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OLD MANOR HOUSE, CHURCH LANE, WEST LAVINGTON, WILTSHIRE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Cathy Tyers and Matt Hurford

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

Research Report Series 66-2014

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SUMMARY

Dendrochronological analysis was undertaken on 15 of the 18 timbers sampled in the roofs of the hall and east wing of the Old Manor House. This resulted in the production of two site chronologies, WLOMSQ01 and WLOMSQ02. These comprise 12 and two samples with overall lengths of 234 rings and 62 rings respectively. The first site chronology can be dated as spanning the years AD 1264–1497, whilst the second chronology is undated, as is the single ungrouped sample.

The results identified that the dated timbers used in the primary construction of the roofs of the hall and east wing are likely to be coeval and all were felled during the first third of the sixteenth century.

CONTRIBUTORS

Cathy Tyers and Matt Hurford

ACKNOWLEDGEMENTS

Mr and Mrs O'Brien are thanked for giving permission to undertake the work. Avis Lloyd arranged access and provided additional background information on the building and Clive Carter provided the roof plan. The dendrochronological work was funded by the English Heritage Scientific Dating Team and coordinated by Peter Marshall.

ARCHIVE LOCATION

Wiltshire and Swindon HER
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The Wiltshire and Swindon History Centre
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DATE OF INVESTIGATION

2009–10

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INTRODUCTION

In 2009 the Wiltshire Buildings Record (WBR) successfully obtained support through the English Heritage Historic Environment Enabling Programme for their project 'Wiltshire cruck buildings and other archaic roof types'. The detailed aims and objectives of the project are set out in the Project Design (Lloyd 2009). The overall aim was to establish a typological chronology of archaic roof types and hence elucidate the development of carpentry techniques in the county. This would then facilitate detailed comparison with other counties allowing Wiltshire to be placed in a regional context. Investigation of these late medieval buildings (*c* AD 1200 – *c* AD 1550) combined building survey, historical research, and dendrochronological analysis.

A series of 25 buildings identified by the WBR as having the potential to contribute to the aims and objectives of the project was assessed for dendrochronological suitability during 2009. In order to maximise the potential for dating, these detailed dendrochronological assessments and the WBR assessments of the significance of each building informed the final selection of buildings subsequently subjected to detailed study.

A single final Project Report produced by Lloyd (2012) summarises the overall results. However each building included in the project has an associated individual report produced by the WBR, whilst the primary archive of the dendrochronological analysis is the English Heritage Research Report Series.

A brief introduction to dendrochronology can be found in the Appendix. However further details can be found in the guidelines published by English Heritage (1998) which are also available on the English Heritage website (http://www.english-heritage.org.uk/publications/dendrochronology-guidelines/).

Old Manor House

The Grade II listed Old Manor House is located to the west of the Church of All Saints, West Lavington, Wiltshire (Figs 1 and 2). The medieval portion of the house is located in the eastern half of the overall building and consists of a central open hall with cross-wings to the east and west (Figs 3 and 4). It is aligned on a north-east to south-west axis (for ease of reference within this report the front north-west facing elevation is described as the north face of the building). Although there may have been an earlier manor house on the site, the extant building is thought to originate in the early part of the sixteenth century, although the west cross-wing is somewhat less well understood. The following information is from Wiltshire Buildings Record (2012).

Hall

The roof over this part of the building is of collar and principal-rafter type; the collar of truss 8 being straight, whilst that of truss 7 is cambered (Fig 5). Truss 6, at the junction with the west wing, has arch brace and collar mortices. There are two tiers of trenched purlins to the east end, a single tier of purlins in the centre section, and two tiers of purlins to south side of the west end; some appear to be replacements. The common rafters are a mixture of primary and reused timbers (perhaps from the same source as those timbers of the west cross-wing – see below). Stylistically the hall is thought to date to the early part of the sixteenth century.

East cross-wing

This roof is also of collar and principal rafter type. The principal rafters of both trusses 1 and 2 (Fig 6) have mortices for arch braces, however, these are not mirrored on the straight collars, which appear to be reused. There are two tiers of trenched purlins and there is some evidence for the previous existence of windbraces as demonstrated by the housing on a purlin but also the suggestion of housing on a principal rafter from truss 2. Stylistically the east cross-wing is also thought to date to the early part of the sixteenth century.

West cross-wing

Surviving over the northern half of the west cross-wing, and fragmentary in the southern half, is a fourteenth-century coupled-rafter roof. Each rafter pair forms a light truss with either a cambered or a straight collar and central block below. The trusses were formerly arch braced although this bracing only survives on the truss immediately in front of the north gable wall. Other empty mortices on the rafters are presumably for vertical posts or ashlaring. This roof, with its random assembly marks, is not thought to be primary and it has been suggested that it may have been salvaged from an earlier manor house, potentially on the same site.

SAMPLING

Dendrochronological sampling and analysis of the oak (*Quercus* spp) timbers associated with the east cross-wing and hall roofs at the Old Manor House was commissioned by English Heritage. Timbers of the west cross-wing were found to be unsuitable as they contained too few growth rings for reliable analysis and the elm timbers in both the hall and east cross-wing were also excluded. It was hoped to provide independent dating evidence for the construction and subsequent development of the medieval building and hence inform the overall objectives of the 'Wiltshire cruck buildings and other archaic roof types' project. The dendrochronological study also formed a key component of the

English Heritage-funded training programme for the second author, although the reporting was not completed within the duration of the training programme.

A total of 12 oak timbers associated with the extant remains of the east cross-wing roof and six oak timbers associated with the hall roof were sampled by coring by trainee Matt Hurford. Each sample was given the code WLO-M (for West Lavington, Old Manor House) and numbered 01–18. In one instance two cores were obtained from the same timber, WLO-M06A and WLO-M06B, in order to maximise the information derived from this timber. The sampling strategy encompassed as wide a range of elements as possible, whilst focussing on those oak timbers with the best dendrochronological potential. Only a small number of timbers were sampled in the hall as the majority of timbers were either elm or were derived from fast-grown oak trees and were thus assessed as highly unlikely to provide samples with sufficient numbers of rings for reliable dendrochronological dating.

The location of the samples was noted at the time of coring. A formal plan was provided by the WBR on which the locations of some of the samples from the east cross-wing are shown (Fig 7), whilst locations of the remaining cores are shown on sketch drawings made at the time of coring (Figs 8–14). Further details relating to the samples can be found in Table 1. In this table the timbers have been located and numbered following the scheme on the plan provided. The trusses in the east cross-wing being been numbered 1–3 from the north gable and those in the hall numbered 4–8 from the west.

ANALYSIS AND RESULTS

Each of the cores was prepared by sanding and polishing. It was seen at this point that three samples, WLO-M07, WLO-M15 and WLO-M16, had too few rings for reliable dating (the lower limit applied within this project was generally 50 rings), and so they were rejected from this programme of analysis. The annual growth rings of the remaining samples were measured, the data of these measurements being given at the end of this report.

The ring sequences derived from these 15 timbers were, in order to maintain consistency between all of the dendrochronological reports on individual buildings within this project, compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This allowed a group of 12 series and a group of two series to be formed, the samples of each group cross-matching with each other as shown in the bar diagrams (Figs 15 and 16; Tables 2 and 3). The analytical process was aided by software written by Tyers (2004) which facilitates cross-matching and dating through a process of qualified statistical comparison and visual comparison. It uses a variant of the Belfast CROS programme (Baillie and Pilcher 1973).

Site chronology WLOMSQ01 was compared to an extensive range of reference chronologies for oak, this indicating repeated cross-matching when the first ring in the sequence is AD 1264 and the last-ring date is AD 1497. The evidence for this is given in

Table 4. Site chronology WLOMSQ02 was also compared to the reference chronologies but there was no satisfactory cross-matching and so it remains undated.

The site chronologies were compared with each other and the remaining ungrouped sample but there was no further satisfactory cross-matching. The ungrouped sample was then compared with the reference chronologies but again there was no satisfactory cross-matching and it must, therefore, remain undated. The analysis can be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span (where dated)
WLOMSQ01	12	234	AD 1264–1497
WLOMSQ02	2	62	undated
	1	51	undated
	3	---	unmeasured

INTERPRETATION

The hall roof is represented by three dated samples and the east cross-wing roof by nine dated samples (Fig 15).

None of the three samples from the hall roof in site chronology WLOMSQ01 has complete sapwood, and it is thus not possible to calculate a precise felling date for the timbers represented. However, two did retain their heartwood/sapwood boundary ring, the average date for this being AD 1496. Again, in order to maintain consistency, the 95% confidence limit of 15–40 sapwood rings generally applied by the Nottingham Tree-ring Dating Laboratory, was used and an estimated felling date in the range AD 1511–36 can be calculated for these timbers. The overall variation of the heartwood/sapwood boundary date is only a single year indicating that they are likely to represent a single programme of felling.

The remaining dated sample from the hall roof in site chronology WLOMSQ01 has no trace of sapwood and thus it is not possible to calculate its likely felling date range. However, the date of its last measured ring is AD 1401, indicating that it could have been part of the same felling programme as the two other dated timbers from the hall roof.

None of the samples from the east cross-wing roof in site chronology WLOMSQ01 has complete sapwood, and it is thus not possible to calculate a precise felling date for the timbers represented. However, five did retain their heartwood/sapwood boundary ring, the average date for this being AD 1490. Using the same 95% confidence limit of 15–40 sapwood rings as above, an estimated felling date in the range AD 1505–30 can be calculated for these timbers. The overall variation of the heartwood/sapwood boundary date of all five samples on which it is present is 14 years, which does not preclude these timbers representing a single programme of felling.

The remaining four dated samples from the east cross-wing roof in site chronology WLOMSQ01 have no trace of sapwood and thus it is not possible to calculate their likely felling date ranges. However, the dates of their last measured rings vary from AD 1453 to AD 1481 which, combined with the very high level of cross-matching (Table 2), implies that all dated timbers from this roof form a coherent group and are probably part of the same felling programme dating to AD 1505–30.

All twelve dated timbers from both roofs are clearly broadly coeval. The very high level of cross-matching (Table 2) implies that all the timbers form a coherent group and are probably part of the same felling programme dating to AD 1507–32 based on an overall average heartwood/sapwood boundary date of AD 1492.

The undated samples in site sequence WLOMSQ02, one from the hall and one from the east cross-wing, are broadly coeval with a heartwood/sapwood variation of only four years (Fig 16; Table 3). However, these two purlins remain undated and it is thus unproven as to whether these are coeval with the primary construction of the roofs or whether they represent either reused timbers and/or later insertions.

DISCUSSION AND CONCLUSION

The tree-ring analysis indicates that the dated timbers from the hall and east cross-wing roofs are coeval, and were all probably felled in the range AD 1507–32. This clearly supports the stylistic evidence of a date in the early part of the sixteenth century. The high overall level of cross-matching (Table 2) between the individual timbers in site sequence WLOMSQ01 suggests that they probably originated from the same woodland source. Particularly high *t*-values in excess of 10.0 can be found between various samples suggesting that they could be derived from either the same tree or trees located in very close proximity to each other. There are two instances where this is the case between samples from the east cross-wing and hall, further supporting the interpretation that the dated timbers from the two roofs are indeed coeval.

The dated timbers from the east cross-wing roof, all appear integral to the roof structure with no evidence of insertion or reuse. Timbers from all three trusses and one of the bays (bay 1) were successfully dated indicating that this roof was constructed in the first third of the sixteenth century. The majority of the dated timbers appear likely to have been derived from relatively slow-grown trees, well in excess of 100 years old and in some instances over 200 years old when felled. However, the collar of truss 1 and the lower purlin of bay 2 were notable as being wide-ringed and as such unlikely to provide samples with sufficient numbers of rings for dendrochronological analysis; these are perhaps more similar in growth characteristics to the undated timber WLO-M09 in WLOMSQ02. The failure to date WLO-M12 successfully is probably due in part to it being a relatively short ring sequence being derived from a rather faster-grown, shorter-lived tree. Short individual ring sequences are generally more difficult to date than longer well-replicated site chronologies and, in this instance, it also appears possible that this timber is a later insertion.

Of the six timbers sampled from the hall roof only three dated; one being a principal rafter and the other two collars and all three from different trusses. There is no suggestion that these timbers are not associated with the initial construction of this roof and thus the results indicate that the extant hall roof is coeval with that of the east cross-wing. The two unmeasured samples, both from common rafters, and the undated purlin, WLO-M18 in WLOMSQ02, again, show similarities in growth characteristics, all being derived from faster-grown shorter-lived trees.

Site chronology WLOMSQ01 produces the highest *t*-values, and thus shows the greatest degree of similarity, with reference chronologies from Wiltshire and the surrounding counties (Table 4). This suggests that it is likely that the timbers were derived from relatively local woodland sources.

Site sequence WLOMSQ02 incorporates two measured but undated samples, both upper purlins; one from the hall and one from the east cross-wing (Fig 16 and Table 3). There were no obvious growth abnormalities such as compressed or complacent rings which would make cross-matching and dating difficult. It could be that they were from a different woodland source to the other dated timbers; they are clearly derived from much faster grown trees than the other samples (Table 1). This difference in growth characteristics raises the possibility, but does not by any means prove it, that they could represent a different felling programme, perhaps related to later modifications/repairs or alternatively that they could be reused timbers. However the architectural analysis has so far not identified them as later insertions, nor was any evidence of reuse noted.

The only measured but ungrouped sample, WLO-M12, is a short ring sequence that probably accounts for its failure to be successfully dated. It is perhaps of note this timber is also derived from a relatively fast-grown tree.

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TABLES

Table 1: Details of tree-ring samples from the west wing roof of the Old Manor House, West Lavington, Wiltshire

Sample number	Sample location	Total rings	Sapwood rings	Average ring width (mm)	Cross-section dimensions (mm)	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
WLO-M01	East wing Truss 1 east principal	109	no h/s	1.03	300x120	1362	---	1470
WLO-M02	East wing Bay 1 east lower purlin	199	h/s	0.78	180x120	1299	1497	1497
WLO-M03	East wing Bay 1 east upper purlin	159	no h/s	0.89	180x120	1295	---	1453
WLO-M04	East wing Bay 1 west upper purlin	59	h/s	0.97	180x90	1432	1490	1490
WLO-M05	East wing Bay 1 west lower purlin	157	h/s	0.58	180x120	1328	1484	1484
WLO-M06	East wing Truss 2 west principal	141	h/s	0.73	280x120	1357	1497	1497
WLO-M06A	*ditto*	*139*	*no h/s*	*0.75*		*1357*	---	*1495*
WLO-M06B	*ditto*	*102*	*h/s*	*0.55*		*1396*	*1497*	*1497*
WLO-M07	East wing Truss 2 collar	nm	---	---	not recorded	---	---	---
WLO-M08	East wing Truss 2 east principal	153	no h/s	0.88	280x120	1315	---	1467
WLO-M09	East wing Bay 2 east upper purlin	53	h/s	3.08	not recorded	---	---	---
WLO-M10	East wing Truss 3 east principal	187	no h/s	1.40	260x110	1295	---	1481
WLO-M11	East wing Truss 3 tie beam	220	h/s	1.06	350x190	1264	1483	1483
WLO-M12	East wing Bay 2 NW to SE diagonal timber	51	6c 15-20mm lost	2.15	240x100	---	---	---
WLO-M13	Hall Truss 8 south principal	116	h/s	1.55	320x120	1380	1495	1495
WLO-M14	Hall Truss 7 collar	106	no h/s	1.39	200x110	1296	---	1401
WLO-M15	Hall Bay 6 south common rafter 2	nm	---	---	100x80	---	---	---
WLO-M16	Hall Bay 6 north common rafter 8	nm	---	---	120x80	---	---	---
WLO-M17	Hall Truss 6 collar	76	h/s	1.36	210x100	1421	1496	1496
WLO-M18	Hall Bay 7 north upper purlin	58	h/s	2.87	190x130	---	---	---

nm = not measured

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

c = complete sapwood was on the timber sampled but part was lost during coring

Table 2: Matrix showing the t-values obtained between the matching ring sequences in site chronology WLOMSQ01. - indicates t-values less than 3.00; \ indicates overlap of less than 30 years, grey shading indicates possible same-tree match

East wing roof									Hall roof		
Filenames	WLO-M02	WLO-M03	WLO-M 04	WLO-M05	WLO-M06	WLO-M08	WLO-M10	WLO-M11	WLO-M13	WLO-M14	WLO-M17
WLO-M01	5.71	4.73	4.68	6.11	8.14	10.40	10.48	6.84	12.50	-	-
WLO-M02		11.35	4.50	12.69	6.19	11.03	6.49	4.39	5.66	5.67	3.45
WLO-M03			\	8.72	6.03	8.31	6.37	4.54	5.45	6.36	3.00
WLO-M04				4.82	-	-	7.12	5.07	5.66	\	-
WLO-M05					7.01	8.19	6.60	4.72	6.44	-	4.30
WLO-M06						14.16	6.81	5.18	6.18	5.25	-
WLO-M08							10.10	6.64	8.44	6.63	3.00
WLO-M10								6.76	16.14	3.89	3.81
WLO-M11									6.93	3.47	6.13
WLO-M13										\	3.10
WLO-M14											\

Table 3: Matrix showing the t-value obtained between the matching ring sequences in site chronology WLOMSQ02

Filenames	WLO-M18
WLO-M09	6.20

Table 4: Results of the cross-matching of site sequence WLOMSQ01 and relevant reference chronologies when the first-ring date is AD 1264 and the last-ring date is AD 1497

Reference chronology	t-value	Span of chronology	Reference
Church of St Nicholas, Bromham, Wiltshire	10.7	AD 1359–1483	(Arnold and Howard 2008)
Church of St Mary Magdelene, Twyning, Gloucestershire	9.2	AD 1251–1452	(Tyers 1996)
Dauntsey House, Dauntsey, Wiltshire	8.9	AD 1393–1580	(Tyers *et al* 2014)
Newnham Hall Farm, Newnham Murren, Oxfordshire	8.9	AD 1414–1551	(Arnold and Howard 2006 unpubl)
Ashleworth tithe barn, Gloucestershire	8.9	AD 1319–1475	(Bridge 2002)
Church of St Swithuns, Compton Bassett, Wiltshire	8.8	AD 1346–1454	(Miles 2001)
The Commandery, Worcester	8.2	AD 1284–1473	(Arnold *et al* 2006)
New Inn House, Kingswood, Gloucestershire	7.7	AD 1191–1519	(Arnold *et al* 2004)

FIGURES

Figure 1: Map to show the location of West Lavington (circled), Wiltshire. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location Old Manor House (circled) within the village of West Lavington. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

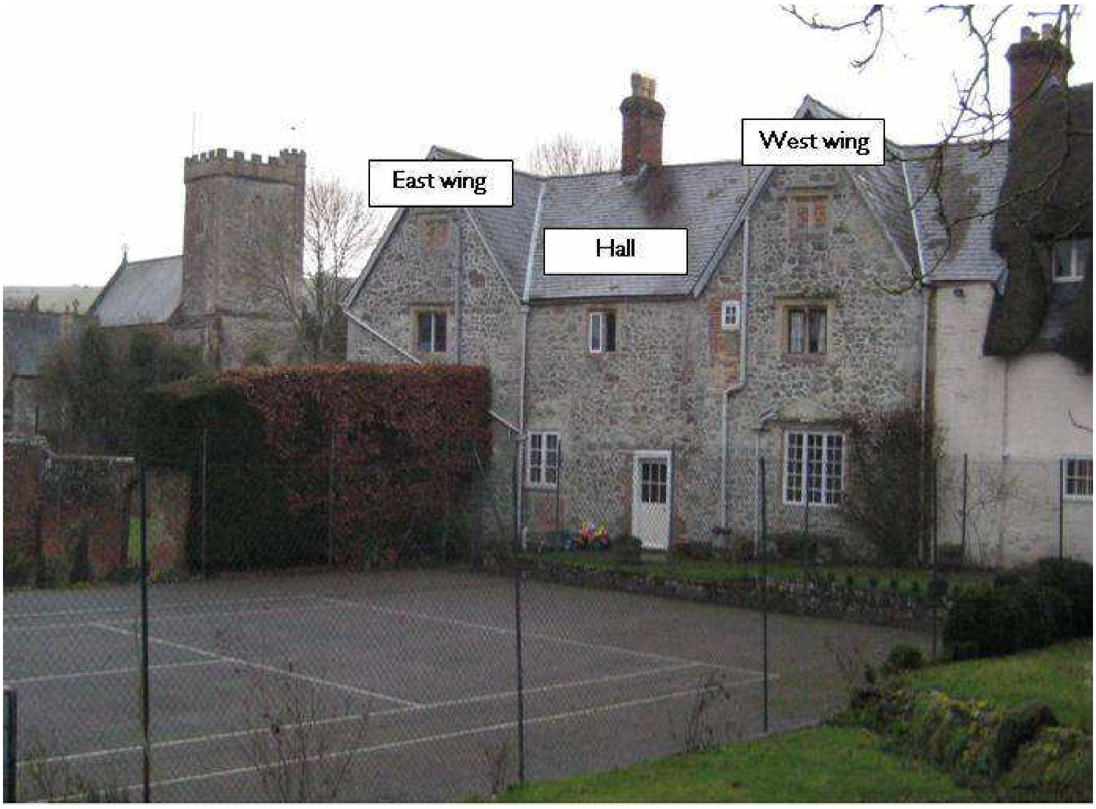


Figure 3: The north elevation of Old Manor House showing hall and wing locations viewed looking south east (Matt Hurford)

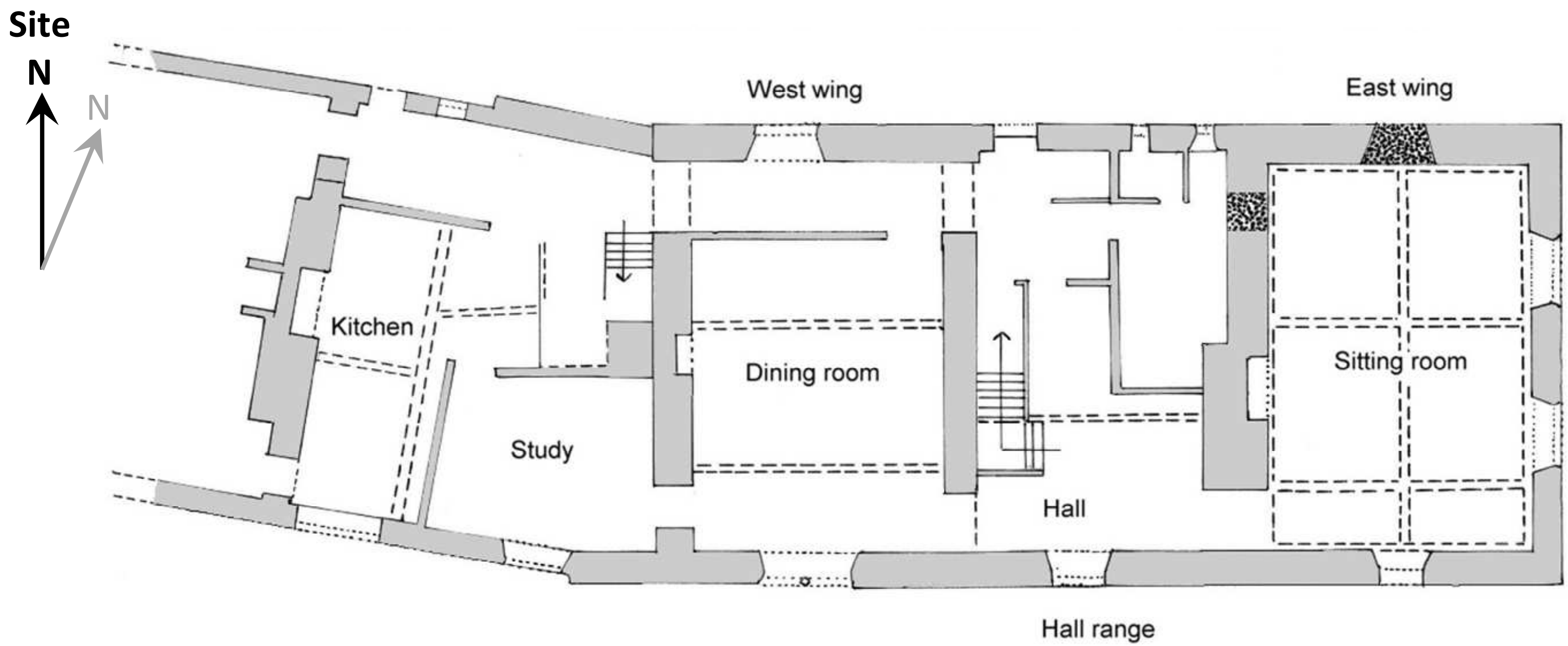


Figure 4: Plan of the eastern half of Old Manor House (based on a drawing by Clive Carter of the Wiltshire Building Record)

Figure 5: Hall truss 7 viewed looking east (Matt Hurford)

Figure 6: East wing truss 2 viewed looking north (Matt Hurford)

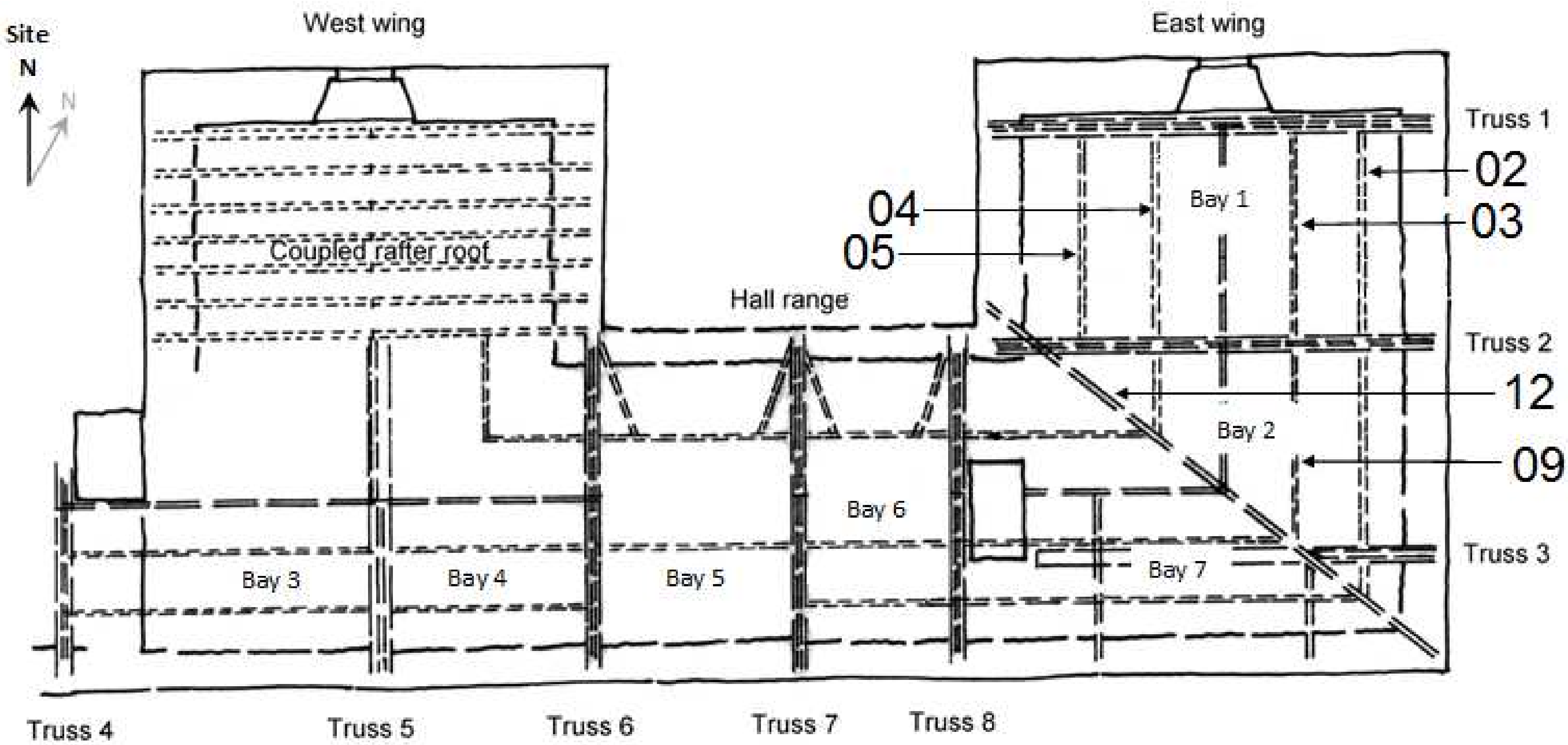


Figure 7: Sample locations from the hall and east wing not shown on the samples below (based on a drawing by Clive Carter of the Wiltshire Building Record)

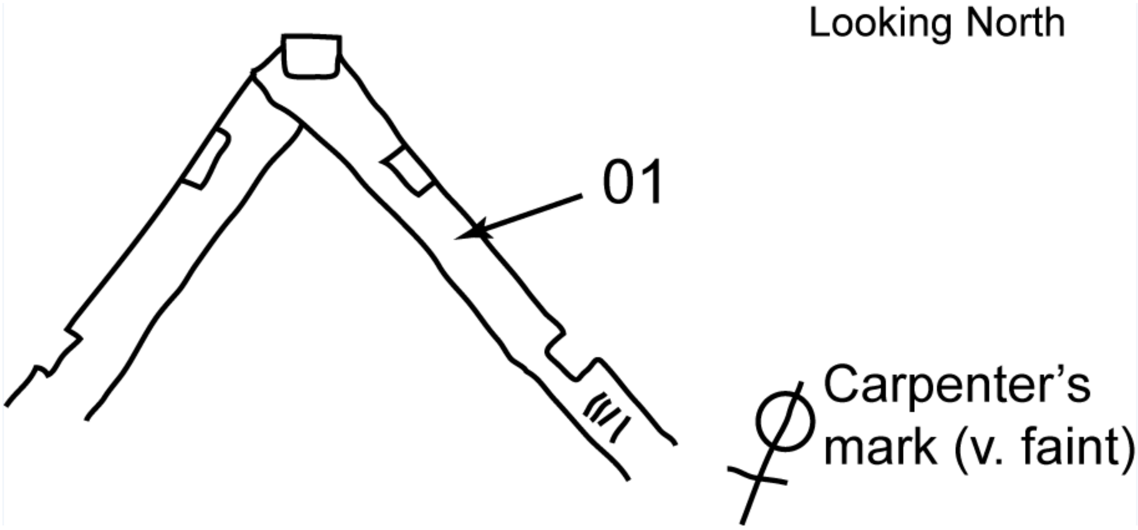


Figure 8: Sketch of truss 1, viewed looking north, showing sample location

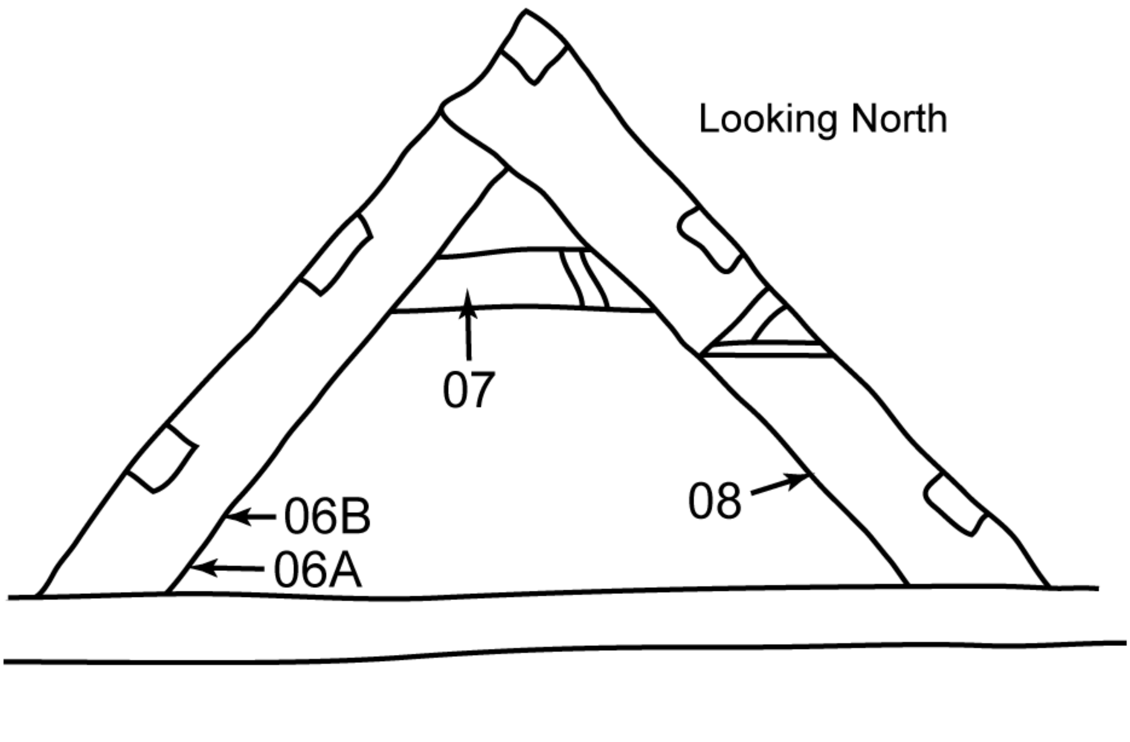


Figure 9: Sketch of truss 2, viewed looking north, showing sample locations

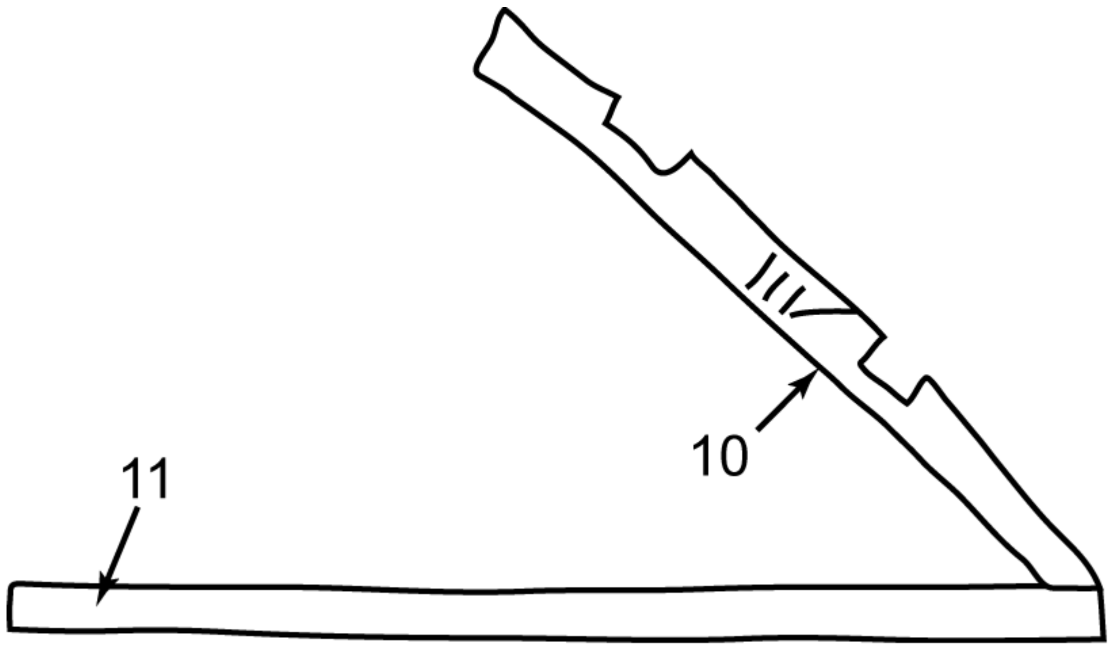


Figure 10: Sketch of truss 3, viewed looking north, showing sample locations

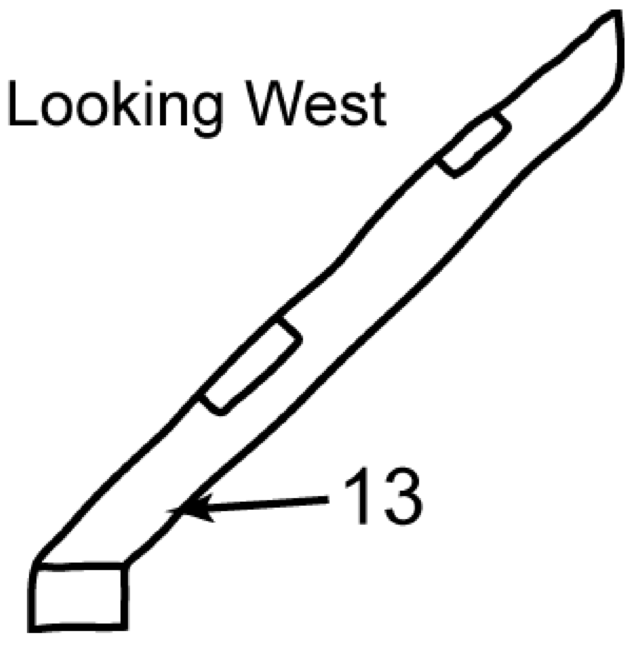


Figure 11: Sketch of truss 8, viewed looking west, showing sample location

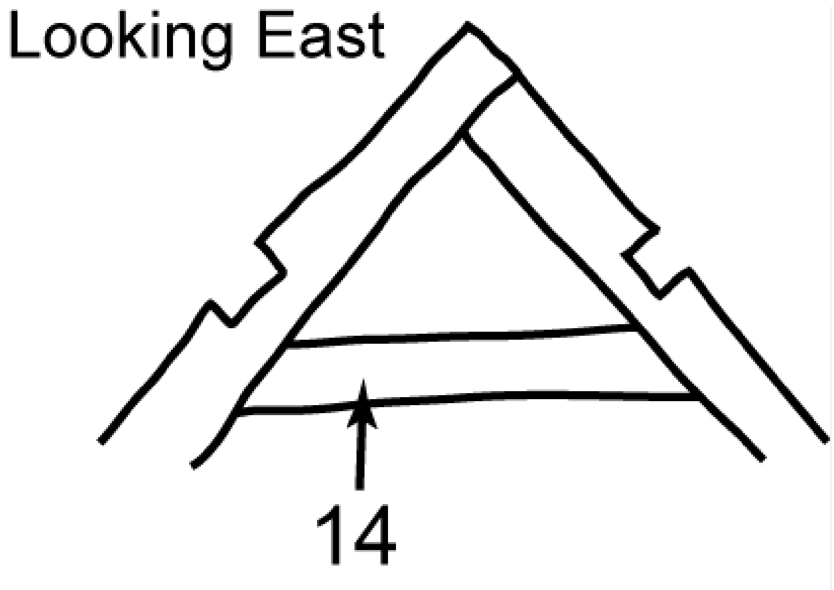


Figure 12: Sketch of truss 7, viewed looking east, showing sample location)

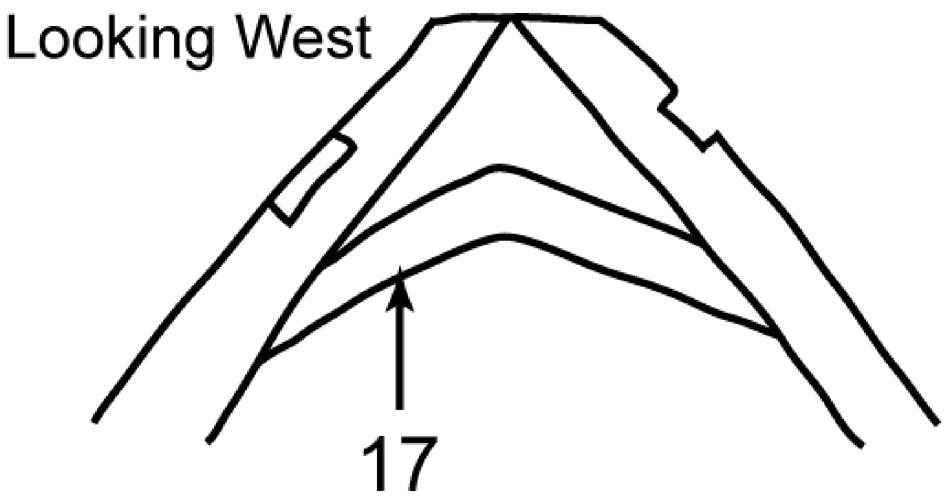


Figure 13: Sketch of truss 6, viewed looking west, showing sample location

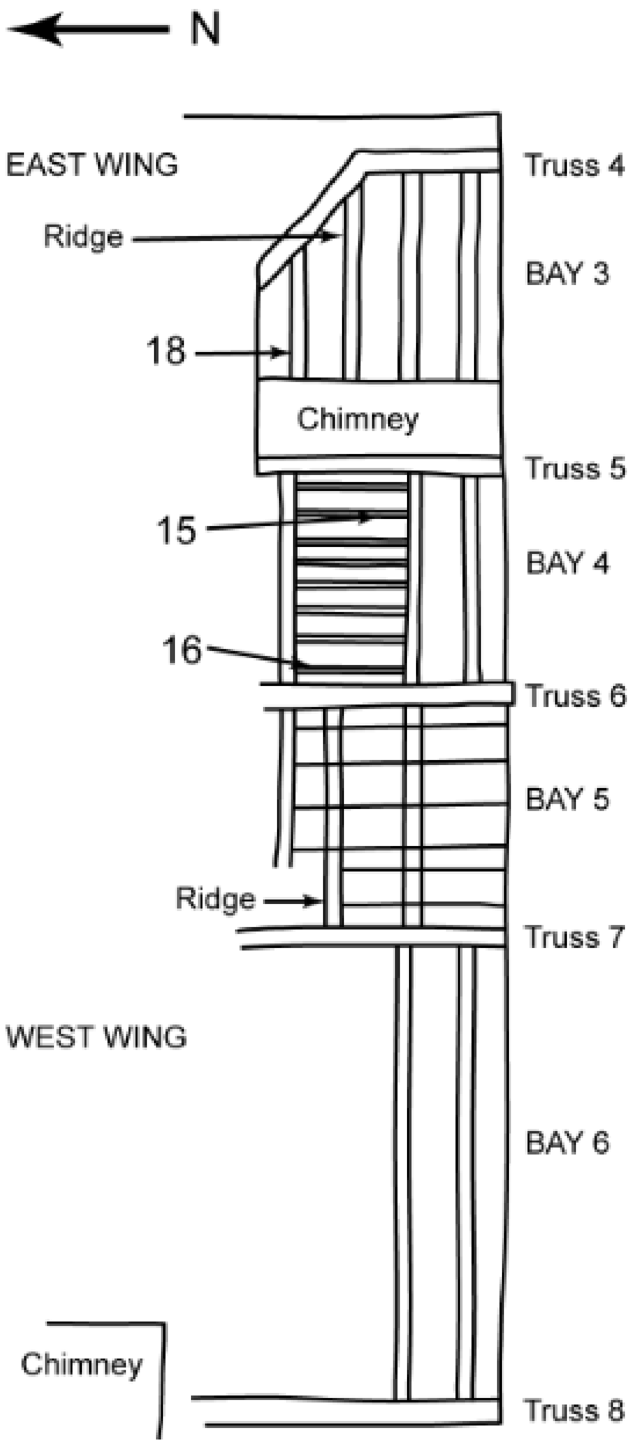


Figure 14: Sketch of roofs showing sample locations

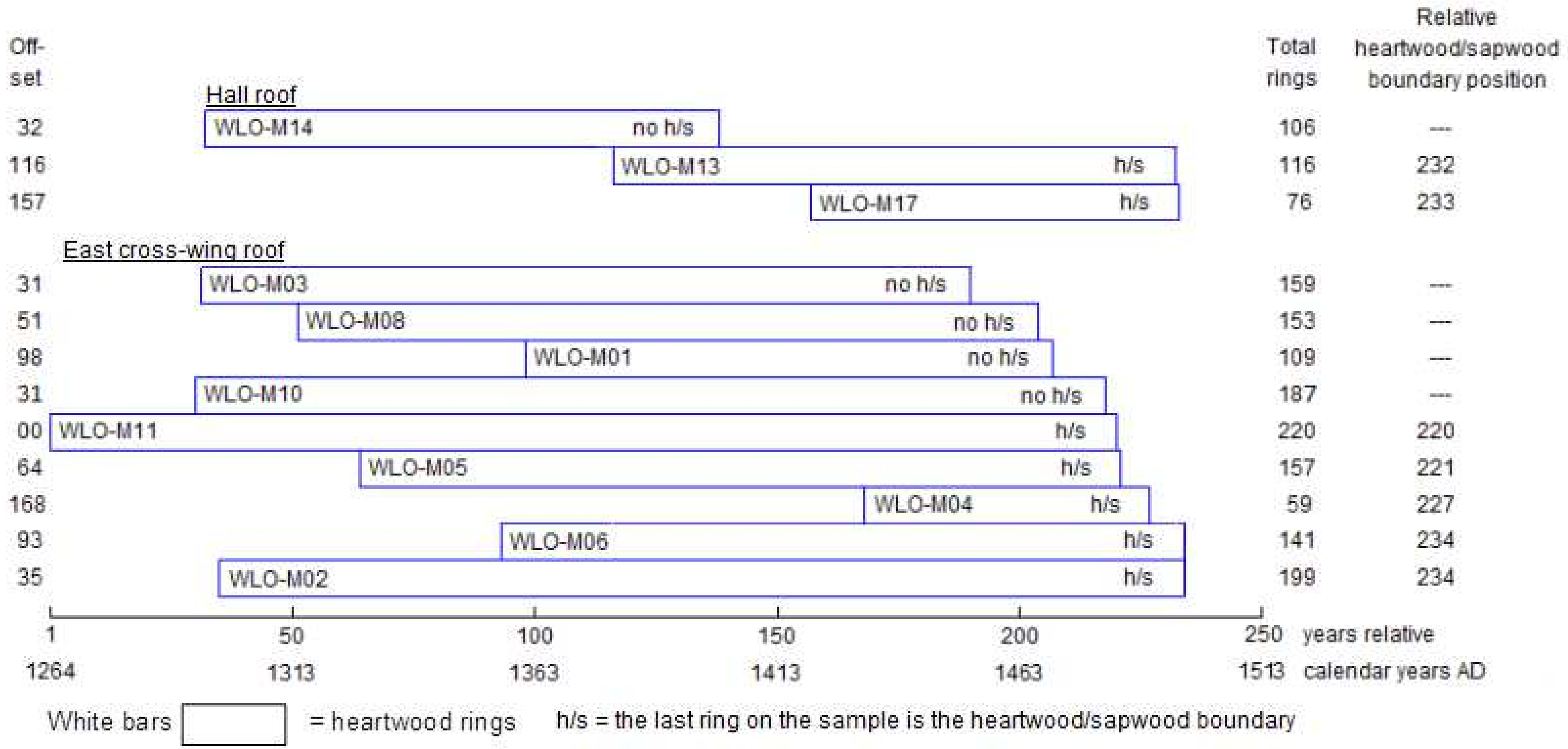


Figure 15: Bar diagram of the samples in site chronology WLOMSQ01

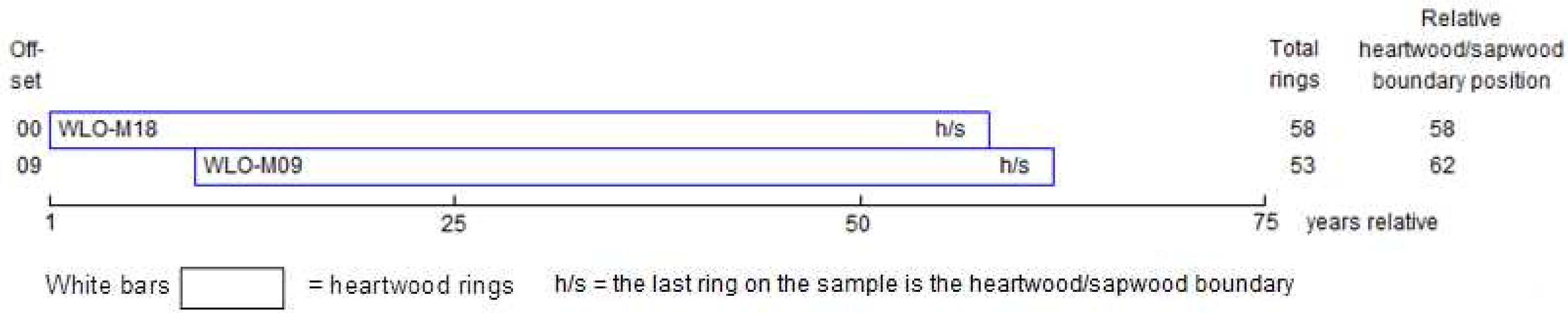


Figure 16: Bar diagram of the samples in site chronology WLOMSQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WLO-M01A 109
204 231 166 103 115 132 135 152 191 85 111 86 115 159 145 128 117 163 122 123
93 120 92 147 121 74 53 38 36 45 72 73 63 88 104 69 94 99 82 124
76 91 66 54 115 68 112 85 95 117 104 89 117 122 103 98 108 68 118 90
66 132 117 96 52 96 121 100 89 104 211 130 117 128 103 136 140 83 73 94
97 90 87 95 119 86 125 88 88 119 94 89 75 92 93 98 96 81 93 75
94 130 59 99 98 76 96 78 104
WLO-M01B 109
202 242 167 98 120 126 141 155 182 95 121 88 107 160 142 126 108 177 121 121
94 123 87 149 120 80 49 41 34 45 62 68 65 93 107 64 88 111 74 133
78 92 63 58 112 69 111 91 91 117 97 81 108 110 109 94 105 73 114 86
68 131 116 96 54 96 122 98 86 108 208 131 118 127 101 134 140 84 73 94
112 94 88 85 114 83 121 88 99 126 98 89 75 93 90 98 98 84 91 74
95 125 60 97 101 78 94 80 105
WLO-M02A 199
142 89 105 117 72 73 81 107 93 92 83 59 52 58 59 75 115 189 140 91
84 122 157 130 133 99 75 59 86 102 91 76 40 48 78 91 113 85 84 89
103 71 52 52 66 49 48 51 35 41 47 90 55 60 75 67 52 54 87 38
43 44 49 112 96 74 39 45 62 54 71 82 48 55 45 34 62 39 34 38
63 122 105 179 137 103 79 101 109 103 73 78 93 73 79 61 54 72 53 46
61 46 90 50 62 48 42 45 43 89 129 76 76 82 70 61 83 62 74 71
53 56 93 101 128 145 78 64 76 85 95 97 93 160 99 84 101 84 94 87
75 83 87 78 68 88 72 86 77 87 85 95 130 84 104 76 79 70 81 85
61 76 50 65 71 52 75 60 91 80 96 92 68 70 63 73 66 66 56 42
74 68 83 55 63 63 73 62 65 63 44 87 85 66 72 74 81 131 132
WLO-M02B 199
141 93 102 120 78 62 80 111 88 88 72 66 60 46 76 75 116 186 139 89
84 122 162 127 148 98 78 49 86 85 92 76 42 60 74 94 109 86 85 94
108 69 60 46 63 54 49 54 38 42 51 85 55 57 72 73 52 55 65 48
41 49 54 107 101 69 44 41 65 51 64 86 45 57 46 39 63 34 34 42
62 128 110 180 136 106 76 101 115 96 71 80 95 62 79 60 56 67 55 46
60 46 90 52 65 51 38 58 46 92 124 80 74 83 69 61 84 62 74 69
53 60 90 100 132 148 82 63 75 92 76 105 97 172 90 86 97 83 92 98
65 86 81 85 66 83 63 86 79 90 86 93 132 95 97 80 72 65 79 90
62 70 55 67 68 57 64 70 82 86 92 92 77 67 73 67 69 60 60 40
77 65 91 46 62 69 66 89 59 46 63 87 96 69 64 76 84 129 135
WLO-M03A 159
206 137 148 141 150 91 79 84 64 70 72 94 126 135 142 132 100 62 71 104
143 161 98 56 45 43 70 60 55 52 43 33 45 42 51 52 31 53 45 50
64 54 43 44 43 41 41 31 45 48 39 49 66 44 37 51 60 64 63 80
38 39 76 64 74 70 56 82 135 109 65 64 80 64 85 68 68 75 67 54
71 70 50 52 64 81 92 175 149 88 78 127 153 175 108 89 172 88 103 90
76 94 81 56 73 60 134 66 83 75 60 70 63 110 114 89 79 93 84 75
95 64 124 88 57 66 90 99 167 149 80 60 68 108 115 115 108 277 136 106
142 131 157 124 65 75 107 157 89 113 94 119 144 144 164 189 156 107 102

WLO-M03B 159
211 135 154 140 151 95 80 84 69 65 68 90 119 147 135 128 106 63 68 105
145 166 97 62 38 50 75 57 52 53 37 31 53 37 54 47 36 53 46 48
70 57 37 48 45 44 35 36 45 39 48 53 60 43 38 52 62 62 66 77
39 38 79 64 83 58 58 87 137 104 68 57 82 68 78 76 64 77 68 54
69 67 48 55 68 87 93 175 152 81 79 123 151 173 108 86 177 87 106 91
69 101 77 61 71 64 123 63 83 75 60 71 62 112 122 80 87 94 80 79
99 60 122 93 56 66 95 96 174 153 89 60 64 118 118 105 109 279 130 107
144 130 151 118 64 84 107 152 98 104 101 126 153 140 164 185 157 118 108
WLO-M04A 59
58 42 40 56 48 79 74 52 47 56 71 53 57 64 95 64 74 63 53 73
60 60 46 45 50 75 105 66 67 87 103 204 79 94 92 126 120 103 239 153
115 126 105 267 178 130 96 122 136 167 114 120 90 119 124 125 100 130 159
WLO-M04B 59
49 49 39 51 53 78 72 58 43 56 75 44 62 67 93 63 71 69 53 73
62 55 51 44 60 65 107 68 58 94 103 200 86 97 78 127 117 109 238 152
113 125 105 265 179 133 86 131 134 167 109 120 96 117 122 119 103 130 157
WLO-M05A 157
61 62 62 42 49 47 45 88 108 90 90 91 77 106 93 107 87 76 63 72
47 62 55 32 56 79 72 52 56 56 45 47 46 52 81 73 64 33 39 65
49 80 50 41 51 41 43 55 44 40 37 57 98 76 86 76 60 51 59 79
54 69 57 59 42 57 57 51 73 49 44 67 43 88 44 62 58 37 49 52
82 114 49 66 58 55 49 49 53 40 54 35 41 61 45 66 82 45 35 35
53 45 43 46 97 57 52 80 73 80 65 47 55 42 63 46 43 45 59 50
58 61 51 83 61 69 44 58 42 48 51 43 60 38 56 70 48 52 48 62
43 63 68 53 55 51 49 51 52 48 23 42 46 54 35 42 57
WLO-M05B 157
67 57 65 43 48 47 45 90 106 91 83 82 73 101 98 103 80 72 63 69
45 61 53 37 51 87 76 52 55 58 45 46 44 52 79 75 67 33 40 66
47 79 52 40 53 38 42 56 39 43 40 59 95 75 88 73 64 50 57 80
57 69 59 59 40 56 57 51 72 48 43 64 43 92 40 61 59 37 49 50
87 114 50 67 55 50 54 53 44 51 48 36 42 53 47 63 76 40 35 37
54 44 46 41 98 69 47 85 70 84 67 51 58 45 60 42 52 41 59 58
54 65 61 71 63 61 51 49 48 43 58 47 56 48 48 73 43 54 48 57
45 67 66 50 59 52 46 51 54 36 40 38 50 54 35 45 54
WLO-M06A 139
108 74 139 102 146 519 351 186 59 61 98 121 101 88 41 56 49 38 77 88
92 94 102 84 74 81 84 90 107 146 126 118 86 76 93 55 81 59 68 93
54 65 116 89 171 104 98 102 49 100 71 115 116 77 81 65 55 49 59 77
71 75 47 84 73 68 139 121 174 50 50 51 46 47 45 91 68 48 89 41
76 94 66 44 63 68 46 47 37 21 17 21 25 28 21 40 30 34 34 39
29 30 37 16 25 25 29 34 28 34 38 34 28 31 40 39 31 36 37 46
51 36 45 49 48 65 52 53 87 71 93 123 86 61 64 58 70 135 171
WLO-M06B 102
75 25 41 81 61 131 75 81 69 42 65 35 70 65 39 63 54 35 41 48
48 56 59 33 61 63 51 112 97 102 35 39 54 43 45 52 93 59 47 74
47 58 104 64 50 57 74 33 43 33 23 16 27 25 21 22 21 23 28 30
32 27 35 24 30 22 26 40 24 30 35 25 18 13 24 36 27 30 32 40
47 53 35 44 54 75 87 62 53 69 69 75 104 66 69 77 55 87 124 157
118 273

WLO-M08A 153
313 345 285 147 149 156 184 199 205 101 101 54 139 146 128 139 81 81 108 127
135 114 122 96 102 83 80 50 59 51 48 57 54 44 55 67 54 53 85 88
69 70 97 75 59 62 81 183 189 159 60 62 84 102 103 105 47 58 50 55
77 99 78 99 132 73 69 78 72 75 97 119 106 103 62 66 74 52 83 73
78 88 59 62 123 97 224 130 128 97 53 139 81 128 131 83 110 80 68 61
77 67 105 97 60 94 84 89 175 129 116 56 68 87 74 78 84 127 86 79
112 74 84 112 81 68 70 78 45 46 36 34 24 28 22 34 43 39 43 35
29 40 33 31 21 31 20 31 35 33 43 32 36
WLO-M08B 153
315 349 296 146 153 145 181 200 202 109 103 48 139 154 131 138 89 84 112 122
144 113 116 96 107 85 76 58 57 52 47 60 51 45 54 71 53 56 86 91
68 65 104 58 67 55 86 177 199 159 54 72 81 107 111 106 50 60 54 57
78 97 80 99 128 80 58 84 79 67 103 118 97 93 73 58 77 58 86 74
79 89 52 60 116 103 237 126 121 98 55 139 81 132 125 80 112 77 73 74
72 68 104 101 56 96 83 89 173 132 118 51 77 84 79 75 83 128 86 80
106 76 80 111 78 70 76 71 45 51 41 34 20 28 24 33 41 39 45 33
36 38 34 32 28 27 16 34 34 33 40 33 41
WLO-M09A 53
355 389 390 332 377 407 266 368 258 249 390 413 357 280 233 394 272 476 387 277
268 226 228 350 238 224 189 257 283 293 403 296 347 379 346 338 306 302 245 317
428 374 328 333 214 205 184 321 253 259 187 224 304
WLO-M09B 53
357 388 390 328 376 413 267 367 265 245 392 411 353 280 235 392 274 471 391 280
267 217 237 350 235 222 190 264 279 299 401 305 346 384 336 349 320 302 251 324
434 375 328 337 211 202 169 319 247 259 186 227 297
WLO-M10A 187
159 144 107 105 77 166 189 229 158 162 157 162 170 195 240 260 179 158 208 175
181 124 131 103 112 124 113 154 145 133 121 77 130 153 152 166 102 90 128 154
197 189 165 152 166 116 99 126 97 90 72 165 115 77 79 95 146 118 146 157
85 111 121 93 139 148 160 273 305 293 165 151 183 148 215 98 121 111 137 135
140 124 125 139 206 132 135 114 138 97 145 130 94 114 76 86 78 96 152 115
92 124 117 154 154 136 210 179 189 149 123 210 145 209 231 182 188 155 139 148
142 129 144 199 141 184 137 119 215 187 142 81 101 141 138 121 125 232 140 133
144 125 137 166 90 84 76 101 79 71 86 96 72 77 72 67 92 77 85 96
107 119 117 142 101 103 90 132 258 125 166 196 129 162 129 206 156 138 163 160
215 144 131 126 163 127 206
WLO-M10B 187
165 139 111 103 86 160 192 239 163 164 160 156 174 196 229 266 174 155 197 164
188 114 128 108 108 117 119 152 147 124 129 82 130 164 157 172 102 84 132 144
204 180 160 157 169 107 113 120 100 93 69 163 114 71 75 95 144 116 147 157
94 101 124 100 129 149 164 282 310 289 155 146 165 153 209 101 128 135 126 132
140 124 125 141 205 141 129 113 138 92 138 135 97 110 80 91 70 102 146 119
85 134 119 150 156 138 215 182 171 148 117 210 145 210 231 175 178 175 119 143
141 132 150 190 133 190 142 101 213 180 141 82 101 135 130 122 124 245 146 124
153 113 141 164 93 73 84 90 90 60 93 90 78 76 73 67 87 78 83 87
107 117 123 139 98 105 87 132 265 131 165 173 158 157 130 201 148 135 173 161
218 140 126 128 159 141 211

WLO-M11A 220
186 156 202 157 120 154 172 123 176 247 108 104 105 91 68 129 158 99 57 126
100 62 81 58 100 95 126 127 95 70 65 62 109 92 94 94 71 172 77 61
49 54 52 166 94 80 59 60 61 54 84 144 92 65 56 86 93 85 77 68
56 45 34 46 50 43 57 31 33 48 76 82 87 59 98 119 118 132 113 152
147 131 134 114 99 79 98 156 102 156 160 122 142 139 96 109 101 145 169 176
210 124 127 110 134 186 180 118 161 97 128 131 141 127 119 121 106 91 93 112
110 110 138 126 107 109 100 66 78 92 86 67 96 60 80 128 79 117 83 93
80 78 98 79 73 69 80 100 94 79 78 87 101 127 102 84 123 114 98 146
132 117 89 92 168 158 127 141 144 128 109 111 166 167 126 126 105 157 143 126
116 98 100 81 105 99 98 111 103 109 110 118 118 112 131 80 136 104 102 137
87 97 97 102 83 68 120 105 92 104 98 129 77 63 69 92 98 150 141 130
WLO-M11B 220
194 162 201 154 127 148 174 125 179 248 105 101 104 91 62 131 155 90 59 124
105 63 84 57 96 99 130 119 101 56 65 58 97 82 109 92 89 169 73 61
52 53 51 165 101 79 69 58 65 57 86 148 91 60 55 84 84 96 65 75
53 47 46 34 54 45 56 24 33 55 86 81 86 46 99 108 117 135 114 154
154 140 132 124 101 81 96 155 106 151 167 115 138 142 97 122 99 146 173 174
201 126 123 118 135 170 189 117 163 98 128 125 147 128 116 120 103 96 91 113
102 111 132 125 122 103 91 75 68 97 92 70 97 61 79 136 77 111 89 87
91 70 109 72 82 74 84 94 108 77 88 85 107 126 101 90 118 107 95 152
131 122 90 93 166 153 131 143 135 139 113 113 167 168 122 124 117 148 149 113
120 100 97 86 100 101 96 111 108 106 115 114 117 117 130 79 138 97 97 149
83 91 106 95 87 72 121 97 102 101 96 129 77 66 78 87 98 149 137 138
WLO-M12A 51
51 95 156 233 398 356 441 424 525 154 81 180 180 211 214 185 197 245 200 356
488 287 198 159 175 181 192 264 157 268 191 157 200 204 213 129 82 65 64 112
201 107 175 261 319 280 239 218 192 170 164
WLO-M12B 51
52 99 157 230 394 356 439 375 489 162 79 176 184 203 202 191 186 258 197 362
488 291 204 155 180 185 191 272 153 269 193 167 195 202 221 120 81 74 67 119
199 108 174 258 329 280 251 220 189 172 165
WLO-M13A 116
197 261 209 240 148 258 233 149 165 113 94 96 129 166 111 119 147 103 133 165
170 245 191 179 138 118 191 124 228 241 180 184 182 167 179 165 168 174 217 154
244 201 138 269 216 196 91 100 170 192 165 167 310 199 148 202 140 198 196 136
130 137 156 156 125 142 183 139 166 133 115 171 115 108 99 93 109 145 158 131
103 113 137 213 98 159 181 142 104 102 163 120 142 169 193 269 207 209 175 154
115 174 110 98 120 61 56 90 59 88 92 94 127 78 135 100
WLO-M13B 116
180 248 213 222 159 253 219 160 169 108 98 100 127 165 109 120 147 98 131 175
173 241 190 209 128 102 188 128 230 251 177 185 183 164 173 170 168 166 218 145
227 194 139 274 223 199 99 99 172 195 172 165 318 201 143 198 151 198 197 127
124 143 150 137 143 134 169 143 160 138 117 173 118 106 103 100 102 146 172 112
118 113 127 209 106 159 185 147 111 98 166 130 129 179 188 272 214 208 177 149
116 170 112 97 128 57 73 75 60 80 94 86 111 96 136 105
WLO-M14A 106
173 208 177 117 164 77 72 77 101 104 177 235 188 167 178 107 120 96 173 237
277 245 150 111 159 237 309 352 319 173 76 102 166 169 138 122 147 140 197 316
209 174 167 239 196 146 162 105 116 182 169 130 145 135 157 337 149 188 192 107
82 109 73 59 55 73 169 244 265 112 97 141 188 171 135 59 63 76 49 101
97 118 86 81 102 82 76 164 100 90 105 86 85 45 50 67 32 67 55 76
102 67 48 77 94 114

WLO-M14B 106
185 220 179 109 161 79 79 78 90 106 176 233 186 165 173 111 114 102 175 236
287 232 170 114 149 231 296 358 311 163 79 104 162 170 136 118 144 135 199 309
211 177 160 239 197 148 166 104 111 184 169 134 145 133 161 334 147 193 192 109
82 114 75 51 59 74 165 244 267 110 103 129 182 168 147 69 63 69 53 91
106 119 85 82 96 71 84 169 99 100 119 96 87 41 52 65 45 61 52 77
97 70 48 78 88 127
WLO-M17A 76
147 101 176 181 87 69 113 172 178 149 168 165 126 126 159 174 135 116 145 153
204 159 127 136 124 102 108 155 149 131 99 116 118 109 120 145 135 117 91 147
101 81 125 86 101 117 107 94 130 218 125 125 143 160 205 143 133 125 192 194
179 139 139 173 153 143 165 135 170 155 90 85 131 104 87 139
WLO-M17B 76
144 108 180 180 83 74 111 175 182 147 177 165 114 132 153 168 129 120 143 152
200 152 120 133 131 96 106 154 151 134 98 119 115 103 124 146 135 110 96 147
101 80 129 86 89 112 109 87 130 224 132 123 142 155 208 138 137 125 198 193
180 144 138 169 155 139 173 131 173 154 91 93 124 110 88 141
WLO-M18A 58
541 440 466 452 618 871 463 328 460 555 576 453 489 445 605 344 580 370 318 399
412 455 309 252 352 245 403 289 240 150 137 134 162 143 102 74 116 196 161 186
168 169 159 132 250 125 159 131 153 147 122 80 134 74 62 58 138 91
WLO-M18B 58
540 437 455 457 616 869 466 320 464 573 576 456 480 448 612 346 552 367 315 401
415 474 325 266 351 230 413 296 233 150 136 131 163 134 95 73 104 206 162 183
167 172 157 138 247 120 165 131 151 147 112 93 128 74 62 59 145 91

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 Building* s (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

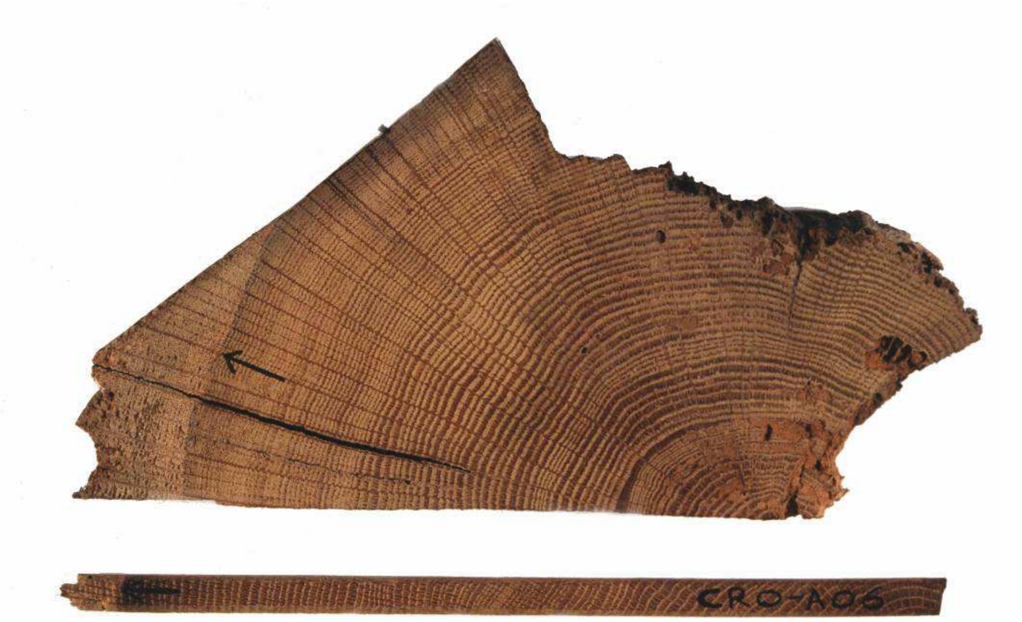


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

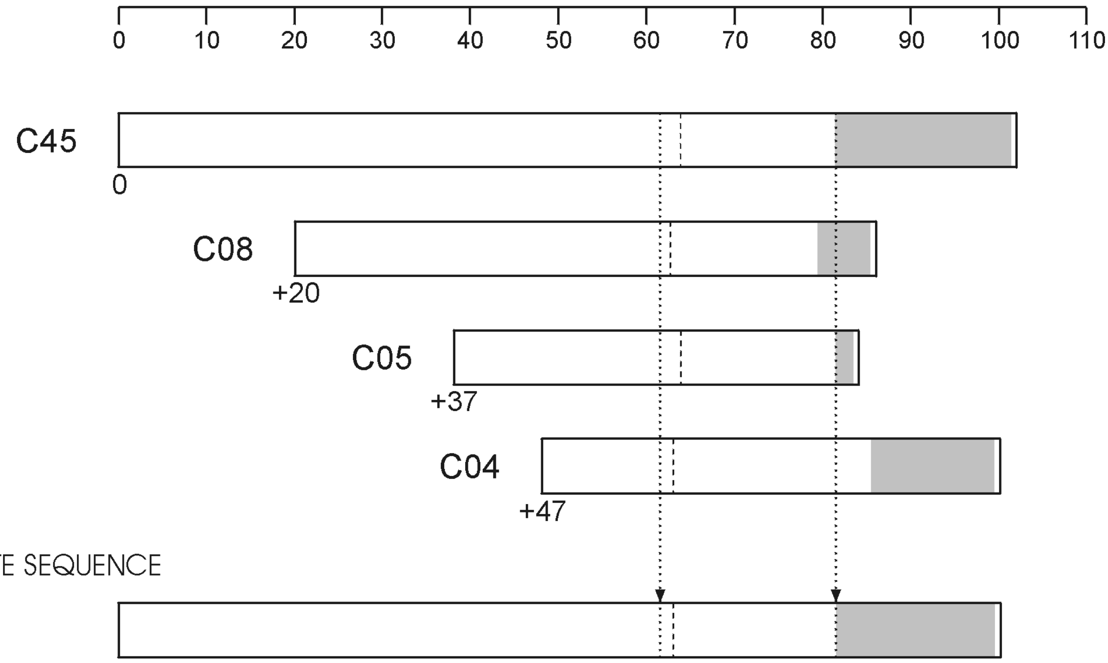


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

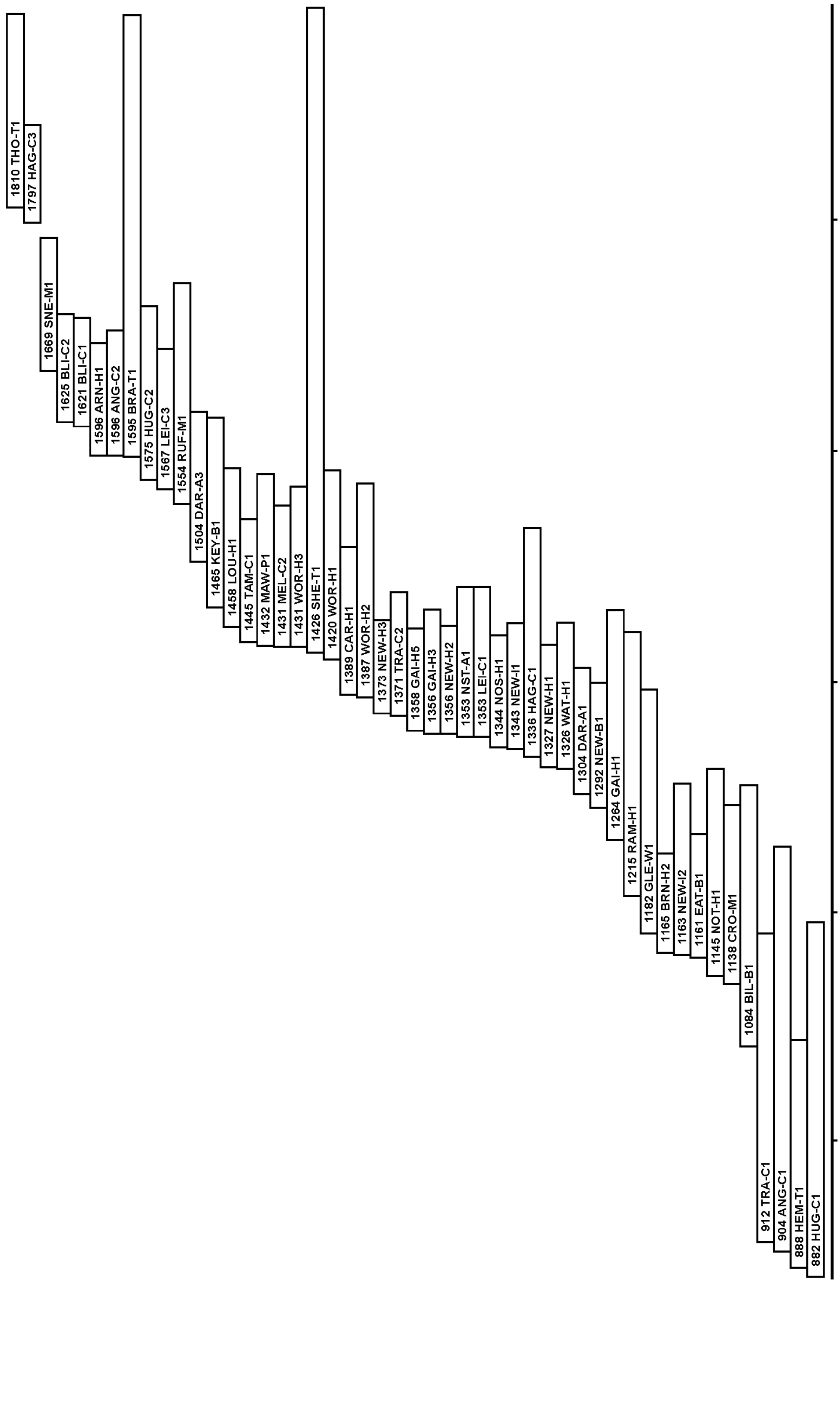
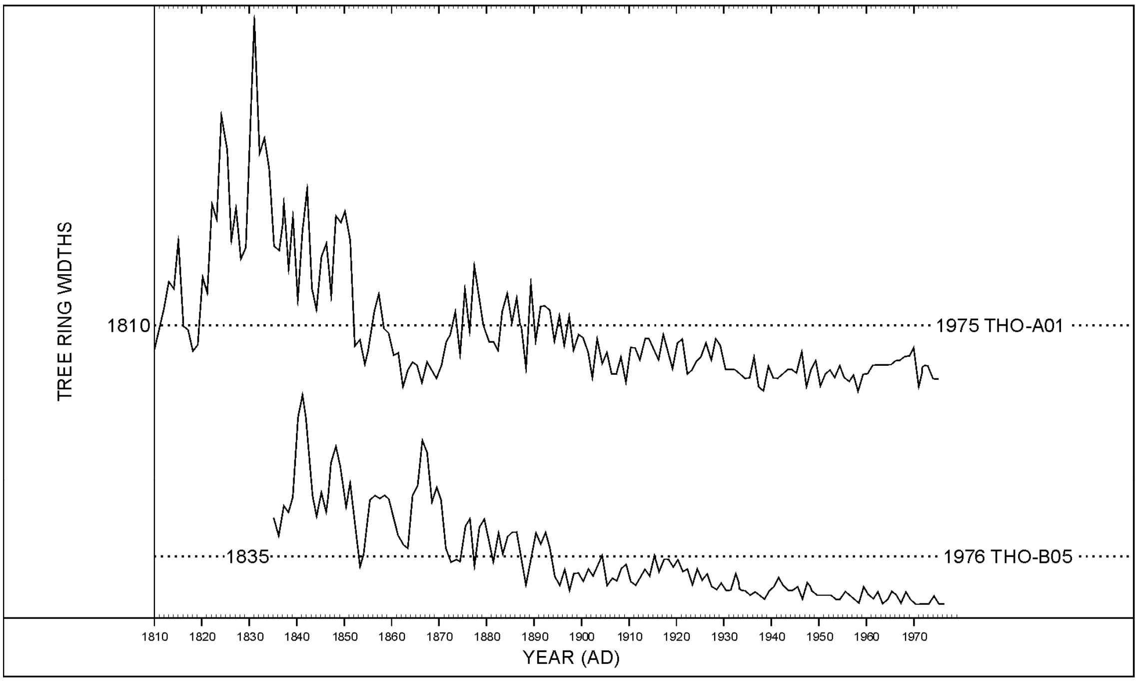


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

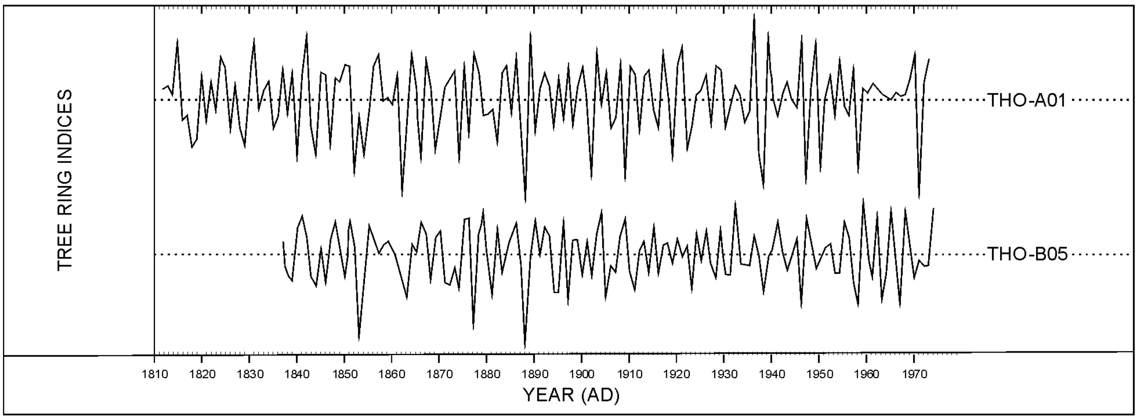


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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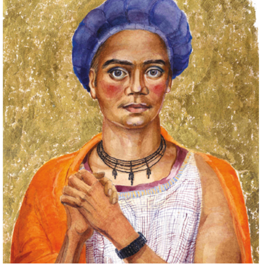



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