ring sequences, are potentially derived from the same tree despite their differences in last measured ring dates. BRM-C21 (felled after AD 1530) matches BRM-C32 (felled AD 1644) at *t* = 14.5, with both timbers potentially being cut from the same tree and hence felled at the same time in AD 1644. Three of the other samples without the heartwood/sapwood boundary match samples with the heartwood/sapwood boundary ring present at *t*-values consistent with them having been also potentially cut from the same tree, and hence, also felled in AD 1638–50 (BRM-C31 and BRM-C23 at *t* = 12.7, BRM-C26 and BRM-C27 at *t* = 11.1, and BRM-C28 and BRM-C13 at *t* = 12.0). Two other samples, also lacking the heartwood/sapwood boundary ring present, BRM-C04 (felled after AD 1450) and BRM-C01 (felled after AD 1534) match each other at a value of *t* = 10.7. Indeed, the *intra-site* matching of samples overall is very good, with all but two samples grouping at a value of *t* = 6.0+, consistent with the timbers utilised being a coherent group of trees from a single woodland and potentially from a single period of felling.

It is notable that the majority of these timbers appear to have been derived from very long-lived trees, some of them likely to have been in the region of 350–400 years old when felled. It is relatively unusual to find trees of such an age used in standing historic buildings and it should be noted that trees of such an age when felled may have more than the standardly applied 15–40 (95% interval) sapwood rings. This raises the possibility that all timbers bar those represented by samples BRM-C02 and BRM-C19 were felled at the same time, but that some had greater than the standard number of sapwood rings.

REFERENCES

Arnold, A J, and Howard, R E, 2014 unpubl *Brockhampton Manor, near Bromyard, Herefordshire, tree-ring analysis of timbers from the cross-wing range*, unpubl computer file *BRKHSQ01*, NTRDL

Arnold, A J, Howard, R E, and Tyers, C, 2015 *Sydenham House, Marystow, Devon, Tree-ring Analysis of Oak Timbers, Panelling, and Trees*, Historic England Res Rep Ser, 45/2015

Bridge, M C, 2001 *Tree-ring Analysis of Timbers from 39–41 High Street, Kingston upon Thames, Greater London*, Centre for Archeol Rep, 113/2001

Bridge, M, and Miles, D, 2011 *The Reader's House, Ludlow, Shropshire, Tree-ring Analysis of Timbers,* English Heritage Res Rep Ser, 108/2011

Miles D, Haddon-Reece, D, and Moran, M, 1995 Tree-ring dates for buildings: List 64, *Vernacular Architect,* 26, 60–74

Nayling, N, 1999 *Tree-ring Analysis of Timbers from the White House, Vowchurch, Herefordshire*, Anc Mon Lab Rep, 73/1999

Sidebotham, A, 1990 *Brampton Bryan Church & Castle*, Ophans Press Ltd

Tyers, I, 2002 *Tree-ring Analysis of Oak Timbers from The Abbot's Hall and Parlour at Wigmore Abbey, near Adforton, Herefordshire*, Centre for Archaeol Rep, 112/2002

Tyers, I, 2008 *Hartlebury Castle, Near Stourport-on-Severn, Worcestershire, Dendrochronological Analysis of Oak Timbers*, Historic England Res Dep Rep, 76/2008

Tyers, I, and Boswijk, G, 1998 *Tree-ring Analysis of Oak Timbers from Dore Abbey, Abbey Dore, Herefordshire*, Anc Mon Lab Rep, 18/1998

Tyers, I, and Price, S, 2017 Tree-ring dates from Bewdley and Droitwich, Worcestershire, List 293, *Vernacular Architect*, 48, 103–8

TABLES

Table 1: Details of samples taken from the Church of St Barnabas, Brampton Bryan, Herefordshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
BRM-C01	South post, truss 1	184	--	1336	----	1519
BRM-C02	Lower brace, truss 2, north	178	h/s(+c20lost)	1388	1565	1565
BRM-C03	North post, truss 3 (combined 2017/2018 cores)	201	h/s	1393	1593	1593
BRM-C03A	*ditto (2017 core)*	*105*	*--*	*1393*	*----*	*1497*
BRM-C03B	*ditto (2018 core)*	*174*	*h/s*	*1420*	*1593*	*1593*
BRM-C04	South post, truss 3	97	--	1339	----	1435
BRM-C05	North hammerbeam, truss 3	331	h/s(+c22lost)	1292	1622	1622
BRM-C06	North post, truss 4	106	--	1332	----	1437
BRM-C07	South post, truss 4	308	--	1268	----	1575
BRM-C08	South hammerbeam, truss 4	207	--	1335	----	1541
BRM-C09	Lower brace, truss 4, south	187	--	1339	----	1525
BRM-C10	North post, truss 5	154	h/s	1461	1614	1614
BRM-C11	South hammerbeam, truss 5	260	--	1335	----	1594
BRM-C12	Lower brace, truss 5, south	116	--	1381	----	1496
BRM-C13	North principal rafter, truss 3 (2021 core)	298	h/s	1310	1607	1607
BRM-C14	Lower hammer post, truss 3, north	177	--	1303	----	1479
BRM-C15	Lower hammer post, truss 3, south	178	h/s	1427	1604	1604
BRM-C16	Brace, wall post to lower hammerbeam, truss 3, north	113	h/s	1497	1609	1609
BRM-C17	Brace, lower hammerbeam to principal rafter, truss 3, north	269	h/s	1345	1613	1613
BRM-C18	Brace, lower hammerbeam to principal rafter, truss 3, south	300	h/s	1314	1613	1613
BRM-C19	Brace, lower hammer post to upper hammerbeam, truss 3, north	145	06	1432	1570	1576
BRM-C20	North principal rafter, truss 4	65	--	1384	----	1448
BRM-C21	Lower hammer post, truss 4, south	217	--	1299	----	1515
BRM-C22	Brace, lower hammerbeam to principal rafter, truss 4, north	300	--	1233	----	1532
BRM-C23	Brace, lower hammerbeam to principal rafter, truss 4, south	187	03	1429	1612	1615

BRM-C24	Brace, lower hammer post to upper hammerbeam, truss 4, south	257	h/s	1357	1613	1613
BRM-C25	North principal rafter, truss 2	115	--	1244	----	1358
BRM-C26	North queen post, truss 2	164	--	1333	----	1496
BRM-C27	South queen post, truss 2	210	h/s	1406	1615	1615
BRM-C28	South principal rafter, truss 3	165	--	1327	----	1491
BRM-C29	North queen post, truss 3	214	--	1327	----	1540
BRM-C30	South queen post, truss 3	174	h/s	1428	1601	1601
BRM-C31	South principal rafter, truss 4	216	--	1381	----	1596
BRM-C32	Collar, truss 4	320	39C	1325	1605	1644
BRM-C33	South tie, truss 4	350	h/s	1238	1587	1587
BRM-C34	North principal rafter, truss 5	328	23	1310	1614	1637
BRM-C35	South principal rafter, truss 5	162	--	1279	----	1440

h/s = the heartwood/sapwood boundary is the last-measured ring
(+xlost) = all or part of the sapwood lost in the sampling process, x = estimated number of sapwood rings in brackets
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BRMCSQ01 and relevant reference chronologies when the first-ring date is AD 1233 and the last-measured ring date is AD 1644

Site reference	*t* – value	Span of chronology	Reference
Wigmore Abbey, Herefordshire	15.8	AD 1055–1729	Tyers 2002
Hartlebury Castle, Stourport on Severn, Worcestershire	14.0	AD 1235–1745	Tyers 2008
Bedstone Manor Farm, Shropshire	12.8	AD 1341–1560	Miles *et al* 1995
White House, Vowchurch, Herefordshire	12.2	AD 1364–1602	Nayling 1999
Dore Abbey, Abbey Dore, Herefordshire	12.0	AD 1363–1612	Tyers and Boswijk 1998
Brockhampton Manor, near Bromyard, Herefordshire	11.7	AD 1304–1505	Arnold and Howard 2014 unpubl
Bewdley, Worcestershire	11.7	AD 1233–1596	Tyers and Price 2017
The Reader's House, Ludlow, Shropshire	11.0	AD 1406–1615	Bridge and Miles 2011
Sydenham House, Marystow, Devon	10.9	AD 1266–1629	Arnold *et al* 2015
39-41 High Street, Kingston upon Thames, London	10.7	AD 1385–1466	Bridge 2001

FIGURES

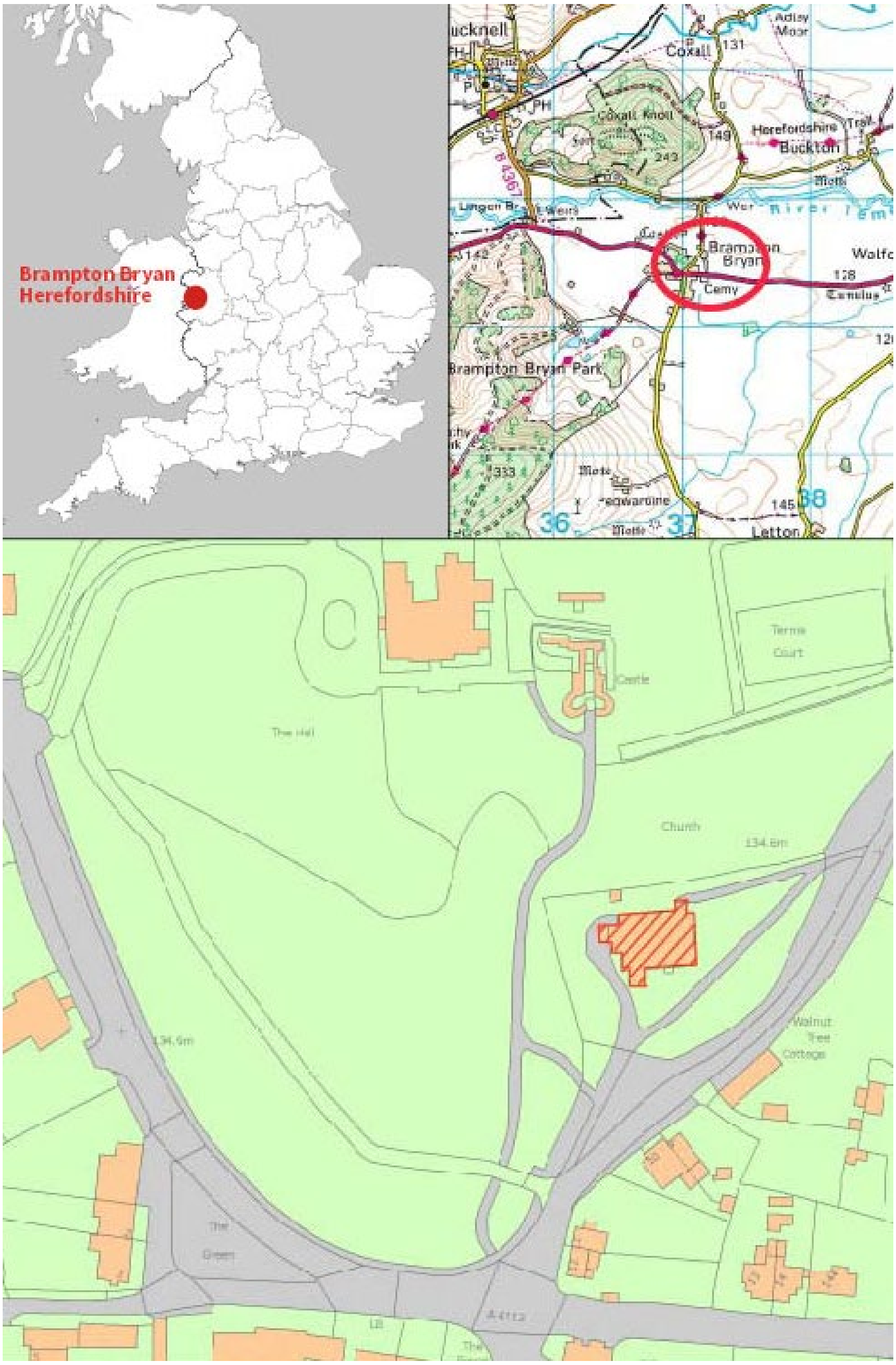


Figure 1: Maps to show the location of the Church of St Barnabas, Brampton Bryan in Herefordshire, marked in red. Scale: top right 1:40000; bottom 1:1250.

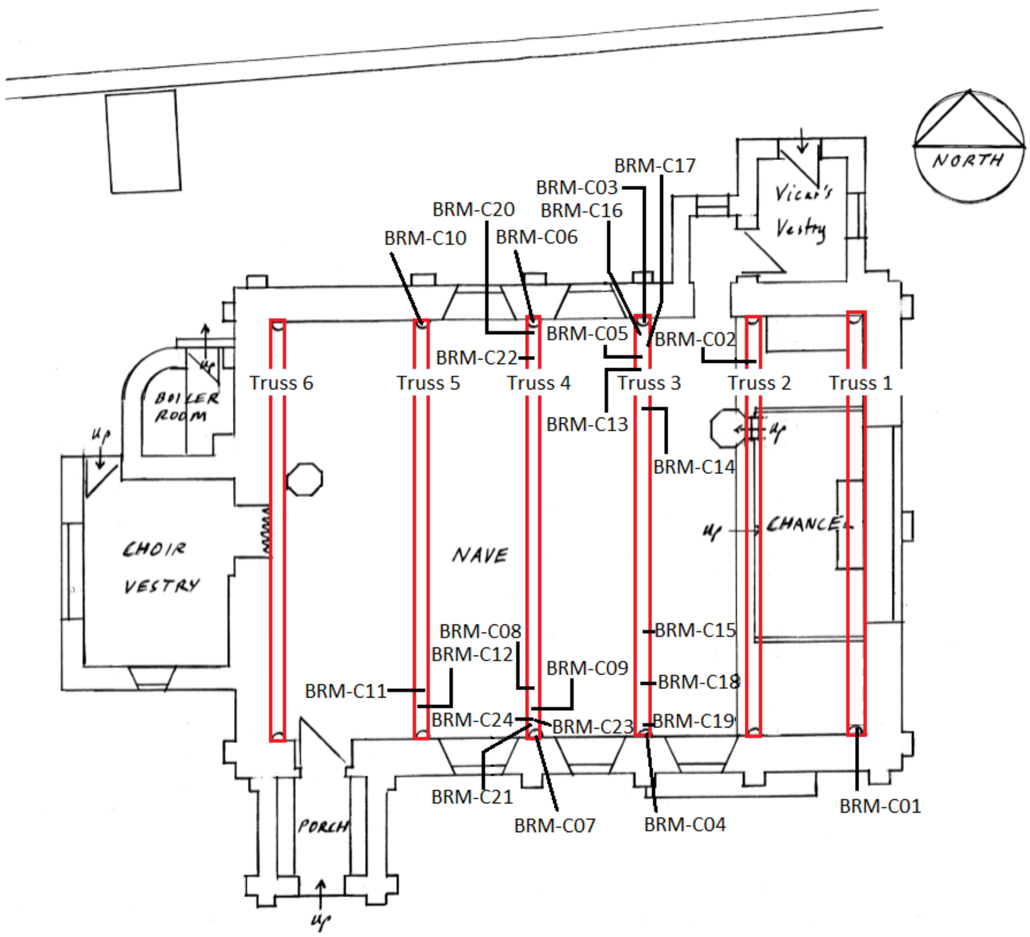


Figure 2: Plan of St Barnabas' Church, showing truss numbering, and the location of samples BRM-C01–24 (after Hook Mason Architecture)

Figure 3: The roof, with truss 3 in the foreground. Photograph taken from the south-east (Robert Howard)

Figure 4: Roof and truss 3. Photograph taken from the east and at above ceiling level (Robert Howard)

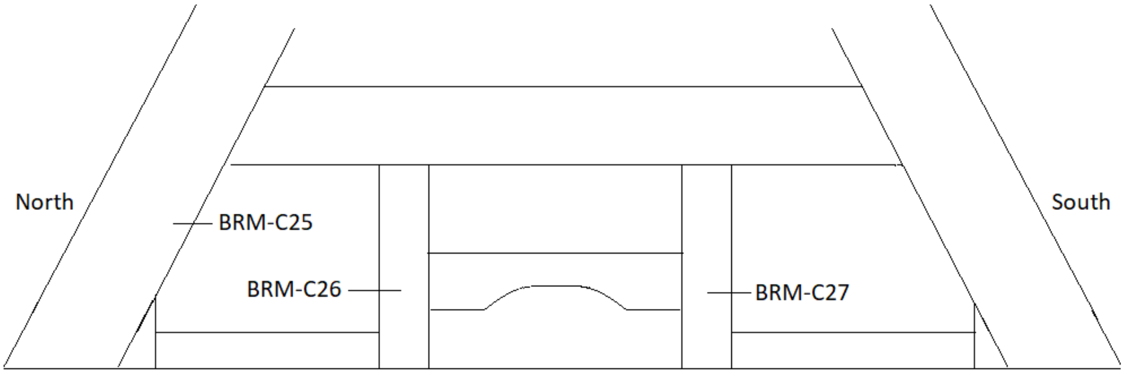


Figure 5: Schematic drawing of truss 2, showing the location of samples BRM-C25–27

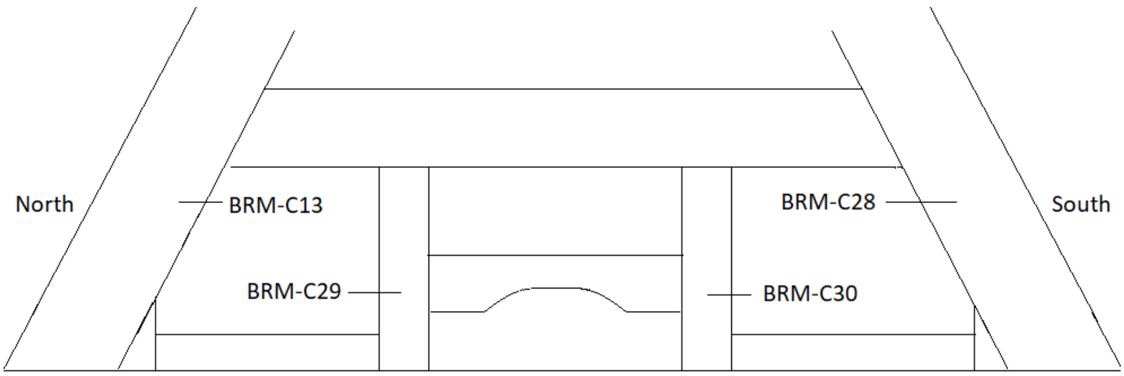


Figure 6: Schematic drawing of truss 3, showing the location of samples BRM-C13 and BRM-C28–30

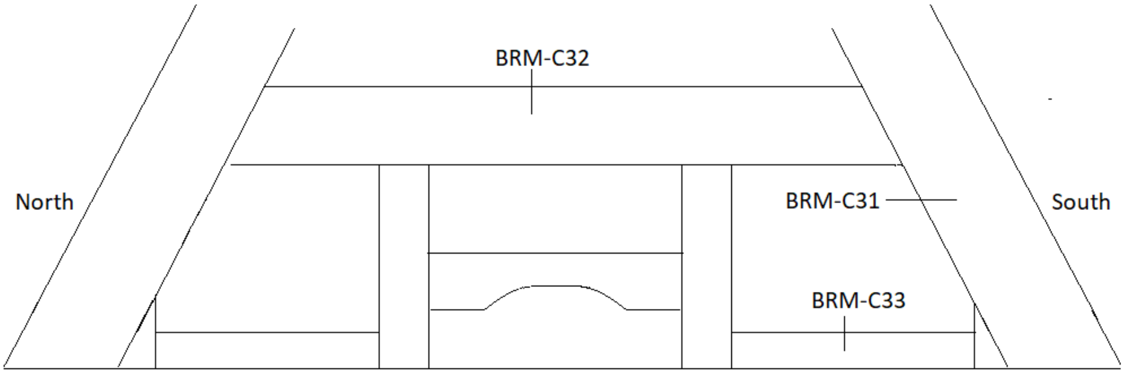


Figure 7: Schematic drawing of truss 4, showing the location of samples BRM-C31–33

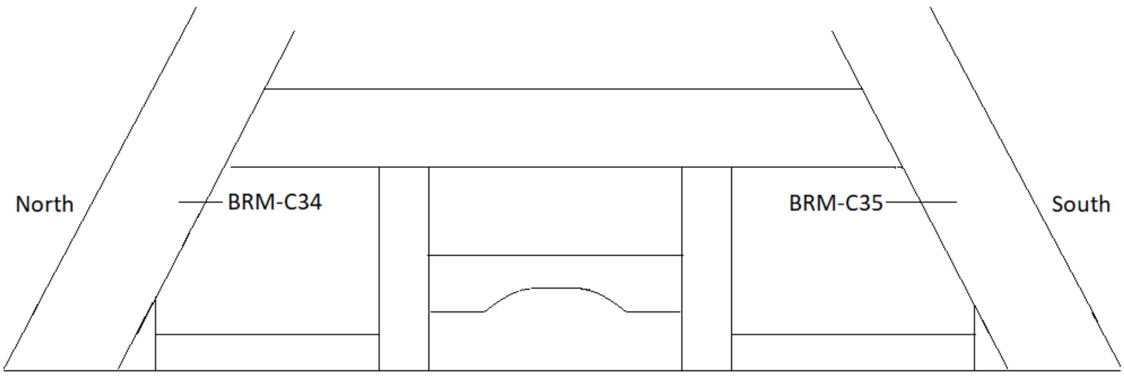


Figure 8: Schematic drawing of truss 5, showing the location of samples BRM-C34 and BRM-C35

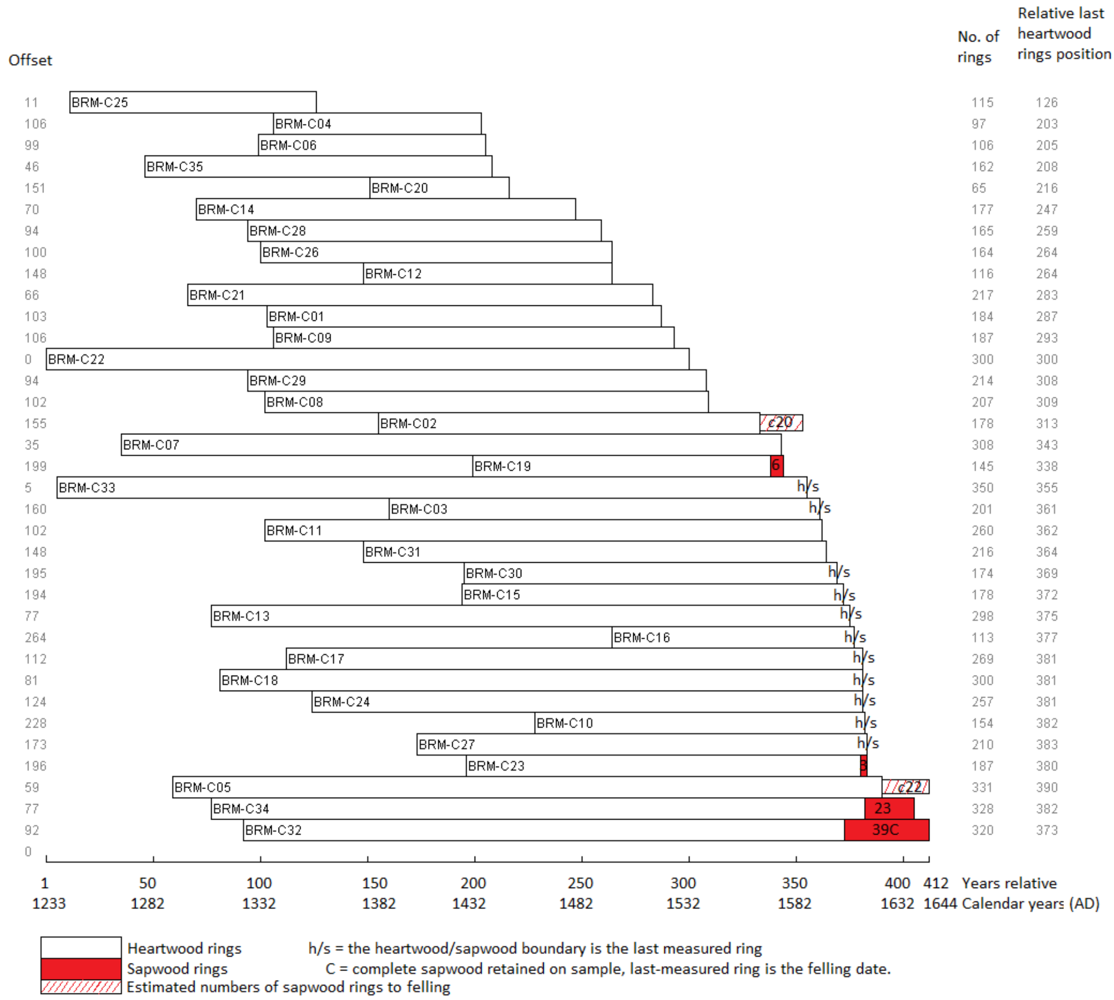


Figure 9: Bar diagram to show the relative position of samples in site sequence BRMCSQ01

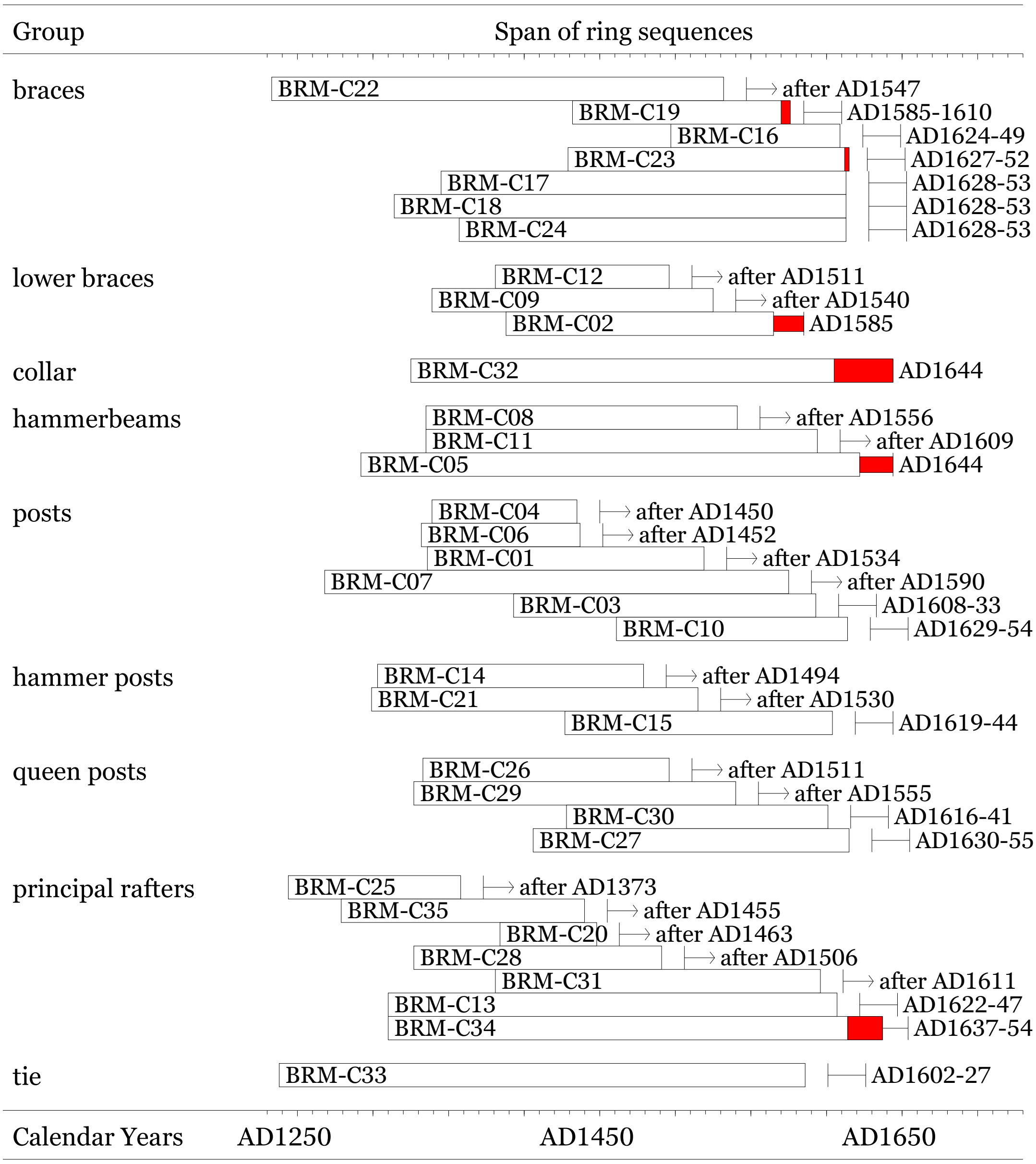


Figure 10: Bar diagram of dated samples and their individual felling date/range, sorted by element type

DATA OF MEASURED SAMPLES

BRM-C01A 184
155 135 206 207 177 180 171 103 101 156 183 174 189 219 147 137 150 140 144 183
197 236 224 265 116 171 138 218 250 178 204 133 103 166 185 120 157 163 166 154
153 128 134 215 126 141 159 161 157 154 159 130 144 109 87 108 112 92 123 85
162 144 183 205 150 150 131 205 176 152 114 102 132 102 99 82 81 59 47 64
64 80 106 73 125 144 105 237 157 179 115 118 147 144 151 163 168 169 169 200
133 159 142 111 123 122 91 99 126 100 134 137 174 211 171 170 172 192 199 175
194 176 184 150 154 134 152 133 119 114 115 119 129 168 171 127 106 70 92 90
100 94 87 87 68 74 54 69 66 74 81 84 70 75 76 87 77 87 89 92
129 126 100 118 95 92 96 129 134 191 244 238 235 166 112 181 114 149 135 142
117 123 103 140
BRM-C01B 184
140 133 179 206 188 179 168 104 110 149 163 160 200 214 137 130 130 140 149 178
186 229 226 278 108 173 145 221 255 172 205 132 102 173 176 132 149 169 178 142
154 138 135 204 137 132 149 164 162 162 165 134 141 113 99 110 122 97 116 97
158 133 180 213 156 148 136 205 166 158 123 103 124 110 104 84 76 58 53 68
71 88 100 76 132 153 122 241 166 174 119 116 145 145 133 160 171 168 162 214
124 186 116 106 121 111 98 97 117 100 136 141 179 192 173 168 192 172 192 173
178 167 176 134 157 144 157 129 120 123 111 131 119 168 169 132 100 82 82 88
100 100 82 93 65 80 58 60 63 77 80 83 67 78 75 83 76 96 88 93
138 115 131 112 105 98 80 134 145 201 304 245 185 139 112 147 115 130 129 133
122 128 117 154
BRM-C02A 178
120 120 110 102 80 83 79 69 77 102 95 122 112 107 104 103 109 91 76 70
83 62 115 67 67 57 53 53 70 99 117 81 114 111 87 124 128 126 115 98
112 101 107 101 143 108 154 118 141 132 94 78 88 104 65 103 81 80 80 87
89 107 103 98 85 115 109 100 117 112 117 86 106 84 114 87 73 87 73 93
89 105 95 90 84 73 63 86 90 105 77 72 59 84 63 70 87 91 98 120
76 78 65 83 79 86 97 79 96 99 92 93 76 68 79 73 72 76 74 63
67 76 66 88 92 80 89 77 68 75 75 73 57 83 72 76 45 50 53 50
58 50 50 51 57 56 68 61 72 72 54 47 64 76 53 54 61 44 54 52
62 81 57 59 41 41 54 55 44 43 46 45 55 56 51 53 52 58
BRM-C02B 178
120 119 110 104 88 78 85 61 81 90 91 117 112 106 82 99 101 82 72 75
74 67 107 70 69 52 50 53 70 102 113 90 122 104 88 121 130 123 115 94
118 95 103 103 145 103 149 123 135 143 95 83 83 101 67 102 81 86 80 89
86 108 98 101 92 111 114 99 111 117 116 89 102 96 115 83 71 83 70 102
105 82 94 91 85 71 65 77 95 92 70 69 64 90 52 78 82 80 93 107
74 74 68 80 83 92 87 78 99 88 86 84 75 70 69 72 76 72 73 58
65 77 73 76 94 72 87 72 78 65 81 65 50 76 65 84 53 50 52 51
52 54 43 47 59 61 66 62 79 68 48 52 65 73 55 61 62 43 61 56
59 80 52 62 40 49 49 58 43 46 39 50 59 58 54 53 57 56
BRM-C03A 105 (2017 core)
100 125 99 166 148 154 162 170 151 122 127 169 165 172 147 177 167 234 163 161
170 112 94 115 131 131 116 144 192 155 206 157 166 142 134 140 137 141 163 152
148 160 150 122 140 126 115 121 120 92 95 117 115 112 130 118 149 143 128 141
155 155 140 163 151 131 121 159 139 167 151 114 132 134 154 134 142 101 135 123
97 99 108 116 110 87 100 65 87 84 90 79 111 120 140 125 104 108 102 90
97 97 98 108 98
BRM-C03B 174 (2018 core)
130 174 128 215 162 150 107 117 116 145 127 152 149 154 149 125 109 128 106 108

87 100 83 82 96 89 104 94 103 110 102 90 85 106 108 99 97 101 99 96
104 97 112 93 79 90 93 97 101 90 78 81 83 66 75 74 96 82 75 69
47 98 68 72 73 85 75 96 71 66 72 86 79 74 67 77 62 77 73 68
56 53 51 57 63 57 59 49 51 58 48 52 57 50 61 45 56 63 55 66
58 69 81 71 71 69 76 71 82 85 68 84 70 78 91 67 73 77 67 78
74 96 66 64 69 56 72 66 62 72 58 85 52 63 69 72 56 61 58 55
60 48 63 50 55 64 50 50 56 67 76 84 78 92 80 75 52 44 51 66
62 85 62 63 69 72 62 69 63 69 65 79 73 77
BRM-C04A 97
193 173 160 162 120 122 174 231 207 248 244 169 161 187 180 219 144 141 150 125
165 105 143 178 188 185 120 152 134 110 152 128 113 120 128 180 142 158 125 127
185 176 113 138 123 129 152 155 127 152 172 138 143 149 99 97 95 110 132 127
141 141 138 119 141 143 137 106 99 129 115 118 90 83 69 56 78 100 101 117
87 137 137 102 211 142 160 120 118 130 133 111 128 156 130 144 142
BRM-C04B 97
187 173 160 162 119 113 172 233 200 247 246 161 167 191 176 215 142 143 151 119
167 114 133 179 196 179 123 149 130 108 149 132 112 113 133 181 137 156 123 124
186 155 124 137 133 129 132 157 130 159 163 143 160 139 93 94 86 115 132 124
136 128 138 113 139 137 130 114 106 120 117 129 82 90 65 64 77 101 92 117
86 136 135 110 204 140 158 105 112 123 133 122 128 141 134 149 143
BRM-C05A 330
283 365 240 369 275 118 95 98 128 132 147 53 46 34 36 24 34 43 43 41
56 47 45 42 72 53 57 63 40 60 53 61 52 57 55 35 50 57 44 46
68 54 40 57 60 69 62 63 72 80 61 50 46 55 66 63 62 66 64 62
72 83 102 63 60 97 77 110 76 91 105 102 97 67 95 92 95 84 79 78
120 70 98 97 113 82 83 115 84 81 72 72 88 71 123 73 106 101 101 101
65 66 43 54 50 54 60 54 63 68 44 76 87 71 67 76 85 85 107 68
73 67 55 43 45 55 70 46 61 70 58 77 82 61 81 70 115 114 86 75
91 72 74 69 70 71 86 59 68 59 62 66 61 54 53 64 64 67 67 74
59 68 59 66 80 76 71 65 56 65 67 63 61 76 70 71 67 68 74 76
54 58 65 76 73 67 74 59 50 85 60 80 69 60 73 78 68 64 63 78
55 67 75 57 77 72 63 74 61 58 50 52 58 55 67 48 63 55 55 71
84 73 70 58 64 62 63 65 48 66 71 68 56 41 60 54 69 71 52 77
62 75 70 81 80 68 63 87 119 131 100 110 93 85 85 72 110 104 121 133
78 110 80 120 94 90 81 81 67 85 88 78 86 84 54 52 66 83 91 83
70 69 68 56 55 46 50 77 66 81 59 63 69 50 67 63 47 55 58 51
55 61 54 65 73 42 50 69 49 51 48 56 64 53 53 37 50 52 38 35
41 40 49 40 34 47 51 40 37 44
BRM-C05B 331
280 373 266 333 284 91 93 80 114 120 130 55 43 32 33 28 35 39 45 43
56 41 44 43 67 54 60 65 42 49 59 58 52 55 42 50 53 50 38 39
64 54 39 61 62 61 64 66 68 81 62 49 48 54 60 66 59 72 61 60
75 82 99 67 62 95 78 105 77 97 101 101 98 77 85 87 94 85 79 72
114 79 90 100 112 82 88 115 82 78 77 71 89 72 122 69 102 100 93 88
63 64 58 54 52 64 62 58 78 57 48 78 84 65 67 67 86 82 110 67
81 66 51 51 43 57 70 44 62 72 57 79 78 69 81 90 91 120 93 72
87 76 73 74 69 79 83 58 71 61 63 60 63 61 50 66 61 63 73 66
71 64 64 65 79 77 76 61 59 63 67 62 59 89 63 67 65 69 70 81
54 62 70 80 69 71 71 56 51 82 66 80 68 72 62 78 73 59 67 76
61 72 66 65 74 72 66 66 64 62 43 57 58 50 71 51 60 57 68 58
85 68 72 61 59 50 72 74 49 73 73 66 59 49 57 62 68 69 57 78
46 78 73 82 72 73 66 90 111 122 101 92 88 69 86 78 109 104 120 132
73 111 80 116 102 88 79 83 68 89 86 74 89 82 54 52 63 83 84 81

69 76 67 64 48 49 49 63 75 73 59 64 67 59 64 63 47 61 55 55
59 62 51 62 63 52 50 63 52 53 49 51 64 45 48 42 47 49 43 38
35 46 45 50 30 41 49 43 45 44 36
BRM-C06A 106
218 182 96 170 112 104 143 168 139 135 150 94 77 111 147 154 143 166 138 171
109 132 164 128 107 131 131 129 77 119 129 180 137 87 118 92 65 102 95 89
95 107 129 109 81 74 88 123 89 84 84 87 79 89 100 66 75 79 59 69
71 68 41 69 73 69 67 84 76 73 59 82 72 51 57 54 56 52 64 44
47 45 37 37 28 49 36 46 30 36 39 38 34 38 40 31 36 45 29 28
39 28 44 33 50 46
BRM-C06B 105
178 188 119 158 94 107 142 177 139 129 141 94 86 120 146 162 160 180 142 165
116 123 157 129 105 122 138 138 100 122 137 165 135 92 116 102 68 102 94 92
103 110 133 106 91 76 89 126 92 83 83 89 84 92 111 60 82 69 64 77
70 64 53 64 82 62 74 72 89 75 60 83 70 60 51 47 60 57 65 39
42 46 66 49 36 43 36 38 48 29 48 36 37 40 33 41 43 37 23 42
42 33 50 43 45
BRM-C07A 308
146 116 153 119 127 202 200 105 137 165 164 151 223 147 168 150 69 64 64 72
83 80 144 82 86 119 93 110 103 97 81 88 116 129 117 112 103 94 162 75
101 130 108 106 107 94 67 79 95 120 131 124 120 127 134 95 127 85 80 90
94 84 93 64 144 113 81 97 87 69 79 80 77 57 91 63 51 78 83 115
136 117 92 106 92 80 100 98 76 91 93 99 71 83 79 144 90 107 83 89
68 87 66 77 73 65 59 77 61 64 65 115 78 60 54 58 76 57 79 69
62 59 48 50 45 53 36 43 49 50 48 58 52 42 47 52 67 59 54 36
55 67 61 43 38 34 40 33 41 55 66 43 46 61 45 65 81 41 68 75
73 61 59 52 74 63 55 65 61 54 67 35 40 39 52 35 44 39 40 38
52 48 58 57 42 69 63 58 88 69 71 64 68 81 73 80 57 74 61 77
71 51 56 62 43 47 45 69 70 43 54 32 59 65 44 63 80 59 60 103
64 66 98 83 53 80 68 76 78 116 71 99 74 63 86 74 80 70 99 88
105 125 131 107 109 91 84 101 134 73 87 166 84 121 128 99 104 129 145 115
131 140 106 166 84 145 118 201 144 119 111 148 238 161 123 156 108 158 117 112
145 159 176 165 131 128 113 141 149 87 125 104 137 116 112 88 137 118 102 67
88 116 111 111 73 82 85 121
BRM-C07B 308
204 97 147 126 130 183 190 114 132 154 166 151 217 148 163 147 70 62 65 72
74 81 133 86 85 113 96 116 96 98 85 82 103 121 111 105 98 94 149 96
115 122 98 111 99 97 60 80 98 118 118 126 133 141 131 88 126 91 89 85
88 76 103 62 128 105 83 95 88 65 76 80 66 61 85 76 46 69 81 98
124 124 91 108 98 82 93 95 70 90 88 87 77 84 76 127 95 102 86 93
56 88 71 80 82 54 54 82 72 61 43 109 82 56 54 63 67 54 81 63
66 64 45 45 63 47 33 33 57 49 57 46 44 50 46 56 60 49 49 52
57 72 53 46 41 35 22 40 46 52 58 43 43 67 48 68 76 54 72 64
72 70 51 47 71 57 58 60 55 67 59 40 30 48 49 38 34 43 42 33
45 49 59 57 48 55 68 61 90 72 71 57 71 74 76 82 62 73 64 83
75 62 63 57 66 33 50 58 69 53 45 40 71 50 44 74 75 62 72 87
68 62 78 78 69 75 77 70 78 113 80 99 77 73 78 73 82 67 96 90
105 122 132 108 105 94 82 130 136 69 86 160 74 133 128 88 110 111 165 118
138 136 99 178 89 136 128 206 124 112 125 149 243 178 125 165 100 151 112 108
146 151 193 159 126 118 122 134 142 98 126 124 104 119 106 101 132 122 113 82
91 115 125 113 63 91 81 82
BRM-C08A 207
85 86 73 115 94 92 110 97 78 46 54 60 78 85 117 115 105 135 113 120

89 98 115 114 153 88 91 68 131 113 104 110 66 58 94 66 59 72 67 89
58 62 64 71 110 79 60 60 66 77 57 110 69 93 71 78 80 76 73 65
90 96 89 108 88 105 71 68 104 85 95 81 75 78 86 91 87 90 93 94
76 77 81 103 74 99 104 75 105 91 77 80 73 94 90 94 102 94 84 92
97 99 98 99 68 76 73 62 85 95 91 88 83 80 82 72 85 74 41 54
59 49 57 65 68 68 64 75 69 68 68 59 58 73 75 78 114 82 75 80
119 127 118 134 108 79 106 73 109 96 78 110 89 78 80 83 92 75 74 74
75 96 90 85 90 90 84 74 68 94 81 95 50 66 81 70 76 62 56 65
48 63 56 68 67 62 54 69 65 58 51 79 76 57 67 59 67 64 61 70
78 85 107 71 81 94 108
BRM-C08B 207
91 78 84 102 92 94 100 106 79 43 62 58 73 83 116 112 107 122 103 127
97 83 122 108 149 94 84 81 117 118 103 114 79 54 96 72 54 74 65 85
68 55 61 81 111 72 56 72 58 74 61 95 68 86 82 63 92 64 84 72
78 100 87 103 111 109 80 68 113 78 103 73 79 78 89 88 92 85 91 90
83 75 97 105 71 90 112 70 108 106 70 77 81 91 87 97 98 102 85 86
105 90 93 101 81 84 66 72 75 100 94 80 88 82 88 76 84 77 41 56
52 51 57 68 63 73 66 73 69 70 58 61 68 74 75 84 117 83 78 77
111 128 117 120 114 84 93 80 101 96 81 106 93 77 82 83 76 63 80 88
64 85 87 82 87 86 72 62 70 87 77 68 63 71 70 64 66 60 63 59
69 43 61 58 68 69 70 69 76 67 80 77 63 81 74 64 75 71 50 67
88 84 103 71 76 105 106
BRM-C09A 187
137 120 83 92 48 41 89 81 119 114 96 89 76 93 112 101 103 86 105 112
126 95 118 150 134 146 132 142 107 90 106 89 93 96 73 104 95 70 91 115
122 111 96 94 90 115 108 112 92 97 75 87 76 100 63 84 83 102 90 113
141 130 104 99 125 114 109 80 78 105 102 92 69 74 61 52 75 66 77 83
57 92 91 64 113 96 102 74 78 97 126 88 85 113 81 85 104 73 109 106
76 90 91 69 91 94 89 97 111 124 125 83 117 109 106 124 70 100 100 103
106 82 80 86 95 57 87 94 82 83 89 121 91 93 79 86 79 64 62 69
69 61 66 54 57 65 76 84 81 61 90 66 69 57 68 55 58 77 56 65
75 69 69 56 66 59 64 64 57 61 60 63 63 52 65 69 63 59 69 72
80 57 66 74 65 52 69
BRM-C09B 187
127 111 92 87 56 47 82 86 114 112 103 84 80 81 112 98 105 88 113 126
122 91 119 150 126 151 139 139 100 91 104 93 88 95 78 106 94 78 98 105
123 105 101 101 85 117 99 108 99 86 86 82 79 97 62 86 82 109 85 120
134 128 105 101 125 115 114 79 78 102 108 78 72 68 54 58 64 66 67 82
61 84 95 60 112 95 95 75 86 94 115 78 85 93 83 76 116 73 116 102
79 90 85 73 85 93 91 90 100 123 102 79 104 107 107 110 85 91 102 91
90 78 75 85 91 67 81 100 81 85 96 120 81 92 82 88 83 80 78 66
79 75 64 64 69 70 85 93 80 65 86 72 64 62 67 57 57 73 58 66
76 66 62 62 64 65 68 64 63 52 63 59 69 61 56 67 60 55 85 59
75 63 66 74 66 59 64
BRM-C10A 154
116 93 105 80 96 93 109 95 120 134 126 84 76 80 102 124 101 92 85 67
93 77 87 105 98 102 97 84 78 116 115 91 130 108 108 116 104 87 83 75
72 78 103 100 78 88 95 91 110 117 119 88 81 101 89 87 101 87 128 83
111 135 120 128 119 143 121 113 109 89 119 103 104 145 182 146 119 131 131 140
109 101 106 84 96 78 66 97 88 82 92 82 74 69 87 72 83 75 88 101
101 73 40 53 59 39 44 56 76 86 104 88 99 45 53 66 55 51 51 65
62 69 58 81 83 65 68 69 93 76 87 87 96 67 80 76 67 60 69 65
57 66 72 77 58 62 56 89 65 67 73 63 64 64

BRM-C10B 154
114 90 112 83 85 102 100 101 119 147 120 76 86 80 111 113 114 90 94 65
86 78 98 109 89 105 100 84 72 116 109 103 121 113 103 126 100 82 85 74
67 67 82 81 66 86 90 96 119 111 118 89 82 99 89 92 92 94 129 84
109 136 115 136 118 139 119 110 106 83 130 94 110 142 182 149 117 126 142 136
107 96 102 85 96 76 67 93 95 74 98 74 66 78 91 73 81 86 80 94
101 68 44 53 57 47 48 64 68 82 102 83 104 45 52 65 60 47 47 64
63 67 63 74 85 70 72 64 87 72 79 84 82 77 87 74 61 61 71 69
59 70 66 79 58 59 61 94 67 64 69 58 65 71
BRM-C11A 260
92 120 99 138 128 98 121 95 80 67 105 102 123 128 155 92 108 125 103 111
131 91 157 117 125 77 88 127 143 130 119 131 75 58 111 109 78 91 100 100
89 67 105 81 129 143 91 91 86 110 94 128 96 92 93 60 92 90 80 62
83 57 68 59 96 102 78 84 111 112 97 101 84 69 75 74 73 80 64 68
69 57 82 78 71 88 95 84 113 79 72 67 80 104 90 86 85 90 80 77
92 75 84 80 50 64 60 54 60 82 63 78 69 77 78 88 92 89 73 98
99 115 93 93 65 95 53 82 74 63 73 73 97 76 82 92 78 79 57 86
94 88 88 72 74 78 88 98 75 78 88 74 86 69 82 95 79 61 87 85
75 78 85 57 73 70 77 84 79 69 82 95 102 99 102 90 103 136 110 71
107 67 90 98 108 74 95 124 99 114 85 90 99 115 98 86 100 69 98 57
60 46 62 62 75 80 99 79 81 64 69 77 69 82 77 74 95 78 92 95
88 58 70 82 81 87 83 116 86 98 90 87 73 93 94 109 89 109 86 98
65 89 72 88 77 94 86 101 87 100 92 86 76 92 82 79 87 85 78 110
BRM-C11B 260
86 113 109 138 121 108 120 93 73 68 100 91 109 132 145 105 117 116 112 105
140 98 152 115 119 82 91 126 137 128 120 133 69 63 108 114 70 100 96 106
77 73 101 88 127 137 90 98 83 105 96 122 89 94 92 81 83 99 75 82
63 66 71 65 95 92 86 76 114 116 95 103 78 69 80 71 83 70 81 68
66 66 73 90 52 107 108 87 124 82 67 88 73 106 107 91 103 96 72 81
89 76 80 86 55 64 59 55 65 82 63 76 72 76 73 98 85 90 79 97
96 117 103 92 66 92 67 79 70 59 74 63 94 83 83 89 73 75 59 81
101 91 86 70 86 72 82 94 78 68 80 78 94 65 86 88 89 51 86 87
77 75 84 57 72 73 74 84 73 68 82 87 99 96 102 81 101 127 113 73
90 71 81 103 110 61 101 113 98 116 79 88 101 115 95 84 102 74 95 58
61 46 66 61 73 83 96 81 79 62 70 84 69 68 84 75 87 75 92 96
94 59 89 71 76 101 85 99 84 102 103 73 65 82 99 114 92 86 101 101
70 83 82 74 82 96 99 90 92 89 100 79 85 84 95 74 87 85 80 84
BRM-C12A 116
91 85 111 83 106 77 93 75 83 81 93 65 81 79 102 109 94 119 97 91
84 76 108 100 98 84 77 82 73 81 83 78 63 56 78 74 89 95 69 98
102 86 140 79 83 72 67 77 82 73 70 82 67 58 76 56 82 52 49 58
54 54 46 67 64 71 63 71 76 73 68 74 75 85 66 88 89 81 79 92
82 87 90 59 91 106 87 94 88 75 62 70 57 65 73 65 67 58 58 54
71 72 80 71 86 82 88 77 91 84 89 74 87 78 89 135
BRM-C12B 116
85 83 99 86 105 80 89 66 85 91 78 82 80 82 105 95 108 108 109 92
87 75 109 94 109 79 67 73 81 82 73 74 61 56 65 80 82 102 68 99
109 84 135 85 78 72 72 78 85 66 68 76 73 64 92 54 71 72 51 58
54 44 58 76 63 74 59 73 75 71 71 64 78 83 71 84 89 83 81 90
86 80 88 67 99 101 98 87 81 76 61 71 52 76 62 62 58 57 57 46
69 68 85 72 82 87 92 68 88 87 91 75 84 85 81 128
BRM-C13A 298 (2021 core)
363 297 388 355 316 374 337 334 359 351 314 248 259 301 219 203 183 221 215 234

154 191 244 220 146 154 175 145 215 161 159 181 136 113 119 158 206 160 193 175
168 147 161 115 123 113 94 121 105 112 89 91 71 128 106 114 97 125 106 125
99 112 128 82 94 71 81 74 85 90 86 63 76 84 103 97 100 89 104 120
86 82 73 54 66 61 82 64 86 73 107 76 72 73 58 66 63 73 85 102
107 81 90 60 48 39 45 59 64 53 63 75 74 72 80 53 59 66 96 97
78 61 75 78 74 62 68 72 67 48 66 47 53 45 56 56 55 57 57 61
56 74 63 50 57 50 66 68 60 50 61 58 55 50 49 52 50 64 62 46
55 61 42 50 46 64 61 59 55 41 40 59 54 58 56 41 62 72 57 55
68 55 60 53 64 51 60 53 48 53 46 53 46 52 48 45 59 43 61 53
46 60 83 55 62 46 50 46 53 62 46 47 56 42 49 38 40 56 54 57
55 66 45 54 64 64 50 56 43 54 60 64 34 48 45 42 43 41 47 45
47 41 40 36 56 40 34 51 27 28 34 37 37 35 35 37 40 33 45 43
50 40 35 43 51 40 34 21 31 43 30 37 40 42 49 39 39 44 47 42
42 48 50 41 53 48 44 32 40 42 40 36 39 39 39 40 43 33
BRM-C13B 298 (2021 core)
318 301 396 364 328 360 312 332 355 353 308 247 260 298 222 194 185 221 207 231
155 184 246 223 141 149 181 143 224 167 158 188 138 109 117 160 208 162 192 174
164 153 158 114 122 117 96 116 98 110 98 80 72 124 110 97 93 137 92 124
101 110 128 65 93 70 81 72 90 80 90 71 72 79 96 97 96 86 104 123
85 85 75 56 61 51 80 66 81 81 106 83 62 65 67 65 66 74 89 105
115 95 77 58 47 41 47 59 62 56 53 88 73 76 81 52 60 62 88 93
83 62 75 70 71 69 59 65 72 58 55 47 48 46 44 61 63 57 66 52
59 81 60 51 56 53 63 75 57 49 66 49 53 56 49 49 54 66 60 46
51 60 46 50 56 59 57 51 61 42 44 54 51 63 57 42 54 70 57 53
56 65 58 55 62 60 58 59 50 61 55 55 34 50 48 54 56 49 58 44
53 61 72 60 56 50 55 41 54 64 45 46 57 45 41 46 41 55 49 61
59 61 48 57 53 60 61 60 39 55 58 56 43 49 47 43 45 37 42 42
48 40 43 46 40 42 49 42 34 31 25 44 34 29 35 40 42 36 38 46
47 43 45 37 41 37 37 33 27 41 29 40 38 39 49 40 43 41 43 45
45 46 49 42 54 48 46 29 40 45 39 39 38 38 34 35 38 39
BRM-C14A 177
272 221 229 250 264 223 178 196 129 130 113 125 162 161 175 122 140 130 128 112
135 110 112 100 104 124 133 117 76 93 106 101 124 126 107 119 93 100 86 64
58 52 67 80 76 84 130 90 94 97 101 81 106 82 113 99 110 82 82 100
94 110 95 106 78 61 86 99 80 83 74 95 70 75 63 71 118 114 62 64
59 73 74 75 62 78 66 65 81 70 63 64 54 76 58 80 78 92 77 63
71 71 66 65 64 66 66 70 51 55 45 41 45 47 54 69 52 65 60 50
91 73 63 50 52 69 65 68 65 76 56 58 73 56 81 66 55 59 57 68
57 70 64 54 60 65 60 62 55 50 52 73 68 61 67 57 57 67 60 70
67 74 69 63 85 56 57 89 59 47 52 43 60 66 65 62 49
BRM-C14B 177
255 241 233 279 244 215 178 193 129 147 116 122 153 167 168 131 142 122 125 127
142 106 109 109 102 115 139 101 88 89 108 103 118 131 99 110 107 93 91 62
62 51 73 72 91 97 120 80 85 95 99 96 104 75 115 98 117 74 84 106
90 109 96 111 78 65 72 105 76 76 70 84 75 68 63 73 112 109 70 64
56 73 71 73 60 85 70 60 81 65 64 63 52 86 63 72 84 89 72 56
85 77 75 73 65 73 68 73 50 54 49 44 49 48 63 66 48 68 59 55
90 67 59 57 44 75 61 65 62 75 58 61 72 54 87 59 57 55 57 64
61 69 69 57 62 64 60 58 58 51 54 72 67 62 66 57 56 67 61 64
70 75 69 66 81 64 59 86 57 50 49 44 56 68 63 58 61
BRM-C15A 178
95 135 153 91 116 77 121 123 127 68 118 99 61 62 61 68 71 65 99 133
100 105 99 95 82 130 102 97 108 78 102 95 98 99 117 120 122 100 108 91

100 101 125 124 91 78 76 80 90 114 112 90 88 78 92 83 90 105 92 90
84 70 60 63 67 65 58 64 59 79 70 66 73 68 52 47 56 68 62 61
58 50 63 57 80 86 69 85 76 77 66 69 83 82 85 104 100 93 66 58
84 75 80 59 87 76 74 79 67 96 83 90 85 100 108 109 126 124 101 99
83 91 96 99 110 86 74 85 112 95 67 76 103 95 127 102 99 104 97 65
61 65 79 67 82 85 82 52 50 57 58 68 77 85 78 71 75 90 89 96
84 71 83 77 82 90 84 89 105 111 71 73 101 91 89 72 101 108
BRM-C15B 178
114 155 157 105 102 109 156 153 134 74 121 92 68 67 60 71 71 76 93 128
95 103 126 83 86 128 102 94 100 99 111 99 90 100 118 113 129 99 105 99
96 108 122 123 95 67 82 74 97 113 109 90 86 80 95 74 99 103 92 93
86 70 62 61 72 59 62 64 57 79 65 57 73 67 51 45 60 70 58 61
50 50 62 68 80 78 76 83 78 73 74 65 83 88 77 109 97 85 75 62
82 85 77 67 84 79 65 77 72 82 86 82 96 106 122 105 108 124 103 96
74 104 92 115 124 92 84 91 115 109 72 70 109 93 109 114 103 113 91 71
66 65 78 68 97 71 74 64 52 55 58 73 75 80 77 66 77 85 88 99
83 78 78 85 84 87 86 89 103 104 73 78 97 92 85 82 102 103
BRM-C16A 113
65 55 63 73 74 69 82 83 76 75
80 96 82 96 86 86 75 80 73 89 87 112 103 96 134 160 123 118 98 124
120 101 109 95 124 117 104 107 119 114 103 125 114 161 155 229 182 158 144 118
133 129 133 114 118 115 122 106 115 95 115 82 100 109 121 136 111 126 124 101
87 98 109 119 124 112 122 92 66 68 76 88 85 114 114 92 112 113 165 112
97 85 106 98 121 109 114 121 122 123 101 71 86 78 80 74 85 100 79 80
83 90 94
BRM-C16B 113
58 60 61 66 81 64 83 76 75 80
62 104 90 91 89 83 79 80 73 87 88 116 107 92 142 150 115 122 126 114
108 86 113 92 148 110 111 100 125 115 104 113 113 175 135 231 177 164 144 117
133 128 128 118 116 116 113 109 109 99 112 80 97 109 118 124 111 131 115 102
88 96 118 116 120 128 111 90 63 78 74 78 85 112 109 104 103 119 171 121
117 96 99 100 132 121 118 120 125 121 81 67 77 71 74 78 81 92 74 75
88 87 78
BRM-C17A 269
127 131 94 106 103 101 81 121 114 139 96 84 104 91 141 95 122 108 122 113
81 118 74 78 115 79 81 82 87 88 83 86 63 83 104 80 78 65 67 63
80 81 85 83 48 84 65 84 63 65 57 60 65 58 61 59 54 54 57 56
50 41 55 51 48 63 47 51 52 56 44 30 45 63 42 53 58 43 57 54
53 29 49 54 48 46 38 51 44 40 56 34 51 52 50 47 51 42 57 55
56 49 55 57 59 67 55 62 49 55 49 57 43 57 50 43 30 35 29 32
31 25 34 23 27 38 33 29 35 23 35 37 52 59 65 54 104 64 67 74
64 67 78 69 80 82 80 50 64 62 57 79 60 62 84 62 54 51 51 75
62 59 75 85 63 67 77 84 86 77 81 75 89 84 88 58 97 70 79 64
74 105 81 75 77 83 100 82 82 85 99 85 104 65 55 58 48 46 44 50
50 42 46 48 49 36 58 37 42 40 57 39 52 41 52 48 53 44 43 59
61 44 40 55 56 49 57 60 68 63 41 64 55 40 64 70 66 56 63 62
60 68 65 59 52 67 59 68 68 68 68 69 56 66 70 67 65 80 75 84
58 68 71 84 74 69 74 69 70
BRM-C17B 269
123 131 96 103 110 94 85 112 122 143 91 91 105 91 137 90 118 133 112 111
91 115 92 70 112 72 81 79 86 89 84 77 65 78 104 75 74 65 57 69
78 74 75 75 67 71 59 83 56 63 61 60 61 56 55 48 56 53 55 56
49 41 53 58 45 67 48 56 44 58 37 30 50 58 50 51 52 50 49 54

47 50 45 54 55 40 41 43 41 38 46 42 61 54 45 54 50 46 68 54
55 59 52 57 55 54 61 58 58 57 44 62 44 74 60 50 31 28 36 25
30 36 27 32 29 37 30 28 27 36 46 46 55 60 62 57 94 72 68 70
70 67 77 78 73 83 76 49 70 60 56 78 69 65 85 53 51 52 49 80
70 60 71 84 69 62 83 77 79 68 77 67 92 85 89 53 93 66 79 63
69 93 75 74 61 73 95 79 87 72 88 80 101 69 47 58 60 40 55 50
44 45 43 47 49 43 62 39 45 46 56 41 49 48 51 52 42 42 52 53
58 43 45 50 54 53 64 58 67 57 49 47 46 48 68 64 56 68 50 64
65 59 70 55 55 52 76 67 64 64 71 65 54 69 68 69 70 80 72 81
59 73 69 85 70 75 81 62 75
BRM-C18A 300
84 88 81 99 83 96 74 106 76 123 90 88 95 99 99 97 90 95 121 116
84 122 117 104 149 141 116 112 122 85 89 104 106 101 90 97 87 82 90 100
103 88 64 81 65 84 53 69 71 80 86 66 92 63 64 97 60 71 71 60
72 64 53 54 80 60 65 50 66 52 61 60 71 59 76 53 65 58 65 59
67 65 74 52 65 72 74 61 53 65 52 62 49 47 66 57 68 60 45 56
49 49 36 59 70 46 65 67 60 67 61 63 51 61 67 60 60 48 58 51
54 62 53 65 57 51 57 48 50 60 69 61 54 54 51 61 58 58 58 48
64 41 53 52 56 42 59 41 49 50 46 52 64 38 59 50 52 53 42 46
45 48 45 45 55 44 41 53 49 39 49 43 49 64 38 51 42 53 47 56
53 42 58 36 52 62 54 39 43 37 58 52 58 39 57 45 52 64 63 58
56 62 61 70 65 89 50 91 66 76 54 66 311 161 107 88 106 111 101 123
96 116 110 134 98 156 207 128 75 80 75 72 82 72 73 63 66 78 54 62
49 60 52 63 59 50 63 42 60 43 60 65 57 60 63 61 64 69 69 48
42 40 48 40 40 51 54 48 51 43 52 55 61 63 67 76 55 70 81 58
74 74 84 68 72 75 65 111 65 89 87 85 84 83 90 74 85 71 75 95
BRM-C18B 300
87 91 74 104 87 99 77 108 70 131 92 92 88 97 103 100 86 98 115 116
90 112 115 134 145 135 120 107 123 96 79 99 107 98 91 92 69 70 100 79
89 83 56 77 72 77 59 67 64 90 86 67 94 71 59 92 67 65 65 66
67 61 56 58 69 61 69 53 58 54 72 59 74 64 67 68 53 63 60 70
61 64 82 57 60 75 70 56 61 64 58 57 57 38 60 61 53 61 57 48
47 45 37 55 58 60 56 63 62 67 67 51 55 52 70 58 61 53 56 54
54 55 56 64 54 56 59 45 54 62 62 64 56 48 55 65 49 64 60 42
53 50 51 57 56 50 49 48 52 42 49 64 50 48 62 49 47 45 57 35
37 51 52 52 52 48 38 57 40 41 52 43 44 59 47 44 50 51 43 57
49 44 50 45 56 58 52 48 35 42 53 56 49 48 52 52 49 59 71 59
54 59 64 69 61 88 53 80 76 69 60 57 247 128 99 86 111 116 92 132
106 117 117 132 94 167 190 137 87 78 69 68 78 77 69 73 57 70 63 58
51 60 55 63 65 45 59 50 47 54 60 62 63 50 62 62 51 66 65 42
46 40 49 35 43 55 47 46 53 41 56 61 56 63 70 72 57 67 82 58
67 76 80 66 70 74 73 71 66 89 85 83 86 80 93 70 88 67 58 96
BRM-C19A 145
65 55 60 79 49 67 55 41 41 45 38 35 41 32 37 31 35 38 32 35
30 34 36 29 38 33 35 29 33 33 34 24 29 31 28 30 25 28 25 23
20 20 30 24 23 34 34 30 28 39 38 45 59 46 69 73 62 70 67 86
96 85 93 92 131 99 126 182 88 91 89 113 95 89 88 90 94 129 116 154
143 150 111 116 101 115 117 118 87 102 104 85 91 96 81 80 69 72 60 52
59 60 89 78 92 92 98 98 111 146 122 150 139 76 94 79 101 90 91 91
73 87 102 103 138 114 74 80 89 117 146 143 178 175 127 61 47 63 55 63
37 61 52 56 60
BRM-C19B 145
67 55 59 79 51 63 59 30 41 35 42 34 30 23 38 36 26 31 30 21

38 37 37 26 21 38 42 26 28 26 26 29 26 29 24 18 16 24 27 22
27 22 16 25 21 33 33 40 34 44 42 40 49 59 81 72 62 76 63 101
95 92 91 93 145 96 131 165 102 81 99 96 98 93 85 86 96 134 114 156
149 148 111 118 105 112 114 127 83 109 115 86 92 88 92 87 73 78 58 58
50 58 90 87 96 94 105 102 111 146 121 148 140 73 91 84 97 97 80 93
70 94 96 107 138 100 81 69 87 107 146 130 180 185 133 55 46 74 53 56
39 63 48 53 53
BRM-C20A 65
118 145 177 118 161 152 114 91 64 63 65 58 85 95 88 100 137 104 126 140
140 111 88 131 131 193 176 130 180 130 78 102 138 150 131 88 139 171 182 178
183 175 162 191 247 259 175 146 151 160 187 134 120 119 145 108 157 120 90 79
113 117 107 116 107
BRM-C20B 65
122 136 180 116 141 154 103 85 50 71 67 58 77 98 80 110 133 109 131 136
140 105 92 113 132 187 167 164 191 133 71 100 129 157 135 88 146 168 180 188
204 174 149 197 278 230 186 134 160 158 191 137 126 112 136 106 153 121 84 77
108 103 111 104 110
BRM-C21A 217
85 169 113 122 148 190 208 307 269 265 233 269 219 156 89 50 75 105 166 135
190 129 146 130 138 162 138 159 168 98 125 131 98 143 158 110 135 109 142 218
195 138 153 114 52 54 103 112 113 134 154 127 137 107 104 87 91 92 149 164
166 97 122 150 190 154 146 152 116 74 140 120 110 97 122 143 108 136 114 126
167 137 86 68 69 109 93 145 79 110 112 98 112 65 72 79 70 84 74 78
85 124 77 65 103 81 90 89 74 61 81 84 84 87 81 92 89 93 89 80
66 84 94 72 93 109 74 66 71 81 88 97 70 117 74 113 115 112 112 135
86 99 91 73 62 57 56 59 58 83 80 72 107 86 100 119 113 143 115 104
76 110 120 110 120 109 110 124 168 161 160 183 169 111 121 126 154 122 105 95
110 72 91 61 80 105 103 133 157 115 86 94 111 76 120 131 100 163 128 93
97 76 63 88 86 99 73 81 78 93 116 116 113 113 124 113 123
BRM-C21B 217
97 167 111 125 144 189 206 313 276 263 233 271 218 158 94 51 75 108 158 138
188 135 141 140 135 156 141 154 168 104 121 128 105 142 153 112 131 114 144 215
193 141 151 116 60 54 95 116 103 134 160 122 134 110 101 86 91 90 151 163
168 91 126 154 188 155 146 153 115 74 140 114 105 106 126 147 99 137 114 128
172 136 86 60 71 106 94 148 79 112 116 95 110 69 78 74 75 76 72 80
85 120 77 68 98 89 84 89 73 64 82 87 81 86 83 93 87 95 89 81
60 86 94 69 97 110 74 61 74 82 90 91 78 115 73 116 107 119 113 133
86 101 87 72 66 53 56 63 56 84 76 76 98 94 92 127 114 142 112 109
73 100 128 109 119 106 111 119 171 168 154 185 170 107 126 121 154 123 103 97
115 64 92 63 81 97 109 131 164 126 99 109 117 79 121 123 104 168 127 84
107 67 64 99 81 84 77 76 79 85 125 105 128 112 122 108 150
BRM-C22A 300
118 221 325 235 268 253 245 226 187 206 237 248 175 169 205 192 208 165 161 84
104 114 151 141 149 95 95 105 129 125 139 161 109 107 84 137 112 69 89 105
102 127 114 108 170 112 149 168 153 123 134 110 115 145 96 108 103 96 97 97
106 86 86 49 69 61 73 95 113 96 79 100 97 73 70 64 76 64 52 74
53 48 44 58 62 51 69 69 71 62 82 60 70 60 61 75 59 65 53 64
80 66 72 74 59 79 71 73 72 98 51 36 55 76 78 92 86 97 94 93
80 72 68 77 67 72 63 68 59 72 78 80 74 72 42 58 71 62 46 69
59 89 72 102 58 85 74 70 68 63 73 83 80 79 74 90 75 72 69 63
51 45 51 61 67 69 55 65 59 66 79 78 63 70 66 62 53 79 62 71
52 40 54 57 56 62 51 48 55 49 59 74 57 71 56 74 109 78 64 71
55 57 69 50 67 67 48 60 67 58 33 46 51 53 50 59 54 70 50 61

55 83 76 47 62 56 46 65 70 54 56 54 47 54 58 66 68 63 55 54
57 54 66 60 53 61 54 52 64 57 52 61 73 75 88 60 59 71 72 61
65 68 69 83 45 57 49 40 48 42 45 58 51 41 50 47 50 56 63 64
64 69 58 60 78 67 75 47 73 68 65 58 65 54 67 74 80 70 96 75
BRM-C22B 300
134 210 327 240 263 257 242 233 187 210 229 251 173 178 215 184 217 170 173 76
115 115 151 143 142 106 85 105 149 118 143 158 118 95 82 119 97 77 93 100
106 118 117 114 157 119 153 174 140 128 134 117 113 146 106 103 116 86 94 97
105 90 85 52 63 59 83 88 120 92 85 88 92 75 62 68 71 61 50 80
47 47 51 57 51 53 64 67 78 56 86 56 63 43 70 82 66 63 48 61
82 65 70 76 62 66 78 68 77 88 60 45 67 68 70 89 81 102 93 110
76 70 69 77 68 72 67 64 64 70 65 88 75 73 47 53 70 55 48 65
60 93 59 97 78 85 86 62 61 71 67 86 74 80 77 83 69 71 74 61
48 54 45 70 75 61 55 56 58 70 60 86 63 86 59 63 54 73 64 76
53 41 62 50 65 67 43 55 51 52 66 68 57 68 63 74 92 66 78 66
51 65 71 54 71 66 59 68 62 50 33 46 54 55 54 47 46 68 53 66
54 75 69 49 64 52 55 69 63 52 56 49 43 57 57 68 62 68 52 54
43 60 67 58 59 70 43 51 70 61 57 67 73 81 89 70 57 76 67 74
57 72 67 82 41 59 54 41 44 41 55 45 55 48 51 43 42 53 65 54
62 69 59 60 72 64 77 69 60 70 71 61 61 58 72 73 84 66 103 104
BRM-C23A 187
69 65 70 64 73 77 75 51 65 71 45 71 74 40 34 59 65 73 77 57
87 74 63 88 77 89 70 96 72 84 43 76 70 57 63 65 49 73 72 80
69 68 61 37 41 43 73 64 55 49 55 58 80 50 58 56 52 56 88 66
69 76 91 97 90 87 79 128 91 94 73 60 84 84 102 98 90 101 100 123
92 98 105 107 93 98 86 102 120 156 135 114 166 166 171 123 93 116 110 99
89 87 114 89 122 114 79 125 96 77 60 55 56 55 60 65 50 65 68 84
72 58 64 38 41 46 51 45 35 46 84 100 97 87 66 52 61 45 43 51
57 80 72 75 65 40 25 42 35 43 61 52 45 50 37 51 61 62 56 56
55 48 57 44 52 46 43 50 41 49 78 67 76 85 94 77 68 69 74 69
80 84 98 79 95 96 94
BRM-C23B 187
82 59 69 70 63 79 73 44 81 54 48 75 69 47 41 49 65 78 64 71
76 77 66 84 85 81 75 90 85 78 51 79 69 69 66 69 41 78 75 73
66 75 47 39 43 42 63 75 52 47 55 46 78 59 49 57 54 69 80 73
71 79 74 88 83 91 91 131 78 103 77 66 73 85 97 97 95 98 105 118
100 92 109 101 94 100 85 103 116 154 136 120 164 156 172 116 102 115 118 92
86 93 106 92 123 105 79 124 98 80 64 48 54 59 55 66 48 65 68 86
70 59 67 40 47 43 46 30 45 41 94 96 101 82 52 54 59 41 46 53
63 85 63 72 69 41 31 31 44 44 58 54 53 38 34 56 55 62 53 59
63 48 53 50 42 46 54 46 35 47 81 70 76 80 97 74 61 80 73 75
78 81 97 76 100 91 97
BRM-C24A 257
48 71 61 44 50 55 56 44 63 53 43 39 56 40 39 48 43 52 60 66
59 74 75 89 74 75 72 82 82 98 73 66 74 76 86 81 75 84 82 100
65 86 69 78 68 53 80 56 55 66 45 46 49 42 44 40 51 44 44 37
44 45 41 30 45 36 39 54 51 53 38 48 69 66 74 92 78 144 151 167
163 142 101 94 97 90 55 94 114 86 100 87 105 113 135 141 141 168 149 163
163 122 114 117 125 101 93 111 82 90 98 132 105 107 103 73 64 92 101 117
98 128 106 84 108 117 123 135 124 119 192 148 143 139 125 128 123 159 138 159
129 97 96 79 101 116 122 141 112 98 117 135 116 136 105 125 143 131 118 134
126 127 130 119 167 195 143 147 181 129 113 139 122 110 172 131 162 141 84 88
82 84 89 87 104 82 73 77 98 86 78 88 90 102 101 103 91 73 75 75

66 72 85 94 72 95 64 76 84 81 67 71 60 87 73 73 66 66 49 34
65 55 69 73 71 64 52 74 77 73 63 49 66 53 61 81 68 61 77 69
65 62 62 51 63 64 64 82 88 94 80 68 86 80 80 77 82
BRM-C24B 257
46 75 74 40 56 59 49 58 46 60 45 38 51 72 43 35 46 60 50 70
61 68 86 74 78 80 60 93 60 84 76 87 76 88 82 78 80 80 80 83
85 77 73 74 69 62 71 73 55 49 55 54 42 40 49 42 42 45 50 37
38 43 47 37 36 36 45 61 48 52 47 51 55 76 69 93 111 156 175 164
169 153 91 98 104 80 60 90 115 92 101 97 129 114 126 138 140 220 157 170
163 147 120 119 112 110 98 119 74 110 105 139 101 133 110 82 82 94 115 115
97 120 89 83 110 109 125 157 143 140 185 144 137 146 129 122 145 163 131 164
136 99 93 81 104 113 128 134 118 103 116 138 110 121 108 130 154 128 117 129
119 139 146 119 177 202 136 155 180 131 115 145 121 112 171 135 169 141 76 89
79 92 87 89 92 94 70 85 88 90 81 91 90 99 104 98 92 68 77 72
60 74 91 93 77 93 70 72 72 79 64 81 64 83 73 77 68 66 44 40
56 61 75 75 67 65 52 80 78 71 57 55 66 54 58 87 70 60 80 66
67 62 66 50 61 64 66 81 93 85 87 75 80 78 82 70 79
BRM-C25A 115
100 117 191 121 241 189 94 185 114 165 156 309 211 168 114 109 138 190 178 144
164 181 100 71 103 125 140 97 119 166 250 215 177 246 178 203 210 208 212 232
190 223 173 130 92 97 112 122 139 146 149 131 94 40 52 59 83 102 121 97
95 101 94 110 106 83 117 91 101 70 72 132 117 119 101 116 119 120 112 129
139 83 75 117 101 102 82 102 170 153 101 112 80 73 119 131 122 114 117 89
75 84 93 111 111 116 81 81 75 96 84 79 55 77 72
BRM-C25B 115
80 110 167 114 233 181 95 181 118 170 150 321 217 177 117 116 135 195 188 141
162 175 104 81 104 119 149 95 119 185 257 215 170 235 191 202 210 205 216 229
193 221 183 126 102 93 105 125 139 149 146 126 101 43 53 73 95 100 129 98
89 106 96 104 117 90 97 98 102 74 92 127 114 119 100 118 122 116 115 134
135 85 75 116 98 98 90 100 165 153 115 100 87 63 117 127 121 121 113 92
75 83 94 108 112 110 84 77 84 89 95 78 59 77 99
BRM-C26A 164
102 120 145 130 85 121 140 118 130 138 131 125 183 229 196 153 178 124 120 91
152 136 109 100 124 98 117 88 86 86 144 133 79 96 125 104 149 117 124 97
88 91 97 103 103 111 145 107 106 99 112 114 106 123 79 103 99 95 95 87
85 81 82 87 97 81 87 103 89 76 100 89 75 52 60 74 62 99 59 62
65 48 44 51 62 68 67 72 78 58 62 64 55 51 63 75 76 50 39 61
57 50 68 51 62 65 55 55 52 52 42 91 61 59 74 79 101 100 111 107
90 71 111 116 105 120 79 135 117 96 98 84 97 118 103 122 179 129 106 85
86 100 109 135 119 88 120 65 91 97 95 113 99 122 134 96 128 135 141 104
130 137 111 119
BRM-C26B 164
137 117 141 136 91 109 139 120 121 134 131 123 188 244 189 155 193 113 105 98
153 127 106 107 113 110 111 80 89 97 157 130 82 106 118 102 156 118 119 94
87 93 96 98 101 130 128 122 102 94 115 117 104 123 83 99 105 96 104 90
89 77 84 99 98 88 97 116 95 75 96 85 71 54 70 76 63 94 63 67
67 48 56 51 57 71 51 73 75 57 67 63 54 53 59 75 77 48 39 67
48 55 66 53 64 67 52 57 49 49 46 89 61 55 73 83 96 98 107 116
80 75 107 121 115 114 90 145 114 95 100 87 98 115 107 120 178 146 111 97
98 88 111 137 116 92 119 64 101 97 89 122 97 129 138 91 127 142 155 99
126 144 120 118
BRM-C27A 210
86 75 96 81 124 86 80 71 50 78 82 78 99 68 116 117 87 116 94 82

61 74 100 99 77 74 105 89 84 79 70 96 98 74 91 82 62 57 84 77
80 105 128 144 136 169 146 77 94 125 148 127 127 102 153 111 105 100 77 110
103 103 104 114 101 100 80 80 100 104 124 126 97 117 77 96 87 99 105 123
133 113 95 123 116 124 100 115 143 95 112 99 80 100 104 124 104 103 93 89
121 129 104 110 79 96 111 100 82 88 79 80 96 111 98 103 108 129 82 62
76 108 102 82 86 99 73 88 115 125 139 108 101 110 132 126 114 148 117 102
100 80 98 97 84 110 86 75 86 93 91 81 64 81 89 108 101 101 125 118
115 108 107 123 136 120 136 145 103 53 49 62 64 78 83 88 76 86 88 84
105 112 81 96 88 115 99 115 112 134 118 114 101 122 106 120 117 126 124 91
122 96 113 114 112 121 93 146 147 76
BRM-C27B 210
86 73 92 91 119 76 83 74 45 87 61 83 98 75 109 119 78 117 93 85
63 59 107 101 80 75 108 90 80 72 69 100 86 76 91 86 67 67 81 71
78 104 134 127 146 157 136 91 90 116 142 123 124 87 143 115 103 96 87 114
120 96 94 119 93 96 84 76 93 106 124 115 100 119 66 100 91 96 105 123
124 111 94 121 119 118 89 123 132 96 113 98 74 106 105 114 106 107 96 85
115 123 106 100 83 108 112 109 80 91 81 75 105 112 101 107 118 114 93 67
84 104 111 91 90 115 68 98 113 122 129 109 110 110 129 119 118 157 111 91
102 77 98 99 81 105 82 84 74 105 91 80 63 78 93 109 98 93 123 126
106 103 108 112 129 122 125 145 108 63 45 54 61 82 78 80 79 72 88 81
93 104 81 89 86 107 115 102 111 131 112 112 101 122 110 122 112 121 118 94
120 88 110 109 119 109 94 124 137 70
BRM-C28A 165
255 263 241 230 232 310 261 175 178 230 150 250 199 166 209 158 143 116 139 212
171 182 264 175 228 223 161 171 157 150 196 157 262 159 171 184 200 159 143 152
156 129 159 145 148 242 153 236 195 209 149 154 156 159 90 97 124 141 131 194
161 189 187 151 137 134 94 80 98 130 110 137 146 169 143 120 102 95 101 117
145 98 163 223 174 167 116 50 53 61 76 79 60 68 82 85 104 99 75 76
70 94 94 83 86 70 69 63 70 52 61 51 50 59 53 53 41 56 40 58
59 52 47 58 63 68 54 59 75 78 78 66 52 72 73 59 65 54 46 59
63 69 60 74 91 72 72 62 72 66 73 84 54 49 70 75 92 63 53 67
84 85 56 81 50
BRM-C28B 165
249 268 239 230 240 310 254 161 169 240 144 261 193 178 231 154 138 110 139 223
172 185 258 183 219 230 166 175 170 160 204 160 255 172 177 186 208 141 148 145
160 126 174 137 152 227 150 231 195 205 152 144 155 159 89 101 126 138 135 189
154 174 187 150 149 132 89 81 98 132 118 130 139 163 134 119 107 93 98 116
135 109 166 220 176 159 106 48 62 58 73 69 68 74 82 91 99 102 81 74
74 97 95 87 73 65 71 72 61 49 64 58 54 60 49 44 43 51 48 54
54 47 47 62 64 70 58 65 67 80 79 56 55 70 71 63 63 56 52 51
70 75 67 70 87 69 71 60 74 72 83 74 47 54 71 72 90 74 55 67
76 76 68 76 66
BRM-C29A 214
182 195 207 211 184 159 224 209 212 204 139 200 141 126 95 93 77 82 91 142
160 159 229 189 187 195 215 166 169 147 193 186 240 186 210 192 202 191 135 134
140 110 152 135 107 142 129 166 195 193 109 108 115 105 81 70 87 96 101 128
103 109 103 115 109 100 87 76 80 139 147 151 148 179 161 126 124 131 126 133
128 146 170 266 177 135 133 92 131 136 140 128 103 169 154 151 177 144 188 133
90 110 139 113 97 96 90 88 120 95 116 98 68 89 70 75 75 73 74 95
96 109 81 68 72 94 101 84 84 74 77 74 64 64 70 73 86 81 73 82
108 98 94 100 78 91 67 85 84 83 68 68 64 59 65 61 74 67 78 84
79 57 65 53 58 49 63 53 65 73 60 66 62 54 49 45 52 65 55 71
51 65 61 56 71 69 78 77 62 64 53 87 81 66 82 83 88 66 65 66

68 81 72 64 71 65 82 79 75 77 85 83 86 101
BRM-C29B 214
188 192 222 204 183 156 219 213 216 208 143 197 145 128 87 103 67 85 98 149
161 157 230 190 187 193 219 167 157 148 193 181 242 175 219 190 194 236 135 135
142 106 154 137 108 135 132 163 199 193 118 96 116 96 76 73 76 80 89 108
90 115 105 105 123 99 81 84 78 144 142 153 144 173 182 136 133 141 146 151
145 176 212 268 170 124 140 90 127 140 138 134 93 175 154 146 191 147 183 138
86 111 141 108 97 102 88 98 117 95 114 97 75 84 68 83 71 72 80 91
103 108 83 69 73 91 97 86 84 74 83 79 59 59 72 76 82 82 77 76
109 99 93 104 79 86 73 80 93 77 60 73 62 58 68 61 72 77 73 85
84 71 62 52 50 57 60 56 56 77 60 72 65 48 52 51 55 56 50 73
50 62 65 51 67 70 71 66 73 64 57 89 79 73 76 84 79 71 69 72
64 77 76 61 79 84 72 77 58 81 86 84 91 101
BRM-C30A 174
161 143 138 136 197 155 147 143 128 137 113 78 107 119 99 87 95 116 100 108
120 132 136 176 140 123 137 116 116 122 98 90 107 107 80 102 82 89 89 87
96 119 145 97 66 90 98 115 127 107 110 113 94 120 78 119 112 107 118 82
75 65 62 65 62 82 60 64 76 57 74 62 58 59 56 67 62 52 64 76
69 105 83 93 92 87 109 79 57 49 62 73 72 57 71 70 71 59 59 70
81 73 65 77 63 65 73 78 79 79 75 92 101 105 94 102 87 69 55 60
68 74 70 82 59 70 75 73 74 65 59 77 59 74 82 61 74 67 55 56
55 42 49 46 43 51 32 31 39 27 32 38 33 36 39 32 38 43 40 47
34 50 38 41 43 49 39 55 58 43 49 50 48 52
BRM-C30B 174
147 148 145 133 196 155 151 147 126 136 113 79 112 122 95 92 100 126 88 129
122 120 128 164 143 126 134 118 123 122 98 90 110 101 80 98 73 93 91 81
92 125 139 94 73 90 97 111 130 107 107 115 91 112 89 112 116 105 112 94
70 72 60 65 70 79 62 59 71 61 60 67 59 58 54 67 63 54 61 71
75 98 87 93 96 86 110 81 60 46 61 72 72 61 75 67 70 56 65 70
81 73 62 78 64 59 80 77 81 82 72 89 102 109 95 101 91 69 58 57
62 69 66 78 58 66 70 78 76 65 56 69 65 73 84 58 77 72 50 53
53 46 50 53 35 52 33 37 30 27 32 35 33 42 38 34 37 48 33 40
37 45 40 49 45 47 41 53 59 48 45 53 54 50
BRM-C31A 216
48 42 38 44 40 67 53 41 52 45 63 63 48 37 42 43 61 59 67 94
100 62 55 57 56 72 82 74 54 102 71 61 49 43 48 59 73 77 58 71
59 71 74 72 59 63 77 73 99 85 99 79 57 102 110 82 85 67 74 78
78 49 46 78 85 76 71 65 83 80 92 81 94 114 115 146 105 96 73 83
94 75 74 80 74 97 95 109 100 103 102 59 65 78 90 132 117 97 101 66
123 71 80 84 89 115 143 132 127 111 93 73 114 124 123 179 110 119 115 110
140 118 119 120 105 113 110 119 122 120 115 120 95 88 79 111 118 166 186 136
166 143 154 106 99 107 108 106 93 83 121 101 106 112 83 118 125 100 91 66
83 82 76 93 54 62 68 99 98 85 94 71 71 67 73 66 69 83 109 124
111 104 71 78 72 66 65 76 87 109 81 66 55 45 22 36 45 46 41 46
55 56 38 61 59 58 64 51 53 35 47 48 42 39 39 45
BRM-C31B 216
71 56 42 51 45 58 56 39 46 54 64 63 49 44 37 49 68 65 65 98
111 49 61 61 48 84 92 74 53 109 65 61 60 32 48 56 64 82 57 69
62 72 74 67 47 68 72 65 103 87 104 75 59 110 101 76 92 69 68 78
82 49 47 78 78 74 74 58 86 82 89 82 98 114 100 144 105 94 71 95
85 83 76 73 72 106 90 115 103 89 107 63 66 74 91 137 116 90 100 68
119 74 86 82 88 108 148 131 128 107 96 93 109 131 121 183 109 113 118 104
142 118 117 118 113 109 108 122 119 115 118 119 96 92 84 106 112 175 183 124

151 154 157 108 96 111 117 104 90 81 120 99 106 121 80 123 121 106 86 70
86 80 77 89 54 61 69 96 106 81 92 72 68 74 81 70 61 63 90 114
114 105 74 69 76 57 66 79 79 116 73 75 58 38 36 28 35 47 48 48
50 55 42 58 57 64 51 52 52 45 49 51 43 37 36 50
BRM-C32A 320
114 135 191 170 215 194 176 223 218 146 243 183 162 241 204 183 165 167 96 73
93 108 106 180 236 175 231 181 192 170 142 126 201 155 145 91 143 147 158 161
154 140 91 49 117 104 81 96 98 132 104 156 117 130 173 122 107 102 77 111
96 128 91 114 117 104 126 101 86 87 87 86 63 86 86 117 101 95 144 136
130 104 79 76 53 70 65 71 61 54 54 55 86 86 56 109 108 91 108 116
106 97 109 119 128 111 106 150 91 97 112 98 101 101 75 95 91 73 58 65
78 68 79 97 100 104 94 96 95 134 117 129 90 93 95 117 120 116 127 91
100 98 108 139 171 161 134 96 98 103 118 126 112 115 118 82 96 65 83 93
102 103 99 86 69 72 76 62 76 76 86 111 117 86 96 76 69 83 87 108
93 84 88 82 104 101 77 95 88 88 77 77 91 85 119 72 93 106 89 81
91 82 66 82 78 81 87 64 79 84 131 114 102 111 119 163 148 122 114 111
100 99 103 109 121 128 113 74 104 111 96 95 75 93 83 105 92 100 78 122
104 76 63 75 130 121 103 88 93 71 50 39 24 27 32 28 22 27 30 34
32 30 43 40 41 37 50 55 54 53 55 50 43 34 50 57 69 71 79 83
61 69 67 73 58 78 93 75 60 56 72 58 58 73 70 90 93 84 87 75
62 71 70 84 88 85 77 75 84 67 72 67 80 81 64 65 60 65 45 46
BRM-C32B 320
136 148 171 215 196 187 191 234 235 146 213 169 162 252 218 181 170 164 92 70
95 109 102 178 239 176 226 183 185 161 134 116 195 169 160 95 134 141 161 159
144 130 97 57 121 102 77 95 107 128 115 145 121 134 171 134 103 94 88 115
107 137 99 107 116 109 129 102 87 87 84 85 72 84 90 114 95 98 155 151
134 114 83 75 61 75 63 67 67 47 55 54 87 87 62 113 111 91 121 116
113 96 114 130 125 114 110 155 94 99 116 92 107 101 70 92 90 68 60 67
74 77 78 103 102 102 106 98 100 143 115 133 89 93 97 115 123 120 120 83
105 102 108 145 174 171 135 104 105 118 129 126 118 106 111 91 96 66 80 99
106 103 100 85 77 72 79 63 79 82 80 127 112 87 94 77 71 76 89 107
93 78 86 82 109 103 90 86 107 94 84 75 89 84 122 70 92 108 98 78
93 79 73 84 85 79 86 65 72 88 127 122 112 115 126 149 161 127 117 107
109 109 107 113 122 134 98 77 101 116 109 95 93 90 86 98 102 94 87 106
103 88 61 77 122 123 105 94 95 71 49 43 27 25 27 28 27 34 22 22
37 36 51 35 44 36 54 53 50 59 56 50 37 42 50 54 67 67 91 78
64 77 61 67 66 82 87 69 69 60 79 59 58 80 70 83 78 80 89 62
62 68 78 78 96 76 86 87 71 68 77 67 81 81 77 65 62 62 56 46
BRM-C33A 349
112 206 210 134 132 166 170 193 191 193 211 239 165 204 108 135 221 293 253 163
106 141 196 189 189 174 163 110 109 93 138 160 137 135 191 189 129 124 140 150
106 126 120 84 120 145 123 128 133 103 116 120 87 121 142 116 125 89 48 39
36 63 131 135 84 87 117 96 75 72 103 97 122 88 126 116 90 119 104 128
123 132 99 131 90 77 106 105 92 108 141 110 123 102 102 99 110 129 97 69
72 76 93 92 121 121 90 146 177 156 190 232 211 292 239 137 124 101 84 106
121 140 91 109 99 92 92 84 92 65 65 108 105 74 99 84 82 66 67 59
119 155 85 69 68 85 123 117 153 102 83 64 59 50 47 43 41 46 58 58
82 72 72 63 64 81 75 100 108 92 89 104 152 139 124 107 67 60 68 83
66 58 90 79 76 105 96 91 90 86 106 120 98 94 90 76 77 89 76 84
92 75 63 80 71 60 73 55 58 66 66 67 48 55 59 66 72 73 64 74
68 79 69 67 78 75 61 78 96 75 63 75 81 93 84 73 75 67 81 68
70 81 54 65 55 67 59 70 66 77 66 76 64 78 58 81 74 65 78 61
49 59 43 58 64 53 67 73 82 63 52 66 69 66 66 76 65 68 57 70

70 91 78 80 76 68 63 66 83 77 73 64 56 78 64 59 70 81 87 93
114 101 89 103 94 91 92 86 65 67 77 86 68 86 70 78 69 86 54 54
62 69 94 77 70 61 75 79 70 73 68 74 96 91 69 77 69 68 43 46
47 61 64 65 78 85 71 100 103
BRM-C33B 350
110 207 207 135 139 164 170 216 216 203 217 226 153 212 108 142 225 303 264 167
107 136 192 193 179 171 155 116 105 84 131 163 139 130 173 179 135 121 140 149
108 121 127 84 119 141 129 128 132 106 116 115 79 125 142 110 128 83 47 43
40 61 109 143 79 88 114 95 76 81 98 94 114 93 129 113 85 119 97 131
112 134 97 131 79 84 107 106 98 111 131 105 106 104 96 102 99 123 92 72
81 74 86 99 118 108 87 141 168 153 176 222 207 276 272 137 127 97 93 99
132 143 89 107 105 92 94 84 99 60 67 110 105 77 102 78 87 65 64 67
115 155 91 69 64 84 130 113 159 100 76 68 58 43 53 42 40 43 65 56
81 70 74 62 64 80 81 93 110 87 91 106 158 130 128 106 67 61 67 84
66 61 82 79 79 106 96 92 90 79 110 120 105 96 91 69 82 86 80 82
92 74 62 80 70 61 73 53 55 73 62 63 52 57 57 60 75 76 68 71
72 74 67 65 85 84 61 76 89 75 64 71 87 89 89 68 76 68 83 69
66 81 53 68 57 59 64 67 74 76 67 75 69 73 59 81 75 71 76 55
48 56 53 50 59 58 64 79 71 63 64 64 68 72 62 67 67 64 60 65
77 83 65 79 72 71 61 71 86 76 76 63 62 78 69 54 64 91 90 102
110 103 100 91 98 90 91 86 62 75 75 82 71 90 65 81 70 82 61 53
64 72 88 75 68 68 70 86 70 76 65 75 81 84 80 76 71 70 38 49
48 56 66 70 75 77 69 87 95 90
BRM-C34A 328
151 174 158 139 89 134 161 232 308 292 344 231 230 189 132 74 72 89 89 120
98 91 132 121 80 76 94 70 82 82 68 75 65 54 61 107 90 65 71 73
55 52 57 77 82 71 49 91 67 88 55 53 65 70 77 58 68 60 45 63
46 55 71 71 65 63 60 53 48 65 52 52 44 45 57 36 78 50 61 57
52 60 51 48 54 45 49 59 61 69 86 68 46 69 70 60 54 48 48 59
54 50 43 46 45 44 41 59 60 37 56 57 56 78 63 65 61 70 70 77
62 72 67 58 70 59 52 74 50 53 68 41 52 53 59 57 61 53 54 64
51 74 63 56 59 88 82 60 83 62 82 62 76 70 56 67 79 87 84 86
89 75 90 78 80 83 95 80 88 78 74 66 72 84 89 80 67 91 70 65
66 74 80 72 86 63 88 82 76 81 80 63 67 77 79 82 73 64 71 77
80 77 100 77 85 81 75 64 75 86 68 78 71 65 66 61 60 68 62 70
62 87 66 84 81 84 83 72 77 61 89 82 81 73 72 57 68 67 70 73
68 70 63 72 59 66 58 51 65 63 61 76 69 67 80 80 61 68 68 88
88 85 77 84 70 60 65 56 67 65 74 81 74 70 80 82 84 91 71 82
66 71 83 72 91 87 92 68 78 88 81 87 90 88 89 79 92 86 88 78
72 58 58 65 62 68 65 51 60 54 60 71 52 65 68 50 50 51 53 55
57 56 61 52 50 53 43 65
BRM-C34B 328
151 174 156 137 94 131 157 237 304 296 332 239 226 188 124 81 81 85 80 118
93 84 126 125 89 74 87 67 78 92 75 76 63 56 58 110 91 65 67 73
54 45 58 82 85 65 52 91 75 81 53 60 65 71 72 53 63 62 46 63
51 56 67 69 65 67 52 53 44 64 58 46 44 38 60 40 70 56 61 53
53 60 54 52 55 40 51 62 62 64 84 60 60 63 78 60 43 51 50 56
69 49 58 46 47 39 42 55 62 43 65 58 64 83 64 62 62 65 74 79
70 68 59 66 64 65 59 70 62 48 65 46 56 50 58 63 59 61 45 65
64 63 62 64 67 81 83 69 77 64 79 71 72 65 65 63 69 100 84 89
83 79 84 90 74 93 88 84 78 85 66 66 79 84 89 80 65 86 75 68
69 74 72 77 82 71 86 86 76 86 75 62 69 77 81 82 78 55 73 82
75 82 95 84 86 79 70 76 72 83 66 73 72 77 56 64 59 69 61 67

67 86 73 83 82 80 82 76 71 70 77 95 72 78 71 53 78 61 73 74
62 85 55 67 58 66 52 60 57 68 58 74 72 73 81 76 61 65 69 85
100 81 89 76 71 61 50 66 66 83 76 83 89 72 84 77 78 90 76 80
82 73 79 79 95 84 87 79 83 84 78 94 85 87 95 79 106 91 84 73
84 47 54 66 66 57 70 62 61 49 64 65 56 62 68 59 47 50 54 58
48 53 64 53 52 53 43 55
BRM-C35A 162
82 138 136 123 153 173 136 170 101 109 88 95 88 79 119 90 91 48 47 26
41 56 61 93 71 80 82 78 77 73 76 90 87 94 60 54 53 84 84 91
82 84 99 74 79 100 75 82 86 95 82 53 60 63 72 68 83 59 70 78
74 77 82 71 61 57 60 77 70 72 73 80 84 93 84 78 67 65 94 81
73 61 88 74 83 79 87 79 71 64 71 71 50 58 73 56 54 55 59 56
81 62 54 51 52 71 53 76 65 58 67 55 80 57 60 60 59 63 73 67
59 90 46 50 57 55 61 55 52 61 60 74 52 47 47 58 40 50 47 48
38 50 44 47 54 51 58 81 86 106 113 97 127 124 103 106 78 82 112 112
113 121
BRM-C35B 162
105 125 127 123 153 158 130 166 105 103 82 104 83 84 122 91 92 50 39 31
41 48 65 87 73 78 92 74 82 81 77 80 89 104 68 47 46 79 87 83
85 89 96 73 78 106 79 77 86 91 81 67 64 59 73 68 85 75 65 75
73 82 76 72 53 56 60 63 61 75 91 70 87 88 88 81 68 69 91 80
76 63 85 79 77 84 83 79 66 61 71 67 59 57 61 56 63 54 54 63
77 71 50 48 49 72 57 77 60 64 68 55 77 60 62 58 57 67 71 63
65 87 52 44 66 47 66 61 50 62 62 73 52 47 49 54 40 43 47 51
37 38 55 46 52 52 60 79 83 108 118 97 125 129 98 111 81 87 112 111
122 129

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 Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (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

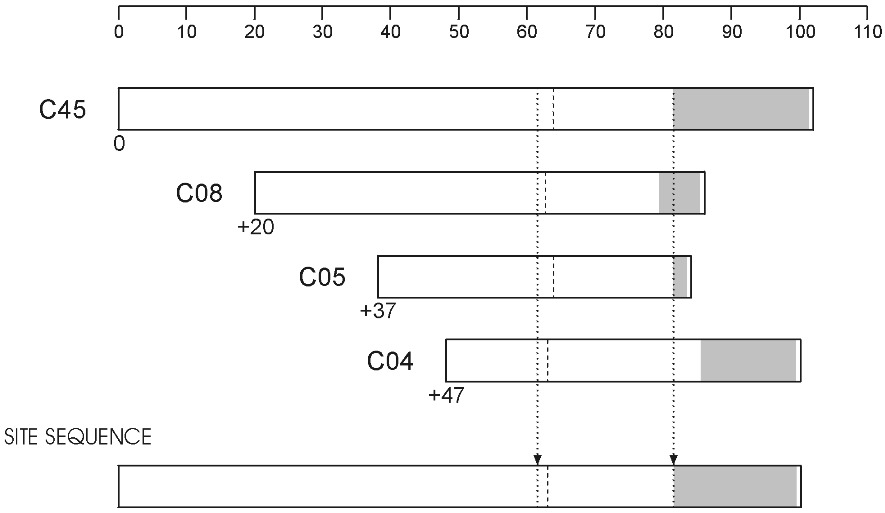


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

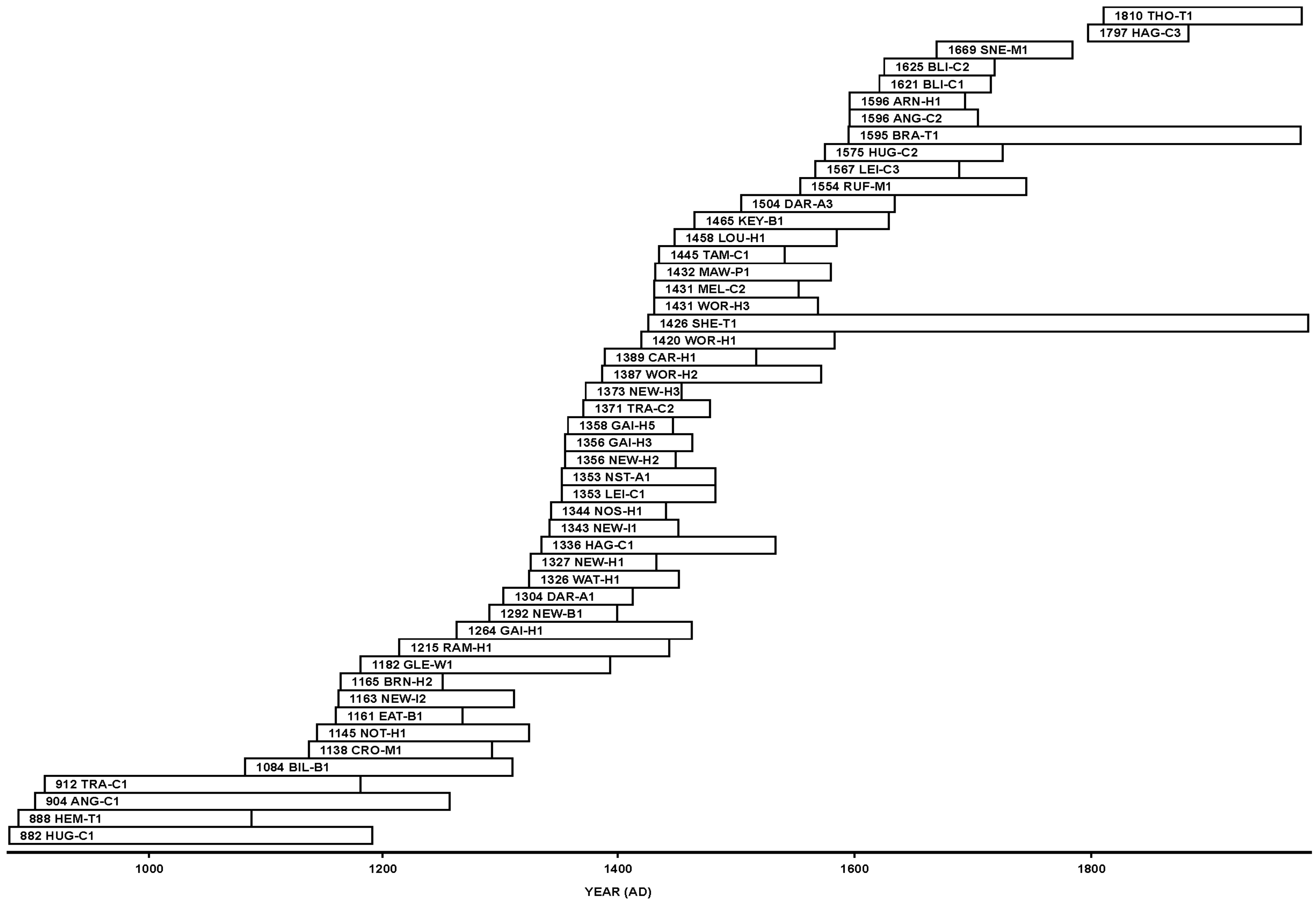
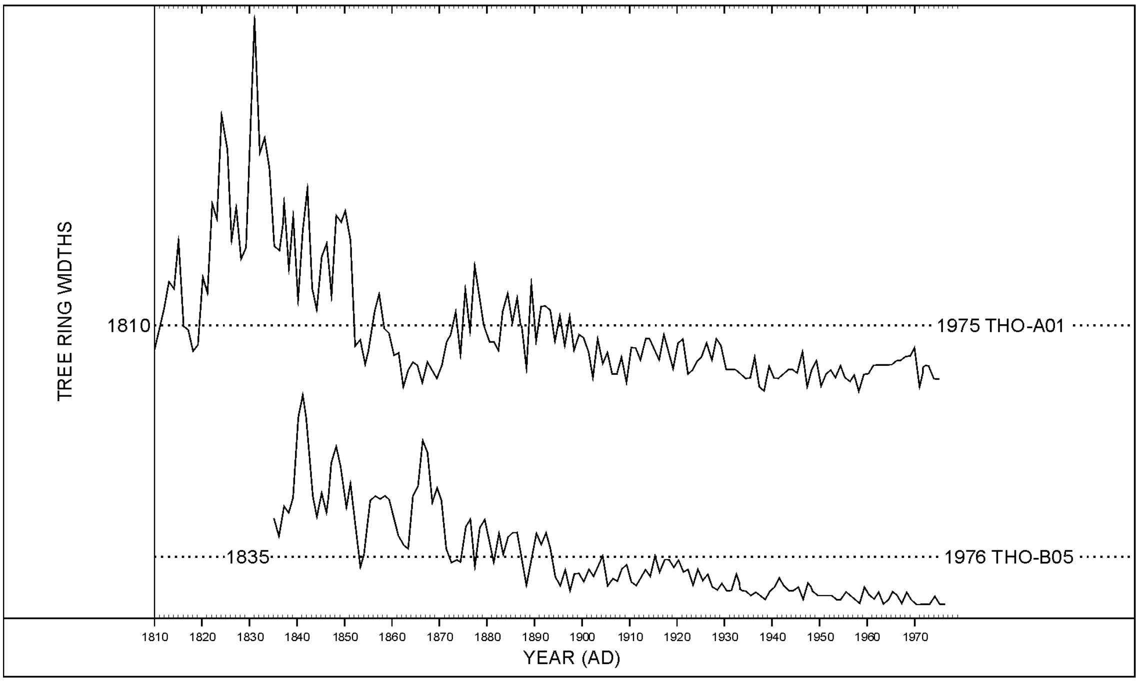


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

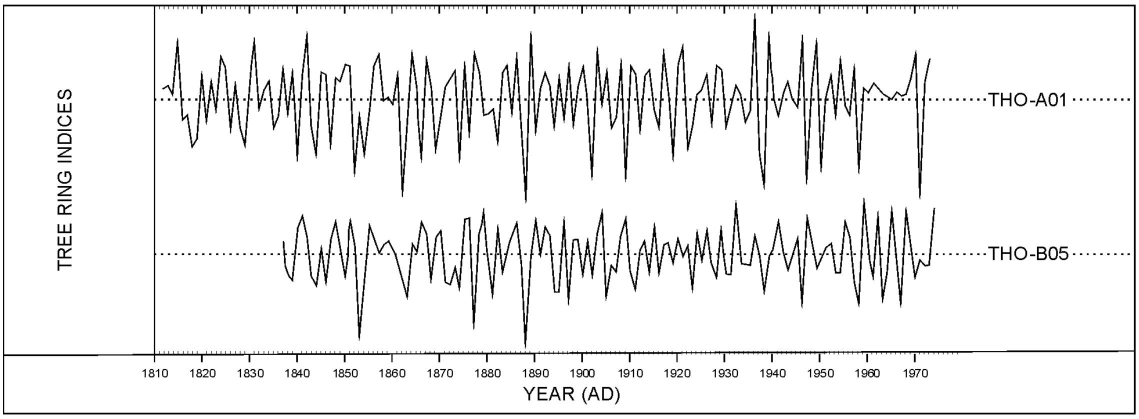


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

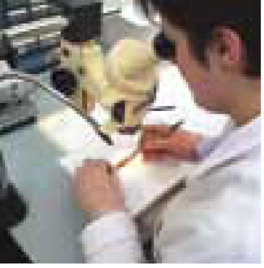
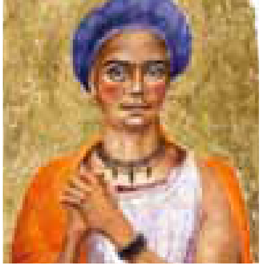
Laxton, R R, Litton, C D, and Howard, R E, 2001 Timber: *Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, 7

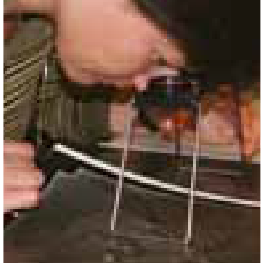
Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸18, 29–40

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


Historic England Research and the Historic Environment

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

Historic England works to improve care, understanding and public enjoyment of the historic environment. We undertake and sponsor authoritative research. We develop new approaches to interpreting and protecting heritage and provide high quality expert advice and training.

We make the results of our work available through the Historic England Research Report Series, and through journal publications and monographs. Our online magazine Historic England Research which appears twice a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.HistoricEngland.org.uk/researchreports

Some of these reports are interim reports, making the results of specialist investigations available in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation.

Where no final project report is available, you should consult the author before citing these reports in any publication. Opinions expressed in these reports are those of the author(s) and are not necessarily those of Historic England.

The Research Reports' database replaces the former:

Ancient Monuments Laboratory (AML) Reports Series
The Centre for Archaeology (CfA) Reports Series
The Archaeological Investigation Report Series and
The Architectural Investigation Reports Series.

ISSN 2059-4453 (Online)