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The Malt House
Blacker Hall Farmhouse
Wakefield
West Yorkshire

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. 206-2020

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NGR: SE 30027 15747

ISSN 2059-4453 (Online)

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SUMMARY
Core samples were taken from timbers in the roof, floor-frame of the first-floor, and lintels at ground-floor and first-floor levels of this building. Additionally, cross-sectional slices were taken from a number of *ex situ* beams. Tree-ring analysis undertaken on all of these samples resulted in the construction of five site sequences, only one of which has been dated.

Timber utilised in the construction of the roof has been dated as felled in, or around, AD 1687, with the floor frame likely to be coeval, containing timber felled in AD 1687–1701. A window lintel is also dated to AD 1687 with a door lintel having a *terminus post quem* for a felling date of AD 1658, and thought likely to also have been felled in, or around, AD 1687. Two *ex situ* beams of unknown origin are dated as felled in AD 1675–1700 and, therefore, are again likely to belong to the same building phase as the rest of the dated material.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank the owner of the building for facilitating access and for allowing sampling to be undertaken, and Helen Bower, Conservation Officer at Wakefield Council, who provided invaluable advice on site. We would also like to thank Andy Laverick at Pearce Bottomley Architects for his help and guidance, and for providing the plans reproduced in this report. Thanks to Nicky Brown too, Historic England Heritage at Risk Projects Officer, who requested the work and helped with practical arrangements, and finally thanks to Shahina Farid (Historic England Scientific Dating Team) who commissioned and facilitated this study and compiled the maps reproduced as Figure 1.

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

HISTORIC ENVIRONMENT RECORD OFFICE
West Yorkshire Historic Environment Record
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Gildersome Spur Industrial Estate
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Morley
Leeds LS27 7JQ

DATE OF INVESTIGATION
2018

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 Malt House, an early-mid seventeenth-century Grade II* listed building (LEN 1135604), is located approximately 15 metres south-west of Blacker Hall Farmhouse (Fig 1). The main building is of two storeys and seven bays with a single bay outshut to the south and an attached gabled kiln to the north end (Fig 2). Entry to the ground floor is via a Tudor-arched doorway with chamfered surround (Fig 3), to the north of which are two two-light double-chamfered mullioned windows (Fig 4a/b). Access to the lime-ash first floor is via a flight of stone steps. The floor is supported by a series of heavy main beams and common joists (Fig 5). The surviving roof consists of three king-post and stop-chamfered tiebeams, with principal rafters, single angle struts, and straight braces to a diamond-set ridge (Fig 6). Amongst a pile of timbers outside can be distinguished a further tiebeam, a possible crown post and rafters. It is known that two of the original trusses had been replaced with trusses of (probably) eighteenth-century fish-bone king-post type, and these are thought to also be amongst the *ex situ* timbers (Fig 7).

The Malt House is a rare and unusually complete survival and, within its setting of the farmhouse and two barns, it represents an impressive group value. It is currently on the Heritage at Risk register due to its dilapidated state and the risk of further deterioration.

SAMPLING

Dendrochronological analysis was requested by Nicky Brown, Historic England Heritage at Risk Projects Officer, to provide independent dating evidence for the primary construction and phasing of the building's development to understand its significance in order to inform structural repairs and long term stabilisation.

A total of 24 core samples were taken from oak timbers of the roof and floor structures and from a number of lintels. In addition, samples in the form of cross-sectional slices were taken from five *ex situ* oak timbers. Each sample was given the code BHF-M and numbered 01–29. Further details relating to the samples can be found in Table 1. Trusses and floor beams have been numbered from south to north (Fig 8) and the location of *in situ* sampled timbers has been marked on Figures 2 and 9–13.

Unfortunately, other *ex situ* oak timbers thought to represent the eighteenth-century replacement timbers were deemed unsuitable for analysis due to being fast grown and having insufficient growth rings. The roof trusses in the kiln house appeared to be conifer and were not safely accessible at the time of this study.

ANALYSIS AND RESULTS

All 29 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. It can be seen that BHF-M16A has two more rings than BHF-M16B, this is simply that on the second measurement of this core the first two rings were omitted in error. All measurements were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 25 samples matching to form five groups.

Firstly, 16 samples matched each other at a minimum *t*-value of 4.6 and were combined at the relevant offset positions to form BHFMSQ01, a site sequence of 138 rings (Fig 14). This site sequence was then compared against an extensive series of relevant reference chronologies for oak where it was found to match securely and consistently at a first-ring date of AD 1550 and a last-measured ring date of AD 1687. The evidence for this dating is given in Table 2.

Two further samples matched each other at a *t*-value of 9.3 and were again combined at the relevant offset position to form a second site sequence, BHFMSQ02 of 76 rings (Fig 15). This site sequence was then compared against the reference material but, despite some tentative matching, no secure or consistent dating was noted and it is undated.

Three further site sequences were constructed: BHFMSQ03 of 104 rings (Fig 16), containing three sampled, formed at a minimum *t*-value of 5.0, BHFMSQ04 of 83 rings (Fig 17) contained two samples which matched each other at a *t*-value of 8.3, and BHFMSQ05 of 75 rings (Fig 18) contained two samples which matched at a *t*-value of 7.8. These, and the remaining four ungrouped samples, were then compared against the reference chronologies but again no secure match was noted and all remain undated.

INTERPRETATION

Tree-ring analysis has successfully dated 16 samples, a mixture of roof timbers, timbers from the floor structure, lintels, and *ex situ* timbers. For clarity timbers from each area are discussed separately below. Felling date ranges and *terminus post quem* for felling dates have been calculated using the estimate that 95% of mature oak trees in this region have 15–40 sapwood rings.

Roof

Nine of the samples taken from roof timbers, representing all three extant trusses, have been successfully dated. One of these, BHF-M08, retains complete sapwood and a last-measured ring date of AD 1687, the felling date of the timber represented. Another seven of the dated roof timbers have the heartwood/sapwood boundary, the dates of which are broadly contemporary and, when combined with the high level of cross-matching, suggestive of a single felling ranging from AD 1647 (BHF-M07) to AD 1667 (BHF-M05). The average heartwood/sapwood boundary ring date is AD 1659, allowing an estimated felling date to be calculated for the seven timbers represented to within the range AD 1687–99, consistent with these timbers also having been felled in, or around, AD 1687. This estimate allows for sample BHF-M01 having a last-measured ring date of AD 1686 with incomplete sapwood.

The final dated sample, BHF-M03, does not have the heartwood/sapwood boundary ring and so a felling date range cannot be calculated for it, except to say that with a last-measured ring date of AD 1655 this would be estimated to be after AD 1670 at the earliest. A number of the samples taken from the roof match each other at *t*-values high enough to suggest they were cut from the same tree. This includes BHF-M03, which matches samples BHF-M04, BHF-M11, and BHF-M12 at a value of $t = 11.8$, 11.5, and 10.9 respectively, making it likely that all four timbers were cut from the same tree and hence felled at the same time.

Floor frame

Three of the sampled floor beams have been dated, all of which have similar heartwood/sapwood boundary ring dates ranging from AD 1656 (BHF-M13) to AD 1664 (BHF-M18). The average of these is AD 1661, allowing an estimated felling date to be calculated for the three timbers represented to within the range AD 1687–1701, again consistent with these floor timbers also having been felled in, or around, AD 1687. This allows for sample BHF-M17 having a last-measured ring date of AD 1686 with incomplete sapwood.

Lintels

Two of the lintels have also been dated. One of these, BHF-M21, retains complete sapwood and has a last-measured ring date of AD 1687, which is the felling date of the timber represented. The second dated lintel does not have the heartwood/sapwood boundary ring and so a felling date range cannot be calculated for it, except to say that with a last-measured ring date of AD 1643 this would be estimated to be, at the earliest, after AD 1658. This matches one of the floor timbers with a $t = 9.5$, again a level of similarity sufficient to suggest that it was felled at the same, similar time, in the later AD 1680s.

Ex situ timbers

Two of these timbers of unknown location have been dated. Although neither have complete sapwood, both of them do retain the heartwood/sapwood boundary ring. The average of these two dates is AD 1660, giving an estimated felling date range for the two timbers of AD 1675–1700, again consistent with having been felled in, or around, AD 1687.

DISCUSSION

Tree-ring analysis has successfully dated timbers from all areas under investigation. It has demonstrated that the roof and floor frame are likely to be contemporary, both utilising timber felled in the last decades of the seventeenth century, in or around AD 1687. Additionally, timber used for the window lintel at first-floor level in the south gable of the building is also dated to AD 1687, suggesting this window is a feature of the primary phase of construction. Indeed, the sample from this lintel can be seen to match two roof timbers (BHF-M07 and BHF-M08) at a level ($t = 9.7$ and 9.8, respectively) to suggest that all three timbers were cut from the same tree, or at least were sourced from the same woodland stand. Samples BHF-M07 and BHF-M08 match each other at t = 17.7 and almost certainly represent the same tree. A second lintel, located over the ground-floor entrance door has a *terminus post quem* for felling date of AD 1658 and almost certainly also belongs to the same phase as that of the roof, floor structure, and window lintel.

In addition to the *in situ* timbers dated, two of the salvaged timbers have also been dated; these are now known to have been felled in AD 1675–1700. Although it is not possible to identify the location within the building from which these timbers came, it can be seen from the *intra-site* cross matching that they resemble most closely the other roof samples (Table 3). It is, therefore, likely that they represent primary roof timbers salvaged from the collapsed northern half of the roof. It is unfortunate that the *ex situ* timbers thought to be the potentially eighteenth-century replacement roof trusses were unsuitable for analysis, as this therefore cannot be proven by tree-ring dating.

Only three of eight sampled floor timbers have been dated. This could be because several different woodland sources were utilised for the timber, but is thought more likely to be due to more than one phase of work being represented amongst them. They can be seen to be of varying appearance and it was thought, at the time of sampling, that some were likely to be replacements. It is known that some of the roof trusses were replaced in (probably) the eighteenth century, and it does not seem inconceivable that if the roof needed repair at this time then parts of the floor frame might also have required attention.

Three of the undated site sequences contain samples taken from the floor structure. Site sequences BHFMSQ02 and BHFMSQ05 each contain two of these samples and it can be seen from the relevant bar diagrams (Figs 15 and 18) that for BHFMSQ02 both timbers represented were felled at the same time and the same is most likely the case with those represented by BHFMSQ05, even though it is not possible to say when this might have been. A third undated site sequence, BHFMSQ03, contains an *in situ* king post, an *ex situ* timber (thought to be a king post), and a floor beam. Again, by looking at the relative offset positions of these samples (Fig 16) it can be seen that the king posts were felled at the same time as each other and it is thought likely that the floor beam was also felled at this time.

The reference chronologies against which the dated site sequence shows most similarity are generally located in northern regions (Table 2), suggesting the woodland source for the timber utilised was likely to be relatively local.

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TABLES

Table 1: Details of tree-ring samples from The Malt House, Blacker Hall Farmhouse, Wakefield, West Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof						
BHF-M01	Tiebeam, truss 1	107	26	1580	1660	1686
BHF-M02	King post, truss 1	82	21C	----	----	----
BHF-M03	East principal rafter, truss 1	94	--	1562	----	1655
BHF-M04	West principal rafter, truss 1	86	h/s	1573	1658	1658
BHF-M05	Tiebeam, truss 2	70	h/s	1598	1667	1667
BHF-M06	King post, truss 2	70	09	1601	1661	1670
BHF-M07	East principal rafter, truss 2	116	18	1550	1647	1665
BHF-M08	West principal rafter, truss 2	123	42C	1565	1645	1687
BHF-M09	Tiebeam, truss 3	85	11	----	----	----
BHF-M10	King post, truss 3	73	15	----	----	----
BHF-M11	East principal rafter, truss 3	92	07	1577	1661	1668
BHF-M12	West principal rafter, truss 3	81	01	1580	1659	1660
Floor frame						
BHF-M13	Beam 2	98	26	1585	1656	1682
BHF-M14	Beam 3	57	h/s	----	----	----
BHF-M15	Beam 4	90	17	----	----	----
BHF-M16	Beam 6	75	07	----	----	----
BHF-M17	Beam 7	107	24	1580	1662	1686
BHF-M18	Beam 8	113	20	1572	1664	1684
BHF-M19	Beam 10	64	16C	----	----	----
BHF-M20	Beam 11	76	22C	----	----	----
Lintels						
BHF-M21	Window lintel, south gable	110	37C	1578	1650	1687
BHF-M22	Ground floor, east door lintel	89	--	1555	----	1643
BHF-M23	Ground floor, east window lintel, bays 3-4	62	--	----	----	----

BHF-M24	Ground floor, east window lintel, bays 5-6	83	--	----	----	----
Ex situ timbers						
BHF-M25	Tiebeam	118	25C	----	----	----
BHF-M26	King post	85	22C	----	----	----
BHF-M27	Common rafter or joist	83	--	----	----	----
BHF-M28	Unknown	75	h/s	1587	1661	1661
BHF-M29	Unknown	79	h/s	1581	1659	1659

h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample, last-measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BHFMSQ01 and relevant reference chronologies when the first-ring date is AD 1550 and the last-measured ring date is AD 1687

Reference chronology	*t*-value	Span of chronology	Reference
Ledston Hall, Leeds, West Yorkshire	8.5	AD 1424–1668	Arnold *et al* 2015
Moseley Wood Farm barn, Cookridge, West Yorkshire	8.3	AD 1511–1659	Tyers 2006
Kent House, Ridgeway, Derbyshire	7.8	AD 1431–1646	Groves and Hillam 1990
28–30 The Close, Newcastle upon Tyne, Tyne and Wear	7.7	AD 1461–1616	Arnold *et al* 2008
Auckland Castle, Bishop Auckland, Co Durham	7.7	AD 1425–1698	Arnold and Howard 2013
Durham Cathedral (north transept repairs), Durham	7.3	AD 1534–1728	Howard *et al* 1992
Durham Cathedral (refectory/librarian's loft), Durham	7.2	AD 1431–1683	Arnold *et al* 2007
Staircase House, Stockport, Greater Manchester	7.0	AD 1489–1656	Howard *et al* 2003
Ling Bob Farm, Horsforth, Leeds, Yorkshire	7.0	AD 1496–1664	Arnold and Howard 2014 unpubl
Tonge Hall, Middleton, Lancashire	6.9	AD 1449–1687	Arnold and Howard 2014

Table 3: Matrix to show the level of cross-matching between the ring-series included in site master sequence BHFMSQ01; the higher the value the greater the level of similarity between samples (values of t≥ 10.0 may represent timbers derived from the same tree; -- = highest t-value not at correct offset). It can be seen that the two unlocated samples (BHF-M28 and BHF-M29) match most highly against samples BHF-M01, BHF-M03, BHF-M04, and BHF-M05, all samples taken from roof timbers.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BHF-M01	1	***															
BHF-M03	2	--	***														
BHF-M04	3	--	**11.8**	***													
BHF-M05	4	--	3.0	3.8	***												
BHF-M06	5	**5.2**	4.3	3.6	--	***											
BHF-M07	6	--	--	3.4	2.7	--	***										
BHF-M08	7	4.1	--	--	--	--	**17.7**	***									
BHF-M11	8	4.1	**10.9**	**12.0**	--	4.1	**4.5**	**4.7**	***								
BHF-M12	9	3.8	**11.5**	**12.7**	3.0	**4.6**	3.3	3.6	**15.0**	***							
BHF-M13	10	3.8	**5.5**	**5.4**	--	**5.9**	--	4.2	**6.0**	**6.6**	***						
BHF-M17	11	**4.7**	--	4.4	3.1	3.0	--	--	**4.6**	--	--	***					
BHF-M18	12	--	3.1	**4.6**	--	--	**5.1**	**5.0**	**5.4**	**4.5**	--	--	***				
BHF-M21	13	3.6	4.2	**5.6**	--	4.4	**9.7**	**9.8**	**6.3**	**5.9**	4.0	3.6	4.2	***			
BHF-M22	14	--	--	--	--	--	3.4	3.3	--	--	--	--	**9.5**	--	***		
BHF-M28	15	**5.2**	4.3	**4.8**	**6.2**	3.1	3.4	3.5	3.4	3.2	--	--	2.5	3.1	--	***	
BHF-M29	16	4.2	4.2	**5.3**	**6.2**	--	2.6	--	4.0	3.4	--	--	4.0	3.2	2.8	**14.7**	***

FIGURES

Figure 1: Maps to show the location of The Malt House, Blacker Hall Farmhouse in Wakefield, West Yorkshire, marked in red. Scale: top right 1:30000; bottom 1:2000. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

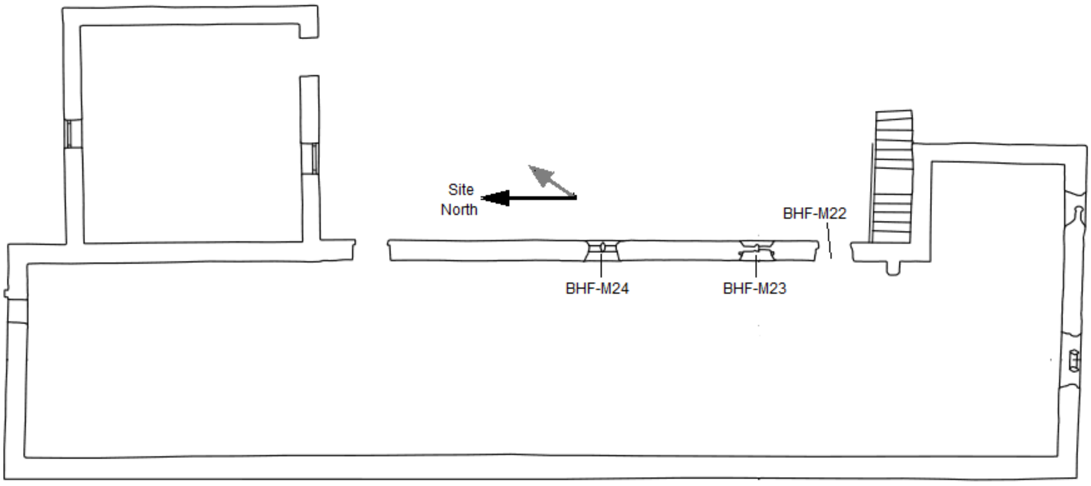

Figure 2: Ground-floor plan also showing the location of sampled timbers BHF-M22–24 (Archeritage)

Figure 3: Main entrance to the ground floor, photograph taken from the west (Alison Arnold)

Figure 4a/b: Windows in the east wall (above and below), photograph taken from the west (Alison Arnold)

Figure 5: Floor structure, beam 4 in foreground, photograph taken from the south (Alison Arnold)

Figure 6: Truss 3 showing principal rafters, single angle struts, and straight braces to a diamond-set ridge. Photograph taken from the north (Alison Arnold)

Figure 7: Pile of ex situ *timbers, possibly discarded original trusses (Alison Arnold)*

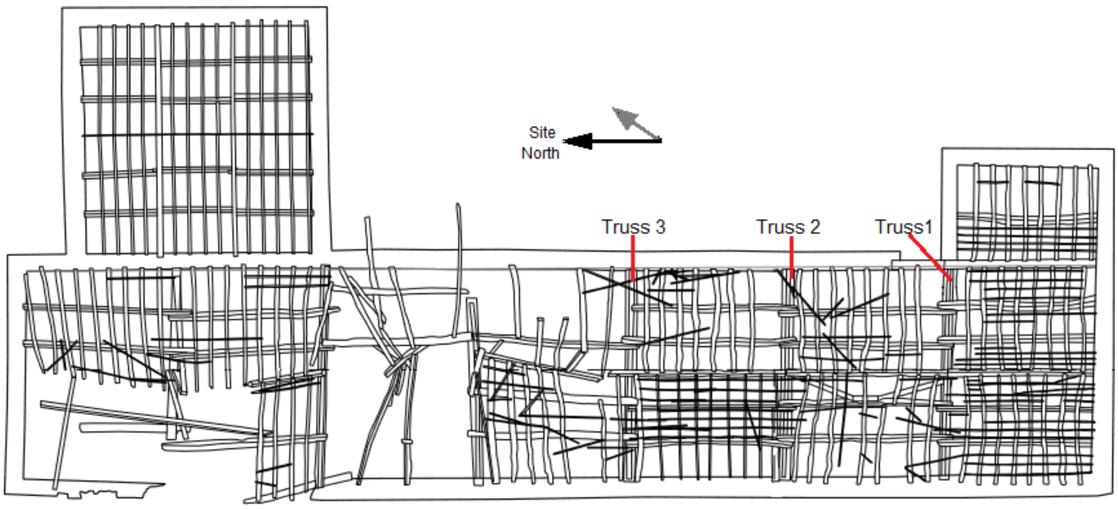

Figure 8: Roof plan, showing truss numbering (Archeritage for Pearce Bottomley Architects)

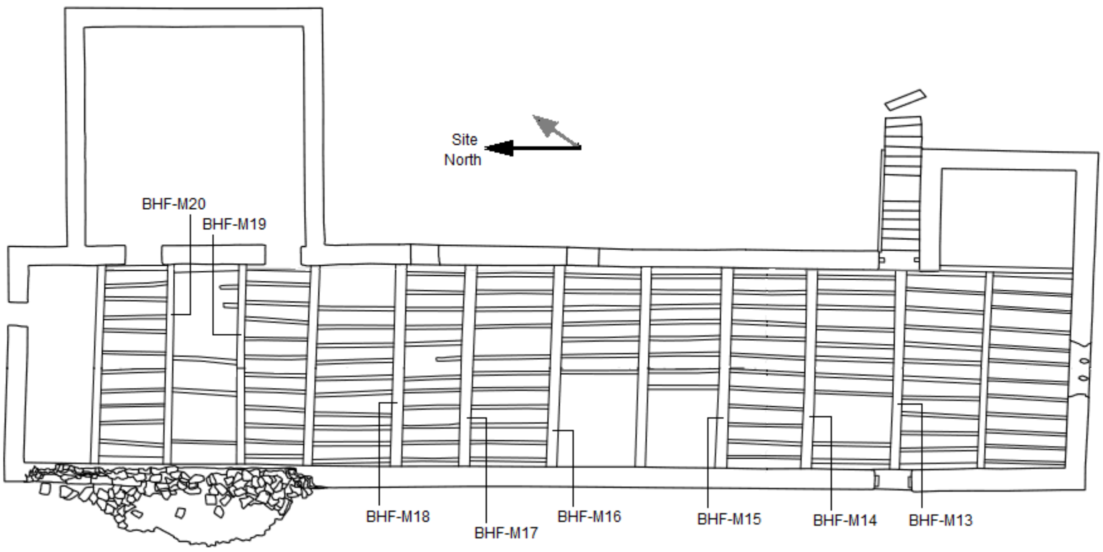

Figure 9: First-floor plan, showing the location of sampled timbers BHF-M13–20 (Archeritage for Pearce Bottomley Architects)

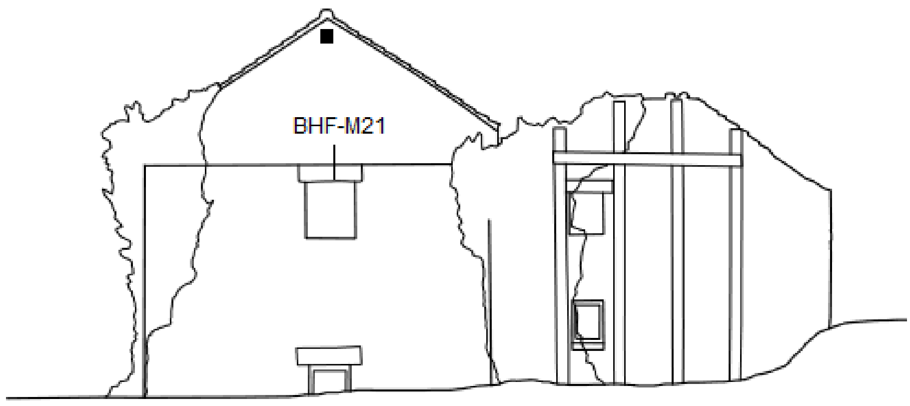

Figure 10: South elevation, showing the location of sampled timber BHF-M21 (Archeritage for Pearce Bottomley Architects)

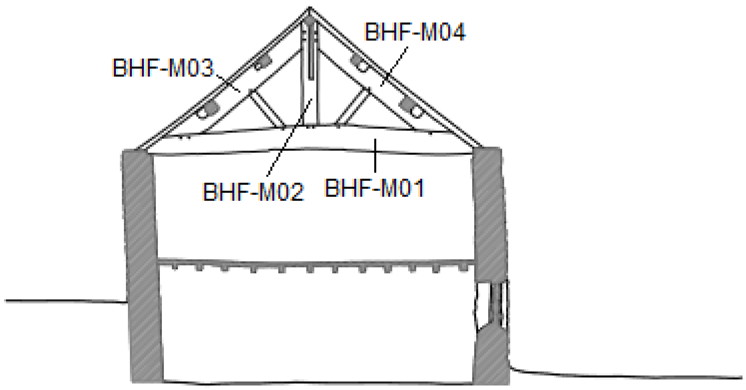

Figure 11: Truss 1, showing the location of sampled timbers BHF-M01–04 (Archeritage for Pearce Bottomley Architects)

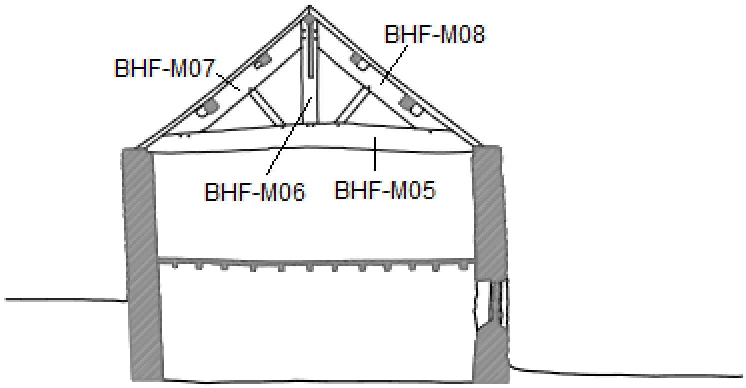

Figure 12: Truss 2, showing the location of sampled timbers BHF-M05–08 (Archeritage for Pearce Bottomley Architects)

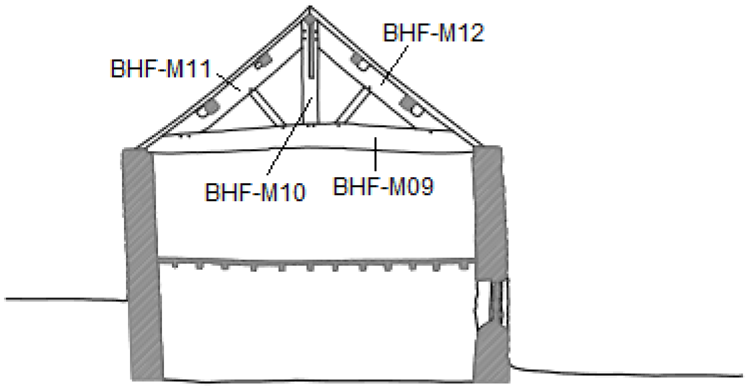

Figure 13: Truss 3, showing the location of sampled timbers BHF-M09–12 (Archeritage for Pearce Bottomley Architects)

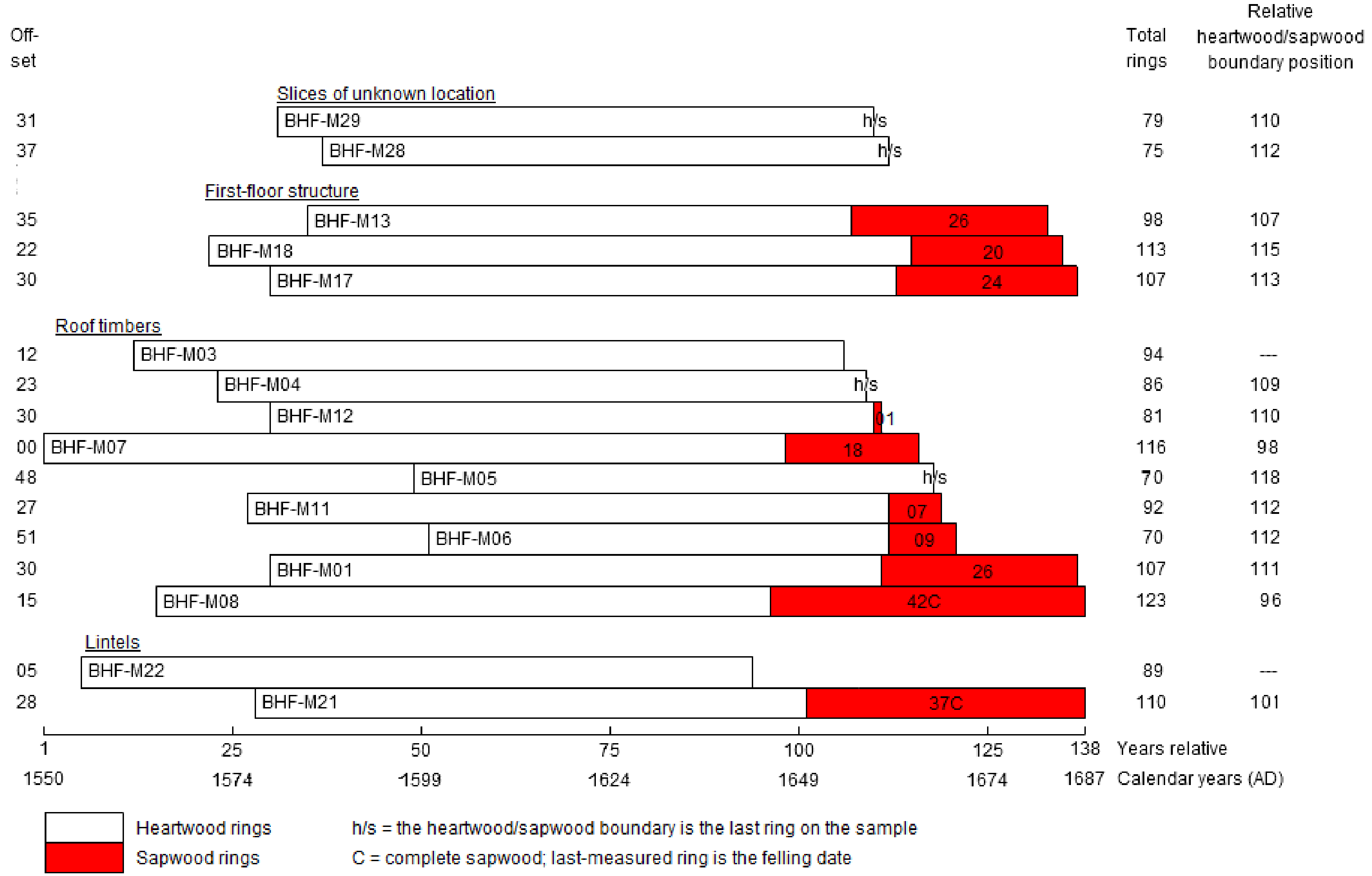

Figure 14: Bar diagram to show the relative position of samples in site sequence BHFMSQ01, sorted by area

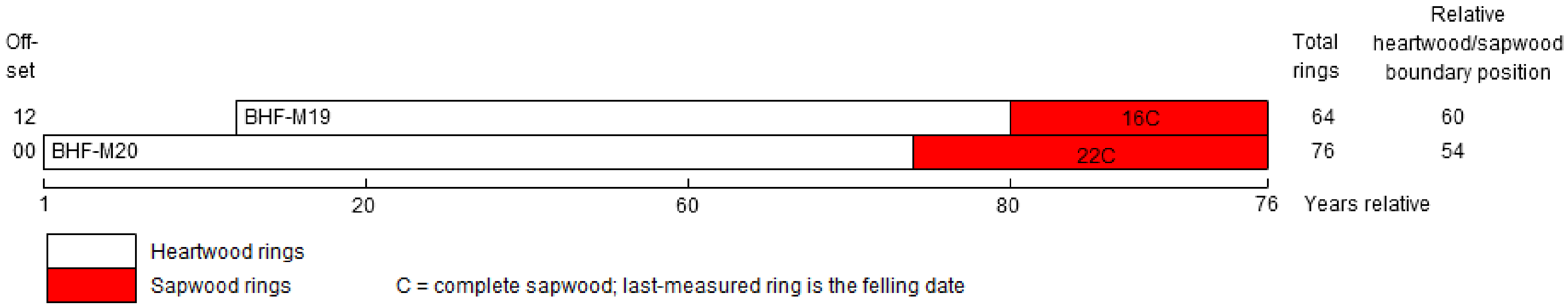

Figure 15: Bar diagram to show the relative position of samples in undated site sequence BHFMSQ02

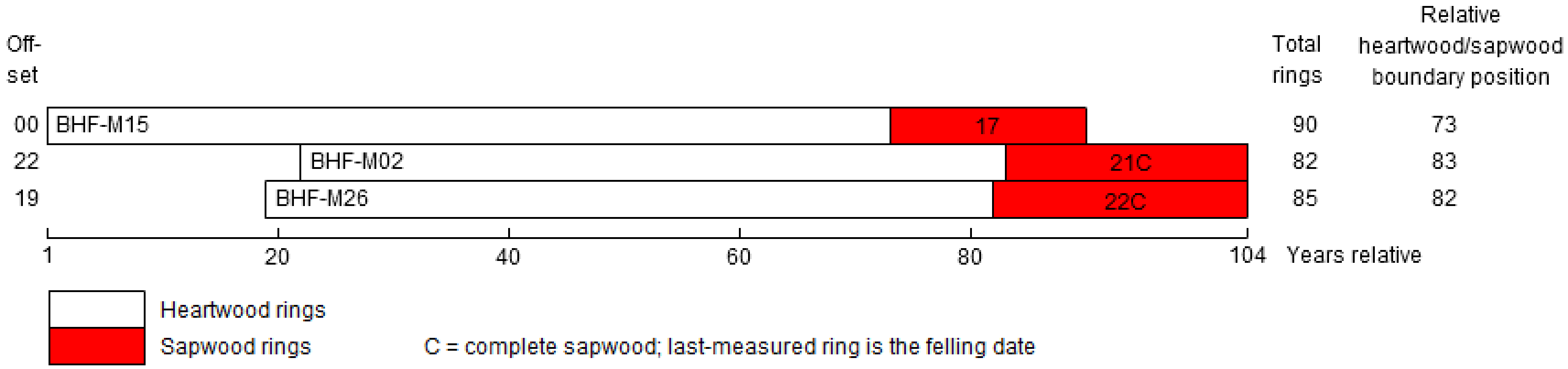

Figure 16: Bar diagram to show the relative position of samples in undated site sequence BHFMSQ03

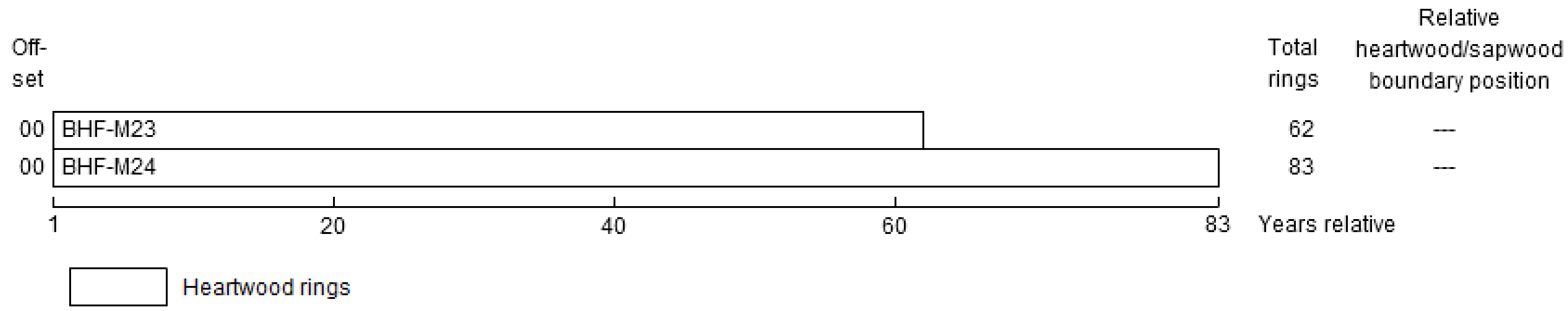

Figure 17: Bar diagram to show the relative position of samples in undated site sequence BHFMSQ04

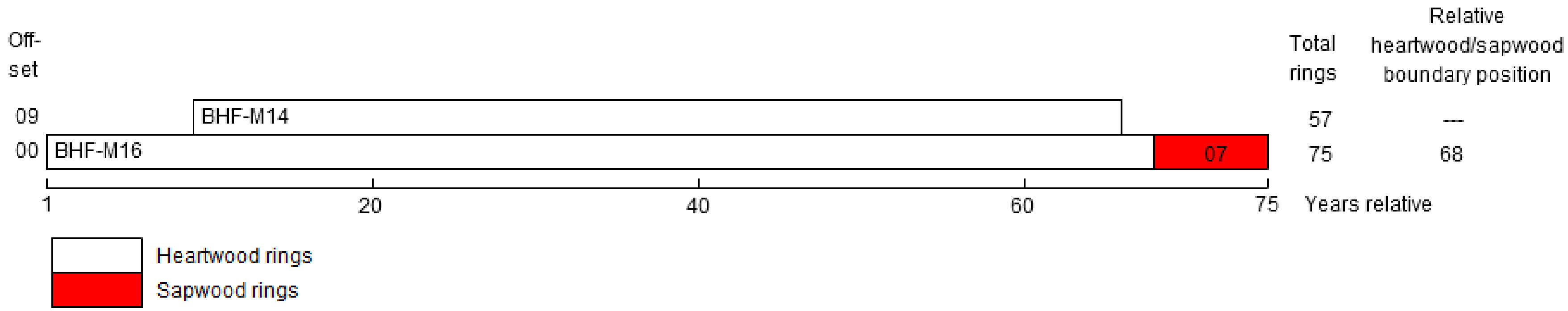

Figure 18: Bar diagram to show the relative position of samples in undated site sequence BHFMSQ05

DATA OF MEASURED SAMPLES

Measurements are in 0.01mm units

BHF-M01A 107
300 223 279 223 304 355 254 228 256 228 170 155 179 248 265 221 270 249 261 262
244 234 182 183 213 199 199 134 105 150 115 109 126 155 148 151 142 153 221 277
384 330 323 329 282 256 340 329 356 487 299 137 110 83 66 90 80 116 201 211
177 257 233 214 187 230 283 268 258 222 169 175 114 80 88 127 145 145 171 144
149 119 114 153 140 162 119 170 143 147 207 183 148 197 158 86 69 63 72 106
86 85 153 97 89 94 133

BHF-M01B 107
337 234 278 224 310 364 248 224 250 229 167 156 181 243 274 215 291 226 263 265
259 226 186 180 219 197 190 134 111 141 108 106 141 170 153 136 150 150 219 282
383 339 289 316 258 265 321 330 347 484 302 146 108 88 66 87 78 121 201 213
193 274 207 222 193 228 279 275 258 231 163 179 110 86 84 127 145 139 174 139
156 119 111 146 134 146 118 157 130 144 216 181 155 218 164 80 54 98 75 112
89 80 161 94 98 92 131

BHF-M02A 82
283 293 242 246 223 260 171 202 188 157 177 45 44 47 34 57 49 37 60 69
49 77 73 94 104 59 100 121 164 120 101 75 136 225 197 193 249 171 182 167
171 224 171 150 112 125 197 213 193 209 148 233 157 196 276 191 149 160 210 255
211 166 175 123 175 238 208 174 166 241 150 187 160 137 200 142 182 203 166 188
142 130

BHF-M02B 82
289 306 225 266 214 240 173 209 201 161 181 47 41 43 39 56 44 43 61 57
52 85 75 95 104 60 103 127 166 118 98 82 131 219 189 193 249 174 181 172
177 217 167 152 108 137 193 208 192 209 151 230 155 196 275 191 143 159 205 255
208 171 171 128 173 235 210 172 168 247 151 175 169 143 205 156 175 199 168 185
142 121

BHF-M03A 94
416 351 369 219 299 169 218 274 363 228 174 292 404 304 292 267 336 310 297 272
251 228 283 258 224 273 149 150 118 137 161 215 256 164 201 177 166 169 171 153
93 103 144 227 425 254 364 219 205 109 166 219 132 118 79 61 46 31 49 65
77 95 72 62 108 142 147 185 118 192 187 183 142 131 98 140 284 63 68 83
85 104 83 83 138 126 196 124 87 75 65 100 149 143

BHF-M03B 94
412 372 375 224 302 167 230 282 346 163 179 327 363 311 331 282 336 309 292 285
264 239 289 242 240 276 159 149 118 141 152 216 257 167 200 180 170 176 165 145
98 105 143 224 431 261 358 218 203 112 168 221 131 111 84 58 46 35 48 63
81 92 72 61 114 141 152 184 117 184 195 182 142 131 99 139 285 71 61 83
90 106 81 83 135 132 193 113 75 72 75 98 147 137

BHF-M04A 86
166 189 201 142 144 147 173 152 182 134 115 147 213 138 117 56 46 57 54 57
89 133 97 76 53 55 30 35 52 42 36 76 148 241 120 190 124 147 82 105
194 109 66 43 42 53 40 36 67 99 162 110 57 160 150 163 187 85 158 158
159 92 90 86 143 289 77 65 89 63 70 68 44 94 95 130 97 58 55 57
125 185 178 183 172 171

BHF-M04B 86
165 189 201 144 146 150 172 157 177 133 108 161 211 138 112 53 47 66 52 71
91 144 94 81 46 52 41 36 45 40 44 78 143 234 121 191 125 144 77 108

194 109 70 46 32 54 46 34 67 106 155 109 70 155 149 174 183 85 155 153
161 91 88 88 144 290 71 66 89 61 73 56 58 82 103 124 96 49 74 55
116 189 177 188 158 178

BHF-M05A 70
409 319 283 281 233 246 296 284 393 402 366 319 282 224 337 310 228 210 83 82
133 102 146 130 113 106 109 84 121 114 120 146 96 82 84 75 62 56 65 121
160 158 174 201 126 155 119 166 154 156 139 108 94 62 66 95 129 116 117 122
179 149 77 126 100 98 100 130 116 171

BHF-M05B 70
410 330 288 280 243 253 290 277 383 387 371 318 265 219 330 311 236 213 83 86
126 109 145 127 113 107 103 94 144 119 115 162 94 81 67 88 65 58 64 115
158 156 170 211 131 167 143 162 155 164 135 114 99 60 71 95 122 121 114 121
182 150 74 124 95 99 111 126 116 165

BHF-M06A 70
131 110 102 119 168 230 280 280 293 419 252 240 269 206 155 86 180 192 161 194
212 291 220 229 208 353 308 245 400 213 166 285 286 197 289 127 172 291 140 128
238 231 200 153 210 294 242 261 263 268 221 114 49 36 88 100 117 151 136 149
124 110 145 173 191 146 150 208 201 160

BHF-M06B 70
123 116 89 134 172 227 286 289 287 386 234 226 253 200 163 90 178 194 161 197
213 293 219 230 212 347 311 243 399 212 172 280 293 185 283 130 171 286 128 129
210 225 205 155 195 300 236 266 257 260 215 103 51 42 76 95 122 143 128 154
129 106 155 177 184 148 147 204 202 157

BHF-M07A 116
144 160 145 150 138 303 195 209 148 204 281 185 214 185 260 193 215 229 253 325
465 388 445 354 487 459 276 317 346 388 586 405 115 76 86 142 246 223 184 210
125 128 144 204 363 195 58 50 35 32 41 46 48 50 67 96 119 88 98 106
132 85 128 192 115 124 69 51 53 63 94 71 99 86 74 55 72 98 83 176
96 162 70 65 36 53 40 71 97 178 95 118 80 137 88 75 117 146 87 76
58 46 38 44 53 87 90 83 114 81 85 70 54 70 55 77

BHF-M07B 116
155 149 151 152 142 293 172 167 146 195 282 190 214 178 264 196 216 226 252 325
464 392 442 355 492 459 273 315 346 388 579 410 114 75 85 143 244 222 187 215
122 135 142 200 367 195 65 50 35 33 39 45 45 45 70 99 116 87 101 100
126 82 126 195 117 137 67 47 62 56 98 66 93 90 73 50 75 98 83 174
95 158 76 62 40 56 49 65 91 185 94 118 87 132 74 83 120 142 87 82
48 47 40 41 54 84 87 93 107 82 90 63 55 68 61 74

BHF-M08A 123
286 382 319 258 449 600 420 430 389 520 475 319 330 264 315 560 326 131 66 76
202 255 289 296 220 144 190 165 268 427 230 77 50 34 39 45 60 48 70 104
127 107 116 131 114 152 81 127 210 124 154 81 43 59 59 85 83 84 85 73
59 93 110 84 128 81 96 67 43 32 41 43 48 79 135 88 125 108 117 93
90 128 128 71 61 39 46 41 45 69 85 100 93 126 116 122 86 51 81 49
67 53 82 77 79 84 77 107 131 101 72 82 89 97 141 79 74 84 56 91
66 70 82

BHF-M08B 123
296 383 305 258 437 606 410 448 369 528 475 311 331 257 318 558 336 145 64 76
191 253 283 253 207 141 176 174 251 417 237 78 49 36 38 50 57 47 74 102
131 104 119 131 116 150 81 123 212 135 148 81 47 58 62 86 83 87 83 72
64 90 108 89 126 87 85 71 43 35 40 40 47 78 136 84 131 104 117 94
93 128 126 71 60 41 42 40 55 69 81 95 92 121 127 115 92 55 69 52

69 54 79 77 76 92 79 105 134 99 74 78 93 95 140 81 81 80 61 87
71 62 86

BHF-M09A 85
564 386 314 341 405 550 547 528 494 355 348 422 456 205 159 188 142 122 120 132
261 217 291 277 264 299 340 249 222 392 316 330 284 190 177 164 99 169 348 178
262 163 64 67 77 104 118 116 117 143 172 109 129 215 314 364 305 216 215 177
195 227 217 166 143 165 168 151 137 175 248 384 269 279 210 143 113 161 222 384
206 187 273 169 160

BHF-M09B 85
587 370 330 334 392 549 550 521 488 340 341 436 469 216 150 181 124 128 136 140
262 203 316 281 237 297 338 254 219 393 311 337 293 192 174 165 104 156 347 177
264 161 60 76 77 101 121 112 117 142 162 108 128 212 308 379 317 210 233 183
197 230 219 164 153 154 155 149 155 177 227 381 264 272 218 131 120 159 227 375
225 169 267 171 169

BHF-M10A 73
284 270 187 157 123 134 142 178 175 173 189 256 267 234 318 81 73 104 118 213
234 152 192 174 203 192 235 251 318 232 231 227 226 262 217 248 150 168 62 69
145 132 118 189 198 251 137 164 193 201 199 134 124 123 66 71 65 93 81 84
91 106 111 73 83 78 64 70 82 69 78 72 102

BHF-M10B 73
263 270 192 154 124 134 137 182 181 176 201 259 237 233 295 84 49 74 61 140
201 141 187 170 203 191 243 248 315 256 231 230 227 266 208 258 149 162 65 63
147 133 116 191 197 243 144 162 189 209 186 146 124 114 76 74 62 96 70 88
91 113 100 74 83 82 61 70 78 82 64 68 120

BHF-M11A 92
341 444 401 444 358 225 113 242 296 332 340 168 146 124 105 132 149 188 138 126
94 108 88 100 90 65 97 207 187 254 167 194 151 179 92 126 187 132 82 59
43 54 41 57 61 76 107 82 52 92 122 141 155 81 132 141 128 88 94 73
116 216 57 65 96 73 72 89 61 112 124 143 102 74 77 78 139 167 206 314
196 228 132 137 65 87 92 87 63 51 91 110

BHF-M11B 92
357 474 396 448 345 205 114 245 317 309 322 167 157 123 104 139 145 190 142 127
96 110 83 101 98 62 100 211 188 271 150 199 155 174 104 128 194 119 81 60
44 53 42 56 62 70 107 77 63 94 119 137 158 81 124 137 137 87 95 67
120 213 64 62 97 71 75 84 60 119 130 143 96 73 76 78 133 170 199 336
194 236 135 137 67 92 94 73 59 55 87 110

BHF-M12A 81
352 244 186 108 198 286 220 251 144 171 124 152 176 269 345 333 245 202 163 151
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38 44 55 84 72 60 116 160 179 209 107 196 185 254 141 116 89 129 306 59
56 78 79 85 60 75 95 117 130 90 64 45 47 65 112 145 180 140 162 122
95

BHF-M12B 81
342 244 186 117 203 281 220 252 156 163 118 156 182 265 330 330 261 203 172 161
165 187 109 122 213 241 317 262 329 323 363 161 202 272 188 94 70 42 42 44
28 39 63 73 80 59 103 151 173 202 102 208 196 256 148 124 98 139 341 52
51 74 69 76 64 73 89 110 126 80 50 49 50 60 101 143 183 135 164 117
100

BHF-M13A 98
165 197 161 129 138 110 104 210 402 444 432 409 459 509 470 428 335 321 262 314

351 394 364 398 383 507 354 366 432 134 95 94 90 140 123 133 136 213 178 218
226 352 404 367 260 164 262 282 290 205 201 113 165 331 168 183 257 214 172 130
183 176 155 235 172 182 146 84 59 59 83 79 97 118 90 116 82 87 118 121
92 72 83 91 115 142 187 136 112 96 48 56 80 78 74 91 63 66

BHF-M13B 98
157 204 156 132 133 112 113 224 395 456 426 419 454 509 473 432 337 320 259 326
351 397 354 402 389 475 335 371 441 129 94 90 88 143 123 132 143 209 179 220
219 359 436 369 267 160 273 292 296 206 201 109 164 322 181 187 245 205 178 137
178 184 155 210 175 195 142 88 70 60 72 75 99 124 87 112 77 79 116 111
94 72 82 89 102 122 185 139 112 93 59 56 71 79 71 90 79 97

BHF-M14A 57
188 244 349 344 205 269 99 74 155 110 139 202 248 234 212 265 311 218 59 108
104 110 117 124 178 194 213 204 227 225 198 198 233 191 189 186 191 211 154 242
329 394 292 371 312 319 270 204 235 279 153 197 206 176 134 130 299

BHF-M14B 57
195 242 350 351 198 271 85 90 156 105 156 200 259 227 201 262 287 226 65 106
106 108 124 127 170 200 212 207 218 224 223 189 223 226 188 213 193 207 174 249
343 379 249 374 321 319 247 208 237 271 164 188 210 176 122 136 299

BHF-M15A 90
132 143 274 300 279 273 232 234 240 373 556 466 183 302 311 210 192 182 176 280
207 173 255 311 299 249 203 303 243 278 226 233 248 40 34 33 25 28 42 50
79 105 183 166 148 184 130 115 123 205 323 248 223 183 176 194 159 207 253 228
273 201 244 181 186 178 66 84 137 163 145 175 136 219 205 173 176 204 183 124
143 142 220 123 162 146 211 168 158 85

BHF-M15B 90
133 147 274 305 279 251 219 231 231 376 558 468 188 304 314 203 175 187 183 259
202 170 256 308 299 248 206 307 248 267 232 236 241 46 32 36 23 23 43 63
65 115 184 164 146 188 130 116 123 205 320 255 220 179 165 210 166 203 253 232
273 210 255 179 198 189 67 88 136 169 140 173 144 221 189 172 173 190 176 116
140 137 194 136 152 161 209 152 171 84

BHF-M16A 75
73 55 54 68 50 116 129 115 126 133 153 127 127 108 218 45 35 57 52 87
68 79 93 71 112 198 213 61 69 84 84 116 91 118 178 183 173 157 152 196
235 259 353 253 342 264 284 214 172 163 180 119 136 143 116 165 159 162 217 115
186 224 161 80 108 112 119 189 108 92 184 115 118 91 132

BHF-M16B 73
77 51 81 89 133 111 109 136 156 125 125 110 220 51 28 54 63 90 67 74
82 83 98 201 220 61 59 88 79 108 116 122 184 181 180 159 150 193 239 253
365 271 361 293 275 200 179 159 174 118 142 136 137 165 159 155 218 117 185 217
158 85 107 100 123 179 120 106 187 117 117 84 113

BHF-M17A 107
237 257 215 137 204 298 137 154 160 137 159 163 97 155 318 245 241 180 149 162
147 113 67 96 154 163 206 194 210 168 73 71 69 128 110 81 103 91 237 192
179 233 265 263 163 109 131 176 241 294 138 140 225 271 96 99 107 101 166 209
223 258 167 108 98 76 102 123 97 128 71 93 79 63 75 103 148 123 164 113
105 107 102 125 122 155 103 110 127 96 148 213 176 128 115 80 70 88 128 172
313 264 350 157 144 91 100

BHF-M17B 107
237 249 213 133 203 297 134 151 161 132 161 167 90 143 313 238 242 182 136 152
151 111 67 94 151 166 207 189 203 173 67 69 62 136 99 91 108 89 239 185

182 236 262 248 164 100 119 173 239 284 146 138 238 271 92 103 105 106 162 195
225 269 159 110 94 75 107 124 95 123 76 90 80 68 67 107 147 127 160 119
104 101 103 123 124 160 93 108 135 101 137 221 170 128 119 78 71 88 124 168
316 265 351 154 135 95 86

BHF-M18A 113
252 344 326 303 238 152 197 218 245 196 51 45 56 91 98 114 76 106 126 129
90 119 195 209 220 136 106 139 120 128 72 103 240 207 178 134 225 149 168 57
72 89 87 83 47 56 81 87 56 81 137 144 139 171 180 131 139 190 157 188
74 46 46 56 43 48 75 53 87 107 83 116 138 127 229 328 262 135 56 45
52 59 69 73 87 83 89 83 98 94 92 117 135 170 154 166 187 229 276 276
268 116 71 59 48 53 57 85 83 94 143 107 171

BHF-M18B 113
265 340 316 303 240 146 202 220 246 197 47 52 46 102 88 134 73 102 126 131
93 110 185 197 197 137 111 139 127 138 74 110 221 209 209 124 231 147 167 63
64 96 84 76 64 53 78 79 64 83 139 143 146 148 198 131 149 187 160 182
59 50 41 52 39 58 77 53 84 102 92 113 136 130 229 300 262 129 57 55
46 58 70 72 85 81 92 77 73 117 97 117 134 167 146 167 181 226 265 276
125 65 66 44 57 59 82 87 96 152 120 154 87

BHF-M19A 64
202 207 193 266 303 144 217 215 268 177 144 270 327 454 314 344 301 366 454 367
354 410 363 351 395 436 393 399 318 364 401 387 421 364 452 325 336 229 271 320
332 337 240 219 192 237 371 384 308 294 357 425 443 444 458 380 322 208 188 263
259 311 292 309

BHF-M19B 64
188 208 186 263 300 148 219 209 258 176 134 261 327 485 307 339 292 372 443 379
347 415 366 306 419 432 405 400 316 359 400 389 429 359 450 327 337 228 269 329
324 333 243 220 192 238 371 388 306 286 364 421 435 455 458 371 320 215 190 254
258 299 244 311

BHF-M20A 76
170 217 216 227 196 183 170 176 177 144 203 200 237 196 211 232 340 257 261 210
278 203 166 287 338 439 293 358 302 297 378 287 305 303 304 295 442 538 433 339
331 355 396 407 424 395 418 317 321 149 234 325 266 313 221 179 162 224 338 341
311 283 280 286 366 368 360 238 172 158 116 184 188 220 153 177

BHF-M20B 76
166 217 219 224 193 183 171 179 175 147 203 201 249 186 202 240 352 246 258 222
261 214 164 297 335 424 298 335 306 292 376 285 305 317 304 293 446 546 434 338
328 355 394 407 426 388 421 321 309 160 227 313 271 302 225 188 156 230 341 339
311 280 279 288 364 364 357 233 184 157 120 183 190 212 167 172

BHF-M21A 110
272 314 364 228 147 119 204 202 326 320 219 294 204 233 208 264 358 241 78 48
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83 97 129 120 195 188 131 92 131 104 84 130 91 133 102 100 69 70 66 83
159 121 125 171 123 121 110 102 128 128 117 156 78 82 68 71 106 117 135 121
139 132 151 97 112 113 84 105 85 79 108 126 103 122 129 175 135 94 102 103
147 161 155 144 189 98 90 72 71 107

BHF-M21B 110
255 324 357 229 144 118 197 207 324 308 222 289 209 216 219 261 353 246 73 55
45 49 65 69 62 56 94 128 141 159 146 110 120 90 82 151 111 83 86 63
82 99 127 123 196 173 127 92 117 125 78 133 95 130 106 93 73 77 58 89
152 123 134 177 130 122 103 102 122 127 106 161 91 70 73 76 94 115 141 116
140 132 154 113 76 90 87 104 85 94 106 106 128 122 126 177 138 102 97 109

153 161 148 148 188 95 88 75 70 97

BHF-M22A 89
339 206 170 158 173 234 271 358 227 253 198 163 89 114 68 97 165 202 336 420
418 195 173 178 208 170 146 41 49 39 70 68 102 49 81 82 106 73 78 87
95 74 63 57 96 98 119 81 179 230 158 79 52 48 46 63 35 48 63 45
66 76 70 164 124 92 192 263 177 182 212 321 152 174 243 243 326 111 73 44
61 53 82 138 156 121 226 143 90

BHF-M22B 89
363 207 168 164 175 226 267 346 217 228 203 157 102 113 71 81 171 206 280 407
415 201 173 191 210 164 142 48 42 42 42 63 104 58 85 88 110 79 73 89
95 81 65 49 98 95 126 86 180 233 164 71 42 52 40 67 53 47 64 63
79 69 79 166 118 82 201 256 176 177 214 319 152 167 242 251 317 114 83 45
62 48 90 136 155 123 216 152 83

BHF-M23A 62
197 150 201 166 204 249 250 261 179 173 134 145 148 230 239 178 173 191 178 197
174 147 113 148 148 166 182 100 48 64 57 54 90 83 76 75 71 88 148 128
122 90 72 105 117 124 133 108 150 186 126 129 135 99 111 74 89 83 103 60
62 66

BHF-M23B 62
196 154 194 165 212 235 259 254 187 178 133 148 141 248 232 196 156 185 171 187
183 154 111 152 136 154 180 88 57 55 58 53 89 83 72 81 67 84 153 120
125 93 70 102 121 120 143 110 145 185 126 126 138 111 106 76 84 81 97 67
72 60

BHF-M24A 83
313 243 286 237 284 310 344 277 205 221 143 115 166 263 321 317 268 281 228 270
205 138 113 189 129 204 136 82 34 34 41 47 68 66 67 102 65 96 200 205
148 119 141 189 139 151 236 147 208 333 191 123 145 133 118 56 90 90 97 37
42 53 33 33 38 41 66 79 85 92 70 75 82 130 77 115 102 103 97 129
103 67 135

BHF-M24B 83
274 248 288 245 283 312 321 289 194 233 138 117 157 253 333 313 253 281 217 257
217 165 104 199 124 207 136 84 42 34 35 58 71 69 70 93 70 92 219 208
142 123 136 184 151 153 226 145 209 326 191 134 150 129 107 66 82 85 98 28
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104 64 141

BHF-M25A 118
228 130 312 289 359 354 217 205 148 172 184 188 166 165 236 250 235 176 161 134
112 106 107 142 205 207 319 300 477 400 382 411 285 267 314 346 395 230 111 133
185 138 125 202 141 116 178 225 365 269 249 277 313 272 184 130 66 72 78 106
88 122 107 101 80 87 86 78 109 157 226 262 234 235 204 91 84 75 91 108
70 42 74 111 210 310 253 242 267 189 264 249 308 377 395 321 252 253 107 87
63 63 60 81 73 79 96 136 53 81 60 53 116 88 60 66 112 104

BHF-M25B 118
253 126 349 300 347 297 235 230 152 178 178 186 168 172 234 257 228 179 157 145
122 118 106 133 200 203 331 294 492 425 375 420 275 266 312 350 377 202 116 122
202 144 128 200 134 113 164 222 363 271 256 288 307 273 186 134 61 75 83 102
87 125 124 98 74 88 88 83 116 150 219 269 235 234 203 96 78 79 92 109
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62 68 63 85 75 109 70 115 57 68 56 61 80 92 75 65 104 80

BHF-M26A 85

114 219 202 203 227 280 295 245 280 184 206 209 195 175 57 44 41 39 34 49
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123 117 157 132 103 137 127 173 207 175 184 200 166 152 206 142 194 412 243 257
361 214 160 113 134

BHF-M26B 85
122 221 199 200 231 275 301 242 286 182 199 209 192 179 58 47 38 36 43 53
35 62 65 45 73 67 62 111 80 108 123 157 146 162 214 295 317 209 203 270
158 133 110 170 252 217 163 135 163 203 171 149 220 224 182 110 122 161 136 129
127 113 169 130 108 151 131 182 257 206 192 223 163 159 183 133 157 405 231 229
334 208 156 123 123

BHF-M27A 83
273 206 100 74 68 47 53 78 88 88 74 58 47 73 56 82 77 83 82 103
108 105 108 92 98 111 147 135 189 187 227 155 187 156 143 158 141 112 86 129
162 180 161 160 202 189 149 165 123 115 107 95 97 93 104 104 85 105 113 120
101 116 144 193 159 134 158 155 192 182 217 180 193 204 247 213 198 233 253 242
227 216 165

BHF-M27B 83
243 207 110 79 62 38 63 75 88 95 72 54 41 74 50 82 82 80 93 95
112 104 127 110 101 111 171 131 178 196 233 149 179 154 137 145 140 128 84 120
144 183 142 153 188 201 152 181 127 125 110 108 116 98 91 95 84 92 104 100
96 125 122 145 148 141 168 160 195 205 207 186 208 214 258 243 218 239 268 260
260 194 163

BHF-M28A 75
267 131 195 175 246 275 348 334 243 277 324 308 277 225 219 151 156 92 99 169
146 175 169 176 114 174 217 163 187 93 57 75 104 82 107 152 125 103 85 265
149 194 271 134 71 66 61 53 67 72 85 189 191 173 239 138 135 101 99 162
138 164 137 79 85 71 148 199 213 157 191 212 145 125 189

BHF-M28B 75
257 142 197 172 244 282 351 337 240 284 334 314 276 230 223 153 153 86 113 164
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141 163 132 90 77 83 145 193 217 156 188 214 140 137 180

BHF-M29A 79
196 202 335 479 533 518 354 177 179 167 208 236 321 332 239 284 332 303 253 227
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200 136 159 141 136 184 143 167 137 98 80 83 163 172 216 179 187 204 105

BHF-M29B 79
206 203 284 481 531 526 363 173 184 178 218 235 323 345 249 325 382 316 235 244
214 139 157 118 131 187 157 178 170 174 110 169 231 131 158 95 85 151 125 92
87 85 107 76 84 188 105 120 182 130 70 51 54 42 54 55 88 168 136 199
225 163 164 131 136 204 173 190 153 76 72 74 120 146 170 192 184 212 122

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	

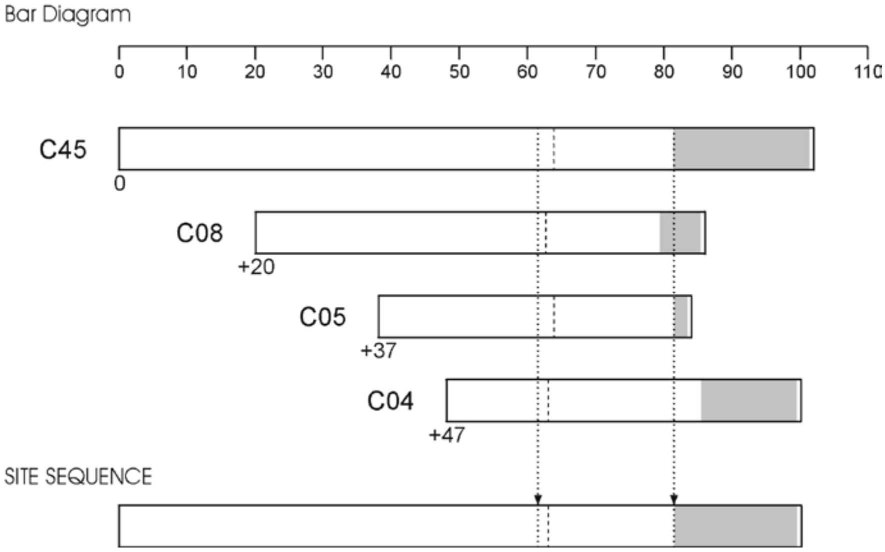


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

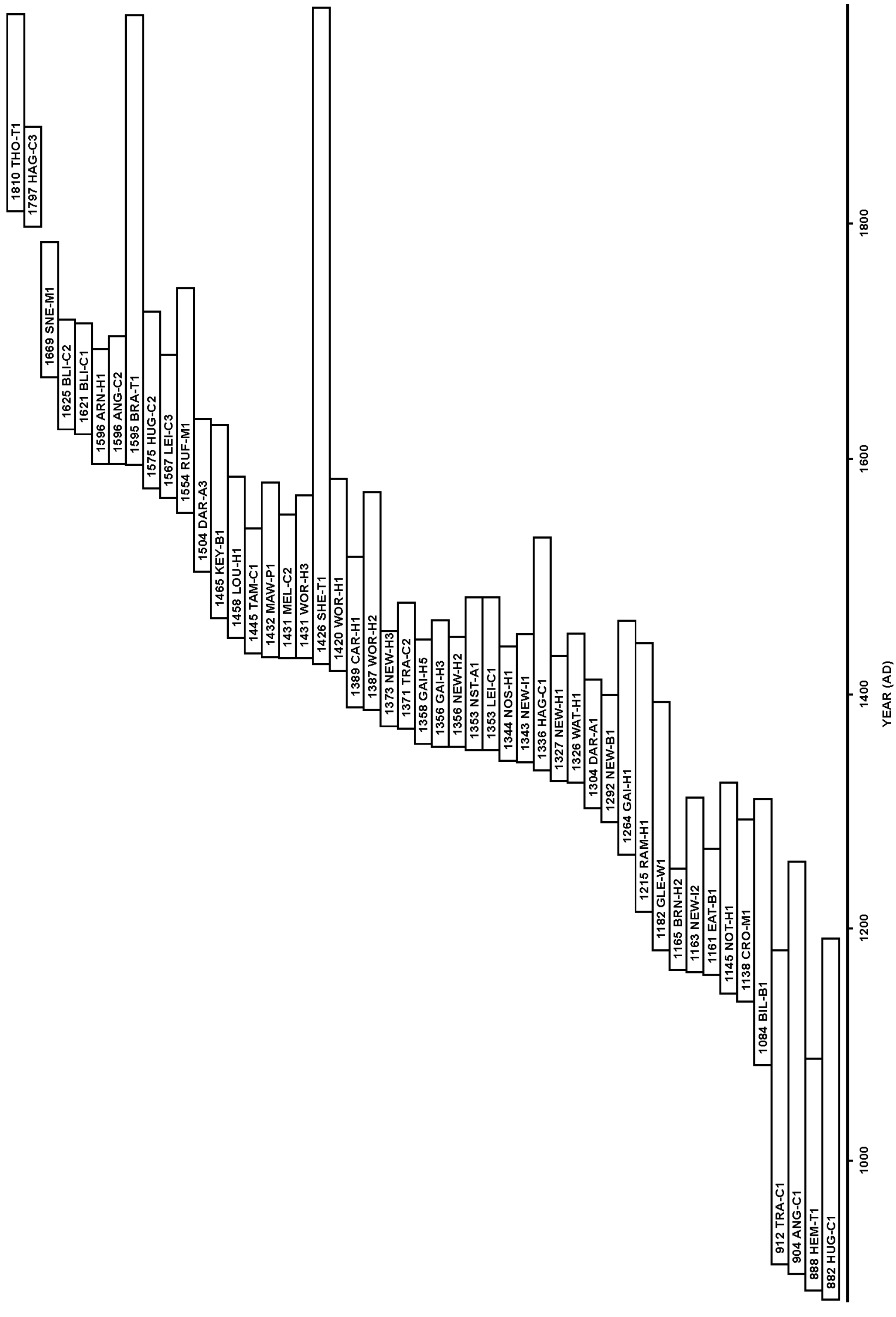
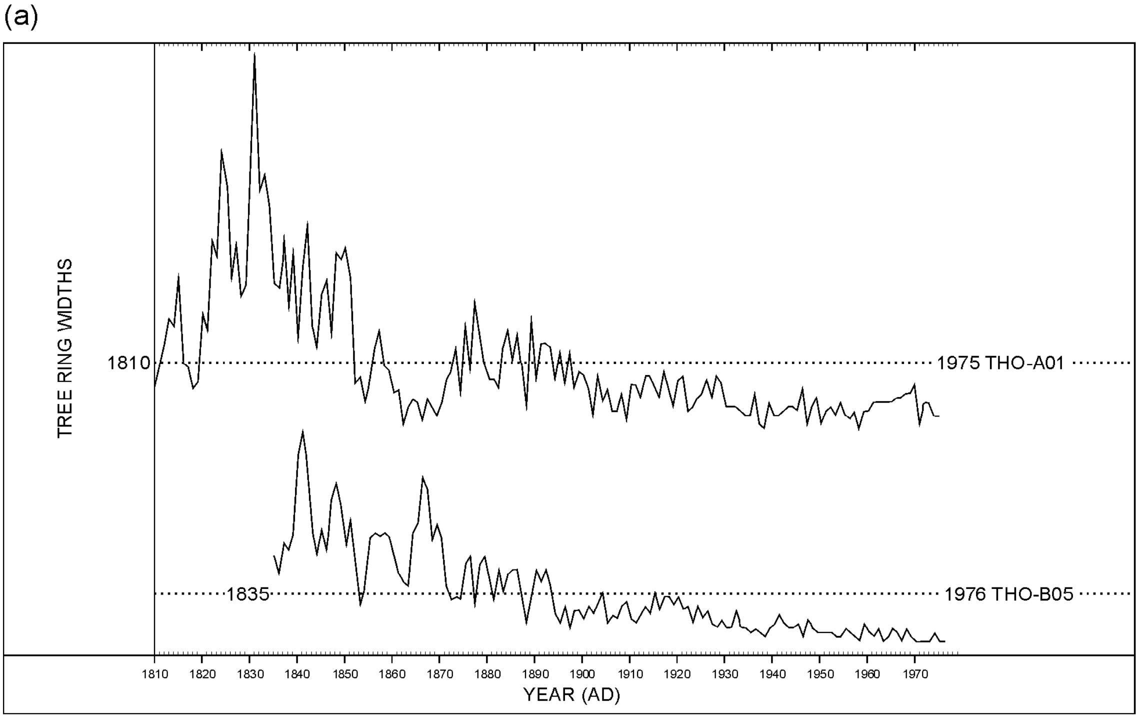


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



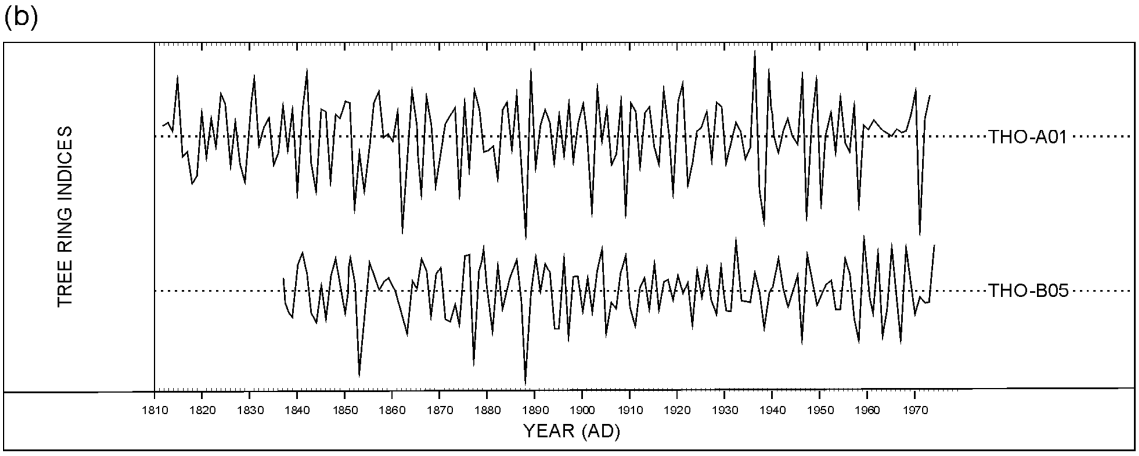


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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ISSN 2059-4453 (Online)