RESEARCH DEPARTMENT REPORT SERIES no. 3-2010 ISSN 1749-8775

MONKS' HALL, ECCLES, SALFORD, GREATER MANCHESTER
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

Research Department Report Series 3-2010

MONKS' HALL, ECCLES, SALFORD, GREATER MANCHESTER

TREE-RING ANALYSIS OF TIMBERS

A J Arnold and R E Howard

NGR: SJ 7757 9891

© English Heritage

ISSN 1749-8775

The Research Department Report Series incorporates reports from all the specialist teams within the English Heritage Research Department: Archaeological Science; Archaeological Archives; Historic Interiors Research and Conservation; Archaeological Projects; Aerial Survey and Investigation; Archaeological Survey and Investigation; Architectural Investigation; Imaging, Graphics and Survey, and the Survey of London. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series and the Architectural Investigation Report Series.
Many of these are interim reports which make available the results of specialist investigations in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation. Where no final project report is available, readers must consult the author before citing these reports in any publication. Opinions expressed in Research Department reports are those of the author(s) and are not necessarily those of English Heritage.

Requests for further hard copies, after the initial print run, can be made by emailing:
Res.reports@english-heritage.org.uk
or by writing to:
English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD
Please note that a charge will be made to cover printing and postage.

SUMMARY

Dendrochronological analysis was undertaken on timbers associated with the original sixteenth-century timber-framed structure and a floor, thought likely to be inserted, within the northern range at this building complex.

A single site sequence containing 21 samples, from both elements, has been dated to the period AD 1416–1585. It is now known that a main beam from the floor was felled in AD 1584 and two common joists, a tiebeam, and a rail from the timber-framing were felled in AD 1586. Interpretation of the sapwood on the other dated samples suggests felling of these timbers also occurred in the mid-AD 1580s.

Tree-ring dating has demonstrated rather unexpectedly that the timber-framing and the floor appear likely, in the absence of any evidence of resetting or reuse of timbers, to be contemporary, with both elements dating to the later-sixteenth century.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

The Laboratory would like to thank Mark Hammond of Leaway Manchester Limited, the owners of the building, for allowing access and for the work to be undertaken. Thanks are also given to the University of Manchester Archaeological Unit for figures 3, 4, and 8–12, which have been used to locate the samples. Ian Tyers of Dendrochronological Consultancy Ltd carried out the initial assessment, with on-site advice from Darren Ratcliffe, English Heritage Buildings Inspector, North-West Region, Mike Nevell from University of Manchester Archaeological Unit, and inspectors from Salford Council. Thanks are also given to the Scientific Dating Section at English Heritage and Cathy Tyers of the Sheffield University Dendrochronology Laboratory for their advice and assistance throughout the production of this report.

ARCHIVE LOCATION

Greater Manchester Historic Environment Record
Greater Manchester Archaeological Unit
University of Manchester
3.22 Mansfield Cooper
Oxford Road
Manchester M13 9PL

DATE OF INVESTIGATION

2009

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

CONTENTS

INTRODUCTION

Monks' Hall is a grade II listed building, located in Eccles, to the west of Salford (Figs 1 and 2; SJ 7757 9891). It is built on land which was owned by the monks of Stanlaw (later Whalley) Abbey from the thirteenth century until the abbey's dissolution in AD 1537. Although there are possible earlier documentary references to the house itself, the first secure reference is in AD 1465, when the then inhabitant 'John Reddish of the Monks' Hall' is mentioned. By the AD 1580s the site was occupied by Ellis Hey I, whose family continued to live here until the mid-seventeenth century, at first as tenants. In AD 1632, Ellis Hey II purchased the house from Christopher Anderton. By AD 1649, following a decline in the family's fortune, Monks' Hall was sold to Thomas Minshull. In the late-seventeenth century, ownership passed to the Willis family, who retained possession until the mid-nineteenth century. In the AD 1850s, the estate was sold for development as housing and the house itself underwent substantial remodelling. Since then it has been a doctor's surgery and a museum, and the present owners are now planning further development of the site.

The earliest standing remains, thought to date from the sixteenth century, are to be found in the two-storey northern range (Figs 3–5), where there survive elements of a timber-framed structure. Surviving fabric represents two bays divided on the north and south elevations into nine panels defined by posts and rails (Fig 6). This range is thought to have been the service wing of a larger timber-framed hall that occupied the footprint of the existing southern range.

A floor was thought to have been inserted in this part of the building in the late-sixteenth/early seventeenth century. Elements of this flooring can be seen within the southern two-thirds of room G13, with the survival of chamfered ceiling joists and chamfered bridging beams (Fig 7). At the same time, a doorway was also inserted in the northern wall-frame; redundant slots in some timber posts suggest that a passageway ran across the northern range to this door and onto another room (presumed to be a kitchen range), since replaced by a conservatory. A central hall is thought to have been located to the south of this service wing, and to have been abutted in turn by an accommodation wing.

Later developments of the mid-seventeenth to early-eighteenth century include the addition of a small, single-storey, timber-framed room against the western gable of the northern range, and the partial rebuilding in brick of the central hall and southern accommodation wing.

The mid- to late-eighteenth century saw the complete rebuilding of the central hall and southern wing to form a substantial L-shaped block. The northern timber-framed range was refurbished, with the wattle and daub panels being replaced by brick.

The building underwent further work in the mid-nineteenth century with the upgrading of the southern wing and the extension of the L-shaped block to create a double-depth, double-pile structure. Further additions/alterations were undertaken in the late nineteenth/early-twentieth century. This introduction is based on the Manchester Archaeological Unit's survey of the building, undertaken on behalf of the owners (Arrowsmith *et al* 2007).

SAMPLING

Tree-ring dating was requested by Darren Ratcliffe, English Heritage Inspector for the North-West region, to inform Listed Building Consent for a proposed restoration of Monks' Hall, to inform a possible listing upgrade, and to contribute to the understanding of the site in light of the proposed Enabling Development of new-build apartments surrounding the building. Following the assessment carried out by Ian Tyers of Dendrochronological Consultancy Limited, and in accordance with the brief supplied by English Heritage, samples were taken from the northern range. Timbers of the primary extant sixteenth-century structure, identified as 'the framing to the north side', and the later sixteenth-century or early seventeenth-century inserted flooring in the southern two-thirds of room G13 were sampled.

A total of 25 timbers was sampled, with each sample being given the code MNK-H (for Monks' Hall) and numbered 01–25. Samples MNK-H01–13 were taken from timbers of the 'primary' structure and samples MNK-H14–25 are from timbers of the 'inserted' floor. The location of samples was noted at the time of sampling and has been marked on Figures 8–12. Further details relating to the samples can be found in Table 1. Trusses, beams, and bays have been numbered from east to west.

ANALYSIS AND RESULTS

At this stage it was noticed that two of the samples (MNK-H03 and MNK-H13), from the 'primary' structure, had insufficient rings for secure dating to be a possibility and so these were discarded at this point. The remaining 23 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. The samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

This analysis resulted in 20 samples matching each other at a least value of t=4.5. These samples were then combined at the relevant offset position to form MNKHSQ01, a site sequence of 170 rings (Fig 13). Attempts to date this site sequence by comparing it against a series of relevant reference chronologies for oak resulted in it being found to match securely and consistently at a first-ring date of AD 1416 and a last-measured ring date of AD 1585. The evidence for this dating is given in Table 2.

Attempts were then made to date the three ungrouped samples by individually comparing them against the reference chronologies. This resulted in sample MNK-H05 being found to span the period AD 1431–1585. The evidence for this dating is given in

Table 3. The other ungrouped samples (MNK-H11 and MNK-H18) could not be matched and are undated.

It was then noticed that sample MNK-H05 matched site sequence MNKHSQ01 at the expected offset position at an acceptable value of t=4.2. A second site sequence was then constructed, containing all samples from MNKHSQ01 and MNK-H05 at the relevant offset positions (Fig 14). This new site sequence, MNKHSQ02, was then compared against the reference material, where it was again found to match consistently and securely at a first-ring date of AD 1416 and a last-measured ring date of AD 1585. The evidence for this dating is given in Table 4.

INTERPRETATION

The tree-ring analysis has resulted in the successful dating of 21 of the samples, with dated samples being from both the 'primary' structure and the floor frame (Fig 15). Four of these dated samples, two from the 'primary' structure and two from the floor frame, have complete sapwood and the last-measured ring date of AD 1585. When all four of these samples are looked at under the microscope, it is possible to see the spring growth cells of the following year, giving all four timbers represented a felling date of AD 1586. A fifth sample, taken from a main beam of the floor frame, also has complete sapwood and the last-measured ring date of AD 1583. Again, the spring growth cells of the following year can be seen on this sample, giving this timber a felling date of AD 1584. Fifteen of the other dated samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary and, therefore, suggestive of a single felling (Figs 14 and 15). The average heartwood/sapwood boundary ring date is AD 1563, allowing an estimated felling date to be calculated for the 15 timbers represented to within the range AD 1578–1603. This felling date range encompasses both of the absolute felling dates (AD 1584 and AD 1585), and makes it likely that these timbers were also felled in the mid-AD 1580s.

The final dated sample, MNK-H24, does not have the heartwood/sapwood boundary ring, and so an estimated felling date cannot be calculated for it. However, with a last-measured ring date of AD 1558 it is possible that this timber was also felled in the mid-AD 1580s.

All felling date ranges have been calculated using the estimate that 95% of mature oak trees in this area have between 15 and 40 sapwood rings.

DISCUSSION AND CONCLUSION

Prior to tree-ring analysis being undertaken, it was thought that the extant timber-framing within the northern range was part of the 'primary' structure and dated to the sixteenth century, whilst the floor within this part of the building was thought likely to be a later insertion of the late sixteenth/early-seventeenth century.

The dendrochronology has clearly demonstrated that the timbers associated with both the 'primary' structure and the floor frame were felled in the mid-AD 1580s. In the absence of any evidence to suggest that the timbers of the floor frame are reset or reused, these results point to both elements being contemporary, dating to shortly after the felling of the timbers utilised. It is probable that this work can be associated with Ellis Hey I, who was known to have been living at Monks' Hall by AD 1588.

The contemporaneous nature of these two parts is further supported by a closer look at the relative heartwood/sapwood ring positions on the dated samples. When sorted by heartwood/sapwood ring position and colour coded (Figs 15 and 16) it can be seen that the samples do not fall into areas, with no suggestion that felling of the timbers for one area occurred earlier than for the other. Additionally, the intra-site matching between samples is generally very good, with the majority of samples from both areas grouping at a level of t=6.0. Again, this level of matching suggests the use within both elements of a coherent group of timbers from the same woodland source. Finally, it is of interest to note that within, the timbers of the floor frame we see a number of matches of a level indicative of a single tree being utilised (samples MNK-H16, MNK-H19, MNK-H20, and MNK-H21 group at a least value of t=17.0).

BIBLIOGRAPHY

Arnold, A J, Howard, R E, and Litton, C D, 2005a *Tree-ring analysis of timbers from the Gazebo, Shifnal Manor, Shifnal, near Telford, Shropshire*, Centre for Archaeol Rep, 60/2005

Arnold, A J, Howard, R E, and Litton, C D, 2005b *Tree-ring analysis of timbers from All Saints' Church, Main Street, Fenton, South Kesteven, Lincolnshire*, Centre for Archaeol Rep, 46/2005

Arnold, A J, Howard, R E, and Litton, C D, 2006 *Tree-ring analysis of samples from Middleton Hall, Middleton, Warwickshire*, Res Dep Rep Series, 13/2006

Arnold, A J, Howard, R E, and Hurford, M, 2008 unpubl Site chronology for Rose Cottage, Lount, Leics, unpubl computer file *LNTBSQ01*, NTRDL

Arnold, A J, Howard, R E, and Hurford, M, 2008a *The Market House, Ledbury, Herefordshire: tree-ring analysis of timbers*, Res Dep Rep, Series, 53/2008

Arnold, A J, Howard, R E, and Tyers, C, 2008b *Ulverscroft Priory, Ulverscroft, Charnwood Forest, Leicestershire: tree-ring analysis of timbers*, Res Dep Rep Ser, 48/2008

Arnold, A J, Howard, R E, and Litton, C D, 2008c Nottingham Tree-ring Dating Laboratory: additional dendrochronology dates, *Vernacular Architect*, 39, 107–11

Arrowsmith, P, Hradil, I, and Nevell, M, 2007 *Monks Hall, Eccles, Salford: An Archaeological Desk-Based Assessment and Building Survey*, UMAU, rep 35

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1987 Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect*, 18, 53–4

Howard, R E, Laxton, R R, and Litton, C D, Morrison, A, Sewell, J, and Hook, R, 1994a Nottingham University Tree-Ring Dating Laboratory: Derbyshire, Peak Park and RCHME dendrochronological survey 1992–93, *Vernacular Architect*, 25, 41–3

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1994b Nottingham University Tree-Ring Dating Laboratory: results, *Vernacular Architect*, 25, 36–40

Howard, R E and Litton, C D, 1997 *Tree-ring analysis of timbers from Astley Castle, Warwickshire*, Centre for Archaeol Rep, 83/1997

Howard, R E, Laxton, R R Litton, C D, and Cleverdon, F, 1998 Nottingham University Tree-Ring Dating Laboratory: Staffordshire Moorlands Dendrochronological Project, *Vernacular Architect*, 29, 105–07

Howard, R E, Laxton, R R, and Litton, C D, 1999 *Tree-ring analysis of timbers from The Dower House, Fawsley Park, Fawsley, nr Daventry, Northamptonshire*, Anc Mon Lab Rep, 29/1999

Howard, R E, Laxton, R R, and Litton, C D, 2003 *Tree-ring analysis of timbers from Staircase House (30A & 31 Market Place), Stockport, Greater Manchester*, Centre for Archaeol Rep 12/2003

TABLES

Table 1: Details of tree-ring samples from Monk's Hall, Eccles, Greater Manchester

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
'Primary' timbers						
MNK-H01	North wallplate, truss 1-2	102	21	1483	1563	1584
MNK-H02	Western wall post , bay 1, north wall	61	01	1505	1564	1565
MNK-H03	Western mid rail, bay 1, north wall	NM	--	----	----	----
MNK-H04	Door jamb north	79	h/s	1473	1551	1551
MNK-H05	Tiebeam, truss 2	155	36C	1431	1549	1585
MNK-H06	Door jamb south	71	h/s	1486	1556	1556
MNK-H07	Rail, east gable	73	h/s	1504	1576	1576
MNK-H08	South post, east gable	48	h/s	1521	1568	1568
MNK-H09	Eastern mid rail, bay 1, north wall	60	18	1520	1561	1579
MNK-H10	Middle mid rail, bay 1, north wall	77	17C	1509	1568	1585
MNK-H11	Cut off rail, south wall	50	h/s	----	----	----
MNK-H12	East brace from western wall post, bay 1, north wall	68	h/s	1495	1562	1562
MNK-H13	Wallplate, south wall, by truss 2	NM	--	----	----	----
Floor frame timbers						
MNK-H14	Main beam 2	83	h/s	1492	1574	1574
MNK-H15	Main beam 1	168	20C	1416	1563	1583
MNK-H16	Joist 2, bay 3	69	15C	1517	1570	1585
MNK-H17	Joist 5, bay 3	44	h/s	1516	1559	1559
MNK-H18	Joist 7, bay 3	53	--	----	----	----
MNK-H19	Joist 1, bay 2	62	12	1521	1570	1582
MNK-H20	Joist 4, bay 2	65	15	1520	1569	1584
MNK-H21	Joist 6, bay 2	70	15C	1516	1570	1585
MNK-H22	Joist 8, bay 2	48	h/s	1517	1564	1564
MNK-H23	Joist 3, bay 1	62	02	1500	1559	1561

Table 1: cont.

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
MNK-H24	Joist 4, bay 1	66	h/s	1493	1558	1558
MNK-H25	Joist 7, bay 1	86	--	1473	----	1558

*NM = not measured;
**h/s = heartwood/sapwood boundary is the last measured ring;
C = complete sapwood retained on core

Table 2: Results of the cross-matching of site sequence MNKHSQ01 and relevant reference chronologies when the first-ring date is AD 1416 and the last-ring date is AD 1585

Reference chronology	*t*-value	Span of chronology	Reference
Staircase House, Stockport, Greater Manchester	6.6	AD 1489–1656	Howard *et al* 2003
The Market House, Ledbury, Herefordshire	6.6	AD 1485–1617	Arnold *et al* 2008a
Whithough, Ipstones, Staffordshire	6.6	AD 1496–1594	Howard *et al* 1998
Raynor House, Bradfield, South Yorkshire	5.9	AD 1468–1593	Howard *et al* 1994a
Bedehouses, Wirksworth, Derbys	5.6	AD 1479–1583	Howard *et al* 1994a
Astley Castle, Warwickshire	5.5	AD 1495–1627	Howard and Litton 1997
Middleton Hall, Warwickshire	5.3	AD 1390–1646	Arnold *et al* 2006

Table 3: Results of the cross-matching of sample MNK-H05 and relevant reference chronologies when the first-ring date is AD 1416 and the last-ring date is AD 1585

Reference chronology	*t*-value	Span of chronology	Reference
Shifnal Manor Gazebo, Shifnal, Shropshire	6.9	AD 1455–1628	Arnold *et al* 2005a
Ordsall Hall, Salford, Greater Manchester	6.6	AD 1385–1512	Howard *et al* 1994b
All Saints' Church, Fenton, Lincolnshire	6.4	AD 1434–1617	Arnold *et al* 2005b
Fawsley, Northamptonshire	6.2	AD 1427–1575	Howard *et al* 1999
Ulverscroft Priory, Ulverscroft, Leicestershire	6.1	AD 1388–1533	Arnold *et al* 2008b
Rose Cottage, Lount, Leicestershire	6.2	AD 1498–1612	Arnold *et al* 2008 unpubl
Sinai Farm, Burton on Trent, Staffs	6.1	AD 1445–1635	Arnold *et al* 2008c

Table 4: Results of the cross-matching of site sequence MNKHSQ02 and relevant reference chronologies when the first-ring date is AD 1416 and the last-ring date is AD 1585

Reference chronology	*t*-value	Span of chronology	Reference
Staircase House, Stockport, Greater Manchester	7.0	AD 1489–1656	Howard *et al* 2003
The Market House, Ledbury, Herefordshire	6.6	AD 1485–1617	Arnold *et al* 2008a
Raynor House, Bradfield, South Yorks	6.7	AD 1468–1593	Howard *et al* 1994a
Whithough, Ipstones, Staffordshire	6.7	AD 1496–1594	Howard *et al* 1998
All Saints' Church, Fenton, Lincolnshire	6.5	AD 1434–1617	Arnold *et al* 2005b
Mansfield Woodhouse Priory, Nottinghamshire	5.8	AD 1432–1579	Howard *et al* 1987
Bedehouses, Wirksworth, Derbys	5.8	AD 1479–1583	Howard *et al* 1994a

FIGURES

Figure 1: Map to show the general location of Eccles, circled

© Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

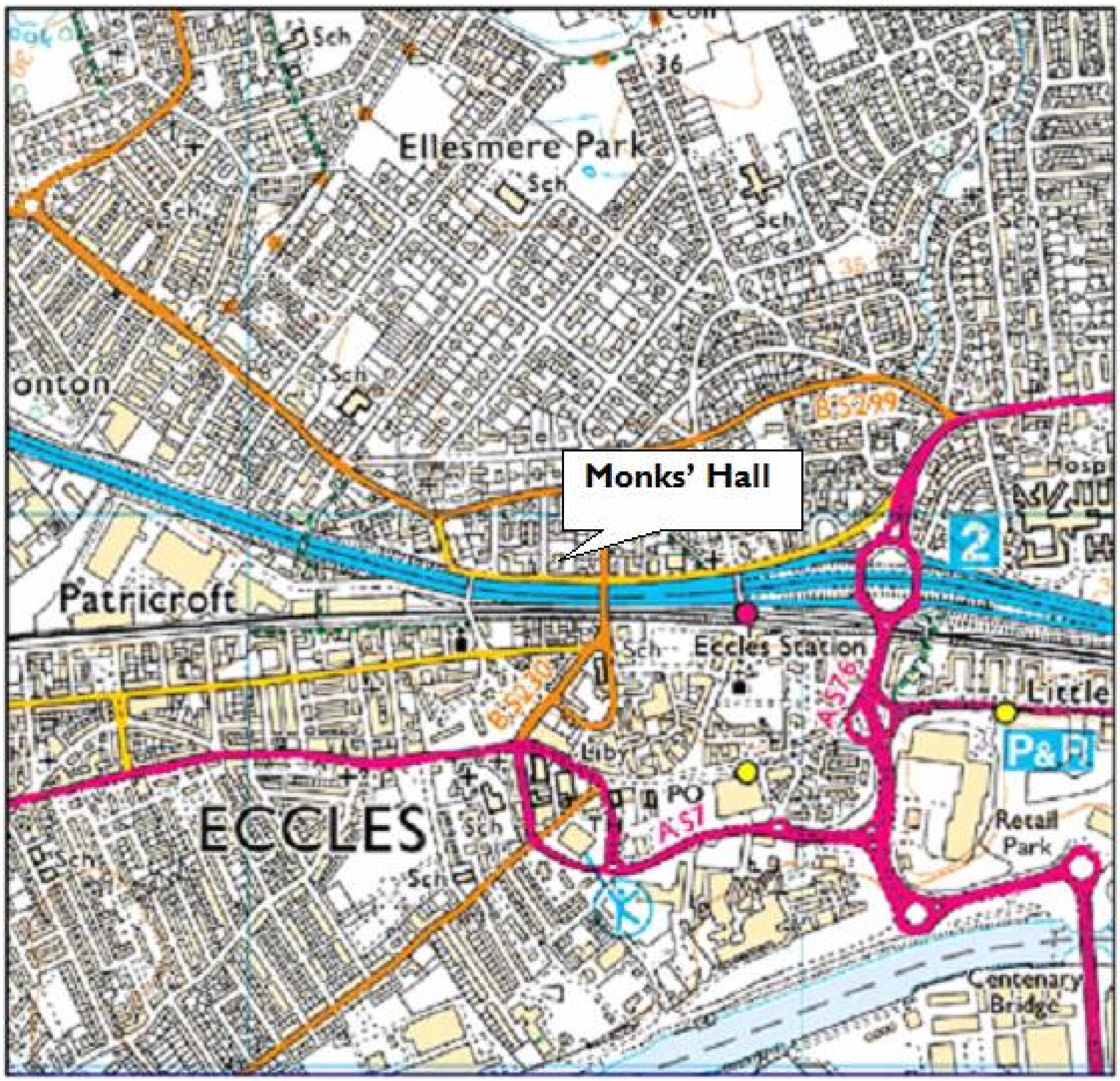


Figure 2: Map to show the location of Monks' Hall

© Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

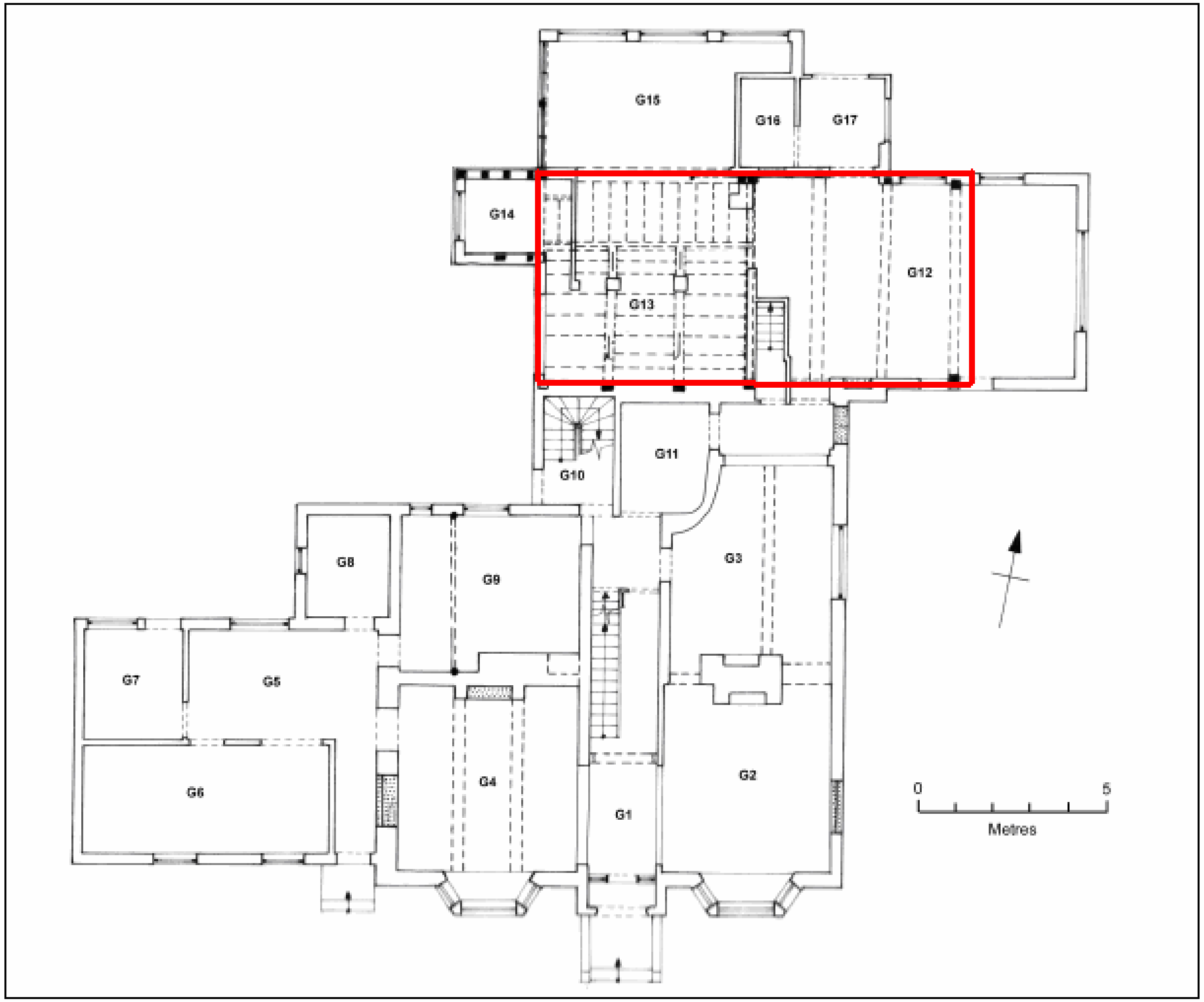


Figure 3: Ground-floor plan, northern range outlined in red (University of Manchester Archaeological Unit)

© ENGLISH HERITAGE

© ENGLISH HERITAGE

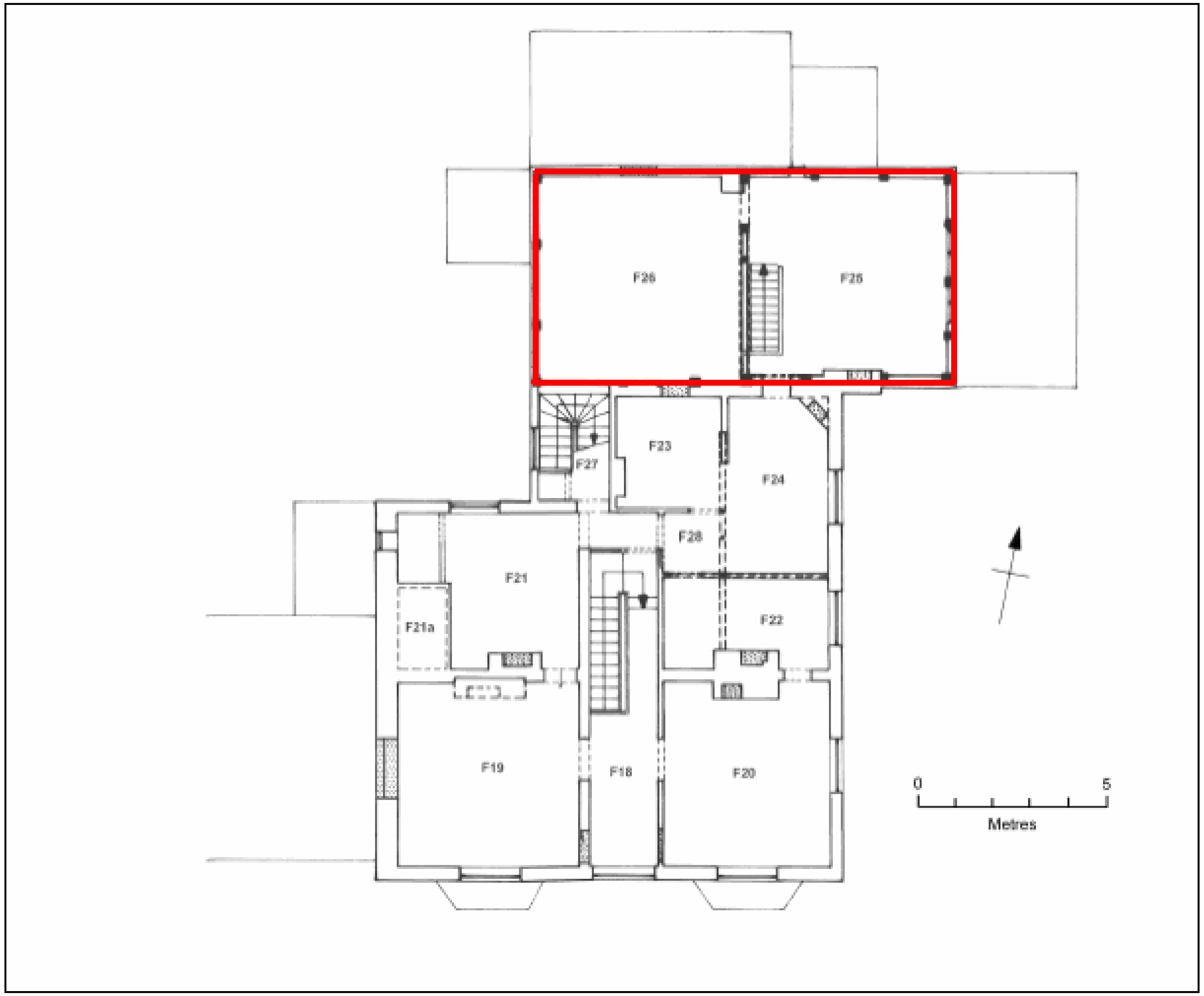


Figure 4: First-floor plan, northern range outlined in red (University of Manchester Archaeological Unit)

© ENGLISH HERITAGE

Figure 5: Two-storey northern range, photograph taken from the north-east

© ENGLISH HERITAGE

Figure 6: Northern range; first-floor framing in room F25, photograph taken from the south-west

Figure 7: Ground-floor ceiling, northern wing, photograph taken from the north-west

© ENGLISH HERITAGE

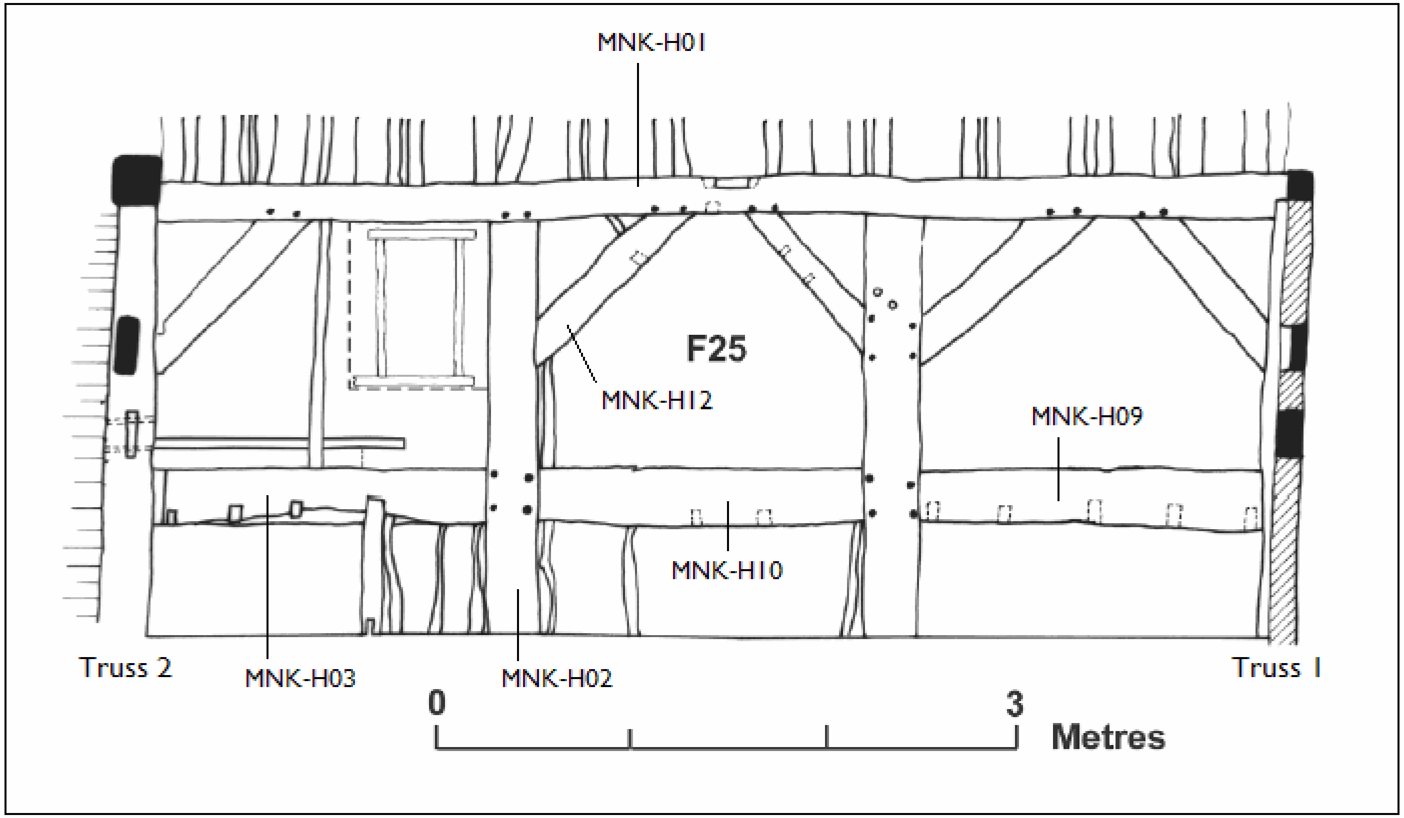


Figure 8: Drawing of northern range internal elevation in room F25, showing the location of samples MNK-H01–03, MNK-H09–10, and MNK-H12 (University of Manchester Archaeological Unit)

© ENGLISH HERITAGE

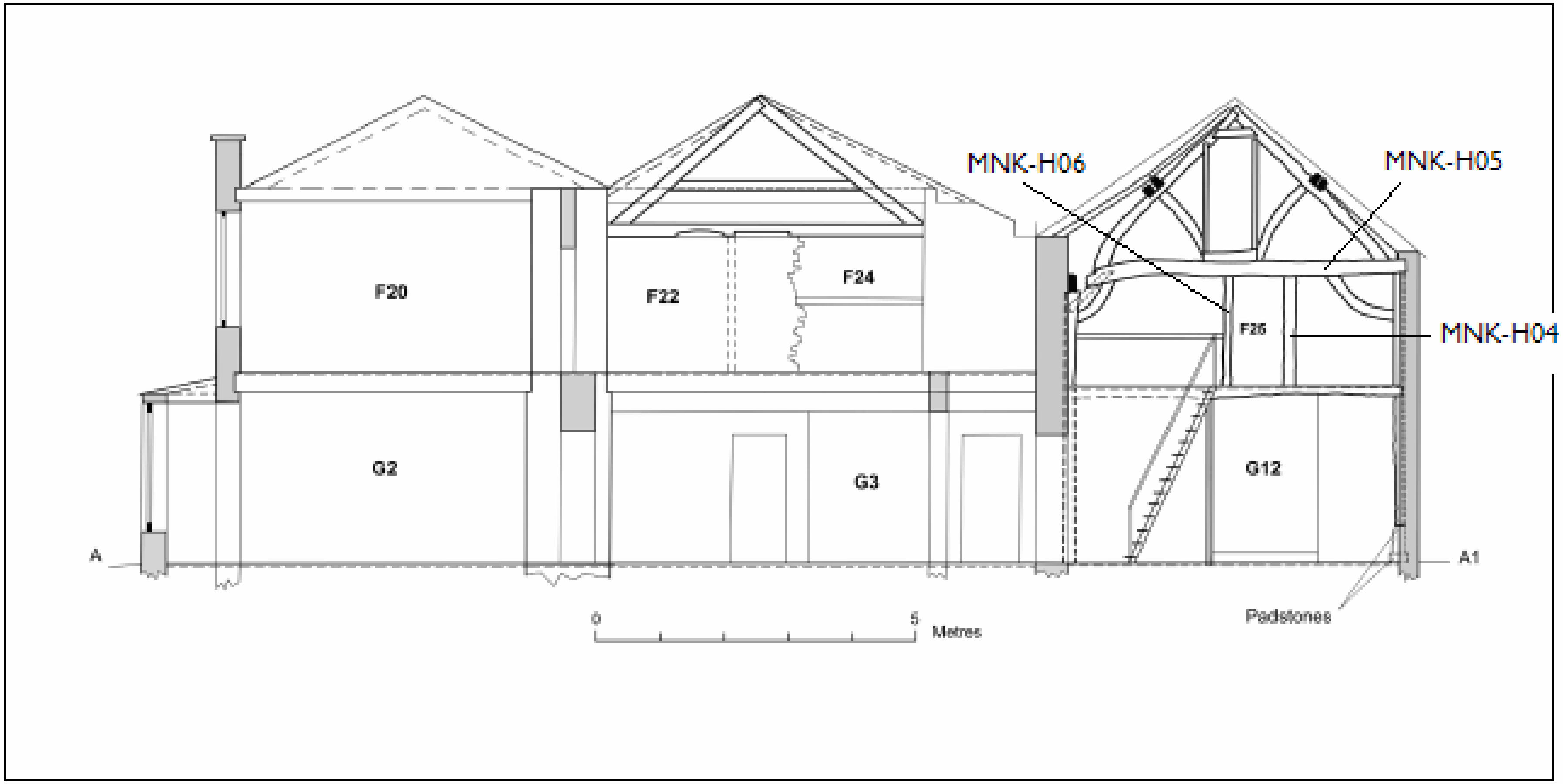


Figure 9: Section A–A1, showing the location of samples MNK-H04–06 (University of Manchester Archaeological Unit)

© ENGLISH HERITAGE

19

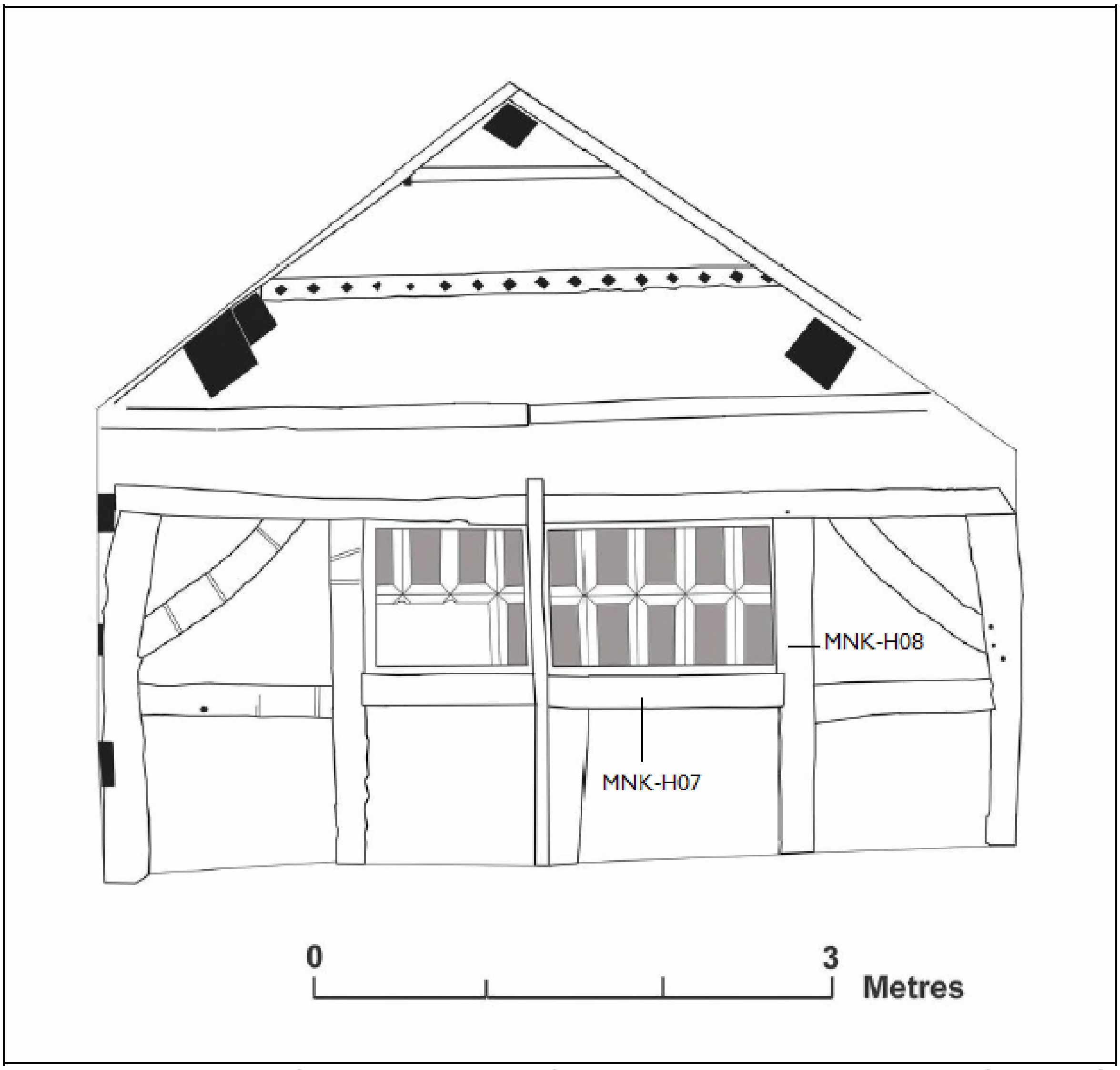


Figure 10: Drawing of northern range eastern elevation in room F25, taken from photographs, showing the location of samples MNK-H07 and MNK-H08 (University of Manchester Archaeological Unit)

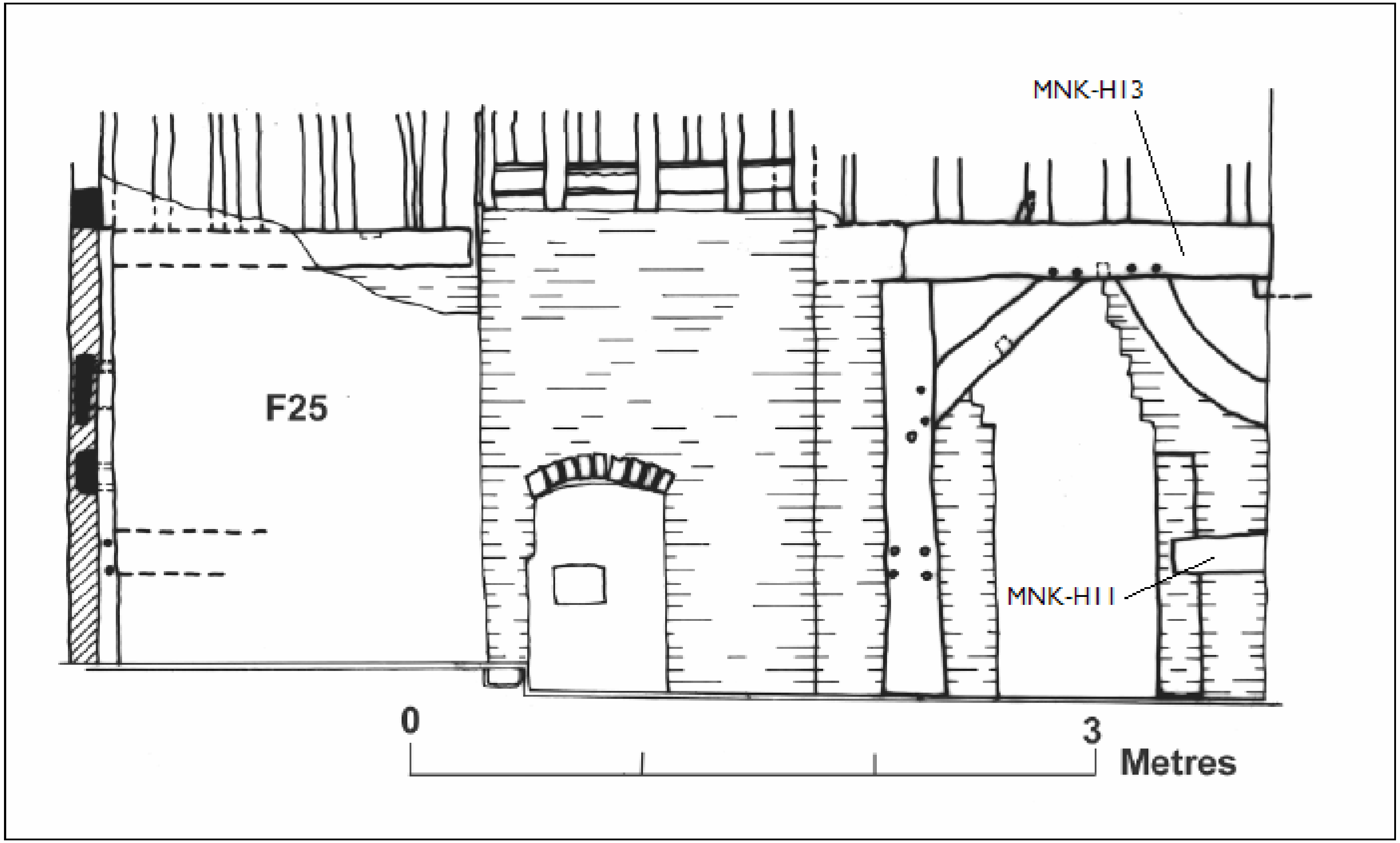


Figure 11: Drawing of the northern range southern elevation in room F25, showing the location of samples MNK-H11 and MNK-H13 (University of Manchester Archaeological Unit)

© ENGLISH HERITAGE

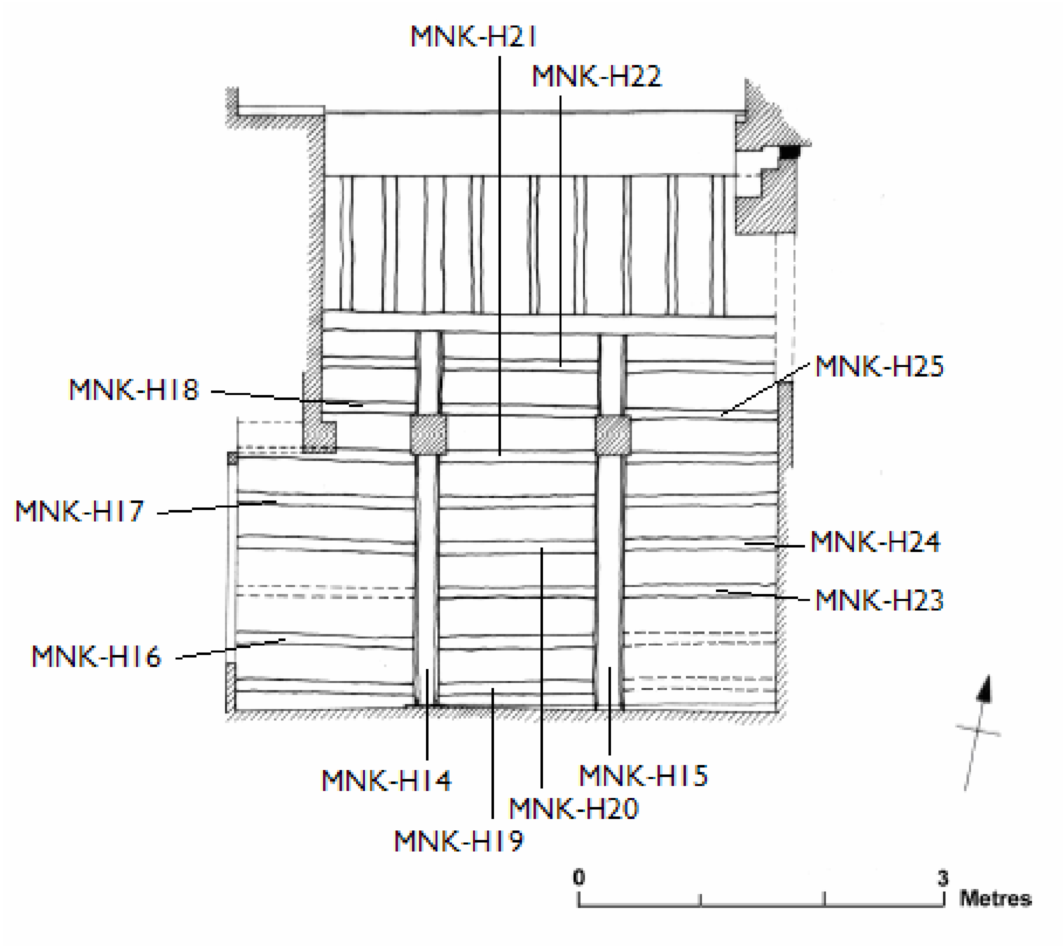


Figure 12: Drawing of the ceiling timbers in room G13, showing the location of samples MNK-H01–25 (University of Manchester Archaeological Unit)

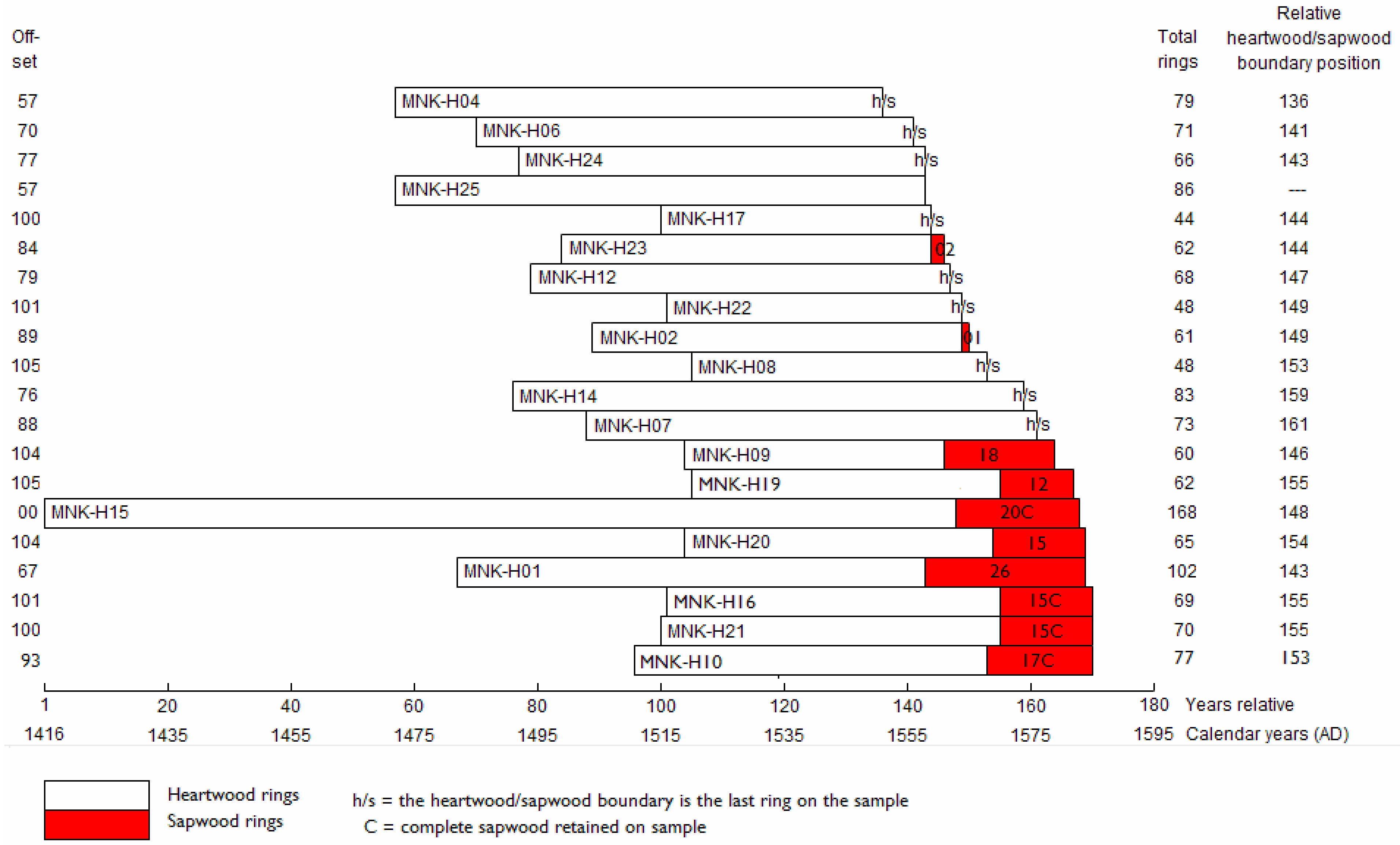


Figure 13: Bar diagram of samples in site sequence MNKHSQ01

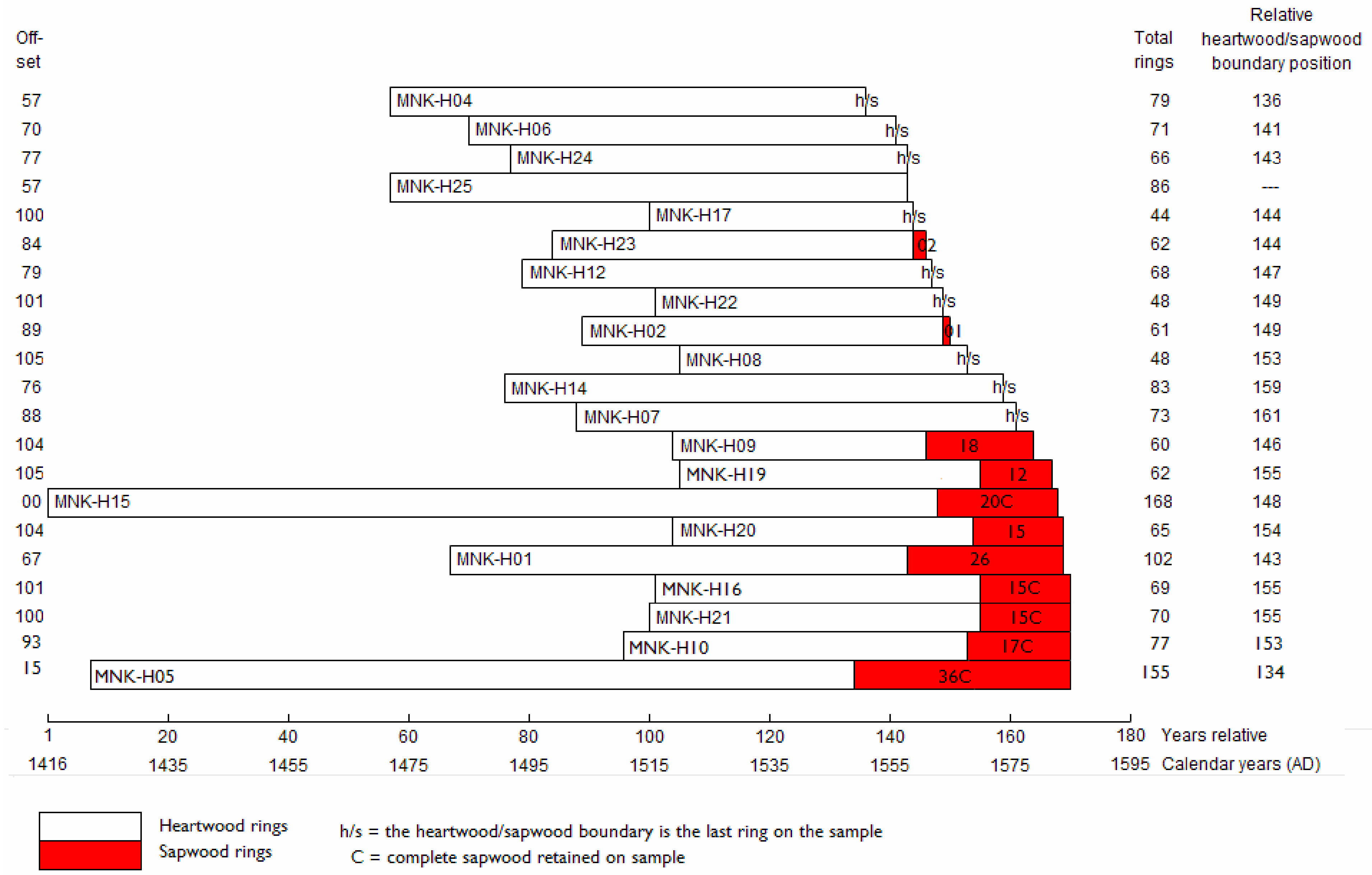


Figure 14: Bar diagram of samples in site sequence MNKHSQ02

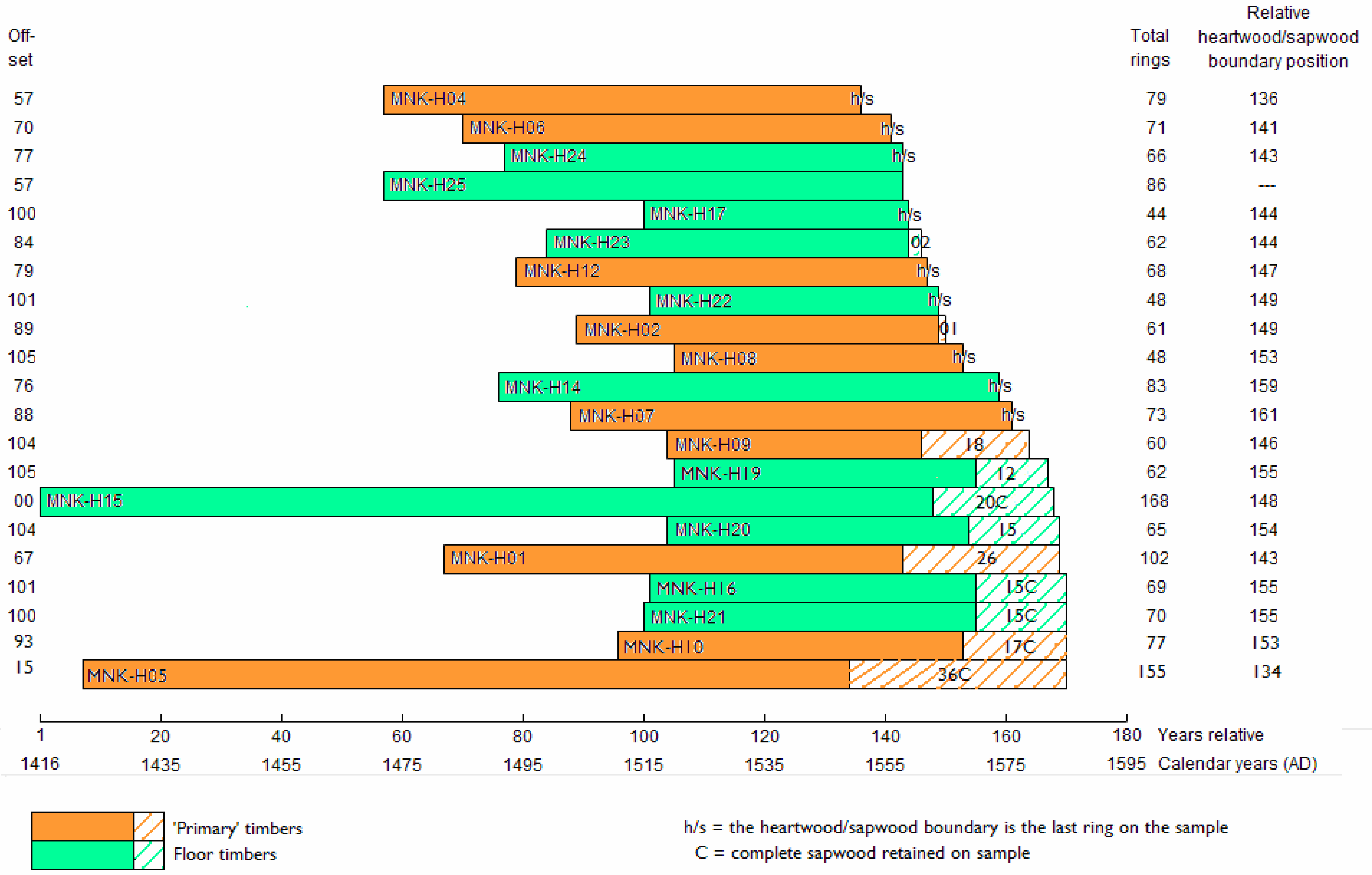


Figure 15: Bar diagram of sample in site sequence MNKHSQ01, colour coded by area

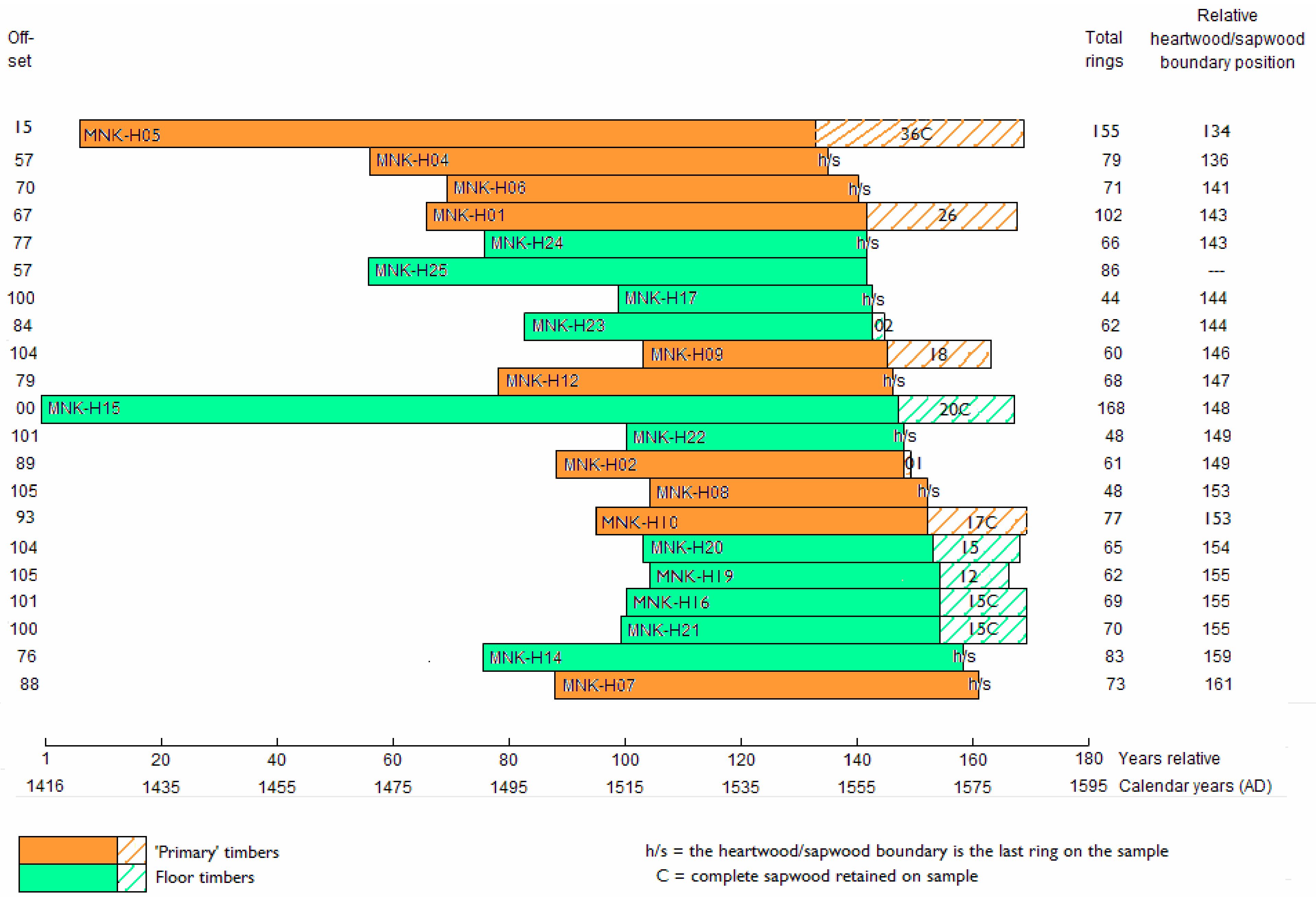


Figure 16: Bar diagram of samples in site sequence MNKHSQ02, sorted by heartwood/sapwood boundary ring date and colour coded by area

DATA OF MEASURED SAMPLES

measurements in 0.01mm units

```
MNK-H01A 102
 109 112 124 122 168 118 105 115  87  80  85 129 118 141 113 110 104 113  98  59
  72  79 135 125 140 140 161 184 206 184 120 147 132 156 115 182 158 179 172 185
 130 163 141 144 108  97 109 116 126 122 111  66 101  93 105  88 100 147 105 105
 104  92 105  85  69 103  88  82 119  90  96  62  89  40  34  67  52  46  81  77
  81  67  42  36  27  39  30  54  36  29  38  36  43  31  23  28  39  58  37  48
  83 152
MNK-H01B 102
 111 104 138 122 165 113 111 114  87  77  85 133 119 143 121 101 106 122  87  75
  68  72 120 129 134 131 162 188 202 169 111 151 135 152 114 178 164 181 174 183
 124 161 145 143  94  97 111 101 112  98  91  86  95  91 105  86 102 151 101 106
 102  86 106  81  73 102  91  78 128  79 103  63  89  38  40  64  48  48  94  78
  80  65  38  40  26  38  31  49  37  38  32  34  46  29  26  26  41  57  44  39
  86 149
MNK-H02A 61
 415 493 400 353 371 377 388 453 408 290 313 288 319 363 322 218 244 266 182 264
 217 207 161 146 126 108 129 138 158 156 153 122 131 111 121 177 161 130 117  85
  95  76  78  95 107 123 119  76  64  41  48  44  52  65  77  62  87  78  75 103
  91
MNK-H02B 61
 420 501 375 360 342 375 394 453 402 289 310 297 315 377 330 263 240 274 183 248
 218 213 160 145 124 112 125 139 155 153 153 131 129 114 116 177 159 127 123  83
  94  76  74  92 114 124 112  72  61  44  48  41  54  65  76  67  91  68  77 103
  92
MNK-H04A 79
 186 199 172 129 110 143 175 181 240 170 208 207 247 230 192 137 113 119 106  93
 100 169 152 192 173 147 133  77  57  44  52  74 212 269 206 135 131 173 151 131
 110 109 100 111 128 185 166 179 147 180 150 230 156 158 132 115  83  63  82  93
  88 110 108  75  76  63  65  83  88  72  95  57  72  72  57  65  90  89 105
MNK-H04B 79
 175 189 169 133 139 138 173 187 240 172 209 205 251 227 188 142 112 118 110 106
 137 176 169 191 172 148 124  73  59  43  50  77 212 272 205 135 131 173 150 137
 103 108  93 114 120 179 168 192 145 173 134 218 155 156 138 116  78  68  83 101
  89 106 116  75  74  59  79  76  84  69  97  57  72  68  61  59  97  90 105
MNK-H05A 155
 104 101  77  62  96  63 102  56  56  81  78 125 125 126 109  71  98  81 125  95
 124 160 131 117  80  88  69  53  45  66  57  64  71  85  74  96  79  90  64  71
  91  69 105 109 134 116  64  91 109 121 128 110 121 129 136 140 139 103  67 103
  74  83  73  98 150 175 110 111  74  87  57  53  61  75  74  90  48  96  98  97
  92  85  67  75  51  66  39 103  99  72  68  71  48  83  70  78  52  43  39  39
  53  49  62  54  42  44  48  45  49  56  42  42  54  50  59  73  51  59  77  63
  56  50  57  42  42  35  50  48  56  49  36  47  48  58  56  40  39  49  42  33
  43  34  40  28  34  32  29  23  44  49  42  31  31  39  41
```

MNK-H05B 155
109 101 79 61 80 76 96 65 50 80 86 116 109 131 114 71 99 82 121 99
120 165 131 127 74 84 66 54 44 67 58 67 65 92 71 96 79 89 71 70
91 74 101 103 136 115 64 90 100 125 116 90 118 133 131 143 152 104 59 104
79 75 72 104 142 175 119 118 72 84 56 48 63 72 70 92 48 96 97 103
84 90 67 72 52 67 42 109 100 71 66 67 45 93 73 69 53 43 38 34
59 48 61 63 33 42 51 46 55 38 55 43 48 46 69 73 48 66 73 68
52 51 56 49 41 32 43 57 56 38 43 50 46 52 59 45 32 41 44 42
35 35 44 32 35 28 24 25 51 46 37 32 44 36 45
MNK-H06A 71
245 287 209 172 223 182 143 155 165 179 179 168 153 129 130 83 52 52 82 274
343 339 255 241 227 261 210 167 174 139 166 122 171 179 148 183 206 128 139 154
174 129 115 77 72 103 76 68 81 87 53 60 63 58 69 87 71 101 68 81
58 53 99 95 117 134 174 188 107 73 46
MNK-H06B 71
251 279 216 170 223 180 150 173 162 199 204 180 152 118 125 77 50 53 79 274
351 307 240 239 202 258 224 165 176 127 161 117 170 180 150 184 202 128 138 154
179 128 123 74 71 101 79 65 89 82 53 66 56 58 73 80 80 99 66 80
63 54 93 91 121 130 169 188 110 66 59
MNK-H07A 73
216 312 223 265 159 317 360 295 208 264 123 294 193 448 414 355 192 401 313 237
323 375 375 336 326 266 270 242 207 174 214 287 237 179 269 115 230 260 266 241
256 247 160 205 162 228 184 281 191 173 132 197 57 52 77 121 124 222 184 153
197 173 122 133 86 82 149 69 69 61 108 98 96
MNK-H07B 73
186 302 232 262 155 317 371 272 202 242 126 293 196 446 415 353 187 406 325 244
325 381 388 361 330 279 278 227 209 177 220 280 236 179 266 125 213 260 265 253
252 244 161 221 156 224 189 269 207 167 129 204 57 57 78 118 129 221 178 151
201 171 122 129 83 88 153 69 66 67 104 96 82
MNK-H08A 48
302 209 150 199 296 280 267 224 160 152 121 98 131 179 329 253 239 291 150 320
419 340 266 255 219 151 196 183 228 222 321 266 197 175 212 95 82 141 172 194
313 259 264 290 238 178 139 102
MNK-H08B 48
309 200 149 154 230 250 273 218 164 150 121 88 137 182 331 252 240 287 144 327
416 334 270 248 225 147 171 183 227 218 324 268 200 170 206 90 87 141 176 195
308 261 259 284 244 180 124 103
MNK-H09A 60
386 433 307 211 238 265 288 389 347 307 287 254 223 241 181 202 192 152 157 159
224 209 173 191 231 253 192 230 209 217 236 244 198 206 167 197 94 76 114 142
154 197 206 167 185 153 154 123 98 130 140 97 67 72 60 52 41 35 42 75
MNK-H09B 60
376 424 307 209 239 262 288 383 345 306 277 254 219 235 188 195 192 157 161 159
222 213 173 192 256 247 195 230 211 217 237 246 197 202 171 195 83 74 112 141
169 198 203 168 185 149 159 126 100 121 141 99 67 63 68 58 33 36 49 65
MNK-H10A 77
110 112 120 163 162 168 187 152 131 218 248 331 368 274 203 212 239 245 252 220
183 178 184 163 152 131 154 128 139 145 154 235 222 165 201 191 126 163 120 163
165 173 218 163 155 122 121 44 65 97 103 95 144 149 118 119 77 90 70 89
77 98 66 79 100 125 83 79 65 89 157 202 178 178 194 229 187

© ENGLISH HERITAGE

MNK-H10B 77
109 111 126 162 172 170 180 154 137 222 248 353 361 272 202 212 251 236 256 226
188 180 186 169 155 134 147 129 138 147 158 231 218 165 201 196 123 158 132 166
168 158 214 160 167 112 123 43 74 87 108 93 141 150 131 116 75 76 73 87
80 90 76 69 108 117 88 80 68 85 155 202 185 181 197 231 186
MNK-H11A 50
211 305 328 306 275 372 421 277 208 211 293 226 188 194 226 251 215 247 244 234
258 246 245 203 176 132 155 167 144 118 156 152 143 151 121 141 169 105 101 158
115 123 144 87 132 157 161 155 111 138
MNK-H11B 50
203 310 326 298 278 365 422 276 220 225 238 229 189 205 225 251 217 252 229 236
240 245 234 199 193 126 166 171 156 121 181 138 154 153 117 143 168 116 92 157
118 125 141 81 138 151 164 149 114 142
MNK-H12A 68
80 182 124 101 93 101 66 69 71 130 228 102 69 70 167 182 153 108 93 99
90 111 157 177 139 130 121 116 98 112 98 121 95 83 72 46 90 82 78 93
110 102 111 73 89 100 126 71 124 104 90 79 77 111 130 126 154 113 139 76
99 85 58 79 94 90 118 132
MNK-H12B 68
94 181 121 101 96 103 68 61 69 122 236 100 67 72 167 183 151 110 87 105
88 113 157 172 138 135 125 107 86 110 92 113 94 88 66 56 81 84 73 91
105 93 97 96 76 108 126 70 129 95 95 75 79 105 135 129 154 109 140 77
99 92 65 68 89 91 117 130
MNK-H14A 83
196 308 191 299 271 217 293 283 282 270 185 239 268 507 394 258 260 299 262 245
220 214 220 163 162 106 188 148 151 180 178 122 200 120 146 98 111 80 89 147
141 123 126 154 153 137 127 187 235 156 107 135 114 123 111 104 108 148 160 152
164 174 94 134 74 66 83 102 79 132 114 127 152 109 88 61 91 66 89 45
54 86 106
MNK-H14B 83
196 313 192 298 267 215 293 288 280 264 179 238 267 458 371 294 281 323 266 240
219 218 221 163 157 107 185 149 159 175 184 118 198 128 135 119 100 85 109 152
146 121 133 134 149 141 130 172 222 150 115 135 113 128 110 106 121 126 161 142
151 173 97 138 71 65 89 99 85 131 124 130 154 116 86 55 98 65 92 46
50 88 114
MNK-H15A 168
23 27 28 31 26 32 30 54 79 57 42 37 26 17 53 76 75 63 90 77
69 70 70 60 59 43 69 87 90 44 41 63 45 56 40 47 36 39 58 27
50 35 41 46 49 48 89 60 61 63 59 81 59 66 69 52 42 86 53 98
135 83 147 146 125 114 78 112 135 138 155 187 113 101 108 90 66 80 89 109
112 103 114 87 62 65 65 65 224 244 278 173 167 159 167 126 123 101 91 93
100 76 107 98 104 110 102 74 102 91 105 95 96 74 79 88 110 140 124 111
102 103 74 115 127 90 75 74 62 82 71 55 69 67 69 98 70 70 58 76
51 69 76 79 53 71 47 70 89 54 44 52 77 64 91 58 62 70 60 58
52 57 67 99 124 81 81 62

MNK-H15B 168
22 25 31 33 19 35 30 58 74 54 43 41 22 18 50 77 71 74 83 79
57 74 74 61 53 55 61 88 83 47 41 61 48 54 42 45 38 37 55 28
50 36 44 43 52 49 81 63 60 67 68 83 66 69 63 57 53 64 48 92
140 87 146 140 106 110 73 113 132 138 155 189 114 90 104 101 68 72 87 108
122 107 115 87 63 66 63 66 226 238 280 173 166 164 163 130 122 99 94 104
96 85 100 104 97 119 97 78 98 84 112 100 99 81 81 92 112 127 120 124
89 95 78 122 122 91 72 83 55 89 82 49 69 61 75 89 65 88 64 66
47 64 80 79 46 72 60 67 84 57 54 51 67 57 91 62 68 65 64 63
46 63 73 98 115 83 76 71
MNK-H16A 69
226 380 388 309 404 364 294 303 312 334 376 325 295 299 299 231 233 235 265 297
213 238 158 287 243 168 234 139 170 158 133 141 151 147 192 154 165 79 108 48
53 77 101 70 123 73 104 125 104 66 73 89 63 114 68 57 66 83 48 37
45 61 131 199 119 86 108 131 90
MNK-H16B 69
227 384 382 345 416 351 295 313 318 331 372 333 294 290 308 237 245 246 281 314
241 259 169 292 231 171 231 145 174 148 142 141 153 144 194 158 157 86 104 61
42 75 98 71 126 77 98 129 101 68 67 96 60 116 74 54 69 72 55 35
44 63 126 205 106 96 102 138 88
MNK-H17A 44
201 314 405 425 348 364 360 244 290 313 336 297 265 222 242 184 185 217 196 290
246 284 269 247 362 295 197 186 162 150 121 114 108 140 131 176 138 154 140 133
97 87 170 183
MNK-H17B 44
203 318 408 427 344 366 354 240 288 316 334 293 265 218 247 181 186 214 195 291
246 276 272 247 361 289 196 179 154 159 119 115 114 146 126 169 122 143 139 136
94 87 171 179
MNK-H18A 53
123 59 59 79 206 163 82 139 274 367 325 331 237 261 222 276 245 204 158 208
147 163 217 216 203 270 217 176 235 260 243 278 253 245 256 278 223 201 239 314
286 218 264 209 266 232 164 192 152 210 175 161 225
MNK-H18B 53
129 60 57 83 209 164 74 138 280 364 361 336 250 255 227 289 232 194 144 206
148 175 222 214 202 264 219 190 225 262 248 272 270 228 255 283 218 206 240 311
292 206 276 215 265 237 163 192 155 210 172 156 181
MNK-H19A 62
338 296 212 245 248 280 334 298 256 253 304 234 222 216 257 283 243 277 173 295
283 174 210 164 206 173 169 145 199 179 261 220 206 111 157 81 60 87 122 83
154 82 100 151 103 82 66 99 93 153 96 79 127 133 67 57 53 76 112 213
126 154
MNK-H19B 62
346 288 210 245 249 276 319 295 254 262 310 229 228 201 251 282 246 276 173 304
290 172 203 157 202 158 160 131 180 173 248 219 206 107 156 74 57 82 149 81
168 81 98 136 104 75 69 97 101 171 93 85 127 132 73 56 56 70 120 215
130 147
MNK-H20A 65
227 304 265 229 280 255 298 280 312 229 267 294 239 229 221 250 296 208 258 173
250 224 164 186 140 169 141 136 146 174 188 205 188 177 94 116 59 52 71 103
64 98 72 81 119 85 56 53 79 81 119 58 71 79 80 52 40 50 65 87
157 106 85 96 103

MNK-H20B 65
237 298 253 242 267 271 278 263 322 236 268 314 254 216 217 264 295 212 253 184
242 225 166 168 139 158 143 138 146 176 192 200 192 171 94 121 53 52 79 104
59 100 72 89 108 86 52 55 81 78 129 67 66 80 72 58 37 46 63 94
157 102 85 90 99
MNK-H21A 70
176 252 272 255 235 300 244 207 236 271 260 266 264 222 201 313 242 249 230 263
266 256 288 197 294 222 184 173 126 184 158 154 170 223 170 217 172 170 98 134
56 41 85 135 64 130 81 107 141 81 76 62 83 86 136 86 74 91 108 75
58 55 65 121 208 124 108 117 125 129
MNK-H21B 70
177 254 270 257 221 305 244 216 244 256 268 268 275 212 222 291 262 264 246 277
267 255 286 200 291 225 186 179 124 177 161 146 168 222 166 204 180 166 94 132
62 47 79 132 67 132 80 102 139 83 73 59 94 81 130 87 75 91 110 73
60 57 63 121 208 127 126 125 121 133
MNK-H22A 48
284 410 416 257 363 335 182 186 282 291 275 237 234 263 219 181 191 169 252 192
201 268 215 341 405 260 274 229 219 171 173 134 162 158 189 144 200 139 138 86
88 229 275 141 196 220 247 193
MNK-H22B 48
275 415 416 259 367 329 181 182 273 293 277 227 240 265 219 177 187 172 243 193
200 269 205 362 411 271 275 233 200 167 169 137 157 146 196 141 191 134 144 88
92 235 266 136 206 223 233 203
MNK-H23A 62
88 113 70 54 60 204 180 182 214 303 267 274 247 218 143 225 192 394 389 375
260 267 248 147 165 205 224 201 148 136 156 140 134 126 132 237 195 177 195 200
316 344 291 237 175 181 143 162 127 137 131 163 123 125 105 110 79 68 144 136
111 135
MNK-H23B 62
103 105 61 53 61 198 164 182 206 311 260 265 252 213 144 231 188 392 394 377
260 281 249 144 165 205 207 194 147 152 154 147 127 134 129 235 206 177 196 196
316 357 290 238 174 177 150 160 123 147 126 163 120 134 104 105 80 69 143 138
113 133
MNK-H24A 66
111 127 106 75 118 65 80 106 132 95 56 89 291 242 188 238 298 218 193 159
133 76 119 125 219 194 212 153 195 197 115 152 187 232 221 198 176 243 193 133
111 137 214 177 181 182 126 191 220 213 260 212 200 128 142 132 132 118 173 126
179 121 112 48 41 120
MNK-H24B 66
125 135 92 87 97 75 78 141 145 93 55 83 302 248 181 213 283 232 180 138
133 82 112 114 237 187 219 151 200 180 104 136 177 209 246 198 177 247 204 137
114 136 225 182 171 184 131 191 228 227 275 253 221 118 159 132 120 121 166 125
178 112 116 60 52 104
MNK-H25A 86
20 32 37 53 44 102 86 30 53 47 96 121 57 34 39 33 57 69 68 85
56 140 72 55 75 42 59 111 143 90 44 92 235 188 140 233 284 272 274 263
212 139 212 197 228 295 292 296 331 266 150 173 200 209 211 165 158 204 168 154
145 153 290 223 243 249 179 270 237 231 223 178 201 177 138 172 134 129 161 108
144 90 83 47 35 104

MNK-H25B 86
23 41 34 40 42 97 87 35 74 44 97 148 59 31 39 28 57 58 80 82
56 130 76 52 70 38 62 116 139 91 38 98 260 192 138 229 275 274 277 261
234 143 214 190 233 303 289 273 326 256 152 170 206 213 215 169 161 208 169 157
143 157 286 235 239 250 181 270 232 240 219 181 202 180 135 174 139 117 168 118
138 83 93 45 30 96

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). 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

© ENGLISH HERITAGE

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

© ENGLISH HERITAGE

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

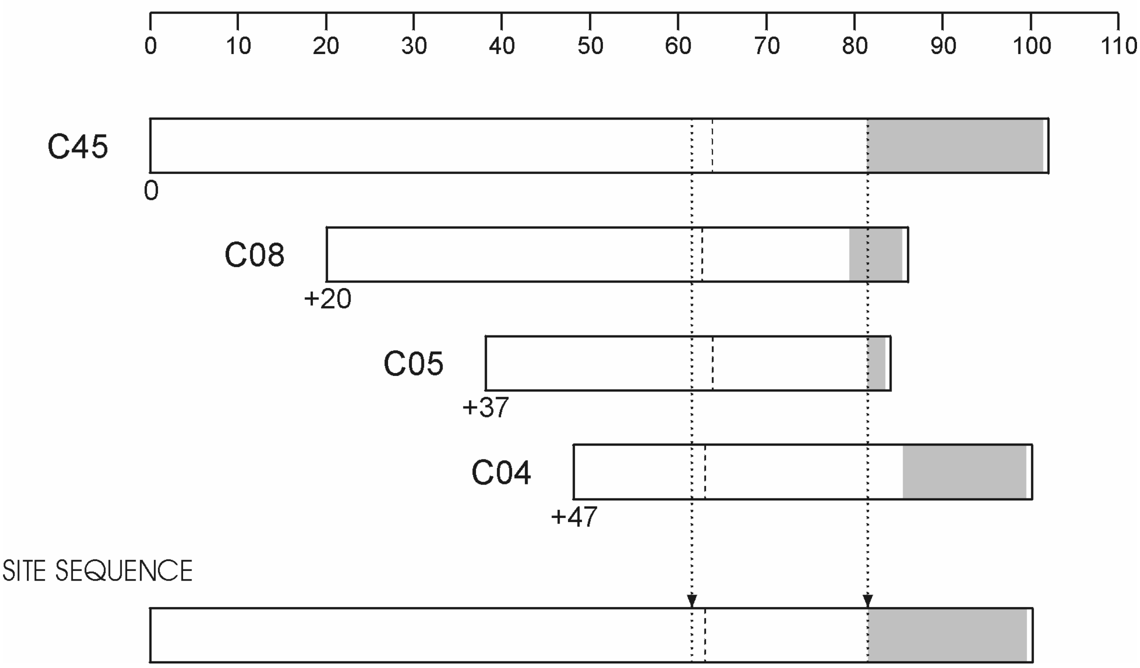


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

© ENGLISH HERITAGE

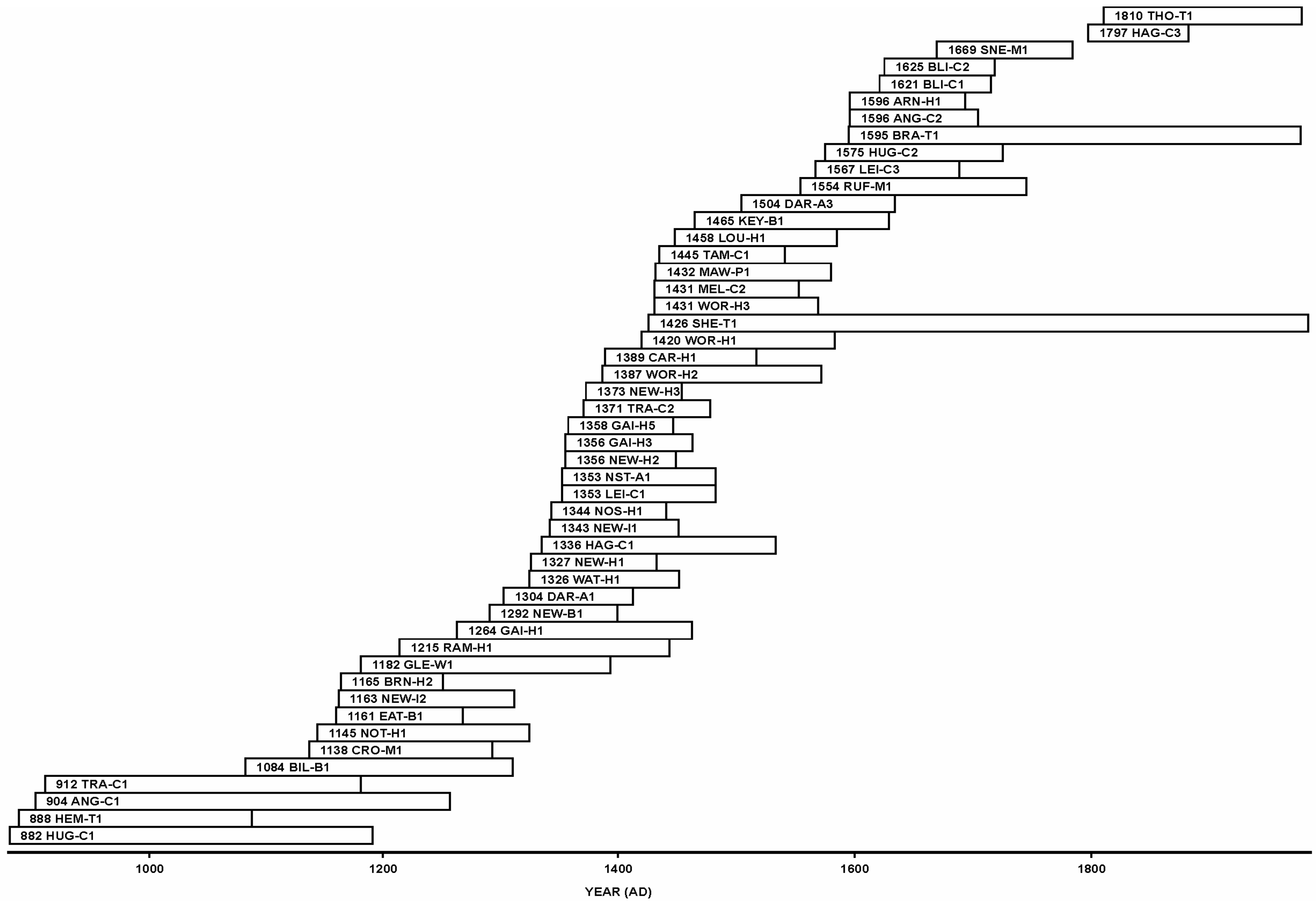
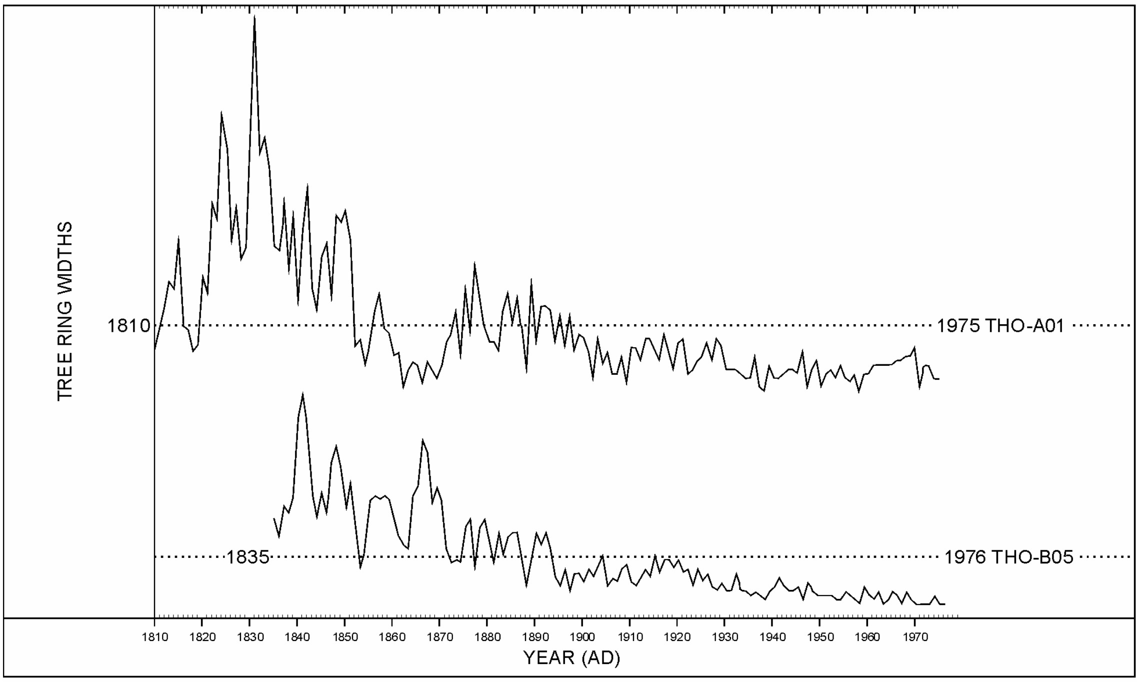


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

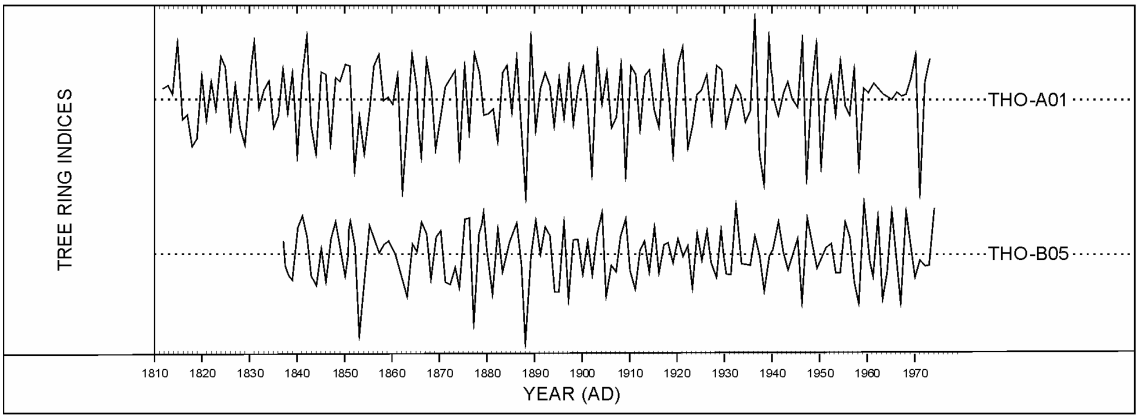


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

References

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

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

Hillam, J, Morgan, R A, and Tyers, I, 1987 Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, 3, 165–85

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

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, 8, 381–90

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

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

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

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

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

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

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

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