RESEARCH REPORT SERIES no. 3-2015

WHALLEY ABBEY, WHALLEY, LANCASHIRE
TREE-RING ANALYSIS OF TIMBERS FROM THE GREAT HALL AND NORTH RANGE

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

This report has been prepared for use on the internet and the images within it have been down-sampled to optimise downloading and printing speeds.

Please note that as a result of this down-sampling the images are not of the highest quality and some of the fine detail may be lost. Any person wishing to obtain a high resolution copy of this report should refer to the ordering information on the following page.

Research Report Series 3-2015

WHALLEY ABBEY,
WHALLEY,
LANCASHIRE

TREE-RING ANALYSIS OF TIMBERS FROM THE GREAT HALL AND NORTH RANGE

Alison Arnold and Robert Howard

NGR: SD 73118 36043 and SD 73159 36090

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)

The Research Report Series incorporates reports by the expert teams within the Investigation & Analysis Division of the Heritage Protection Department of English Heritage, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.

Many of the Research Reports are of an interim nature and serve to 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 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
Tree-ring analysis undertaken on timbers of the great hall roof and the north range resulted in the construction and dating of a single site sequence containing 48 samples and spanning the period AD 1362–1559.

Timbers of the great hall roof have a felling date range of AD 1493–1518. In the north range, the primary timbers associated with the whole of the stables roof are thought to have been felled in AD 1521. Timbers reused as backing rafters to modify this roof have been dated to AD 1490 and AD 1504, whilst a series of purlins are believed to be a mixture of reused, primary, and later insertions with felling dates ranging from the late fifteenth/early sixteenth century to the third quarter of the sixteenth century. A ground-floor ceiling beam in the stables also dates to AD 1521, whilst a lintel was felled a few years later in AD 1524 and two other lintels were also potentially felled in the AD 1520s. Again, in the north range, the bothy roof contains what appear to be primary timbers felled in AD 1559 but also appears to utilise reused timbers from AD 1504. The roofs over the north range carriage house and lobby each contain at least one, presumably reused, timber of AD 1496–1521 and AD 1480–1505, respectively. The partition wall between these two areas contains timber of AD 1524 and AD 1550–75.

CONTRIBUTORS
Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Laboratory would like to thank Nigel Neil of Neil Archaeological Services and Christine Nelson of Whalley Abbey for facilitating access and The National Autism Society for allowing sampling to be undertaken. Thanks are also given to Shahina Farid and Cathy Tyers, English Heritage Scientific Dating Team, for commissioning this work and their advice and assistance throughout the production of this report

ARCHIVE LOCATION
Lancashire Historic Environment Record
LCC Environment Directorate
PO Box 100, County Hall
Pitt Street, Preston
Lancashire PR1 0LD

DATE OF INVESTIGATION
2014

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

CONTENTS

INTRODUCTION

The Grade I listed Whalley Abbey is located in the village of Whalley, Lancashire (Figs 1–3). It was a Cistercian monastery, established in AD 1296 by the transfer of monks from Stanlaw Abbey in the Wirral, Cheshire, and was one of the last Cistercian houses to be founded in England. Building work began in *c* AD 1320, with the abbey church being completed in AD 1380. The east range is late-fourteenth century and the infirmary and abbot's lodgings' fifteenth century. The north-east gateway is also thought to be fifteenth century, dating to *c* AD 1480. Following the Dissolution (AD 1537) the abbey site was leased out by the Crown and then sold in AD 1553 to Richard Assheton, who converted parts of the abbot's house and infirmary into a residence. Assheton's descendants owned it until AD 1834 after which it had a series of different owners. In 1919 the west range and adjacent farmhouse were sold to Salford Roman Catholic Diocese and in 1922 the manor house and remainder of the site sold to Manchester Anglican Diocese, later taken over by Blackburn Diocese. At this point it was developed as a retreat and conference centre.

Great Hall

Within the Assheton manor house, now the conference centre, is a first-floor hall which is open to the roof. There are six trusses of king-post type, with high collars, and moulded archbraces. Between the purlins and principals are carved triangular braces (Fig 4). This roof is thought to be *c* AD 1500 in date. The hall is supported on large beams dendrochronologically dated to AD 1478–1508 (Bridge 2007).

North range

The description of this range is largely based on the report on the building produced by Nigel Neil (2014).

This multi-period range of largely two-storey buildings measures approximately 47m x 9m and abuts the late-fifteenth century north-east gatehouse at its west end. Contained within this range are, from the east, the stables, the former bothy, the carriage house, the lobby, and the gatekeeper or porter's lodge (Figs 3 and 5). This range is thought to incorporate medieval fabric although to what extent is unclear. Historic illustrations appear to show this range and the east range to be linked (Fig 6); the demolition of the link is thought to have occurred during the period AD 1727–62.

Stables

This consists of seven bays, plus half bays at each end. Each bay is separated by a principal rafter truss with king post-type from which braces rise up to the ridgepiece. The easternmost trusses (1 and 2) also have high collars and clasped rather than the trenched purlins seen elsewhere along the roof (Fig 7). The tiebeams of trusses 3 and 4 are canted (Fig 8), rather than straight as seen in the other trusses that are not modern replacements. It was thought possible that the east end of the building had a different status or function than farther west and may even have been of a different, possibly earlier, date. At some point the roof pitch has been modified and backing rafters inserted on the northern side above the principal rafters (Fig 9). These backing rafters are believed to be reused principal rafters, perhaps cruck blades. A number of the purlins and some tiebeams exhibit redundant mortices implying reuse. It has been suggested that the stables date to *c* AD 1558 and that the change in roof pitch dates to the eighteenth century.

At ground-floor level there are two surviving, apparently primary, ceiling joists (Fig 10). The easternmost one (beam 1) has a slot, possibly for a plank-and-muntin partition and widely spaced bars. The joist to the west of this (beam 2) is chamfered.

Bothy

To the west of the stables is the single-bay former bothy. This originally had a staircase in the south-east corner and a north-south partition which had the effect of creating a very narrow room to the west. The ground-floor is believed to have been a kitchen. The only visible roof timbers are two tiers of purlins and a ridgepiece (Fig 11); at least one of the purlins is clearly reused as it has redundant mortices.

Carriage House

The roof of the carriage house consists of two principal rafter trusses with king posts with squared projecting heads, and raking braces (Fig 12). This part of the north range does not appear on illustrations of AD 1727 (Fig 6) but is shown on the Ordnance Survey map of AD 1848, suggesting a nineteenth-century date for it.

Lobby

The roof over this part of the north range consists of modern common rafters, a ridge piece, and two tiers of purlins (Fig 13). This roof is also thought to be nineteenth-century in date, although there is evidence it replaced a steeper (probably thatched) roof, the scar of which can be seen in the unplastered wall (once an exterior wall) separating this bay from the carriage house. Also visible in this wall are the remains of a doorway, as shown by a surviving lintel and post (Fig 14). The dating of this part of the building is unclear.

SAMPLING

A dendrochronological survey was requested by Andrew Davison, English Heritage Principal Inspector of Ancient Monuments, to complete the dendrochronology programme undertaken previously (Bridge 2007) as part of an English Heritage grant-aided condition survey and conservation plan. Obtaining dates for the north range and the great hall roof would inform the overall project, guide future works, and enhance the presentation of the abbey site as a whole.

A total of 71 timbers from the north range and the great hall was sampled by coring. Each sample was given the code WHL-Y and numbered 01–71. The location of all samples was noted at the time of sampling and has been marked on Figures 15–30. Further details relating to the samples can be found in Table 1. Trusses have been numbered from east to west.

ANALYSIS AND RESULTS

Five of the samples taken from the north range had too few rings for secure dating and so were rejected prior to measurement. The remaining 66 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. All samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 52 samples matching to form three groups.

Forty-eight samples matched each other and were combined at the relevant offset positions to form WHLYSQ01, a site sequence of 198 rings (Fig 31). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to span the period AD 1362–1559. The evidence for this dating is given in Table 2.

The four other matched samples form two groups and were combined at the relevant offset positions to form WHLYSQ02, a site sequence of 73 rings and WHLYSQ03 of 63 rings, respectively (Figs 32 and 33). Attempts to date these two site sequences and the remaining ungrouped samples by comparing them against the reference material were unsuccessful and all remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 48 timbers. To aid interpretation each area is dealt with separately below and illustrated in Figure 34. Felling date ranges have been calculated using the estimate that mature oak trees in this region have 15–40 sapwood rings (95% confidence range).

Great hall

Ten of the samples taken from the roof have been successfully dated, four of which have the heartwood/sapwood boundary. The dates of these rings are broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1478, allowing an estimated felling date to be calculated for the four timbers represented to within the range of AD 1493–1518. The last-measured rings of the other six dated samples from this roof range from AD 1444 (WHL-Y71) to AD 1472 (WHL-Y68), and thus have *terminus post quem* dates for felling ranging from AD 1459 to AD 1487. These are thus also consistent with having been felled in AD 1493–1518, an interpretation supported by the high level of cross-matching between some of the dated timbers.

North range

Stables

East end roof

Six of the samples taken from trusses 1 and 2 have been dated. One of these, WHL-Y07, from the king post of truss 2, has complete sapwood and the last-measured ring date of AD 1521, the felling date of the timber represented. The five other dated samples from these two trusses have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary, and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1503, giving an estimated felling date for the five timbers represented of AD 1518–43, consistent with these timbers as also having been felled in AD 1521.

Main roof

Ten samples from the timbers of trusses 3–8 have been successfully dated, eight of which have the heartwood/sapwood boundary ring. In all cases, this is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date of these samples is AD 1496, giving an estimated felling date range for the samples represented to within the range of AD 1511–36. The other two dated samples (WHL-Y09 and WHL-Y22) do not have the heartwood/sapwood boundary ring date, but with last-measured ring dates of AD 1483 and AD 1488 these would be estimated to have *terminus post quem* felling dates of AD 1498 and AD 1504, respectively. This combined with the good level of crossmatching between all of the timbers suggests that they are also likely to have been felled in AD 1511–36.

Other timbers - backing rafters

Two of the backing rafters have been dated, both of which have complete sapwood. Sample WHL-Y20 has a last-measured ring date of AD 1490, the felling date of the timber represented whereas WHL-Y19 is slightly later with a last-measured ring date (and hence felling date) of AD 1504.

Other timbers - purlins

Six purlins in this roof have been dated, five of which have the heartwood/sapwood boundary ring, the dates of which suggest that several different fellings may be represented. These timbers produce a series of overlapping felling date ranges: the earliest heartwood/sapwood boundary ring (AD 1475) belongs to WHL-Y32 and produces an estimated felling date range of AD 1490–1515; WHL-Y31 (AD 1486) gives an estimated felling date range of AD 1501–26; WHL-Y29 (AD 1496) produces an estimated felling date range of AD 1511–36; WHL-Y27 (AD 1510) gives a felling within the range AD 1525–50; and lastly sample WHL-Y28, with a heartwood/sapwood boundary ring date of AD 1534, has an estimated felling date range of AD 1549–74. Thus, whilst some of the five timbers may have been felled at the same time, they clearly represent more than one phase of felling. The final dated sample WHL-Y25 has a last-measured heartwood ring date of AD 1434, giving the timber represented a *terminus post quem* for felling of AD 1449 and so could have been felled in any of the ranges above, or equally could represent a totally different felling.

Other timbers - lintels

Three lintels have been dated, of which all three have the heartwood/sapwood boundary ring. The earliest belongs to WHL-Y35 (AD 1482), taken from the lintel over the south door at ground-floor level, and an estimated felling date can be calculated for the timber represented to the range AD 1497–1522. Sample WHL-Y36, from a lintel over the ground-floor door between the stables and bothy, has a heartwood/sapwood boundary ring date of AD 1491, giving an estimated felling date range of AD 1506–31. The latest heartwood/sapwood boundary ring date (AD 1503) belongs to sample WHL-Y24, from a lintel in the east gable wall, which produces an estimated felling date for the timber represented of AD 1518–43.

However, it should be noted that sample WHL-Y35 matches with sample WHL-Y54 (a door lintel in the partition wall) at a *t*-value of 12.2, a level high enough to suggest that both timbers were cut from the same tree. It is known that sample WHL-Y54 was felled in AD 1524 (see below) and hence it appears likely that WHL-Y35 was also felled at this time. The felling date ranges calculated for the other two lintels (AD 1506–31 and AD 1518–43) encompass the AD 1524 felling date making it possible that all three lintels were felled at this time but this cannot be proven.

Other timbers - ground-floor ceiling

Only one of the two samples taken from the ground-floor ceiling has been dated. Sample WHL-Y33 has complete sapwood and the last-measured ring date of AD 1521, the felling date of the timber represented.

Bothy

Five samples taken from purlins and the ridge of the roof over this part of the building have been dated. Sample WHL-Y38 has complete sapwood and the last-measured ring of AD 1504, the felling date of the timber represented. Sample WHL-Y37 also has complete sapwood but has the somewhat later last-measured ring date (and hence felling date) of AD 1559. The other three samples have heartwood/sapwood boundaries which suggest two separate fellings. The heartwood/sapwood boundary ring date of sample WHL-Y41, the ridge, is AD 1482, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1497–1522, compatible with an AD 1504 felling. The heartwood/sapwood boundary ring dates of the other two samples are both later and broadly contemporary to each other. The average heartwood/sapwood boundary ring date is AD 1533 which, allowing for sample WHL-Y40 to have the last-measured ring date of AD 1551 with incomplete sapwood, gives an estimated felling date for the purlins represented of AD 1552–73, consistent with a felling of AD 1559.

Carriage house

Only one of the samples taken from this roof has been dated. Sample WHL-Y42, taken from a tiebeam has the heartwood/sapwood boundary ring date of AD 1481, giving an estimated felling date range for the timber represented of AD 1496–1521.

Lobby

Roof

A single sample from this roof has been dated. Sample WHL-Y59, from a purlin, has the last-measured ring date of AD 1465. This is the heartwood/sapwood boundary ring which allows an estimated felling date to be calculated for the timber represented to within the range AD 1480–1505.

Partition wall

Three samples from this partition wall have been dated. Sample WHL-Y54, taken from a lintel (east side) over the door between them has complete sapwood and the last-measured ring date of AD 1524, the felling date of the timber represented. WHL-Y56, a plate south of the door has a heartwood/sapwood boundary ring date of AD 1505 giving an estimated felling date of AD 1520–45. This felling date range is consistent with an AD 1524 felling, however, given that there is no clear relationship between these two beams it is also possible that this timber represents a separate felling. The final dated sample, taken from the west lintel over the door between the carriage house and lobby, has the heartwood/sapwood boundary ring date of AD 1535, giving an estimated felling date of AD 1550–75.

DISCUSSION

The great hall roof was thought to date to *c* AD 1500 and previous tree-ring analysis undertaken on the beams supporting this first-floor room had produced a felling date range of AD 1478–1508. Adding support for an end of fifteenth-/beginning of sixteenth-century construction date for this room is the felling date range of AD 1493–1518 now obtained for the roof timbers.

It was unclear as to whether the stables roof was the product of a single phase of construction or whether the east end represented a slightly earlier phase. It is now known that the trusses of the east end contains timber felled in AD 1521 and that the timber used within the rest of the roof was felled in AD 1511–36, a felling date range which encompasses AD 1521. Furthermore, it can clearly be seen (Fig 34) that there is no discernable difference in heartwood/sapwood boundary ring position between samples taken from the east end and the rest of the roof. This, and the evidence of good intra-site matching between samples from both parts (Fig 35) suggests that the timber used in all eight trusses is likely to be of a single felling. Also dating to AD 1521, is one of the two surviving ground-floor ceiling beams from the stables, whilst at least one of the three dated lintels from the stables has been dated to AD 1524. The two other lintels have felling date ranges of AD 1506–31 and AD 1518–43 and it is therefore possible that they were also felled in AD 1524, although this cannot be proven. The dendrochronology has demonstrated not only that both parts of the stable roof are contemporary but has also identified the survival of an apparently primary main floor beam. It therefore appears likely that construction of the stables occurred in the AD 1520s, making it slightly earlier than the *c* AD 1558 previously suggested for it.

Alterations to the stable roof are thought to have occurred in the eighteenth century, although the timber used to undertake this modification can be seen to be reused. One of these backing rafters has now been dated to AD 1490, with a second one, slightly later, dating to AD 1504. It had been suggested that these backing rafters (possibly reused cruck beams) might represent timbers from an earlier stable roof. These timbers have been dated to slightly earlier than the bulk of the material within this building (AD 1521/AD 1524), though clearly broadly coeval with the dated material from the great hall. This raises the possibility that the timber originated from a different structure on site, possibly the linking building of the east range, thought to have been demolished in the eighteenth century.

In addition, in relation to this stable roof, there had been discussion as to whether all of the purlins related to the original construction or were later insertions. The tree-ring dating has produced a series of felling date ranges ranging from the late-fifteenth/early sixteenth century until the third quarter of the sixteenth century for five of these purlins and a *terminus post quem* for felling of AD 1449 for a sixth. The estimated felling date range for one of these timbers (AD 1490–1515) negates it being primary to the AD 1521 roof but it could have originated from the same structure as the backing rafters (dated AD 1490 and AD 1504). Two of the purlins have overlapping estimated felling date ranges (AD 1501–26 and AD 1511–26), which encompass AD 1521/1524, and so may represent primary timbers, and two are later (AD 1525–50 and AD 1549–74), and thus, presumably, represent later insertions.

Roof timbers of the bothy have been dated to AD 1504 and AD 1559. At least one of the earlier purlins with empty mortices is thought to have been reused. This potentially suggests construction of this roof shortly after the felling of timbers in AD 1559, but utilising reused beams of AD 1504. Construction therefore potentially occurred shortly after the acquisition of the site by Richard Assheton in AD 1553 and hence was associated with the work undertaken to transform the former monastery into a manor house.

The roofs over both the carriage house and the lobby were both thought to date to the eighteenth century on the basis of style and, in the case of the carriage house, on the evidence of early illustrations, which do not show this building. Both of these structures are now known to contain medieval timber, with a tiebeam in the carriage house dating to AD 1496–1521 and a purlin in the lobby to AD 1480–1505, though the vast majority of sampled timbers remain undated. The implication is that these two dated timbers are likely to be reused from another structure. At least one of the timbers (door lintel, east) in the partition wall, which separates these two areas has been dated to AD 1524, and it is possible that the plate to the south of the door, with a felling date range of AD 1520–45 is coeval. However the other door lintel (west) is clearly later with a felling date range of AD 1550–75.

Traditionally, the north range was thought to be post-dissolution in date but the tree-ring dating has demonstrated that the majority of the timber in the stables is in fact pre-dissolution, dating to the period of the last abbot John Paslew's tenure (AD 1507–37). It was already known that he was responsible for the rebuilding of the abbot's lodgings and adding a lady chapel, but it would now appear that he was also the architect of the stables. However, the tree-ring dating does suggest that the bothy is post-dissolution, dating to, or soon after, AD 1559. It is possible that the bothy and the lobby are broadly contemporary with the latter containing timber of AD 1550–75, consistent with an AD

1559 felling. However, the interpretation of some areas of the north range remains complex due to the presence of reused timber.

BIBLIOGRAPHY

Arnold, A J, Howard, R E, and Tyers, C 2006 unpubl Tree-ring analysis of timbers from Tithe Barn, Bolton, West Yorks, unpubl computer file *BLTASQ01*, NTRDL

Arnold, A J, and Howard, R E, 2009 unpubl Tree-ring analysis of timbers from 2–4 Church Street, unpubl computer file *LEKCSQ01*, NTRDL

Bridge, M, 2003 *Tree-ring analysis of timbers from Worden Old Hall, Chorley, Lancashire*, Centre for Archaeol Rep, 47/2003

Bridge, M, 2007 *The Conference Centre, Whalley Abbey, Whalley, Lancashire, Tree ring analysis of timbers*, English Heritage Res Dept Rep Ser, 2007/66

Buck, S, and Buck, N, 1727 The south view of Whalley Abby (sic), in the County of Lancaster, *A collection of engravings of castles, abbeys and towns in England and Wales*, 1720–42, London

Esling, J, Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1990 Nottingham University Tree-ring Dating Laboratory results, *Vernacular Architect*, 21, 37–40

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1991 Nottingham University Tree-ring Dating Laboratory: general list, *Vernacular Architect*, 22, 40–3

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

LUAC, 1997 *Whalley Abbey: archaeological works 1995–96, unpubl report, Lancaster* Lancaster University Archaeological Unit

Neil, N, 2014 *Proposed Refurbishment Works to the North Courtyard Range Whalley Abbey Lancashire, report on Archaeological Desk-Based Assessment and Statement of Significance*, Neil Archaeological Services Report

Tyers, I, 1999 *Dendrochronological analysis of timbers from Apethorn Fold Farmhouse, Hyde, Tameside*, Anc Mon Lab Rep, 59/1999

TABLES

Table 1: Details of tree-ring samples from Whalley Abbey, Whalley, Lancashire

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Stables – east end roof						
WHL-Y01	Tiebeam, truss 1	100	h/s	1411	1510	1510
WHL-Y02	North principal rafter, truss 1	78	h/s	1421	1498	1498
WHL-Y03	South principal rafter, truss 1	66	02	1444	1507	1509
WHL-Y04	North principal rafter, truss 2	77	08	1431	1499	1507
WHL-Y05	South principal rafter, truss 2	84	h/s	----	----	----
WHL-Y06	Collar, truss 2	95	h/s	1406	1500	1500
WHL-Y07	King post, truss 2	141	17C	1381	1504	1521
Stables – main roof						
WHL-Y08	Tiebeam, truss 3	94	12	1416	1497	1509
WHL-Y09	Tiebeam, truss 4	89	--	1395	----	1483
WHL-Y10	South principal rafter, truss 5	112	h/s	1385	1496	1496
WHL-Y11	King post, truss 6	88	h/s	1404	1491	1491
WHL-Y12	North principal rafter, truss 6	115	h/s	----	----	----
WHL-Y13	Tiebeam, truss 6	112	04	1388	1495	1499
WHL-Y14	Tiebeam, truss 7	94	h/s	1399	1492	1492
WHL-Y15	North principal rafter, truss 7	109	h/s	1394	1502	1502
WHL-Y16	Tiebeam, truss 8	62	h/s	1442	1503	1503
WHL-Y17	North principal rafter, truss 8	108	h/s	1388	1495	1495
WHL-Y21	North wallplate truss 3-5	49	h/s	----	----	----
WHL-Y22	North wallplate, truss 5-6	70	--	1419	----	1488
Stables – other timbers						
WHL-Y18	Backing rafter, truss 4	50	--	----	----	----
WHL-Y19	Backing rafter, truss 6	75	43C	1430	1461	1504
WHL-Y20	Backing rafter, truss 7	116	33C	1375	1457	1490
WHL-Y23	Lintel, first floor south door	NM	--	----	----	----

Table 1: (cont)

WHL-Y24	East gable, lintel	98	h/s	1406	1503	1503
WHL-Y25	South lower purlin, truss 2-3	72	--	1363	----	1434
WHL-Y26	South upper purlin, truss 2-3	74	--	----	----	----
WHL-Y27	North lower purlin, truss 3-4	70	h/s	1441	1510	1510
WHL-Y28	North upper purlin, truss 3-4	85	h/s	1450	1534	1534
WHL-Y29	North upper purlin, truss 4-5	97	h/s	1400	1496	1496
WHL-Y30	South lower purlin, truss 4-5	NM	--	----	----	----
WHL-Y31	South lower purlin, truss 5-6	111	03	1379	1486	1489
WHL-Y32	North lower purlin, truss 6-7	96	h/s	1380	1475	1475
WHL-Y33	Ground-floor ceiling beam 1	100	20C	1422	1501	1521
WHL-Y34	Ground-floor ceiling beam 2	65	13	----	----	----
WHL-Y35	Lintel over ground floor south door	94	h/s	1389	1482	1482
WHL-Y36	East lintel, door between bothy and stables	57	h/s	1435	1491	1491
Bothy						
WHL-Y37	North lower purlin	84	19C	1476	1540	1559
WHL-Y38	South lower purlin	95	34C	1410	1470	1504
WHL-Y39	North upper purlin	68	h/s	1468	1535	1535
WHL-Y40	South upper purlin	110	20	1442	1531	1551
WHL-Y41	Ridge	99	18	1402	1482	1500
Carriage house – roof						
WHL-Y42	Tiebeam, truss 1	58	13	1437	1481	1494
WHL-Y43	North principal rafter, truss 1	73	21C	----	----	----
WHL-Y44	South principal rafter, truss 1	66	15	----	----	----
WHL-Y45	Tiebeam, truss 2	61	14	----	----	----
WHL-Y46	North principal rafter, truss 2	NM	--	----	----	----
WHL-Y47	South principal rafter, truss 2	48	10	----	----	----
WHL-Y48	North lower purlin, east end to truss 1	55	17	----	----	----
WHL-Y49	South lower purlin, east end to truss 1	51	17	----	----	----

Table 1: (cont)

WHL-Y50	North lower purlin, truss 1-2	50	29C	----	----	----
WHL-Y51	South lower purlin, truss 1-2	44	24	----	----	----
Wall between Carriage house and Lobby						
WHL-Y52	North post	NM	--	----	----	----
WHL-Y53	Plate, north of door	NM	--	----	----	----
WHL-Y54	Door lintel (east)	126	30C	1399	1494	1524
WHL-Y55	Door lintel (west)	129	h/s	1407	1535	1535
WHL-Y56	Plate, south of door	72	h/s	1434	1505	1505
Lobby						
WHL-Y57	North upper purlin	62	h/s	----	----	----
WHL-Y58	North lower purlin	56	h/s	----	----	----
WHL-Y59	South upper purlin	66	h/s	1400	1465	1465
WHL-Y60	South lower purlin	61	h/s	----	----	----
WHL-Y61	Beam to west wall	98	19C	----	----	----
Great hall roof						
WHL-Y62	North principal rafter, truss 1	91	h/s	1385	1475	1475
WHL-Y63	South principal rafter, truss 1	77	h/s	1398	1474	1474
WHL-Y64	South principal rafter, truss 2	97	h/s	1380	1476	1476
WHL-Y65	Tiebeam, truss 2	90	--	1375	----	1464
WHL-Y66	King post, truss 2	86	--	1376	----	1461
WHL-Y67	King post, truss 3	91	--	1362	----	1452
WHL-Y68	East brace (king post to ridge), truss 3	61	--	1412	----	1472
WHL-Y69	King post, truss 4	89	--	1374	----	1462
WHL-Y70	Tiebeam, truss 5	60	h/s	1426	1485	1485
WHL-Y71	King post, truss 5	73	--	1372	----	1444

NM = not measured; h/s = heartwood/sapwood boundary; C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence WHLYSQ01 and the reference chronologies when the first-ring date is AD 1362 and the last-measured ring date is AD 1559

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Ordsall Hall, Salford, Greater Manchester	10.7	1385–1512	Howard *et al* 1994
2–4 Church Street, Leek, Staffordshire	9.8	1406–1512	Arnold and Howard 2009 unpubl
Worden Old Hall, Chorley, Lancashire	8.8	1415–1531	Bridge 2003
Tithe Barn, Bolton Abbey, West Yorkshire	8.7	1371–1518	Arnold *et al* 2006 unpubl
Apethorn Fold Farmhouse, Tameside, Greater Manchester	8.6	1379–1512	Tyers 1999
Nether Levens Hall, Kendal, Cumbria	8.5	1395–1541	Howard *et al* 1991
Mousley Bottom, New Mills, Derbyshire	8.5	1417–1566	Esling *et al* 1990

FIGURES

Figure 1: Map to show the general location of Whalley, Lancashire. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: Map to show the location of Whalley Abbey, Whalley, Lancashire. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

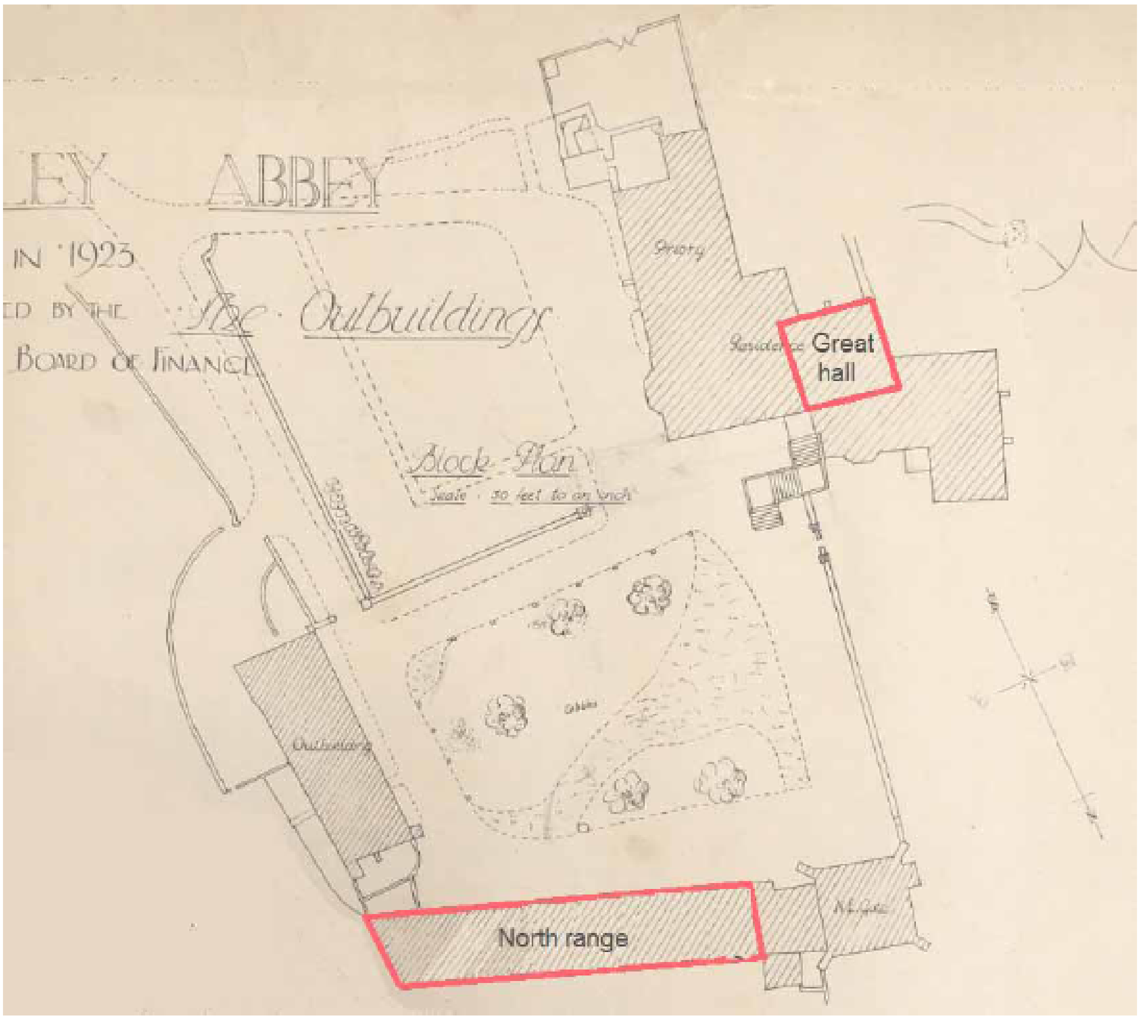


Figure 3: Plan of Whalley Abbey, showing the areas under investigation (Robert Martin, architect to Manchester Diocese (LA DRB acc 7633/37)

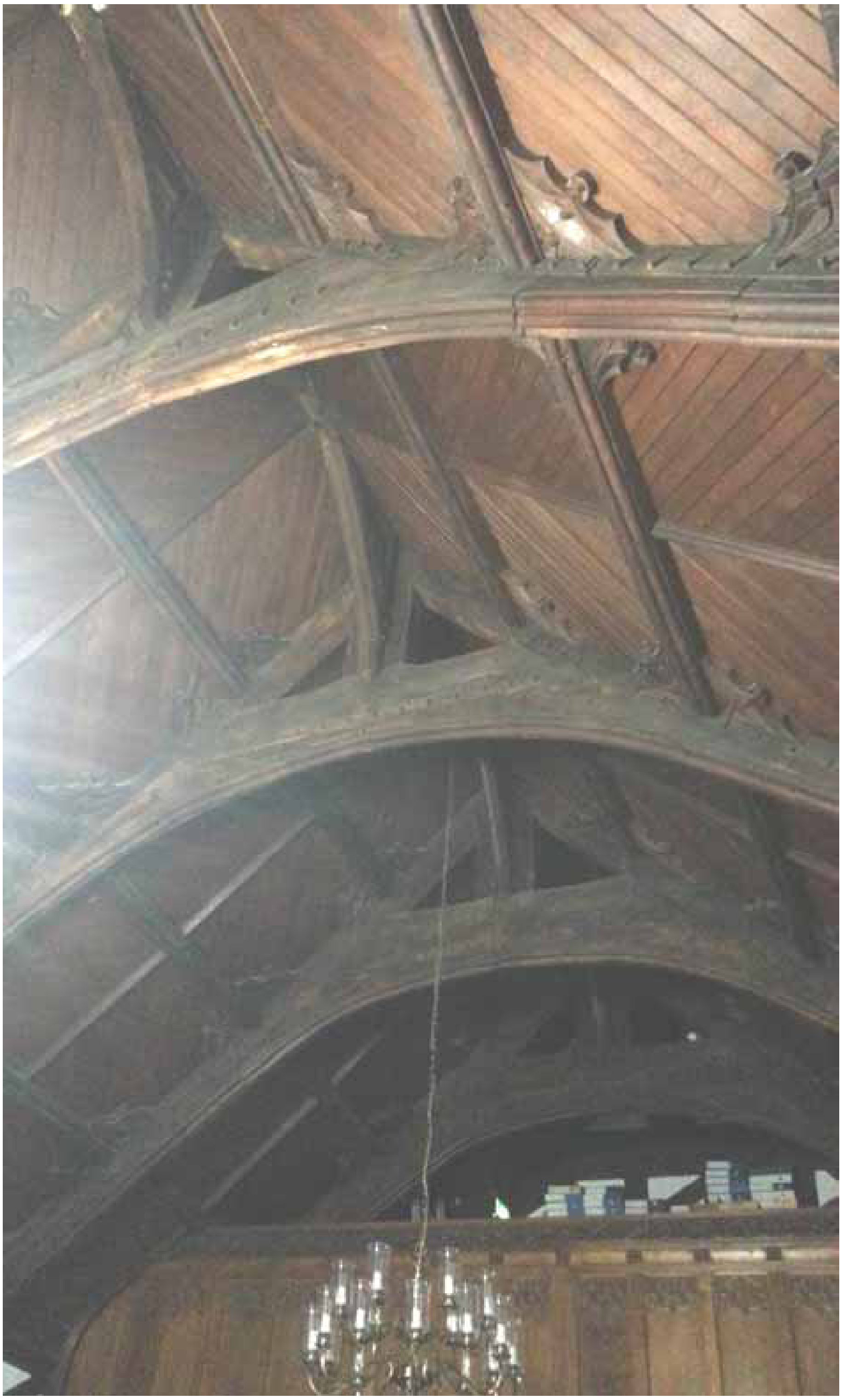


Figure 4: Great hall, photograph taken from the east (William Howard)

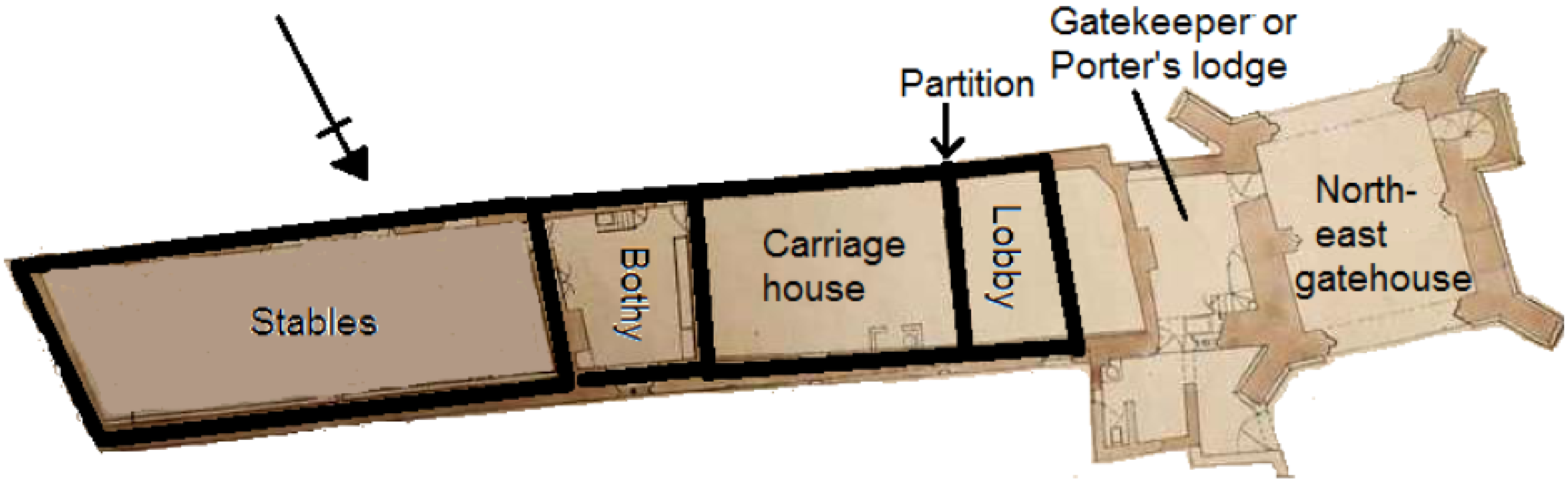


Figure 5: Plan of the north range, showing component parts (Robert Martin, architect to Manchester Diocese (LA DRB acc 7633/37)

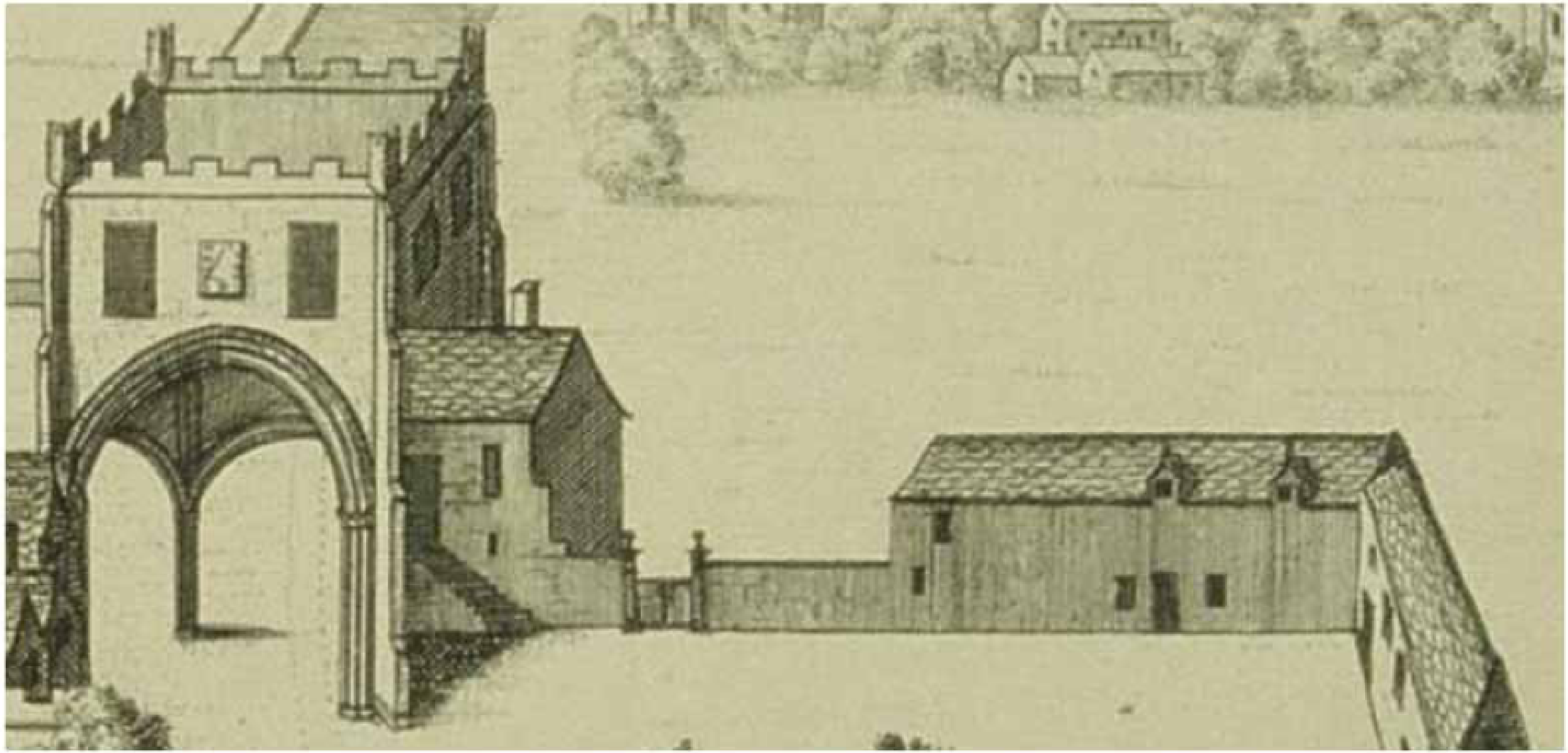


Figure 6: Detail from Samuel and Nathaniel Buck's AD 1727 view of the abbey (north-east gatehouse to the left)

Figure 7: Stables, truss 2 with high collar and modern tiebeam, photograph taken from the east (Alison Arnold)

Figure 8: Stables; truss 4 with canted tiebeam, photograph taken from the west (Alison Arnold)

Figure 9: Stables, one of the backing rafters used to modify roof pitch, photograph taken from the west (Alison Arnold)

Figure 10: Stables, ground-floor ceiling beams (beam 2 in the foreground), photograph taken from the north-west (Alison Arnold)

Figure 11: Former bothy roof, photograph taken from the north-east (Alison Arnold)

Figure 12: Carriage house, truss 2, photograph taken from the east (Alison Arnold))

Figure 13: Lobby roof, photograph taken from the north (William Howard)

Figure 14: Partition between carriage house and lobby, photograph taken from the carriage house (Alison Arnold)

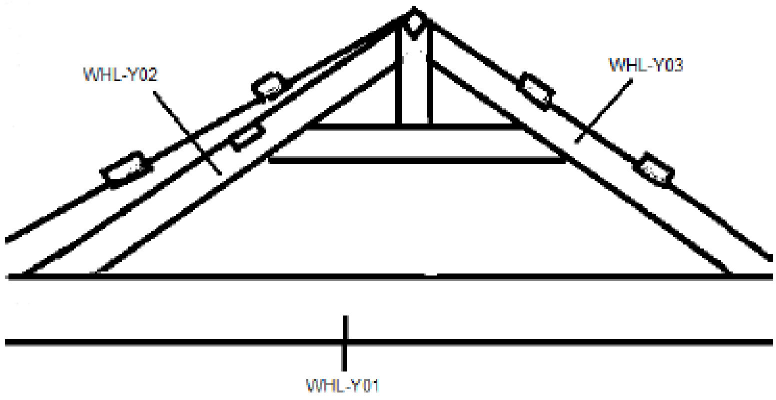


Figure 15: Sketch of truss 1, showing the location of samples WHL-Y01–03

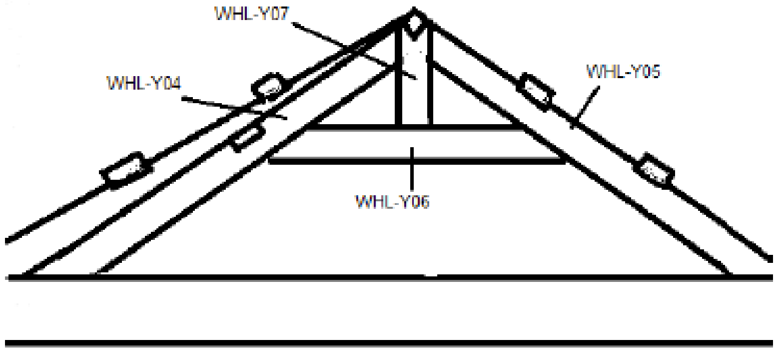


Figure 16: Sketch of truss 2, showing the location of samples WHL-Y04–07

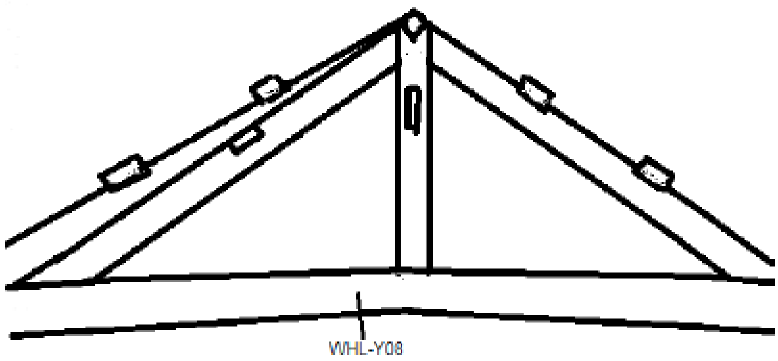


Figure 17: Sketch of truss 3, showing the location of sample WHL-Y08

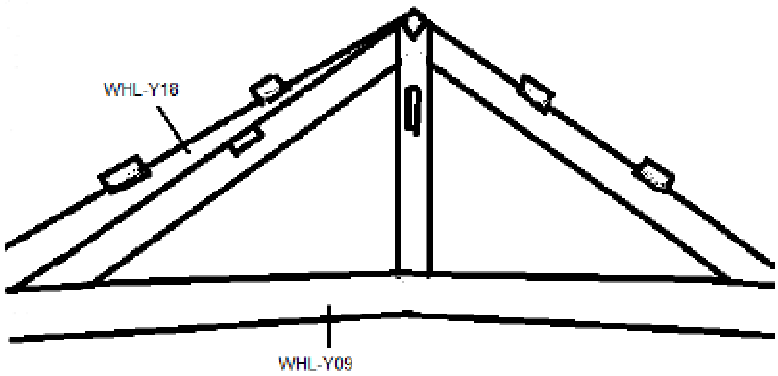


Figure 18: Sketch of truss 4, showing the location of samples WHL-Y09 and WHL-Y18

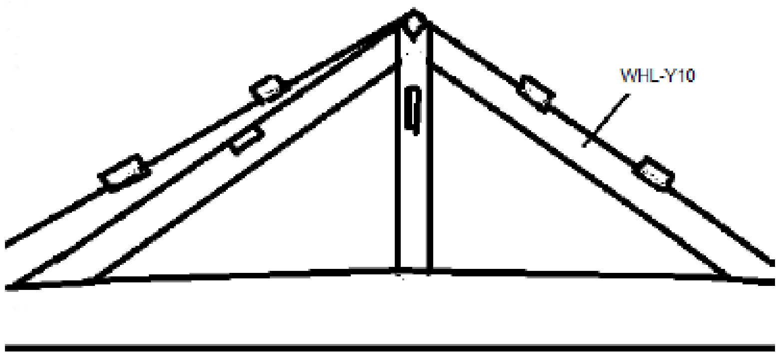


Figure 19: Sketch of truss 5, showing the location of sample WHL-Y10

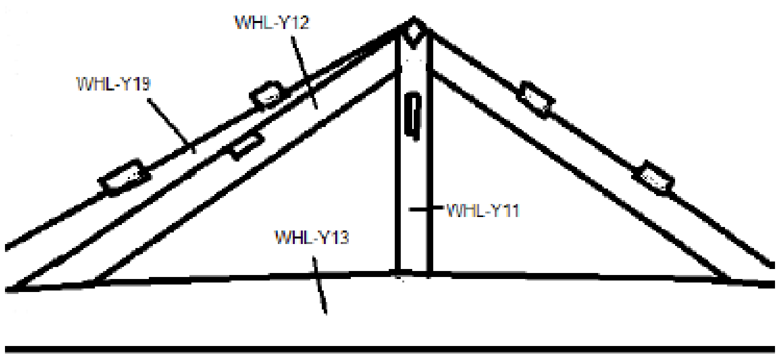


Figure 20: Sketch of truss 6, showing the location of samples WHL-Y11–13 and WHL-Y19

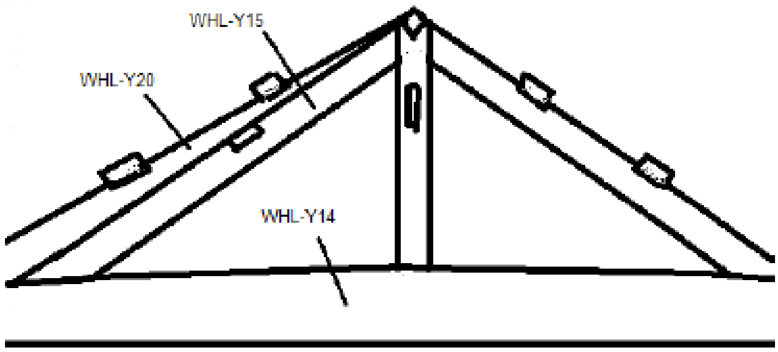


Figure 21: Sketch of truss 7, showing the location of samples WHL-Y14, WHL-Y15, and WHL-Y20

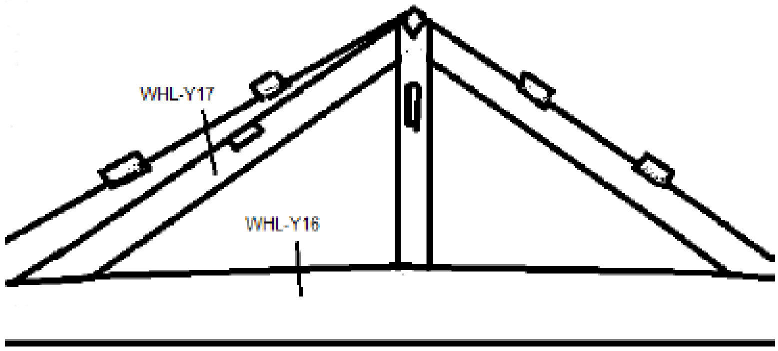


Figure 22: Sketch of truss 8, showing the location of samples WHL-Y16 and WHL-Y17

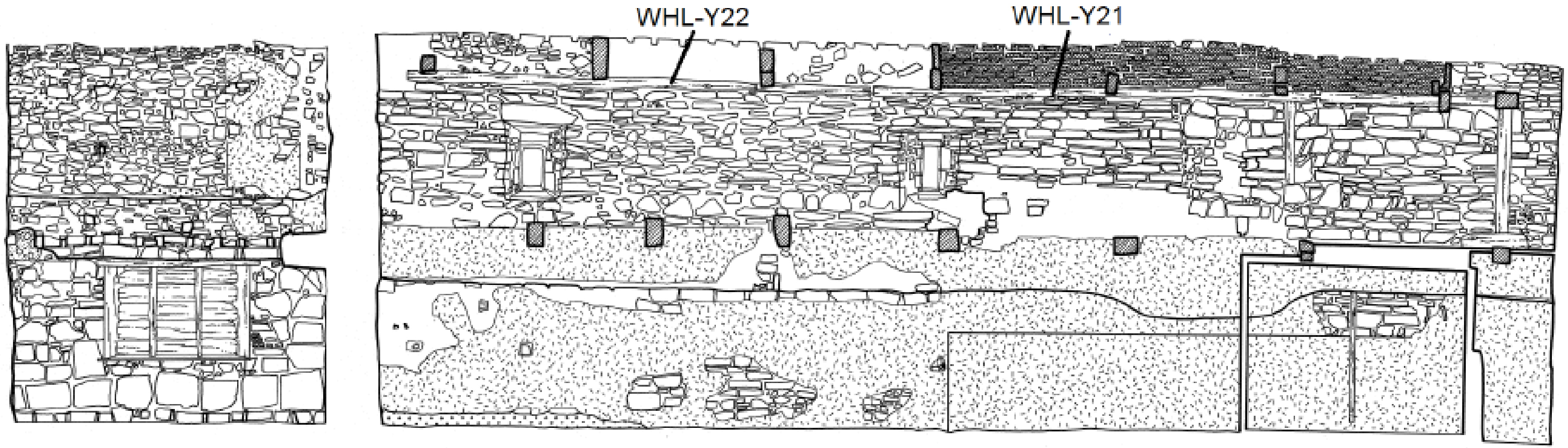


Figure 23: Stables and bothy, north wall (south face), showing the location of samples WHL-Y21 and WHL-Y22 (LUAC, 1997)

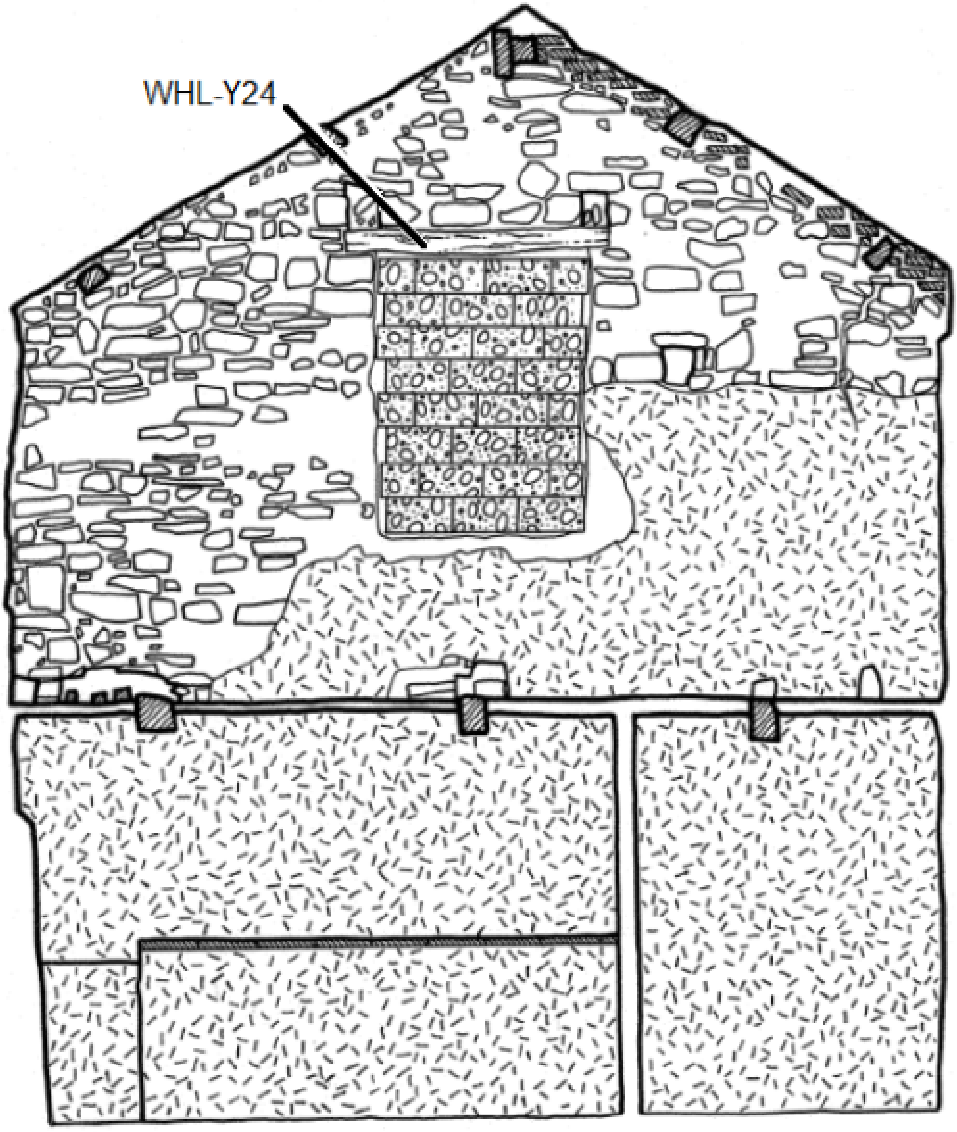


Figure 24: Stables, east wall (west face), showing the location of sample WHL-Y24 (LUAC 1997)

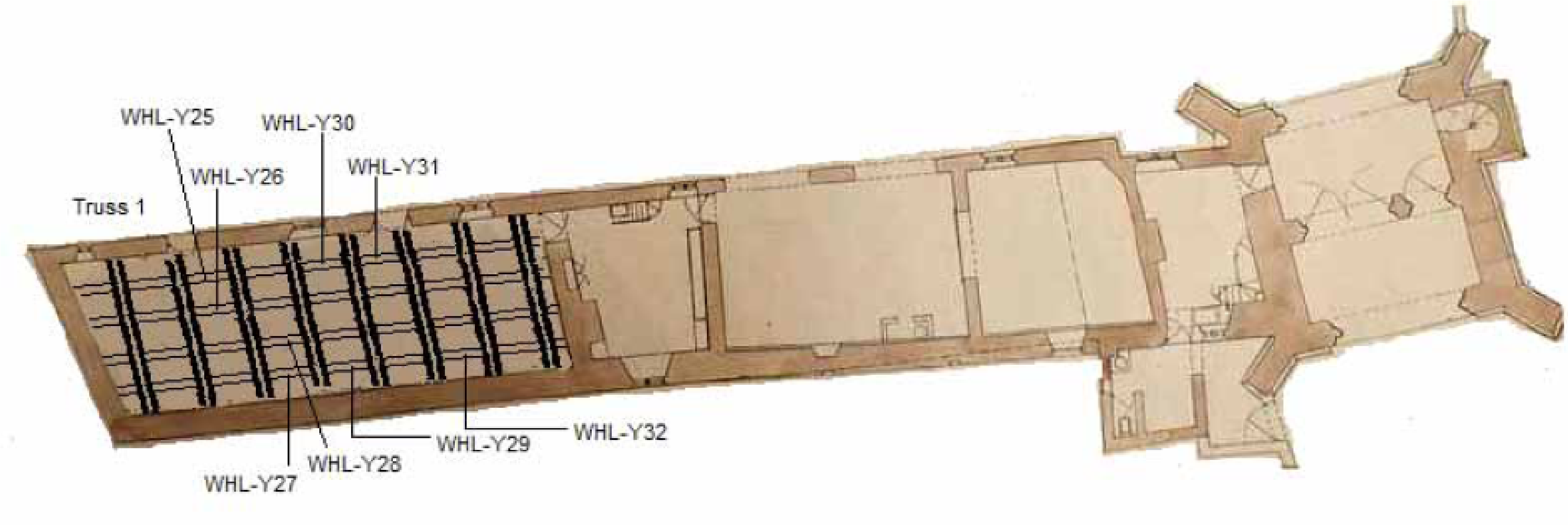


Figure 25: Plan of the Stables, showing the location of samples WHL-Y25–32 (Robert Martin, architect to Manchester Diocese (LA DRB acc 7633/37)

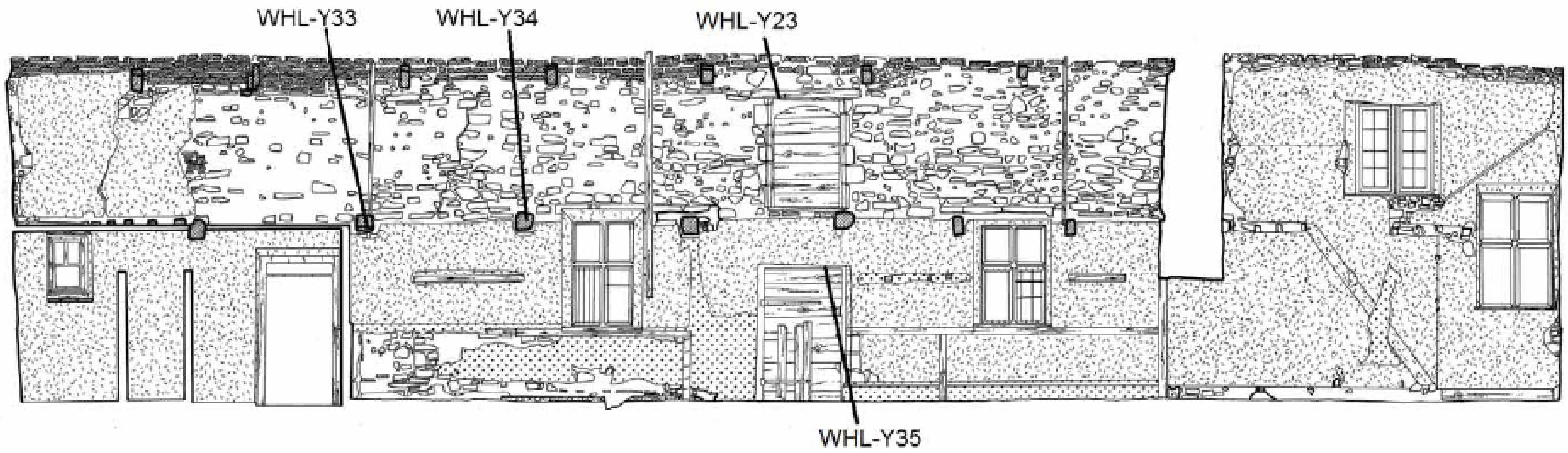


Figure 26: Stables and bothy, south wall (north face), showing the location of samples WHL-Y23 and WHL-Y33–5 (LUAC 1997)

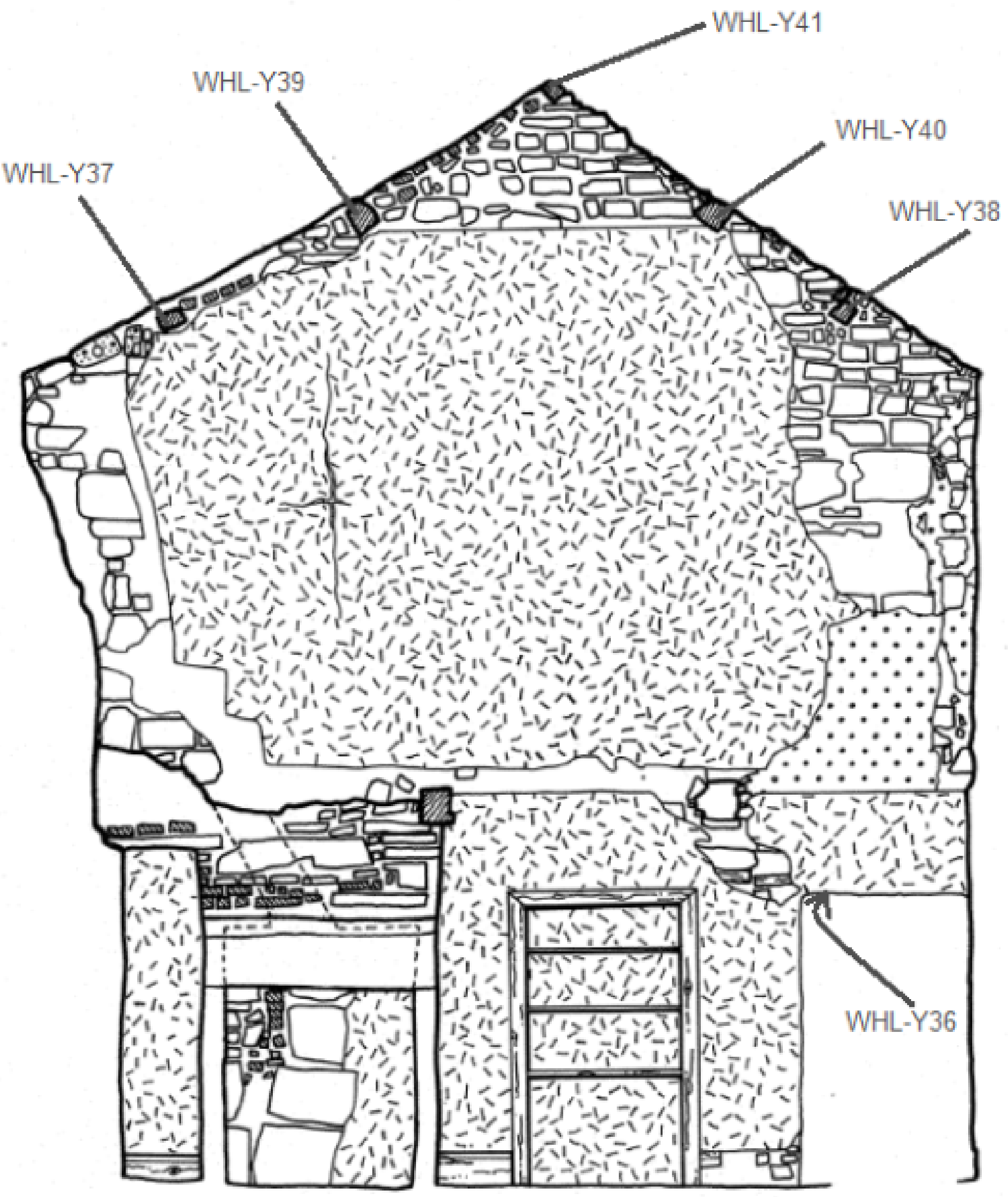


Figure 27: Interior wall between stables and bothy (west face), showing the location of sample WHL-Y36–41 (LUAC 1997)

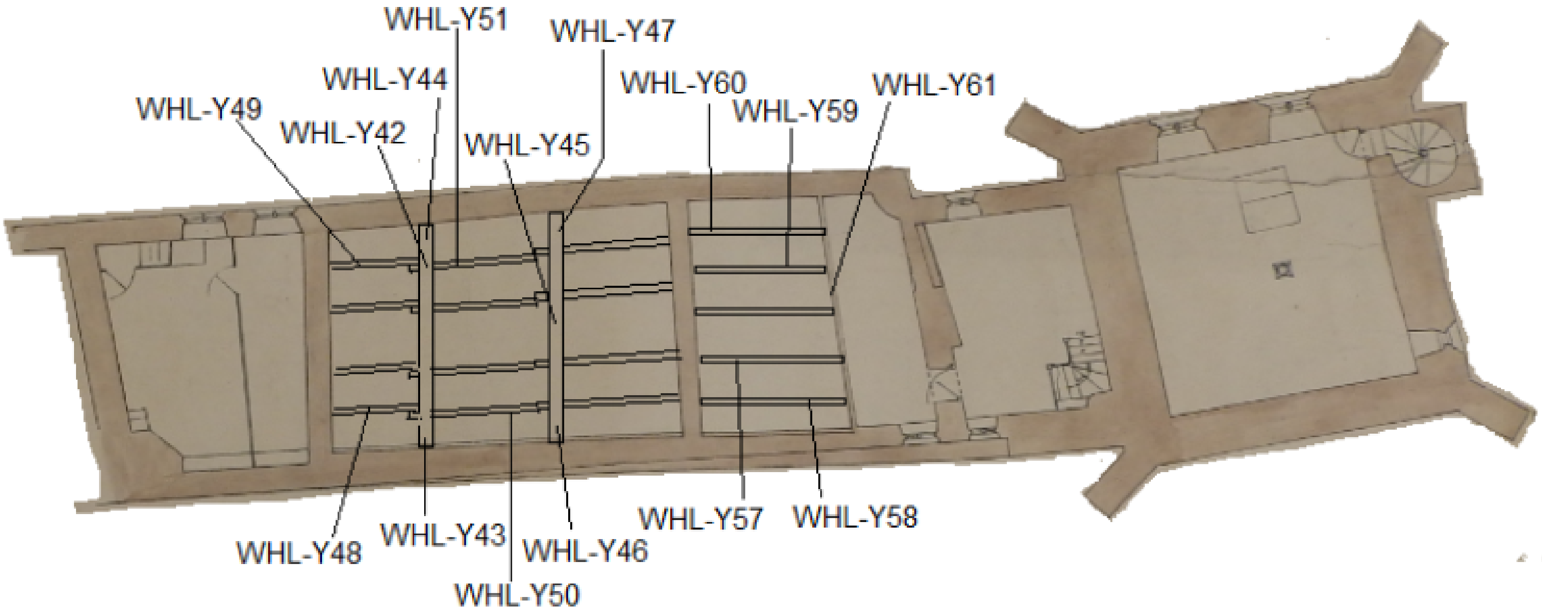


Figure 28: Plan of the north range, showing the location of samples WHL-Y42–51 and WHL-Y57–61 (Robert Martin, architect to Manchester Diocese (LA DRB acc 7633/37)

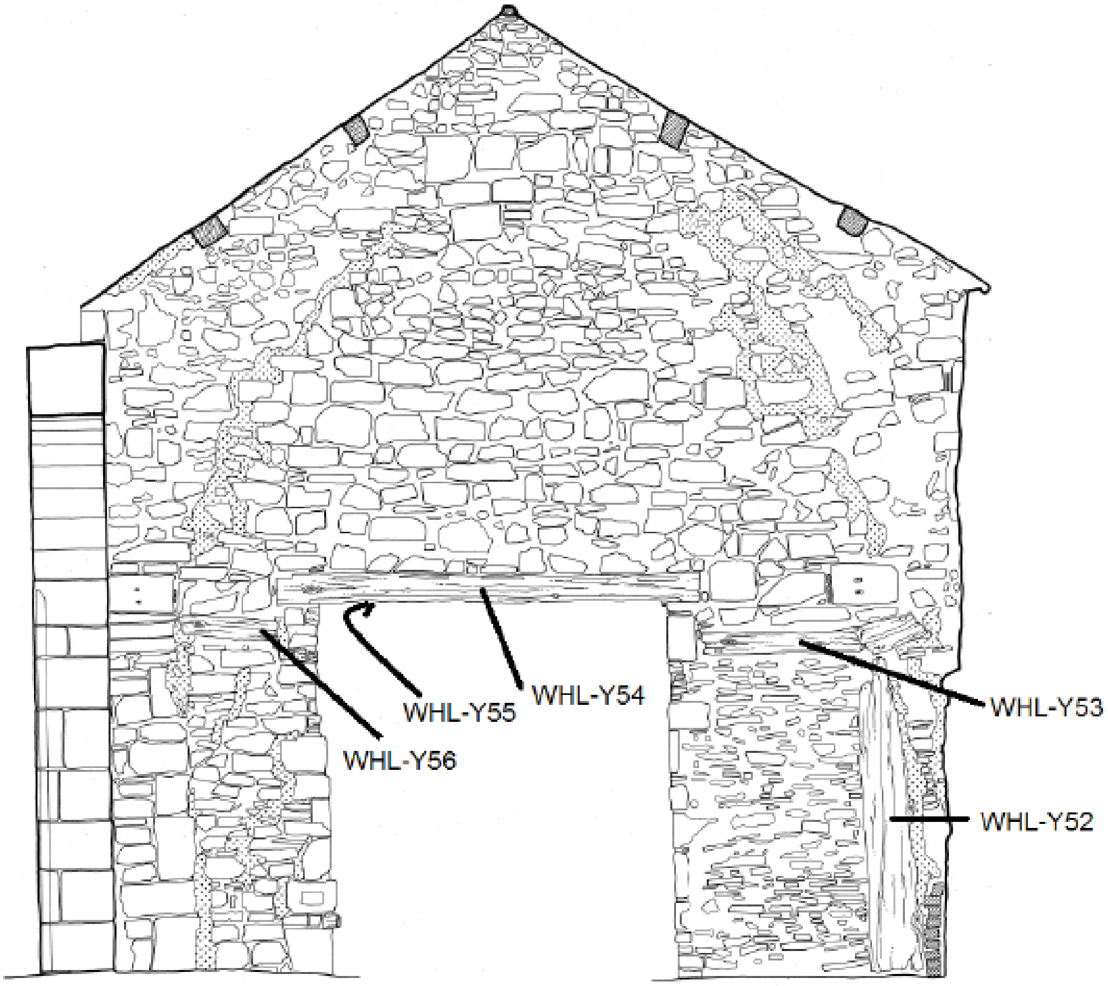


Figure 29: Dividing wall between carriage house and lobby (east face), showing the location of samples WHL-Y52–56 (LUAU 1997)

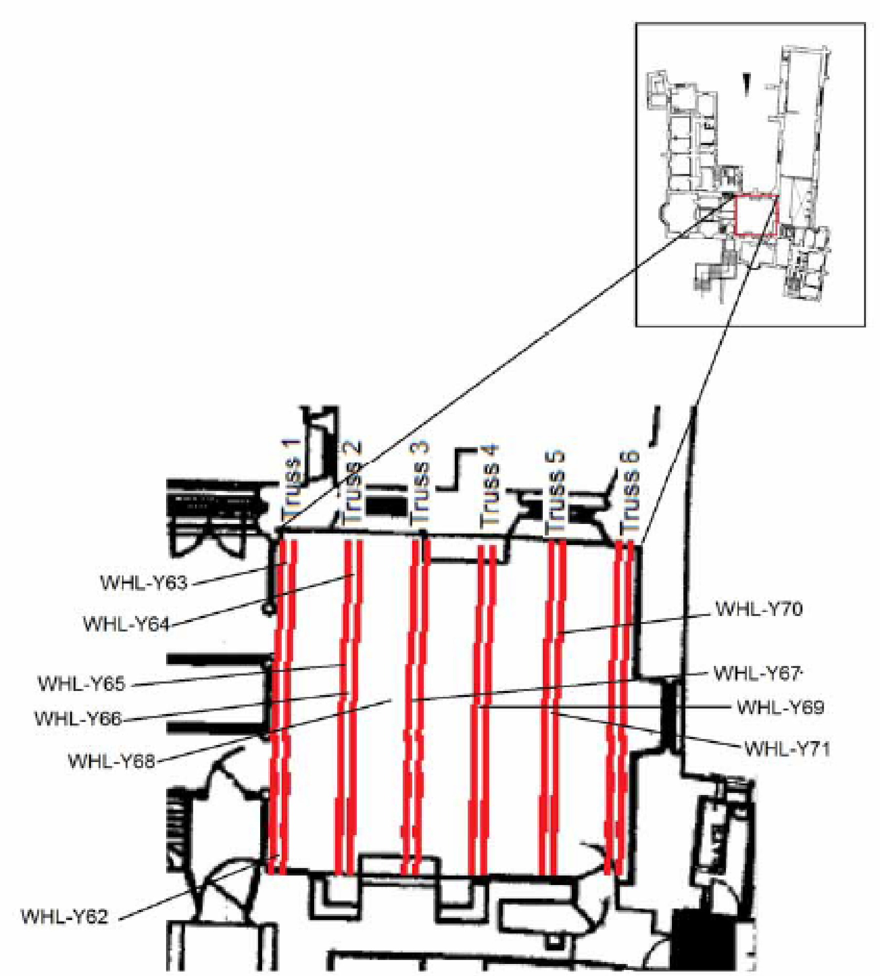


Figure 30: Plan of the great hall, showing the location of samples WHL-Y62–71 (Ashworth Burke Partnership)

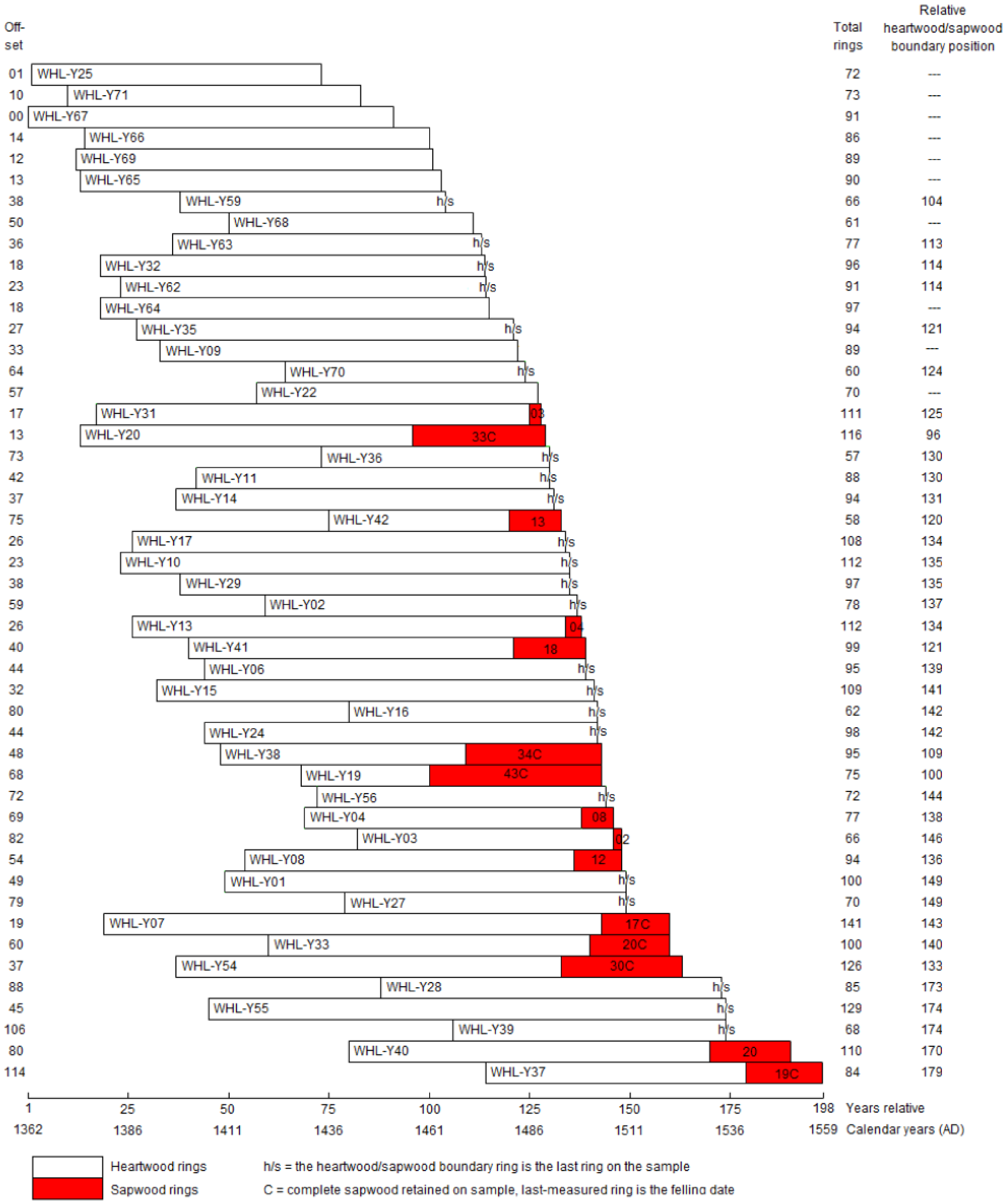


Figure 31: Bar diagram of samples in site sequence WHLYSQ01

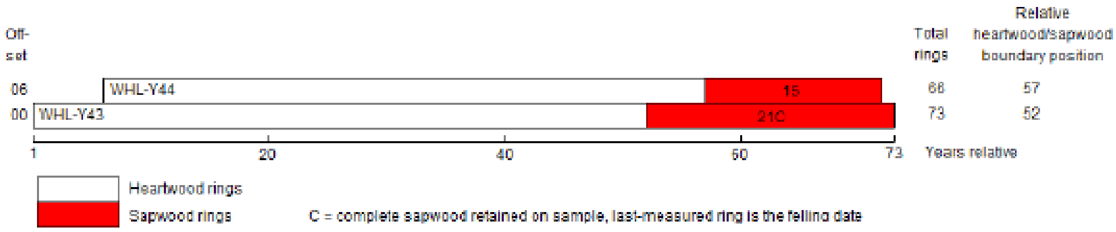


Figure 32: Bar diagram of samples in undated site sequence WHLYSQ02

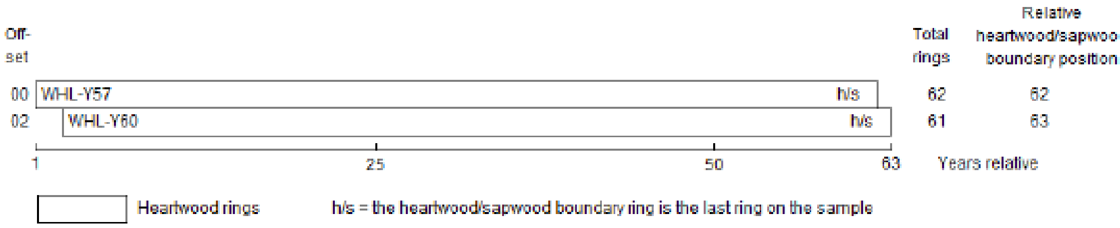


Figure 33: Bar diagram of samples in undated site sequence WHLYSQ03

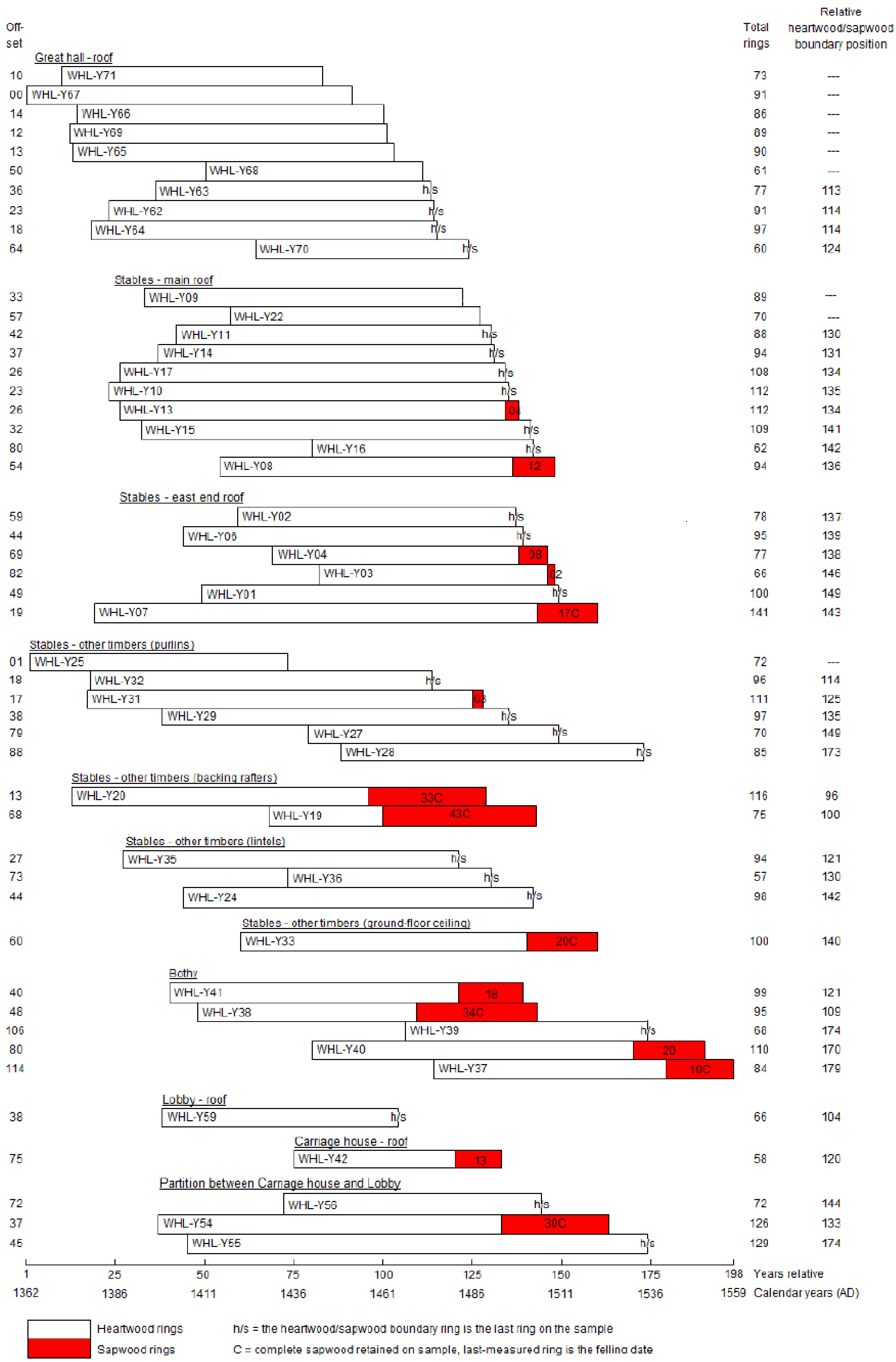


Figure 34: Bar diagram of all dated samples, sorted by area

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
WHL-Y01	1	***	-10	-8	-20	-19	-31	30	-5	-20	10	-36	43	23	41	17	-39	23	-34	-8
WHL-Y02	2	**4.0**	***	-23	20	27	10	35	0	-14	36	-23	49	53	17	-16	-26	28	-19	2
WHL-Y03	3	**4.0**	**8.0**	***	26	33	27	38	49	38	-8	29	60	56	34	54	6	45	4	14
WHL-Y04	4	3.2	3.3	2.9	***	20	20	63	15	-13	46	27	4	-23	-25	37	3	61	-23	12
WHL-Y05	5	3.2	3.0	2.6	**4.4**	***	32	57	-16	-1	-22	39	-24	-34	44	44	-4	55	-8	24
WHL-Y06	6	2.6	**4.2**	2.0	3.2	3.3	***	26	-10	-17	21	2	39	12	7	12	-36	18	-43	-13
WHL-Y07	7	**4.3**	**4.7**	2.9	3.1	3.8	**5.2**	***	-35	-14	-4	-23	-6	-7	-18	-13	-61	-7	-21	-38
WHL-Y08	8	**4.1**	3.5	3.2	2.6	3.0	**6.9**	**5.9**	***	21	31	12	-15	28	17	22	-26	28	-41	-3
WHL-Y09	9	3.6	2.8	2.0	2.7	2.3	3.0	**5.5**	**4.7**	***	10	-9	62	-7	-4	1	2	7	-26	-39
WHL-Y10	10	2.7	2.7	2.5	2.5	3.2	**5.2**	**6.2**	**4.8**	**5.9**	***	-19	6	28	-14	-9	-57	-3	-9	-34
WHL-Y11	11	3.1	3.6	3.1	3.4	3.7	**5.7**	**7.2**	**4.0**	**5.0**	3.9	***	17	-2	5	10	-38	16	2	-15
WHL-Y12	12	3.2	3.3	2.8	2.7	3.3	2.6	3.1	2.4	2.5	2.7	2.4	***	-1	-6	-1	-28	5	-30	-27
WHL-Y13	13	3.6	3.0	3.1	3.2	3.0	3.8	**4.8**	2.9	2.8	2.7	2.9	3.4	***	-11	-6	-54	0	-22	-31
WHL-Y14	14	**4.1**	3.8	3.0	2.5	**4.0**	**4.2**	**7.5**	**6.6**	3.3	3.2	**6.0**	2.5	**5.5**	***	5	-43	11	-3	-20
WHL-Y15	15	**6.3**	**4.2**	3.6	3.4	2.5	**4.2**	**7.4**	**6.0**	**4.6**	3.3	**6.0**	3.5	**5.5**	**7.5**	***	-48	6	-8	-25
WHL-Y16	16	3.1	2.8	2.0	2.2	2.8	**5.4**	**7.2**	**5.5**	2.7	3.5	**5.1**	3.3	3.3	**4.0**	**5.1**	***	54	-10	23
WHL-Y17	17	**5.1**	3.6	2.7	**4.1**	3.8	**5.5**	**8.6**	**6.1**	3.5	**4.5**	**6.7**	2.8	3.9	**7.5**	**7.4**	**5.8**	***	-14	-31
WHL-Y21	18	2.3	1.5	1.9	1.6	2.3	3.8	2.7	2.8	3.3	3.0	3.2	2.8	2.6	3.7	**4.1**	1.7	2.0	***	-5
WHL-Y22	19	**4.2**	3.9	3.5	3.3	**5.4**	**4.4**	**5.6**	**5.8**	2.6	**4.0**	3.5	2.7	3.3	**6.1**	**6.7**	3.7	**5.9**	3.2	***

Figure 35: Table showing offset and level of matching between samples of the stables roof; figures in the box show the t-level *matching between samples from the east end against those from the rest of the roof*

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WHL-Y01A 100
320 360 409 307 321 350 255 272 254 423 268 240 307 306 256 187 219 207 238 266
289 339 289 275 297 300 330 267 201 203 248 284 328 303 238 226 177 143 199 189
209 206 121 57 48 63 61 47 57 80 78 87 96 89 93 112 145 140 78 74
130 111 150 202 246 249 181 134 169 177 151 65 103 161 168 196 232 113 84 77
121 152 139 173 239 235 149 104 106 96 67 82 115 129 119 156 116 131 151 151
WHL-Y01B 100
331 352 400 296 327 350 258 308 257 419 251 254 292 311 254 188 209 208 251 251
281 338 288 276 298 288 334 267 193 211 252 285 331 301 243 223 186 141 192 181
202 218 129 64 51 68 62 48 54 76 88 92 93 86 97 112 146 138 79 72
124 114 148 200 249 253 170 131 163 177 152 68 98 158 173 186 231 124 83 85
129 152 139 173 256 237 148 99 112 92 70 77 120 123 119 161 114 134 152 151
WHL-Y02A 78
77 59 83 113 166 201 165 137 130 96 186 242 186 154 153 159 169 154 154 176
176 173 175 174 126 148 139 144 173 172 147 171 239 441 378 424 385 382 239 356
315 287 304 217 216 248 274 202 143 180 195 132 148 190 322 281 156 209 141 204
256 136 185 249 252 219 289 165 137 114 155 169 115 146 201 230 127 128
WHL-Y02B 78
80 56 84 123 155 202 168 138 131 85 170 226 186 165 151 155 158 164 155 186
182 167 179 176 128 150 144 144 177 185 142 177 238 449 395 421 384 371 248 357
309 282 317 215 222 247 265 212 140 183 202 133 150 178 332 282 149 203 147 207
255 143 186 270 252 219 291 161 140 111 162 164 122 150 185 239 122 116
WHL-Y03A 66
216 123 193 162 205 226 225 218 289 337 487 402 362 256 318 280 392 349 399 408
277 241 322 292 281 198 279 256 219 231 228 360 360 273 257 202 168 249 211 249
250 310 220 256 145 130 109 180 231 157 162 205 259 145 160 184 230 211 176 166
198 192 246 139 149 169
WHL-Y03B 66
200 156 181 160 198 230 229 235 284 334 489 397 367 254 315 274 392 350 394 410
277 240 320 294 293 184 247 278 221 240 230 348 376 255 233 198 167 245 222 245
250 306 213 244 145 124 121 186 230 156 147 212 263 144 162 172 242 211 175 164
202 189 259 149 153 179
WHL-Y04A 76
431 335 345 457 366 269 249 243 186 164 167 138 229 187 200 168 171 177 207 176
199 274 237 203 166 203 195 205 137 143 146 189 154 119 130 138 153 136 142 118
116 105 149 144 178 159 156 113 102 102 84 61 82 80 63 65 44 44 43 47
61 60 56 57 48 67 48 46 45 52 51 51 49 53 47 59
WHL-Y04B 77
418 352 342 469 305 265 260 240 183 169 172 138 223 191 170 157 173 175 211 176
200 275 243 200 166 206 186 207 143 142 147 189 154 110 133 139 146 144 133 119
109 101 157 151 169 157 143 111 102 98 84 55 93 80 63 57 47 41 42 44
59 54 53 51 51 61 53 45 45 40 50 42 50 60 77 80 63
WHL-Y05A 84
42 78 73 101 177 196 259 295 213 384 237 296 347 338 435 334 254 206 223 303
323 325 304 310 187 191 171 191 150 120 118 122 190 120 96 104 95 105 128 90
112 144 176 145 137 117 116 105 117 146 145 135 119 107 124 94 92 81 79 80
76 77 91 104 129 145 111 91 68 87 70 67 75 82 68 59 48 48 50 35
53 57 44 50

WHL-Y05B 84
57 65 82 100 168 204 283 311 213 390 267 302 328 349 449 344 270 205 224 305
321 320 302 287 193 190 170 191 148 118 121 124 184 121 97 106 91 111 129 85
115 144 175 147 132 123 118 104 116 150 141 134 119 106 121 95 92 83 79 74
78 78 90 104 125 144 112 93 73 86 69 67 72 83 59 53 64 47 44 34
52 57 46 52
WHL-Y06A 95
293 259 268 271 292 218 240 211 172 228 158 188 143 143 193 188 187 214 191 143
211 201 170 198 195 173 258 160 228 190 210 133 185 111 158 114 141 186 211 155
119 155 141 189 150 183 179 127 125 141 163 149 142 116 120 101 117 138 115 153
101 103 165 155 231 177 143 227 158 285 262 152 173 213 146 218 181 190 226 189
159 229 193 178 185 186 125 163 116 174 179 140 117 152 121
WHL-Y06B 95
297 260 263 276 290 226 238 213 163 233 156 187 143 145 188 197 166 229 204 135
203 193 165 202 188 179 263 173 224 185 213 137 186 113 158 108 142 187 217 166
118 134 163 184 151 181 183 126 126 136 168 149 141 112 124 104 114 131 113 154
105 92 170 150 238 183 139 226 155 275 252 157 167 215 146 226 184 186 225 188
157 235 203 190 178 176 127 151 120 174 182 141 117 142 130
WHL-Y07A 141
362 333 313 370 295 360 372 355 269 304 315 329 295 287 249 269 288 239 226 292
250 179 318 243 228 223 186 198 228 218 154 175 191 110 143 121 161 147 123 120
147 134 150 138 128 160 160 159 170 210 161 176 135 122 125 127 132 98 87 83
99 99 88 115 100 64 94 89 88 91 87 112 79 61 63 81 75 81 75 69
74 64 89 54 71 86 59 48 63 82 93 50 88 77 133 148 87 83 76 95
138 83 130 168 136 156 172 118 160 149 143 133 113 113 130 179 106 89 106 86
74 124 140 143 143 144 94 106 154 105 120 99 142 124 112 129 85 114 118 117
131
WHL-Y07B 141
366 332 308 368 302 359 372 356 272 303 312 326 299 282 252 267 286 239 233 290
249 178 320 238 231 220 192 198 225 211 151 186 198 105 135 127 154 152 121 122
155 151 148 143 136 163 160 165 170 198 176 180 130 123 132 125 129 103 95 82
95 105 86 106 108 61 99 80 93 97 98 114 71 60 68 71 84 70 68 76
72 69 76 55 76 80 59 48 57 82 90 53 90 85 128 147 93 79 83 91
132 95 123 159 141 152 176 114 156 155 150 124 111 116 133 176 110 91 103 90
72 118 141 138 140 136 92 112 150 111 118 101 140 125 94 148 91 105 119 124
118
WHL-Y08A 94
583 539 415 381 539 354 332 316 347 221 259 365 291 266 229 178 295 181 240 263
196 207 194 126 120 144 156 195 243 243 161 183 195 206 188 158 131 110 86 92
132 130 138 113 140 130 127 145 101 127 76 73 56 56 77 106 105 160 101 192
202 156 136 103 93 127 93 109 125 148 132 168 168 151 154 156 134 150 89 121
147 117 77 91 75 50 73 75 106 134 157 124 104 128
WHL-Y08B 94
591 539 420 378 538 370 324 322 352 225 266 368 301 268 230 173 293 182 243 255
197 211 191 129 120 143 157 192 262 241 163 182 194 206 183 156 134 114 82 106
123 137 135 117 142 135 126 146 98 132 87 63 55 61 72 110 105 156 110 194
202 154 137 99 97 118 93 103 124 147 133 173 162 156 145 156 132 149 98 110
154 114 70 94 78 53 76 85 118 127 142 106 108 140
WHL-Y09A 89
624 529 527 591 498 480 561 295 474 490 411 483 454 448 432 469 357 326 388 348
274 279 278 231 176 194 293 242 244 307 220 252 289 254 212 230 185 247 128 204
141 144 138 140 94 98 110 95 79 113 108 58 135 126 78 106 145 98 67 66
57 72 81 58 78 76 80 55 88 65 70 54 62 39 42 42 54 56 89 78

111 113 98 92 66 72 70 58 79
WHL-Y09B 89
636 532 531 586 501 484 565 296 474 501 403 492 457 460 436 469 356 324 384 342
264 287 272 231 173 185 286 246 253 292 217 249 293 251 219 229 171 272 137 203
145 140 140 122 105 96 106 97 79 106 110 64 131 115 94 110 130 109 67 48
77 63 76 63 80 76 72 65 87 67 64 55 65 36 42 44 50 58 88 75
113 107 103 91 71 74 92 54 73
WHL-Y10A 112
277 494 435 335 369 295 358 358 343 306 383 389 345 314 308 325 325 191 384 334
303 336 253 258 274 200 183 208 194 179 186 142 172 159 112 179 197 148 156 166
154 175 178 183 205 157 104 198 123 182 174 170 113 142 122 116 106 92 110 133
112 69 102 93 77 83 86 97 77 72 74 67 73 73 66 85 69 75 76 62
82 61 78 75 84 79 84 54 64 66 132 137 127 116 77 114 104 93 135 140
90 105 145 87 115 94 85 76 75 75 68 79
WHL-Y10B 112
281 488 444 336 345 311 353 361 343 313 381 396 337 317 307 325 328 186 381 330
303 348 259 261 272 197 182 210 192 182 182 145 172 158 109 180 200 154 148 173
150 178 177 188 205 152 99 203 127 184 168 168 117 141 107 124 117 96 109 130
109 70 103 88 76 95 75 95 74 74 73 75 71 74 70 67 70 75 82 62
85 57 78 82 81 73 87 58 66 60 145 135 125 114 80 99 118 90 132 143
97 79 160 93 118 93 85 77 74 79 71 64
WHL-Y11A 88
355 298 360 279 286 325 353 254 221 247 184 202 186 241 212 186 192 209 240 246
199 165 205 167 180 175 182 273 243 177 209 191 221 172 200 131 128 154 141 171
214 176 121 146 135 143 117 169 169 141 133 121 129 137 113 107 115 105 126 135
106 134 93 107 87 131 146 124 97 131 107 163 140 119 106 85 104 130 84 99
119 130 120 115 99 103 100 132
WHL-Y11B 88
355 304 361 276 285 337 361 250 220 245 186 199 192 240 208 188 191 220 239 243
196 166 198 171 186 176 182 277 238 164 210 187 216 163 210 127 137 152 142 177
214 177 123 147 133 140 122 169 169 138 138 116 134 131 119 108 112 104 114 129
115 133 89 110 88 125 146 130 97 134 106 156 140 115 107 93 104 121 82 99
132 129 116 123 82 93 112 117
WHL-Y12A 115
177 186 148 145 118 151 135 182 173 150 161 168 162 188 182 137 155 130 140 144
151 108 105 114 130 144 141 131 117 118 157 136 118 111 128 125 122 125 127 114
116 152 158 171 166 157 157 148 180 215 194 167 165 151 132 148 158 170 156 182
150 159 148 149 165 183 155 114 130 127 132 137 168 162 190 247 250 295 212 197
149 153 224 208 200 159 147 171 232 232 171 175 138 127 133 106 113 133 101 140
88 106 105 117 105 96 117 111 130 116 101 116 117 99 82
WHL-Y12B 115
183 156 145 141 121 153 134 179 163 147 151 177 170 189 179 136 152 144 147 140
146 109 115 111 133 149 148 127 111 119 166 121 120 109 135 115 121 129 121 110
121 160 154 166 163 160 158 146 175 214 194 169 163 150 139 147 160 170 141 184
155 158 161 142 166 183 153 120 122 131 134 139 164 169 185 240 247 292 214 199
146 161 212 228 188 148 139 175 226 229 172 170 139 123 136 104 116 123 107 138
86 115 94 122 106 92 116 114 131 108 112 117 119 90 88
WHL-Y13A 112
261 393 237 292 359 200 280 336 361 326 339 306 339 302 250 399 310 342 315 287
313 353 293 285 210 177 176 157 145 213 225 153 274 143 104 144 105 135 167 150
175 178 222 208 134 155 134 146 125 159 126 94 127 108 184 132 122 129 126 77
90 118 105 101 126 98 65 64 68 89 85 101 96 89 117 137 112 84 66 49
47 54 77 86 70 100 103 167 149 74 96 90 79 114 95 113 105 115 110 124

94 82 85 85 68 56 81 94 128 76 73 74
WHL-Y13B 112
261 386 242 293 366 210 293 330 356 312 328 310 340 298 252 387 303 342 314 295
313 351 299 287 209 168 179 150 146 215 222 155 278 141 107 132 109 136 161 148
177 181 218 204 141 155 132 144 123 155 155 97 139 122 188 128 134 127 113 84
84 128 100 100 129 95 64 58 78 89 82 94 95 88 116 148 108 89 61 56
43 56 84 82 70 93 107 167 142 77 98 85 85 114 85 110 107 119 106 127
90 83 84 85 72 59 77 92 124 76 71 78
WHL-Y14A 94
367 402 359 238 395 387 375 423 319 351 393 376 262 263 235 117 163 234 240 186
178 241 130 121 126 122 98 200 192 177 210 133 149 122 100 107 187 120 138 129
75 114 95 116 116 166 179 93 124 85 120 95 94 96 78 52 60 72 68 75
74 94 90 121 129 121 99 110 69 54 52 81 98 62 99 99 184 152 122 105
84 81 120 73 72 90 151 135 130 100 135 134 113 99
WHL-Y14B 94
360 385 371 232 465 353 415 422 328 354 383 338 257 263 235 119 167 219 242 192
166 256 130 111 136 119 101 180 197 180 208 130 149 118 100 115 184 113 130 139
72 108 101 115 118 170 171 96 130 85 129 95 93 92 77 67 51 70 67 73
78 93 89 116 139 112 106 106 67 34 57 86 93 59 103 98 182 154 125 103
83 82 118 80 64 94 144 130 132 114 131 127 112 98
WHL-Y15A 109
463 493 356 440 486 451 459 532 299 496 416 349 385 276 245 225 245 154 141 182
146 243 159 183 126 122 184 169 150 213 153 94 86 131 171 119 94 101 95 69
94 112 56 72 71 17 48 87 91 132 148 121 52 61 82 71 72 82 104 72
51 57 62 78 71 69 108 112 119 149 97 72 86 57 28 24 35 42 33 49
82 117 132 57 27 35 49 71 26 33 39 71 79 120 91 71 113 113 83 37
91 144 257 88 46 58 56 35 51
WHL-Y15B 109
484 496 361 432 487 448 458 536 295 509 400 357 390 275 238 233 242 153 144 181
145 243 176 197 124 117 193 167 144 214 149 92 83 129 172 116 99 101 92 69
95 115 48 76 69 28 51 76 93 123 156 120 58 63 75 70 79 80 101 69
51 52 66 77 73 70 105 112 129 147 95 77 74 56 30 24 35 38 26 54
80 118 129 54 26 30 69 62 30 30 42 69 76 120 82 69 125 110 86 39
93 142 246 90 47 77 54 27 66
WHL-Y16A 62
270 326 378 313 202 241 260 257 216 292 347 224 248 232 241 254 331 360 339 284
308 321 245 267 292 243 207 252 300 360 329 431 310 438 432 353 292 348 284 323
234 281 323 330 291 405 324 355 319 269 233 219 264 250 378 322 242 218 249 169
246 207
WHL-Y16B 62
260 292 380 315 208 237 253 256 211 316 317 210 234 231 238 219 340 342 363 278
292 327 257 276 282 219 195 235 305 356 316 421 304 440 443 302 291 333 275 300
238 270 313 322 284 407 333 342 311 308 234 216 258 250 367 299 220 250 244 163
231 195
WHL-Y17A 108
368 214 207 204 263 383 363 414 420 448 446 457 542 451 364 354 278 266 276 150
191 195 219 159 183 180 131 168 172 141 174 136 198 159 147 191 130 95 117 207
143 206 208 141 180 111 143 154 162 113 108 68 110 98 116 123 185 131 110 110
129 168 133 140 191 132 97 112 141 139 122 136 128 134 124 146 101 121 129 103
77 109 174 164 147 174 122 185 163 119 113 97 115 124 67 95 142 130 113 159
84 112 125 145 139 96 83 86
WHL-Y17B 108
367 219 214 197 270 377 366 416 420 438 448 468 542 445 363 359 277 273 264 156

184 198 222 159 182 180 135 164 181 159 181 137 190 165 145 196 132 83 125 204
145 202 207 148 183 113 151 153 154 113 108 71 98 111 110 124 179 131 107 108
136 172 133 153 186 135 94 108 142 137 122 135 129 135 130 136 112 110 130 108
76 107 176 169 135 177 119 192 159 128 92 100 124 150 53 83 150 136 102 148
77 109 130 144 148 78 92 72
WHL-Y18A 50
125 178 298 302 315 355 154 163 160 328 409 489 287 504 347 272 307 302 329 335
277 165 170 147 143 145 111 98 91 117 125 107 96 93 97 112 167 161 136 116
123 130 373 314 284 513 495 465 336 285
WHL-Y18B 50
137 170 296 294 322 357 150 170 165 329 419 496 288 501 349 267 323 309 318 329
270 165 171 158 147 147 116 94 93 109 128 118 87 93 90 118 172 145 126 117
122 128 381 308 289 510 491 468 337 269
WHL-Y19A 75
123 124 166 102 113 63 63 79 54 41 49 59 60 62 81 67 52 56 64 66
71 90 82 99 81 56 46 54 46 47 57 59 63 61 72 59 59 59 45 50
60 57 63 67 69 85 105 71 48 37 62 71 44 40 53 62 73 75 47 62
75 89 66 59 65 68 79 58 47 59 54 37 49 126 211
WHL-Y19B 75
116 127 162 100 113 63 61 82 51 42 45 56 59 63 84 62 52 67 66 60
71 92 80 103 83 70 48 52 47 45 52 61 55 66 76 62 51 58 43 52
60 55 63 61 73 88 98 63 53 44 55 77 38 39 52 60 74 78 47 63
77 94 68 60 73 64 74 64 48 56 48 41 48 128 209
WHL-Y20A 116
66 78 74 116 145 169 116 132 82 112 108 164 208 220 290 188 251 218 269 291
325 325 159 228 272 239 203 148 190 153 166 160 127 162 154 145 128 137 107 145
143 124 147 121 103 173 198 157 206 192 205 192 201 179 180 165 187 212 126 158
154 171 134 98 113 92 100 84 113 151 111 85 130 190 159 134 166 161 128 112
117 112 118 159 141 169 127 143 146 105 131 116 93 69 49 47 54 80 93 122
187 142 163 107 98 90 98 56 49 82 86 77 70 65 57 37
WHL-Y20B 116
84 77 74 113 132 167 125 120 87 123 54 156 198 223 299 208 260 222 262 302
324 325 159 222 279 237 200 145 187 161 177 158 121 159 154 148 132 138 105 143
141 128 144 121 98 174 190 156 197 193 203 193 198 186 172 170 184 217 120 158
156 172 133 95 115 96 100 84 116 140 119 86 132 186 159 136 161 167 129 114
119 104 119 160 139 171 124 147 146 97 142 102 109 65 50 51 54 79 89 123
210 144 157 106 100 88 98 60 50 80 84 80 75 67 47 30
WHL-Y21A 49
246 470 442 443 395 352 347 365 377 237 244 235 192 302 264 317 186 153 165 221
205 222 181 210 233 156 193 244 149 172 185 154 132 162 121 143 128 63 108 92
125 135 186 131 122 128 136 164 135
WHL-Y21B 49
243 484 439 446 409 349 347 369 376 237 241 232 189 304 268 321 176 154 155 221
200 227 181 209 232 151 198 239 148 156 191 158 133 161 117 140 131 59 109 89
130 143 190 138 128 122 135 166 144
WHL-Y22A 70
272 352 353 354 339 240 259 278 316 297 322 160 116 173 204 182 194 128 160 168
80 125 119 146 153 199 151 103 122 125 133 127 124 149 134 90 88 90 104 75
64 77 75 89 80 76 89 86 60 62 54 77 100 70 97 115 166 163 93 97
96 100 116 67 102 143 176 151 171 136
WHL-Y22B 70
271 357 353 349 363 256 232 299 333 294 327 150 131 202 197 181 192 124 172 139
106 147 113 155 154 164 171 108 121 127 132 128 120 152 137 93 94 97 104 77

62 74 80 84 89 73 87 80 70 64 52 83 95 67 111 102 181 161 94 99
97 101 117 67 105 144 185 147 176 137
WHL-Y24A 98
140 205 182 175 209 233 330 336 256 348 370 267 198 187 342 313 330 326 326 342
355 351 406 441 408 421 369 324 413 287 305 284 288 276 249 222 183 291 313 263
209 199 254 190 177 246 234 103 128 105 138 90 94 103 154 177 181 220 198 190
226 207 188 149 128 112 114 116 102 161 124 146 152 84 114 107 75 77 68 58
65 85 64 55 42 69 83 62 84 90 86 58 64 56 41 47 68 56
WHL-Y24B 98
149 200 181 179 209 239 331 325 256 345 366 270 202 184 337 319 320 317 331 348
360 348 407 444 411 422 379 325 398 289 299 285 268 274 240 222 188 290 312 264
202 205 244 200 172 245 236 103 140 101 142 84 100 102 157 173 191 214 200 188
214 206 192 150 135 117 109 100 104 148 115 144 156 83 115 109 74 82 65 55
66 86 67 56 35 73 86 58 85 88 85 57 62 59 44 49 61 54
WHL-Y25A 72
385 407 225 267 201 72 127 140 138 268 242 197 143 116 138 127 187 153 152 120
98 122 98 158 183 156 155 171 292 275 394 257 342 306 279 246 256 249 267 152
208 152 110 130 157 115 113 126 124 109 120 89 126 107 114 116 73 103 148 124
121 141 120 102 126 112 112 76 84 122 69 83
WHL-Y25B 72
419 388 220 267 182 70 123 152 150 260 256 201 142 116 135 133 181 158 155 115
98 119 100 155 185 157 158 175 301 271 376 255 355 312 269 254 247 253 257 154
203 151 110 137 153 118 114 128 108 111 126 85 126 112 115 109 70 109 147 125
123 143 111 117 116 114 116 77 87 114 78 83
WHL-Y26A 74
624 387 289 199 200 238 262 166 169 180 156 103 104 132 135 163 198 170 180 184
131 107 108 126 106 129 145 132 160 180 162 97 63 47 27 33 32 47 54 84
78 84 70 56 85 143 149 185 167 134 104 135 140 108 78 61 125 105 43 44
48 50 39 24 22 17 18 27 32 66 64 65 105 76
WHL-Y26B 74
627 386 289 199 200 240 237 186 163 190 149 112 115 129 150 166 197 168 171 189
132 107 106 128 99 123 142 124 160 186 150 101 64 41 32 30 33 49 57 77
79 91 69 55 82 147 153 180 174 129 110 123 143 106 77 55 128 94 52 36
50 53 37 29 27 20 24 29 39 62 61 76 111 71
WHL-Y27A 70
469 592 605 553 547 465 474 509 460 327 433 612 361 329 221 246 192 132 160 178
184 239 254 281 197 310 291 228 166 119 128 102 136 137 171 208 160 159 105 156
137 103 189 78 80 83 136 78 105 68 88 117 69 157 283 102 62 54 57 51
54 85 89 147 75 150 82 157 132 123
WHL-Y27B 70
533 573 603 552 563 462 482 506 461 323 436 604 369 329 218 249 189 139 147 185
185 235 268 272 202 309 289 235 177 147 117 111 152 143 174 196 146 156 100 162
130 101 195 82 85 82 141 71 111 61 98 118 71 158 253 103 60 58 60 43
56 87 90 147 73 146 83 159 133 98
WHL-Y28A 85
362 334 462 317 369 291 342 175 243 171 240 254 288 255 185 191 228 210 213 84
150 181 136 271 237 298 291 247 214 246 161 83 63 131 197 240 197 280 152 116
106 159 220 129 191 233 233 164 122 124 110 124 183 163 231 235 266 108 224 286
176 201 148 139 152 100 113 199 121 96 109 224 212 170 202 145 148 139 146 139
111 145 149 88 138
WHL-Y28B 85
342 325 469 325 359 298 336 181 240 172 239 257 285 256 190 186 227 204 224 85
152 175 144 256 243 286 292 237 217 248 158 83 65 125 203 237 193 276 145 112

109 150 215 133 190 235 234 166 117 134 103 125 184 167 200 238 265 117 224 290
170 197 125 168 151 108 117 187 118 100 92 236 232 164 201 134 161 134 158 132
118 147 153 83 109
WHL-Y29A 97
296 228 216 225 304 253 188 168 175 172 164 158 156 169 110 148 147 139 124 104
132 134 138 206 224 280 339 274 226 226 229 225 275 166 221 178 135 138 152 130
140 164 125 141 156 148 109 106 101 116 116 142 164 143 155 136 168 150 115 145
148 155 158 188 149 150 213 215 218 175 205 212 153 200 153 200 227 190 216 219
171 185 104 84 76 62 66 67 51 57 46 68 60 63 66 90 66
WHL-Y29B 97
295 228 221 223 295 251 189 168 175 172 162 156 158 165 111 138 152 137 130 105
122 141 140 216 226 293 329 276 219 229 231 232 264 175 223 163 151 129 155 130
134 166 127 136 160 155 106 112 103 113 117 133 164 153 152 148 162 155 119 124
144 149 173 206 161 145 202 206 209 181 203 217 187 217 159 223 234 200 233 226
171 173 101 79 66 72 77 65 50 52 38 64 50 59 79 87 90
WHL-Y31A 111
153 120 158 126 150 146 116 128 90 117 98 99 144 143 105 145 129 146 144 127
106 112 74 95 135 140 117 93 110 91 111 118 90 116 87 84 106 90 135 81
68 81 86 115 103 94 145 115 157 185 219 163 172 151 163 185 188 148 177 162
134 118 144 151 143 159 146 153 156 94 124 112 64 129 87 97 88 110 101 75
80 96 121 94 147 95 86 122 65 102 70 91 86 60 101 78 151 156 83 101
120 72 105 60 99 139 123 108 137 86 94
WHL-Y31B 111
144 119 157 132 155 151 102 130 97 109 104 89 146 143 112 133 130 145 144 131
97 104 68 96 142 138 113 99 105 94 119 111 96 112 91 75 107 85 133 83
68 83 79 122 110 111 126 110 162 181 224 183 170 151 169 189 182 135 167 158
140 111 154 150 149 154 141 134 143 101 120 114 61 127 98 97 85 106 129 80
78 82 113 89 145 99 87 122 61 95 71 86 75 70 102 74 147 156 83 96
123 83 92 63 99 139 124 101 144 94 98
WHL-Y32A 96
86 80 95 43 110 73 102 154 117 164 90 91 93 122 81 119 124 113 120 95
77 74 38 62 55 41 38 39 43 36 33 27 37 41 39 36 31 39 38 35
42 62 32 42 50 59 66 88 76 59 48 53 87 58 63 69 57 50 37 31
32 42 30 62 66 60 44 57 59 76 51 80 82 73 50 70 62 54 71 74
96 80 90 103 74 88 83 110 80 56 50 63 46 50 52 83
WHL-Y32B 96
80 82 94 44 116 66 113 154 109 168 95 77 95 128 89 132 122 111 123 92
81 68 47 68 51 43 44 37 42 32 37 33 35 37 42 51 26 30 35 38
44 52 33 50 47 48 66 89 65 71 46 50 92 52 63 71 57 51 44 28
36 47 36 65 69 70 35 53 76 77 52 80 79 71 50 64 68 48 76 77
97 84 91 102 71 90 82 105 82 56 54 67 39 47 50 92
WHL-Y33A 100
156 311 282 358 278 453 431 417 398 350 280 281 309 199 172 190 165 153 170 144
149 238 210 182 105 159 178 144 124 181 158 120 160 159 163 152 123 101 109 116
158 123 83 120 121 159 149 112 120 85 65 112 113 181 165 131 129 95 140 175
140 155 168 161 116 186 165 93 116 136 166 84 154 109 242 108 105 100 120 96
101 88 126 159 126 188 115 146 181 152 162 115 101 87 128 88 132 140 85 76
WHL-Y33B 100
156 305 275 355 274 435 432 413 400 356 269 310 312 195 173 192 162 154 165 144
143 247 212 180 102 154 173 139 130 185 166 120 157 164 164 145 121 98 127 115
156 125 88 119 128 144 155 109 118 81 73 101 112 181 162 131 127 98 141 172
140 155 179 159 120 175 161 86 125 130 164 95 154 108 236 109 102 104 111 105
104 85 129 164 129 188 112 150 167 170 144 113 102 86 120 107 135 114 78 71

WHL-Y34A 65
447 444 436 378 259 348 233 433 376 499 393 389 490 313 373 576 508 474 398 222
363 376 294 423 378 361 282 487 374 366 447 338 316 325 223 141 233 256 254 179
332 322 363 252 354 233 191 209 423 256 368 315 335 125 99 132 107 105 74 85
92 119 158 169 195
WHL-Y34B 65
471 436 433 383 254 331 231 413 376 506 382 396 502 315 375 583 513 481 392 224
358 368 291 395 376 361 283 484 377 361 445 335 318 331 229 135 219 255 250 182
328 323 359 247 352 230 200 218 422 247 360 310 334 132 107 111 100 129 72 61
115 115 154 160 196
WHL-Y35A 94
89 96 115 234 196 250 266 322 376 346 326 454 299 240 369 304 291 294 270 297
323 223 170 242 263 189 185 207 253 254 227 205 222 212 184 205 157 127 149 133
140 142 125 142 135 135 129 100 120 127 91 108 118 97 104 131 116 98 100 102
98 92 72 134 142 137 149 171 158 136 138 136 178 178 181 149 119 153 152 134
134 147 181 123 213 130 157 146 136 124 120 125 97 151
WHL-Y35B 94
66 97 122 231 201 255 245 325 385 346 334 464 287 241 373 312 290 291 279 298
322 221 168 242 262 193 184 207 252 253 224 211 219 213 180 209 155 126 151 135
135 138 131 139 135 139 131 91 125 131 83 109 114 102 111 128 117 89 103 107
104 84 63 140 143 134 153 171 156 139 135 133 179 178 187 150 109 155 157 134
130 143 200 101 195 134 159 155 136 125 142 92 113 149
WHL-Y36A 57
122 189 81 73 72 48 93 127 173 248 247 245 380 313 348 309 292 250 237 311
243 298 255 291 250 283 278 356 265 213 200 292 304 301 115 162 193 171 198 227
330 339 272 315 385 353 292 179 257 305 334 307 356 288 290 360 325
WHL-Y36B 57
137 188 91 71 79 44 89 134 171 258 245 230 341 336 364 307 286 241 241 302
257 287 268 292 249 281 279 354 304 223 218 297 306 295 116 159 194 173 194 234
323 344 274 312 378 361 281 191 249 307 368 328 367 299 292 377 288
WHL-Y37A 84
233 193 161 106 133 160 48 74 132 158 129 197 141 132 117 106 76 96 81 105
94 77 61 43 52 62 45 64 74 89 108 121 107 80 76 81 89 75 86 62
93 75 102 90 84 114 142 112 93 114 118 118 86 76 77 140 91 85 86 127
105 104 85 84 86 60 72 85 76 122 123 123 132 148 143 121 83 66 77 102
84 93 90 104
WHL-Y37B 84
235 193 169 96 139 156 47 79 128 159 129 193 137 132 120 99 89 87 86 91
103 72 66 45 49 54 47 61 75 89 115 113 114 82 80 77 97 69 89 66
91 71 107 87 84 113 149 113 90 117 126 117 91 77 77 137 89 90 85 129
97 103 93 78 79 65 71 90 75 125 126 118 134 151 140 125 84 66 79 98
87 93 94 104
WHL-Y38A 95
281 275 344 367 306 464 263 198 339 234 503 461 344 384 295 339 287 276 243 295
229 382 479 204 153 195 226 228 262 178 251 292 243 464 395 263 188 278 181 159
76 83 103 115 131 107 117 90 93 117 126 124 117 82 127 105 163 152 96 68
49 112 72 129 129 197 141 55 41 47 59 69 33 51 69 49 53 72 34 45
44 55 43 27 26 26 28 24 31 32 39 30 24 31 33
WHL-Y38B 95
270 261 352 340 296 475 258 194 334 230 477 451 335 380 291 331 297 276 243 296
234 377 465 202 150 196 237 224 260 174 250 284 238 458 392 255 178 277 180 162
75 86 104 128 131 97 115 96 91 117 122 122 117 77 131 105 160 149 100 65
46 112 70 128 134 193 137 56 37 41 62 63 43 44 67 52 50 67 38 41

45 50 49 24 27 21 28 27 24 33 36 30 29 32 28
WHL-Y39A 68
363 276 297 268 341 308 278 343 297 236 251 159 187 137 76 142 204 225 191 205
115 87 137 123 112 62 151 176 189 100 105 126 152 132 149 153 165 133 157 129
135 121 119 149 91 80 108 55 72 62 85 75 64 72 102 118 140 76 145 106
83 58 63 81 59 71 85 102
WHL-Y39B 68
363 278 289 270 343 307 271 346 296 230 253 162 185 132 78 143 199 228 193 210
114 94 131 126 107 63 151 174 188 105 102 126 155 131 152 151 164 136 159 126
123 122 112 155 92 80 107 63 66 66 78 79 68 72 106 104 141 76 143 103
77 59 56 80 53 81 85 94
WHL-Y40A 110
242 314 262 211 185 180 201 338 245 270 266 229 264 220 277 264 203 194 134 171
152 169 158 181 159 168 127 136 138 160 117 152 122 190 203 97 110 111 119 89
52 69 97 128 122 110 86 84 140 94 80 48 55 76 61 45 34 49 45 47
48 80 101 75 110 77 75 89 71 87 83 70 65 41 44 48 52 73 71 77
84 95 108 63 88 66 65 76 66 92 71 78 71 65 53 53 42 51 53 50
42 71 32 54 52 74 62 75 59 67
WHL-Y40B 110
274 342 254 215 193 170 207 336 257 254 268 232 270 226 284 254 217 200 132 154
167 179 179 189 161 165 139 126 144 154 112 158 130 185 205 93 111 100 108 86
49 93 94 128 120 111 89 85 148 92 88 43 73 88 69 49 43 48 39 55
50 84 108 72 108 78 77 88 73 83 86 65 70 38 47 45 56 72 72 75
88 89 104 71 86 68 71 76 71 88 65 76 77 68 58 50 42 50 55 51
43 74 36 44 57 76 57 80 57 71
WHL-Y41A 99
95 137 123 119 126 100 96 102 100 122 138 113 115 121 119 114 105 85 102 88
64 80 46 51 48 48 49 47 58 89 98 105 102 102 107 114 140 130 126 119
125 150 120 103 84 93 70 101 82 91 108 136 133 100 124 84 88 89 102 93
116 138 140 118 146 151 136 100 127 150 153 152 148 187 162 139 145 109 101 92
92 99 128 131 131 172 116 116 124 76 109 77 109 144 127 107 116 109 71
WHL-Y41B 99
104 132 123 123 126 100 103 99 99 118 138 120 108 115 128 117 95 91 99 91
58 84 55 45 56 43 47 54 60 88 98 107 101 104 105 115 138 135 122 124
124 145 120 112 99 87 70 93 83 95 110 129 137 106 121 86 84 88 111 88
115 135 141 115 151 134 156 89 133 150 149 151 151 184 163 141 142 112 102 94
76 97 128 134 131 168 120 108 125 95 102 77 100 140 131 110 110 111 72
WHL-Y42A 58
149 133 140 194 193 233 284 355 416 263 311 333 284 247 253 245 183 172 136 297
254 193 274 378 288 191 347 196 220 297 343 369 285 334 276 260 319 256 351 224
231 246 283 231 299 186 237 209 134 153 210 139 83 138 98 99 75 87
WHL-Y42B 58
150 125 147 191 236 183 213 348 419 267 306 336 282 249 253 259 175 170 140 296
259 209 267 383 290 193 344 232 235 293 351 362 301 318 266 282 322 263 324 226
237 250 286 245 285 189 227 212 139 157 208 131 87 137 93 107 75 92
WHL-Y43A 73
207 248 217 223 243 230 331 129 186 227 287 346 328 362 241 273 222 298 255 218
157 321 321 298 396 404 432 407 252 124 142 137 180 217 252 293 291 378 247 201
151 229 249 301 285 248 267 202 280 227 132 175 91 89 77 132 86 120 84 102
78 51 141 77 150 142 196 167 76 63 81 92 91
WHL-Y43B 73
195 253 211 234 256 233 331 130 152 228 295 354 342 365 243 283 205 294 259 224
149 315 317 303 394 413 447 387 250 116 135 138 185 223 248 286 291 379 251 200

152 213 247 304 284 250 266 199 279 221 114 160 90 95 71 139 94 114 80 98
84 52 141 72 156 145 190 164 80 60 79 95 96
WHL-Y44A 66
194 234 230 258 239 316 330 261 241 171 128 280 337 281 208 380 395 356 467 383
404 393 259 198 297 189 305 194 264 298 325 394 333 312 195 251 307 401 382 377
347 273 280 264 249 269 127 112 100 189 74 103 75 67 55 30 74 55 107 171
225 206 80 51 98 108
WHL-Y44B 66
160 254 232 272 248 319 325 267 245 183 133 274 345 276 209 401 382 404 457 388
394 372 286 227 292 205 306 196 274 297 332 393 335 313 199 249 309 402 393 359
357 265 290 275 254 239 134 112 98 197 72 98 72 73 51 33 77 50 117 173
221 204 83 52 101 107
WHL-Y45A 60
310 378 214 246 240 343 317 372 265 236 264 243 226 214 200 275 173 193 199 158
237 263 254 214 193 174 258 244 196 194 262 189 132 139 155 187 212 182 252 201
195 174 147 145 148 112 88 84 73 111 109 77 60 67 76 65 73 66 69 62
WHL-Y45B 61
254 429 215 250 245 346 316 385 264 238 265 243 236 211 206 272 173 199 199 158
239 261 261 206 196 165 263 229 207 196 266 182 144 139 152 178 209 185 265 196
202 173 144 144 153 119 85 86 75 113 101 88 52 66 79 61 70 61 55 58
86
WHL-Y47A 48
281 261 407 416 527 519 501 441 349 261 183 241 220 252 253 247 277 187 271 191
264 270 261 232 169 127 166 180 213 135 176 150 75 133 168 144 114 132 115 113
137 124 114 124 118 103 125 148
WHL-Y47B 48
226 268 407 426 526 566 455 433 370 259 160 236 218 255 259 252 275 184 267 192
273 284 266 242 163 126 170 174 215 146 166 151 69 134 170 146 110 130 118 107
135 114 128 124 112 108 124 155
WHL-Y48A 55
143 314 307 282 278 164 199 236 202 210 226 280 194 107 72 87 71 72 124 144
100 55 85 85 126 201 205 236 207 194 219 263 298 184 228 173 170 151 179 168
121 167 174 185 155 103 74 93 81 127 77 100 74 65 90
WHL-Y48B 55
150 316 312 280 289 156 207 217 206 222 211 277 202 108 88 79 77 57 117 150
99 52 90 79 130 200 190 244 205 190 218 273 293 185 227 185 168 153 181 163
126 154 180 182 160 92 74 97 82 131 81 97 65 80 90
WHL-Y49A 51
286 281 336 320 251 292 275 320 340 292 301 448 442 405 508 415 357 276 208 217
192 222 217 205 190 129 79 126 150 159 143 112 94 63 89 84 78 75 100 108
78 72 68 57 45 85 101 102 119 158 100
WHL-Y49B 51
310 277 328 315 255 305 282 366 342 293 302 452 442 405 504 418 358 272 213 217
190 217 218 210 194 117 78 134 145 166 141 120 93 60 90 85 78 68 97 115
69 77 65 64 30 94 103 109 128 144 116
WHL-Y50A 50
261 244 401 244 232 500 436 248 230 301 296 266 250 406 481 458 363 196 282 301
345 356 257 159 150 238 279 282 253 249 192 134 145 162 148 104 82 98 52 57
54 48 34 49 28 42 35 44 44 50
WHL-Y50B 50
246 423 331 259 256 505 453 254 235 316 297 279 256 407 490 465 392 217 286 299
348 362 264 157 151 240 277 286 249 255 183 144 147 160 148 104 84 109 70 59
58 59 42 49 37 45 45 43 51 67

WHL-Y51A 44
372 675 574 443 449 543 322 330 371 440 340 301 318 219 252 223 197 244 233 209
177 159 134 92 112 107 109 78 119 144 101 108 114 127 58 64 68 58 44 62
85 84 64 62
WHL-Y51B 44
364 678 571 432 449 538 320 302 365 414 352 311 318 219 271 221 200 244 230 208
179 161 134 97 107 108 106 77 124 136 105 103 108 141 52 67 67 50 56 61
82 86 64 65
WHL-Y54A 126
266 410 244 222 394 302 244 233 245 297 314 216 144 243 209 156 153 160 162 231
193 205 234 207 213 229 177 159 169 169 164 139 145 159 130 143 132 94 128 118
120 161 148 119 127 143 142 107 131 128 128 120 103 189 203 162 166 176 164 167
152 163 188 203 193 145 120 131 142 129 104 100 161 113 170 117 126 150 141 121
102 110 113 71 65 55 58 62 73 45 50 52 50 54 50 62 72 81 61 72
52 65 47 58 79 84 82 79 62 53 81 65 81 62 63 58 54 56 66 56
58 52 66 72 74 58
WHL-Y54B 126
310 408 248 227 390 294 242 239 240 297 322 212 143 242 217 153 158 159 159 230
189 211 232 207 218 230 181 160 167 174 157 140 145 153 136 142 126 99 134 114
120 164 153 115 124 148 141 113 126 130 127 117 107 191 202 160 166 176 165 167
154 166 191 197 189 146 118 132 138 126 107 103 160 121 171 106 118 147 127 131
96 111 111 73 65 56 58 64 67 48 52 49 51 54 48 65 68 83 69 59
59 54 54 55 78 82 81 74 67 55 71 66 82 65 61 53 60 46 66 53
66 49 68 70 69 72
WHL-Y55A 129
649 916 810 505 619 653 611 436 604 458 342 346 234 379 281 290 292 272 231 184
222 239 210 222 226 218 154 135 133 129 130 134 126 101 105 92 132 125 150 111
96 51 81 85 82 122 109 120 117 126 104 106 141 157 125 147 144 128 99 182
153 167 65 89 102 88 104 107 134 126 108 130 92 100 105 72 139 122 175 125
186 113 75 89 131 151 115 120 115 144 64 85 73 109 96 94 84 91 105 110
76 96 62 69 77 74 56 57 41 71 65 73 76 66 98 86 45 82 51 55
75 50 71 74 76 70 73 104 84
WHL-Y55B 129
657 924 797 555 616 630 607 446 599 443 344 350 234 384 282 295 292 274 230 183
219 228 220 211 228 218 150 130 137 125 137 126 122 109 103 97 139 120 149 109
93 51 82 90 81 115 106 124 118 120 122 86 151 141 134 144 154 123 108 186
141 167 67 77 107 86 109 111 130 126 116 131 102 98 98 71 142 119 176 118
186 119 76 88 124 157 111 123 113 144 63 86 77 110 89 95 84 91 105 107
73 100 64 66 73 78 58 58 38 75 64 75 76 63 99 88 49 85 51 54
77 55 69 70 75 66 75 111 78
WHL-Y56A 72
69 128 144 125 119 126 164 193 138 182 136 147 114 115 93 122 144 146 164 115
146 132 145 103 89 104 114 113 104 94 99 81 106 114 118 48 77 86 61 98
79 105 129 105 109 86 77 84 58 92 104 98 92 130 74 81 83 104 100 74
102 94 124 51 57 70 65 71 74 74 83 66
WHL-Y56B 72
86 121 145 126 138 112 163 187 136 184 162 149 119 111 102 141 139 145 169 119
151 133 152 103 93 115 124 118 105 104 97 89 113 112 113 47 77 78 62 103
81 108 133 110 104 91 85 97 53 87 106 99 94 126 82 87 74 106 106 68
116 87 137 57 65 61 65 70 74 76 81 72
WHL-Y57A 62
248 221 260 298 336 213 301 218 203 180 165 169 213 236 270 320 242 148 170 221
247 255 229 276 317 297 239 235 278 208 255 223 177 173 108 210 240 236 200 270

326 351 207 345 274 203 203 235 165 147 220 237 180 190 143 119 202 175 148 205
129 112
WHL-Y57B 62
236 215 266 300 342 226 280 213 222 182 158 173 207 245 274 340 240 144 165 221
257 265 232 281 321 291 229 213 267 214 258 221 172 178 108 214 198 250 203 281
329 348 207 358 267 199 206 235 165 154 218 234 175 188 141 124 204 178 159 226
138 105
WHL-Y58A 56
94 103 49 57 168 176 181 172 147 119 139 158 146 131 110 92 64 101 116 216
268 249 308 191 226 252 220 300 274 357 202 160 184 230 242 164 166 181 139 215
349 374 237 375 308 174 154 125 164 167 213 170 108 65 71 60
WHL-Y58B 56
96 96 56 52 169 179 182 177 150 127 127 158 129 136 94 100 56 97 109 213
271 251 304 191 230 252 219 307 283 365 203 165 179 235 237 170 167 181 139 207
355 373 236 375 309 167 156 129 171 171 217 157 103 57 75 66
WHL-Y59A 65
519 376 333 498 475 520 450 275 412 475 378 330 377 373 384 443 397 296 291 230
407 365 263 355 282 289 276 218 245 220 235 245 233 178 143 167 134 148 156 87
129 144 122 142 148 149 113 98 83 50 65 104 162 118 131 114 129 63 51 79
107 107 119 133 120
WHL-Y59B 48
306 217 412 373 254 344 286 313 301 229 238 271 273 279 201 184 148 214 210 212
184 97 147 139 145 138 145 143 112 75 71 53 62 95 147 141 156 121 123 55
55 76 103 104 145 153 129 109
WHL-Y60A 61
355 314 390 312 405 227 183 246 229 226 192 155 182 229 150 144 78 101 219 280
211 162 297 269 244 211 194 185 234 244 188 187 78 147 273 224 179 266 358 408
322 296 227 270 227 336 272 202 210 224 198 230 200 261 460 250 128 194 152 193
187
WHL-Y60B 61
344 307 422 304 392 230 198 270 234 228 187 155 185 207 142 133 81 92 221 278
208 167 301 268 252 204 197 194 229 244 190 183 87 146 267 229 175 271 357 412
312 303 234 267 229 337 302 193 207 231 203 229 202 287 457 243 132 196 147 191
189
WHL-Y61A 98
266 409 423 450 532 507 313 386 372 137 274 396 317 378 350 338 296 242 281 198
354 373 263 249 272 282 242 369 222 201 211 169 160 194 125 179 250 148 160 302
181 199 167 229 228 213 188 154 163 135 98 163 124 123 126 78 80 92 93 140
146 136 147 133 137 113 104 174 135 173 139 155 152 172 216 148 136 188 115 145
150 97 152 128 170 121 147 115 113 134 84 101 92 132 120 115 126 73
WHL-Y61B 98
272 425 471 462 535 532 326 367 376 136 281 392 337 384 357 339 306 234 285 200
355 369 272 249 275 283 253 348 214 212 210 170 158 197 124 178 253 150 160 305
183 194 174 232 232 205 188 159 168 132 103 154 131 126 125 81 89 94 92 134
144 141 146 130 147 110 100 178 139 164 142 165 161 179 211 153 179 193 131 145
155 100 149 128 177 131 155 110 107 135 92 91 94 131 121 131 108 58
WHL-Y62A 91
250 286 307 263 283 273 336 300 275 295 282 271 294 335 334 368 343 283 335 301
333 250 226 251 277 246 232 267 268 232 250 195 201 144 132 165 217 182 223 181
174 154 160 202 199 150 198 211 209 169 156 208 189 197 182 142 154 112 180 178
159 128 112 170 76 71 87 110 103 137 166 163 150 143 145 184 191 207 206 153
198 201 211 224 193 234 186 164 182 147 202

WHL-Y62B 91
245 285 301 253 280 264 336 294 272 283 284 269 294 330 329 369 338 284 338 304
337 249 230 254 268 255 227 264 268 228 245 192 199 147 137 163 219 187 229 181
170 153 161 193 204 149 200 210 209 174 159 207 192 200 180 144 157 114 178 179
168 106 125 168 78 68 90 110 101 136 160 164 156 143 154 184 186 211 198 151
199 202 211 226 197 238 186 164 172 153 211
WHL-Y63A 77
399 381 504 382 312 459 350 302 182 153 214 254 237 212 256 257 213 243 154 181
171 143 221 253 173 305 233 260 239 205 245 247 225 272 251 239 214 187 278 249
190 164 139 143 103 166 188 150 95 110 132 107 116 147 180 148 158 185 188 170
189 196 256 212 233 230 160 170 183 165 209 202 210 177 158 150 167
WHL-Y63B 77
408 402 501 377 318 442 361 301 189 151 206 262 239 203 258 257 201 245 152 164
162 141 221 258 185 293 235 268 239 207 237 240 234 257 262 237 212 184 276 252
196 171 144 146 104 170 183 151 98 110 130 125 114 146 181 149 156 182 188 170
183 194 259 209 233 239 155 165 192 170 212 208 208 168 165 148 163
WHL-Y64A 97
328 338 383 425 453 236 393 361 268 372 309 324 243 384 257 264 199 294 241 194
214 279 166 185 218 180 214 174 191 221 267 250 218 164 153 151 129 127 143 141
223 170 154 236 170 201 157 196 222 227 169 264 221 239 290 172 212 197 227 171
171 204 118 197 178 156 112 151 184 223 219 218 394 260 318 350 218 226 153 194
186 163 238 208 198 180 243 237 256 208 193 158 193 146 146 227 159
WHL-Y64B 97
327 335 382 437 441 233 387 368 270 359 309 328 241 377 261 264 205 288 241 203
204 279 165 180 202 168 208 172 199 221 263 252 227 167 151 151 139 121 141 142
226 169 156 224 176 195 155 201 227 222 181 252 239 240 288 184 196 183 221 163
150 203 116 198 175 162 111 151 183 226 221 215 371 245 311 319 213 215 166 188
167 166 236 218 201 179 245 246 253 211 189 157 191 145 141 221 172
WHL-Y65A 90
300 356 413 554 445 457 465 280 193 206 238 291 312 377 283 332 328 285 184 219
215 304 336 338 302 421 359 477 491 387 365 387 356 348 434 369 286 354 379 288
298 220 209 214 177 333 269 303 335 245 117 228 210 184 216 218 143 128 98 152
109 166 203 224 161 220 160 145 206 196 182 115 207 188 241 184 215 253 243 241
207 215 140 105 131 132 120 133 166 112
WHL-Y65B 90
274 350 415 555 452 424 470 293 188 211 235 280 331 374 284 325 317 284 191 221
207 276 343 338 307 407 349 468 480 366 330 367 354 348 436 373 291 355 378 285
300 219 204 214 176 333 271 307 321 244 129 219 207 196 211 216 128 130 103 147
110 166 203 222 168 217 162 143 207 197 178 120 206 203 223 190 216 239 264 250
210 221 129 117 126 127 128 127 166 108
WHL-Y66A 86
468 382 435 466 541 515 510 555 599 476 657 450 466 401 313 374 244 256 333 383
218 218 176 186 228 249 166 335 229 178 170 111 140 202 194 184 267 189 210 240
241 169 196 168 245 215 189 271 200 240 277 170 206 161 193 203 217 142 248 154
179 207 217 184 143 189 115 315 317 282 146 200 417 561 455 434 683 477 544 332
341 383 401 275 318 333
WHL-Y66B 86
474 379 439 470 556 507 507 565 599 482 671 472 466 400 311 378 244 255 315 370
210 225 179 189 239 250 164 329 233 179 169 111 139 200 202 194 266 193 206 239
244 168 199 164 249 213 183 278 201 235 278 171 206 164 192 198 217 143 250 149
179 212 219 190 150 191 114 297 318 279 148 201 420 575 449 430 684 475 541 335
340 380 398 275 322 380

WHL-Y67A 91
469 424 275 195 263 189 126 180 176 245 286 277 282 273 133 162 174 196 160 181
141 137 175 228 228 238 228 148 220 211 261 202 176 172 222 233 255 206 246 201
119 174 165 206 190 188 223 227 130 138 191 223 187 254 181 214 229 214 297 298
248 271 237 189 144 151 233 236 209 263 219 187 246 185 203 166 194 160 191 216
199 239 255 188 150 218 176 166 154 216 294
WHL-Y67B 91
482 441 287 242 265 190 119 183 173 236 269 272 273 272 145 176 185 198 155 194
145 140 173 220 231 239 229 147 232 224 265 209 173 165 235 222 256 205 247 201
117 169 167 207 192 194 220 226 136 146 189 225 187 253 184 209 237 220 294 299
257 270 241 190 140 144 220 245 209 261 217 198 250 185 207 164 195 160 192 222
200 238 253 185 151 233 173 166 154 205 309
WHL-Y68A 61
257 544 314 250 500 488 420 296 583 282 355 360 401 556 512 377 263 237 181 201
206 163 157 146 118 158 170 142 135 142 112 154 203 182 158 189 215 216 168 191
229 194 246 214 252 255 203 179 233 229 243 271 187 194 210 228 244 234 211 282
162
WHL-Y68B 61
266 552 308 269 483 484 404 330 609 299 350 359 369 568 500 387 259 241 175 186
193 141 143 143 125 157 174 131 134 149 116 151 203 183 148 184 226 229 179 195
225 190 242 212 256 256 204 174 237 229 243 272 185 194 212 219 253 240 205 287
157
WHL-Y69A 89
204 307 117 113 159 256 215 215 180 148 192 238 347 304 272 212 254 249 255 239
174 166 243 247 259 257 289 185 141 200 193 239 216 166 205 198 118 134 214 239
198 241 216 179 193 205 202 208 191 202 192 146 127 167 179 195 211 257 164 160
197 156 190 176 171 166 154 217 218 235 184 184 159 199 192 232 216 163 213 172
132 111 134 129 161 213 179 185 188
WHL-Y69B 89
236 298 117 115 158 244 223 225 177 142 193 243 334 276 263 202 295 238 257 232
171 169 242 249 253 261 287 183 134 203 193 228 204 167 202 202 114 140 204 239
205 245 216 172 182 205 205 206 194 206 193 149 129 168 176 196 205 259 163 158
197 156 189 172 176 160 158 218 217 233 181 182 170 204 192 229 213 163 207 170
137 116 129 123 164 200 169 183 183
WHL-Y70A 60
296 187 151 154 90 150 156 142 131 133 102 128 148 159 139 223 227 382 345 224
160 222 280 420 410 372 566 409 556 371 387 355 436 377 407 297 401 407 289 329
480 539 444 294 337 415 302 388 424 688 624 446 609 724 514 468 366 581 601 645
WHL-Y70B 60
304 194 149 169 81 151 164 140 142 97 109 130 159 154 146 229 205 395 365 263
162 220 293 415 411 375 568 404 559 363 390 362 432 381 436 297 393 403 285 332
466 547 440 293 332 419 338 393 445 657 586 463 593 664 523 457 358 529 632 621
WHL-Y71A 73
327 279 287 298 206 192 231 272 238 292 179 145 202 274 344 318 328 252 321 315
365 253 211 237 270 268 271 285 350 305 112 195 187 230 219 217 216 213 160 159
215 260 219 300 216 233 272 217 313 326 286 295 292 188 137 225 203 250 345 340
280 206 233 154 222 193 243 167 242 224 226 270 191
WHL-Y71B 73
339 284 269 352 206 194 239 252 234 286 184 143 204 276 336 318 341 255 323 343
366 248 214 244 266 275 295 285 358 306 108 203 190 233 215 226 219 214 164 167
218 241 224 303 215 235 278 218 310 326 290 303 292 182 140 219 213 263 340 345
288 213 223 146 236 220 251 179 253 234 234 260 248

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 1998) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

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

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. **Measuring Ring Widths.** Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. **Cross-Matching and Dating the Samples.** Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. **Estimating the Date of Construction.** There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. **Master Chronological Sequences.** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. **Ring-Width Indices.** Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

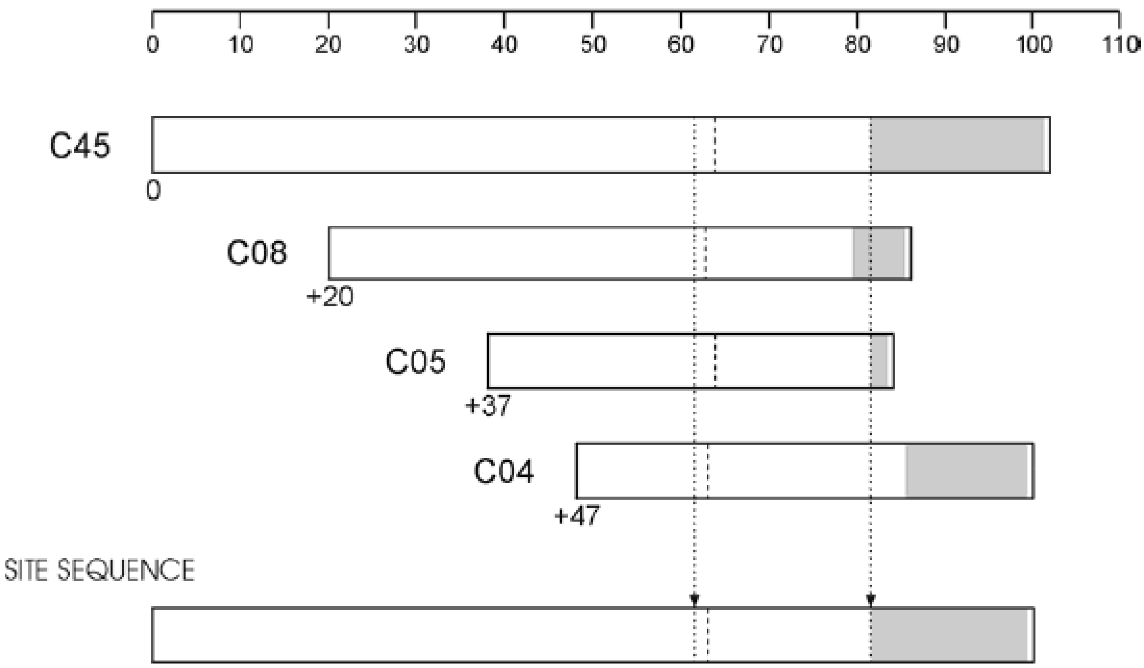


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

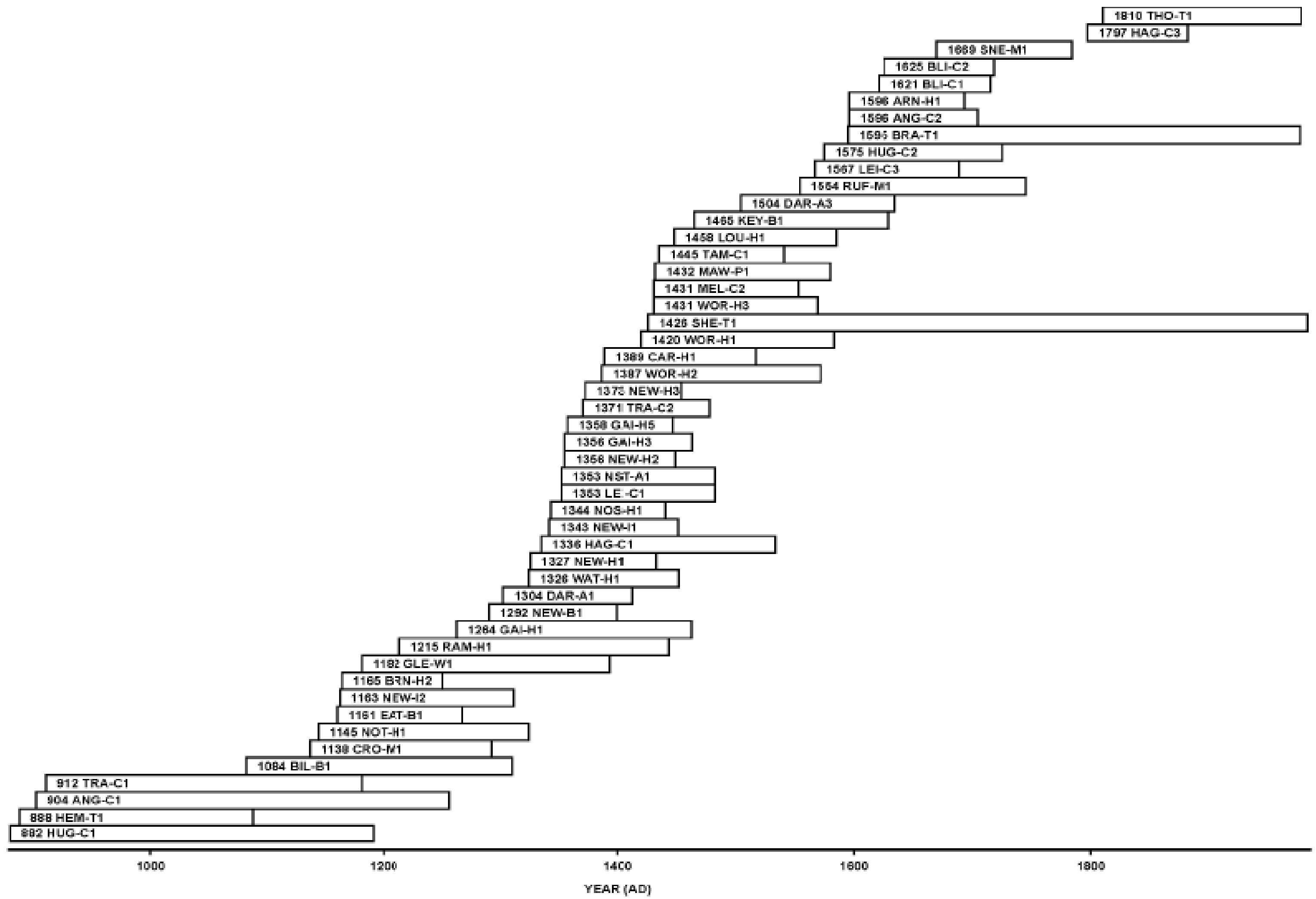
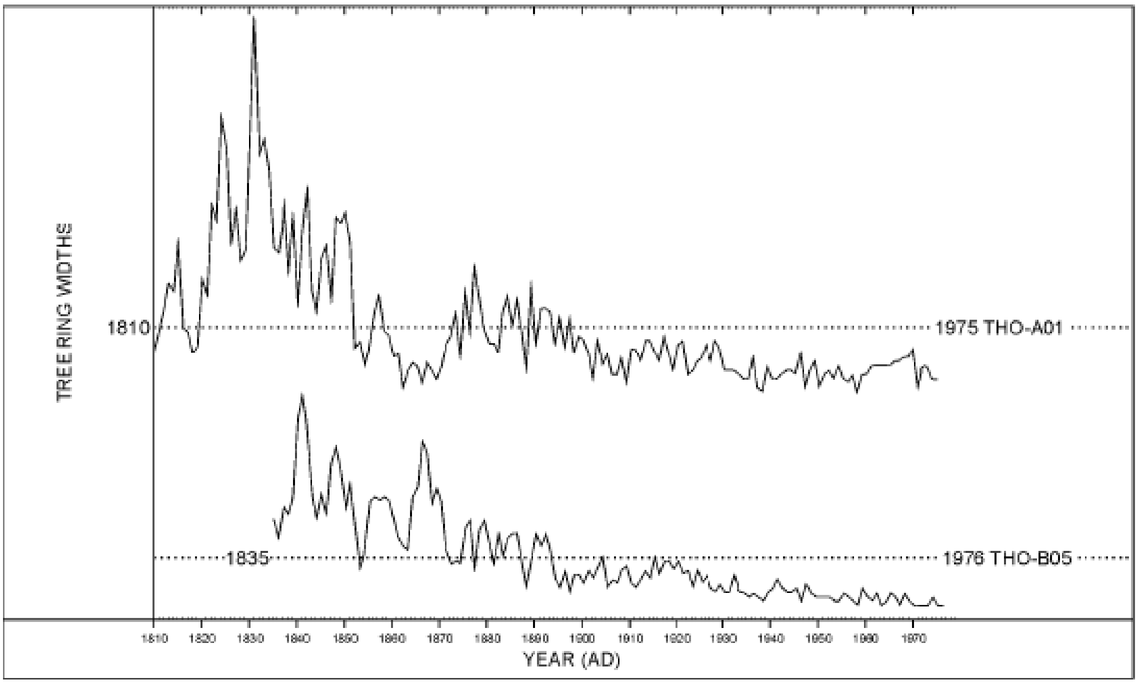


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

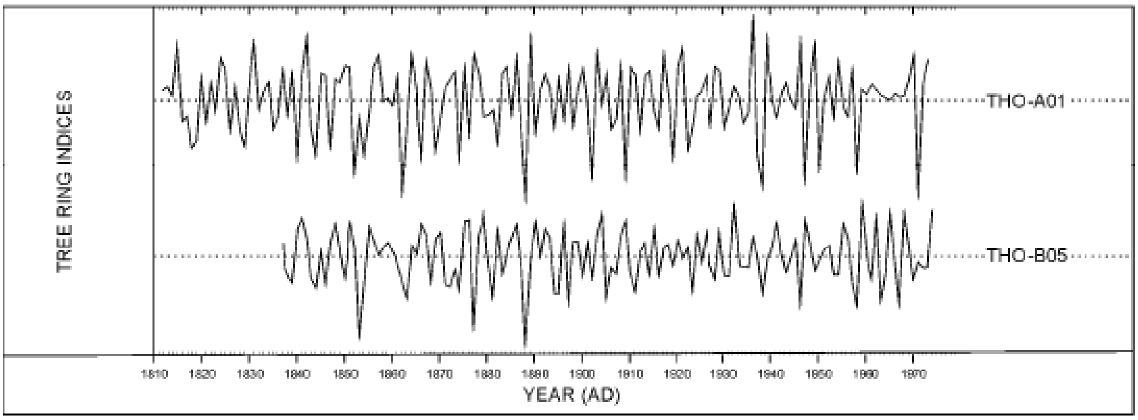


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

References

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

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

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

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, **23**, 51–6.

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

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

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

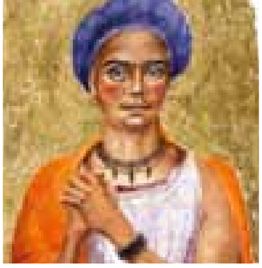
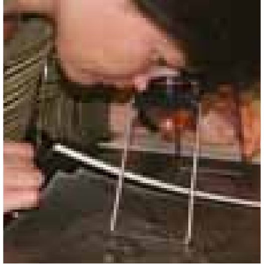
Laxton, R R, Litton, C D, and Howard, R E, 2001 *Timber: Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, 7

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

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

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

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



ENGLISH HERITAGE RESEARCH AND THE HISTORIC ENVIRONMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for the protection and sustainable management of the resource, and to promote the widest access, appreciation and enjoyment of our heritage. Much of this work is conceived and implemented in the context of the National Heritage Protection Plan. For more information on the NHPP please go to http://www.english-heritage.org.uk/professional/protection/national-heritage-protection-plan/.

The Heritage Protection Department provides English Heritage with this capacity in the fields of building history, archaeology, archaeological science, imaging and visualisation, landscape history, and remote sensing. It brings together four teams with complementary investigative, analytical and technical skills to provide integrated applied research expertise across the range of the historic environment. These are:

- Intervention and Analysis (including Archaeology Projects, Archives, Environmental Studies, Archaeological Conservation and Technology, and Scientific Dating)
- Assessment (including Archaeological and Architectural Investigation, the Blue Plaques Team and the Survey of London)
- Imaging and Visualisation (including Technical Survey, Graphics and Photography)
- Remote Sensing (including Mapping, Photogrammetry and Geophysics)

The Heritage Protection Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support community engagement and build this in to our projects and programmes wherever possible.

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

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

For further information visit www.english-heritage.org.uk

ENGLISH HERITAGE

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)