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FLORE'S HOUSE, HIGH STREET, OAKHAM, RUTLAND
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard, Matt Hurford and Cathy Tyers

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M Hurford
A J Arnold
R E Howard
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SUMMARY
Analysis by dendrochronology was undertaken on 48 out of 58 samples (ten having insufficient rings) from three ranges of Flore's House, Oakham: the hall range and the north and south cross-wings. This resulted in the production of four site chronologies, OKMASQ01–04. These comprise 18, 9, 10, and 2 samples, with overall lengths of 220, 184, 90, and 81 rings respectively. The rings of the first three site chronologies can be dated as spanning the years AD 1173–1392, AD 1408–1591, and AD 1570–1659, whilst the fourth site chronology is undated.
Interpretation of the sapwood and the heartwood/sapwood boundaries on the dated samples indicates the presence of four distinct phases of felling. The hall range roof and a single plate from the ground floor represent the earliest dated phase of construction, using timber all probably felled in AD 1378. The south cross-wing utilises timber with an estimated felling date in the range *circa* AD 1407–10. The inserted ceiling and a ground floor post in the hall range use timber felled in AD 1591. The roof of the north cross-wing uses timber felled in AD 1659, despite having a roof of similar design to that of the south cross-wing. Nine measured samples are ungrouped and undated.

CONTRIBUTORS
Matt Hurford, Alison Arnold, Robert Howard, and Cathy Tyers

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ARCHIVE LOCATION
Leicestershire & Rutland Historic Environment Record
Historic & Natural Environment Team
Room 500, County Hall
Leicester Road
Glenfield LE3 8TE

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CONTACT DETAILS
M Hurford and C Tyers
Dendrochronology Laboratory, Archaeology Graduate School, The University of Sheffield, West Court, 2 Mappin Street, Sheffield, S1 4DT
Tel: 0114 276 3146. Email: m.hurford@sheffield.ac.uk, c.m.tyers@sheffield.ac.uk

A J Arnold and R E Howard
Nottingham Tree-Ring Dating Laboratory, 20 Hillcrest Grove, Nottingham, NG5 1FT
Tel: 0115 9603833. Email: roberthoward10@hotmail.com, alisonjarnold@hotmail.com

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INTRODUCTION

Flore's House, a grade II* listed building located on the south side of the High Street, Oakham (SK8604108732, Figs 1–3), is one of the most important surviving medieval houses in Rutland (Hill 2007 unpubl). It has been associated with William Flore, who was controller of the works at Oakham Castle in AD 1373–80 (Barley 1975, 38), or with his son Roger, also a prominent man, who was Speaker of the Commons on four occasions in the early fifteenth century (Roskell 1957).

The following information is summarised from both Barley (1975) and Hill (2007 unpubl). The earliest part of the building is the hall range, oriented at right angles to the High Street (Fig 4). It is of three bays, incorporating two trusses of base cruck type and a truss at each end. The base cruck timbers are set within slots in the stone walls. The trusses have a cranked tiebeam and arch braces with spandrel struts. The upper roof is of crown post type, with bracing to the collar and crown plate (Fig 5). There are seven rafters in each bay, except the northernmost, which has three, due to it being truncated by the north cross-wing. The hall was originally a large, single-volume space, heated by a central hearth, with no chimneystack. The original timbers have heavy smoke-blackening. Over the centre of the hall, there is evidence for a former louvre to allow smoke to escape.

The hall, which is of unusually large size for a town house, had a cross passage at its south end (Fig 6). The timbers in the cross passage comprise a central north-south ceiling beam, from either side of which run five east-west joists. The ceiling of the corridor running north from the cross passage comprises four north-south joists. With the exception of timbers in the cross passage and corridor, only a small section of the inserted floor of the hall range is visible, due to the insertion of modern ceilings. The front doorway has jambs with attached shafts and a moulded pointed arch. Barley (1975) and Pevsner (1974) thought that the doorhead is later-fourteenth century, but that the door jambs may be thirteenth century. Recent structural analysis by Hill (2007 unpubl) suggests that the rear doorway, which had previously been assumed to be later, has an original lintel, which seems to confirm the cross-passage plan.

The north cross-wing replaced the north end of the fourteenth-century hall range. It included a stone-built parlour on the ground floor, with a fine stone window and beamed ceiling. Above, jettied to both the east and north sides, was a single large timber-framed chamber of three bays, incorporating four trusses consisting of cranked tiebeams with heavy bracing on jowled wall posts, with tenoned purlins and raking struts, and three intermediate trusses consisting of cranked tiebeams, braces, and clasped purlins (Fig 7). The walls were probably of close-studding throughout. It seems likely that there was a stair up to the great chamber in its south-west corner, and a lateral fireplace on its north wall. The south cross-wing also had large chamber on the top floor, but beneath this were a ground and first floor of low height, thought likely to be for service and lower-status use. Although the lower parts of this wing have been much altered, the timber-framed upper storey and roof once again survive in fairly complete state consisting of three bays, originally comprising four trusses, the fourth westernmost upper roof timbers no longer extant. The trusses consist of a cranked tiebeam on jowled wall posts with principal rafters, clasped purlins, and raking struts (Fig 8). The roofs of the north and south cross-wings are of rather similar type (Figs 7 and 8) leading to the recent suggestion that they may both date to around AD 1500, when major alterations appear to have been carried out (Hill 2007 unpubl). This is however in contrast to the previously postulated interpretation that suggested that the south cross-wing was a later build of seventeenth-century date (Barley 1975).

SAMPLING

Sampling and analysis by tree-ring dating of the timbers of Flore's House were commissioned by English Heritage as part of the dendrochronological training programme of the first author. The purpose of this work was to clarify the date of the hall range and to provide dates for the two cross-wings. It was hoped that this would establish the extent of survival of original timber and elucidate the building's historic development, hence informing its future management and conservation.

Thus, from the timbers available a total of 58 samples were obtained by coring. Each sample was given the code OKM-A (for Oakham, site 'A') and numbered 01–58. The approximate positions of these samples are marked on drawings provided by Nick Hill, these being reproduced here as Figures 9–21. Details of the samples are given in Table 1, in which the timbers have been located and numbered following the scheme on the drawings provided.

No samples were removed from truss 4 in the south cross-wing as, with the exception of the wall posts, the timbers were no longer extant. Sampling in the north cross-wing focused on trusses 6–8 and adjacent bays, as the timbers in truss 5 were believed to have been derived from very fast grown trees, and thus were considered unlikely to provide samples with sufficient rings for reliable analysis. Access to the inserted floor in the hall range was limited, due to modern ceilings covering the earlier timbers, so sampling was restricted to the cross passage and corridor.

ANALYSIS

Each of the 58 samples obtained was prepared by sanding and polishing. It was seen at this point that ten samples had an insufficient number of rings required for reliable dating, and so were rejected from this programme of analysis (Table 1). The annual growth rings of the remaining 48 samples were, however, measured, the data of these measurements being given at the end of this report. The data of these 48 samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing, at a minimum value of t=4.4, four groups to be formed, the samples of each group cross-matching with each other as shown in the bar diagrams, Figures 22 and 23.

Each site chronology was compared to a full range of reference chronologies for oak, this indicating repeated cross-matches and dates for three of them. The evidence for this dating is given in Tables 2–4. Each site chronology was also compared with the remaining nine ungrouped samples but there was no further satisfactory cross-matching. Each of the remaining nine ungrouped samples was then compared individually with the reference chronologies, but again, there was no satisfactory cross-matching and these samples must, therefore, remain undated.

This analysis can be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span (where dated)
OKMASQ01	18	220	AD 1173–1392
OKMASQ02	9	184	AD 1408–1591
OKMASQ03	10	90	AD 1570–1659
OKMASQ04	2	81	undated
	9	---	undated
	10	---	unmeasured

INTERPRETATION

Hall range

The hall range roof is represented by seven dated samples in site chronology OKMASQ01 (Figs 22 and 24). Two of the samples, OKM–A04 and A10, retain complete sapwood, and were both felled in AD 1378. The heartwood/sapwood boundary is present on only one other sample, OKM–A07. Using the 95% confidence limit of 15–40 sapwood rings appropriate for mature oaks in this part of England, an estimated felling date in the range AD 1370–95 is obtained. This encompasses the precise felling date produced and hence, given that there is no structural evidence to the contrary, it is probable that this timber was also felled in AD 1378. The remaining four dated samples from the hall range roof have no trace of sapwood and it is thus not possible to calculate their likely felling date ranges. However, the dates of their last measured rings range from AD 1317 (A08) to AD 1348 (A06), therefore it is possible that they too were felled in AD 1378. This is supported by the fact that the timbers are integral to the structure, and that there is no evidence for insertion or reuse, as well as by the level of cross-matching within this group.

The lower level of the hall range is also represented by a sample, OKM–A43, in site chronology OKMASQ01, this being from a plate above the east entry to the cross-passage of the hall (Fig 6). This sample also retains the heartwood/sapwood boundary, this being dated to AD 1361. An estimated felling date in the range AD 1376–1401 is obtained, which encompasses the precise felling date obtained for the hall-range roof. It is thus possible that this timber was also cut in AD 1378. Given that it is not directly associated with the roof structure, this is less certain, though it is clearly broadly coeval with the dated roof timbers.

The inserted floor of the hall range is represented by nine dated samples in site chronology OKMASQ02 (Figs 22 and 24). Eight were from the ceiling and one from the front east wall post, which is structurally integral to the ceiling. One of these samples, OKM–A48, retains complete sapwood and was felled in AD 1591. The relative position of the heartwood/sapwood boundary on four other samples is very similar, again suggesting a single phase of felling, and it is probable that these four timbers were felled in AD 1591 as well. The remaining four dated samples from the inserted floor do not have the heartwood/sapwood boundary and it is not possible to calculate their likely felling date ranges. However, the dates of their last measured rings range from AD 1517 (A44) to AD 1543 (A41). It is therefore possible that they too were felled in AD 1591 since, in addition to the level of cross-matching within this group, they are again integral to the structure and there is no evidence for insertion or reuse.

North cross-wing

The north cross-wing roof is represented by ten dated samples in site chronology OKMASQ03 (Figs 22 and 24). One of these samples, OKM-A34, retains complete sapwood, thus the felling of the timber is dated to AD 1659. Six other samples have retained the heartwood/sapwood boundaries, which again, with a variation of only 12 years between them, suggest a single phase of felling. It is thus probable that these timbers were also felled in AD 1659. The remaining three dated timbers cross-match well within the group and there is no evidence, in the form of possible insertion or reuse, to indicate that these timbers were not also felled in AD 1659 as well since their last measured ring dates range from AD 1619 (A56) to AD 1631 (A50).

South cross-wing

The south cross-wing is represented by 10 dated samples in site chronology OKMASQ01 (Figs 22 and 24). Four of these samples retain some trace of sapwood. The heartwood/sapwood boundaries date to within five years of each other, thus being indicative of timbers representing a single felling phase. The average date of the heartwood/sapwood boundary on these samples is AD 1386 which, using the same sapwood estimate as above, would give an estimated felling date in the range AD 1401–26. However, this estimated felling date range can be refined as the outermost approximately 15 mm of sapwood, complete to the bark edge, was lost during coring from sample OKM–A25, due to its fragile nature. It was noted at the time of sampling that this loss represents between approximately 15 and 18 rings. Given that the last sapwood ring on sample OKM–A25 is dated to AD 1392, such a loss would indicate that this timber, and hence the other three as well, was felled in the range *circa* AD 1407–10.

The remaining six dated samples from the south cross-wing do not have heartwood/sapwood boundaries present and it is thus not possible to calculate their likely felling date ranges. However, with last measured ring dates ranging from AD 1324 (A22) to AD 1380, and bearing in mind the level of cross-matching within this group, it is possible that they too were felled in *circa* AD 1407-10. This is supported by the fact that once again the timbers are integral, and that there is no evidence for insertion or reuse.

DISCUSSION

Though it had previously been suggested that the stone door jambs in the hall may be of thirteenth-century date (Pevsner 1974; Barley 1975), no timbers this early were found during this programme of tree-ring dating. The earliest extant timbers at Flore's House to be dated by tree-ring analysis are those from the hall range roof, which were felled in AD 1378. The plate above the east entry to the cross-passage of the hall dates to the late-fourteenth century, and may well be coeval with the hall range roof. These results therefore suggest that the most likely candidate for undertaking this work is William Flore, rather than his son Roger, as he was controller of the works at Oakham Castle at this time. A further phase of work is indicated in the hall range, where a floor and an associated post were inserted using timbers felled in AD 1591.

The south cross-wing contains a series of timbers felled in *circa* AD 1407–10, which suggests a somewhat earlier date of construction than expected, only approximately 30 years after the major works in the hall range. Roger Flore's political career was ascending during these years (Roskell 1957), so it appears that he would have been in a financial position to commission such building work, though it is possible that his father, William, was still alive at this point and that he sanctioned the work.

The north cross-wing roof is constructed of timbers felled in AD 1659. It has previously been thought to be broadly coeval with that of the south cross-wing, due to its similar stylistic features. These seventeenth-century timbers suggest that further reappraisal of the structural evidence is needed, in order to clarify whether these represent a replacement roof inserted during major works on the original building, or whether they represent the construction of the north cross-wing. It should be noted here that there may be additional timbers that are suitable for dendrochronological analysis from the lower levels of the north cross-wing. Unfortunately, at the time of sampling these were either concealed by modern office fittings and equipment, or were inaccessible due to the presence of a busy café. Clearly if access issues can be resolved in the future, it would be worth assessing the timbers as to their suitability for tree-ring sampling, as they may have the potential to aid the understanding of this north cross-wing.

A number of noticeably high t-values, identified during cross-matching, combined with the conversion method for the timbers from which these cores were taken, suggest the possibility that some timbers are derived from the same tree. These comprise: OKM–A06/A12 (t=12.9) from the hall range roof; OKM–A27/A31 (t=11.9) and OKM–A28/A35 (*t*=11.0) from the north cross-wing roof; OKM–A41/A45 (*t*=12.6), OKM–A45/A48 (*t*=11.1) and OKM–A41/A48 from the inserted ceiling in the hall range, all three of which are likely to be derived from the same tree. The intra-phase cross-matching for the inserted ceiling timbers is particularly high, which strongly suggests that this group of material is derived from a single woodland source. However, the inter-phase cross-matching between the late fourteenth-century samples from the hall range and the early fifteenth-century samples from the south cross-wing is slightly poorer, as they come together with a minimum value of *t*=4.4. This suggests that these two broadly coeval groups of timber may come from slightly different woodland sources.

Although dendrochronology cannot be used to identify the precise source of timber (eg Bridge 2000), it would appear that the timbers analysed from Flore's House are likely to be derived from woodlands that were reasonably local to Oakham. As will be seen from Tables 2–4, many of the highest *t*-values, and thus the greatest degree of similarity, obtained during the dating of the three site sequences are with reference chronologies from sites elsewhere in the East Midlands region.

Of the 48 samples which were measured, nine remain ungrouped and undated. Most of these ungrouped samples have ring numbers which are close to the lower limit of statistical reliability; only a few have higher numbers. None of these samples have obvious growth abnormalities, such as distortion or compression of the rings, which would make cross-matching and dating difficult. It is possible that the undated timbers are from different woodland sources, making them, in effect 'singletons'. Such samples are often more difficult to date than longer well-replicated site chronologies. There were however noticeable growth abnormalities with a number of the samples from the north cross-wing roof. The inner rings on cores OKM–A27, A34, A36, A50 and A56 were excluded from the analysis due to distortion of their rings which clearly hampered overall cross-matching between the individuals.

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TABLES

Table 1: Details of samples from Flore's House, Oakham, Rutland

Sample number	Sample location	Total rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Hall range roof					
OKM-A01	Crown post, truss A	156	no h/s	AD 1173	------	AD 1328
OKM-A02	S brace truss A to crown plate	53	no h/s	------	------	------
OKM-A03	N brace truss B to crown plate	77	no h/s	------	------	------
OKM-A04	S brace truss B to crown plate	71	33C	AD 1308	AD 1345	AD 1378
OKM-A05	E brace, crown post to collar, truss B	nm	---	------	------	------
OKM-A06	N brace truss C to crown plate	161	no h/s	AD 1188	------	AD 1348
OKM-A07	E arch brace, truss C	183	11	AD 1184	AD 1355	AD 1366
OKM-A08	E spandrel strut, truss C	93	no h/s	AD 1225	------	AD 1317
OKM-A09	W brace, crown post to collar, truss D	70	no h/s	------	------	------
OKM-A10	E wall plate, truss C – D	104	22C	AD 1275	AD 1356	AD 1378
OKM-A11	Tiebeam, truss D	nm	---	------	------	------
OKM-A12	W arch brace truss D	132	no h/s	AD 1215	------	AD 1346
	South cross-wing					
OKM-A13	N wall post, truss 1	145	no h/s	AD 1236	------	AD 1380
OKM-A14	North principal rafter, truss 1	63	no h/s	------	------	------
OKM-A15	Tiebeam, truss 1	123	3	AD 1268	AD 1387	AD 1390
OKM-A16	S common rafter 2, bay 1	55	12	------	------	------
OKM-A17	Stud post 5, south wall, bay 1	58	no h/s	------	------	------
OKM-A18	N wall post, truss 2	59	h/s	AD 1324	AD 1382	AD 1382
OKM-A19	Tiebeam, truss 2	189	no h/s	AD 1191	------	AD 1379
OKM-A20	N principal rafter, truss 2	53	hs	------	------	------
OKM-A21	N common rafter 1, bay 2	68	h/s	AD 1320	AD 1387	AD 1387
OKM-A22	Stud post 1, south wall, bay 2	140	no h/s	AD 1185	------	AD 1324
OKM-A23	Stud post 3, south wall, bay 2	96	no h/s	AD 1282	------	AD 1377
OKM-A24	Stud post 4, south wall, bay 2	107	no h/s	AD 1240	------	AD 1346
OKM-A25	Tiebeam, truss 3	176	5c*	AD 1217	AD 1387	AD 1392
OKM-A26	South wall post, truss 3	80	no h/s	AD 1259	------	AD 1338
	North cross-wing roof					
OKM-A27	S strut, truss 7	77	h/s	AD 1570	AD 1646	AD 1646
OKM-A28	Stud post 6 from N, truss 5 (E gable)	49	h/s	------	------	------
OKM-A29	Intermediate collar, bay 1	63	no h/s	------	------	------
OKM-A30	S common rafter 3, bay 1	nm	---	------	------	------
OKM-A31	N strut, truss 6	73	6	AD 1579	AD 1645	AD 1651
OKM-A32	Tiebeam, truss 6	74	h/s	------	------	------
OKM-A33	N common rafter 3, bay 2	nm	---	------	------	------
OKM-A34	N strut, truss 7	89	18C	AD 1571	AD 1641	AD 1659
OKM-A35	Tiebeam, truss 7	81	h/s	------	------	------

Table 1 (contd). Details of samples from Flore's House, Oakham, Rutland

Sample number	Sample location	Total rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
OKM-A36	SW windbrace, truss 7	57	no h/s	AD 1570	------	AD 1626
OKM-A37	S common rafter 6, bay 3	nm	---	------	------	------
OKM-A38	Intermediate collar, bay 3	nm	---	------	------	------
	Hall range inserted ceiling and ground floor timbers					
OKM-A39	Joist 1	96	no h/s	AD 1427	------	AD 1522
OKM-A40	Joist 2	111	no h/s	AD 1408	------	AD 1518
OKM-A41	Joist 3	84	no h/s	AD 1460	------	AD 1543
OKM-A42	Front (E) wall post, adj to arch brace Truss B	93	h/s	AD 1477	AD 1569	AD 1569
OKM-A43	Front plate over E cross-passage door	151	h/s	AD 1211	AD 1361	AD 1361
OKM-A44	Joist 8	80	no h/s	AD 1438	------	AD 1517
OKM-A45	Joist 9	86	h/s	AD 1483	AD 1568	AD 1568
OKM-A46	Joist 10	105	18	AD 1485	AD 1571	AD 1589
OKM-A47	Joist 11	94	h/s	AD 1477	AD 1570	AD 1570
OKM-A48	Main central spine beam	129	32C	AD 1463	AD 1559	AD 1591
	North cross-wing roof (contd)					
OKM-A49	NE windbrace, truss 6	55	h/s	AD 1581	AD 1635	AD 1635
OKM-A50	NW windbrace, truss 6	62	no h/s	AD 1570	------	AD 1631
OKM-A51	S strut, truss 6	69	h/s	AD 1573	AD 1641	AD 1641
OKM-A52	SE windbrace, truss 6	61	h/s	AD 1573	AD 1633	AD 1633
OKM-A53	SW windbrace, truss 6	nm	---	------	------	------
OKM-A54	NE windbrace, truss 7	54	h/s	AD 1585	AD 1638	AD 1638
OKM-A55	SE windbrace, truss 7	nm	---	------	------	------
OKM-A56	N strut, truss 8	50	no h/s	AD 1570	------	AD 1619
OKM-A57	S strut, truss 8	nm	---	------	------	------
OKM-A58	SE brace, truss 8	nm	---	------	------	------

*h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber
nm = sample not measured
* - sample OKM-A25 had complete sapwood to bark edge on the timber, but the outermost approximately 15–18 rings were lost during coring

Table 2: Results of the cross-matching of site chronology OKMASQ01 and relevant reference chronologies when first ring date is AD 1173 and last ring date is AD 1392

Reference chronology	Span of chronology	*t*-value	
East Midlands Master Chronology	AD 882–1981	13.7	(Laxton and Litton 1988)
Ulverscroft Priory, Charnwood, Leicestershire	AD 1219–1461	12.3	(Arnold *et al* 2008)
College House, Oakham School, Oakham, Rutland	AD 1172–1307	10.1	(Howard *et al* 1999)
Cross Keys Inn, Leicester	AD 1104–1309	8.7	(Howard *et al* 1988)
Braunston, Leicestershire	AD 1165–1279	8.7	(Laxton *et al* 1984)
Glenfield well, Glenfield, Leicestershire	AD 1182–1393	8.3	(Howard *et al* 1985)
Wymondley Bury, Little Wymondley, Hertfordshire	AD 1184–1379	8.4	(Groves *et al* 2005)
Sinai Park, Burton, Staffordshire	AD 1227–1750	8.1	(Tyers 1997)

Table 3: Results of the cross-matching of site chronology OKMASQ02 and relevant reference chronologies when first ring date is AD 1408 and last ring date is AD 1591

Reference chronology	Span of chronology	*t*-value	
East Midlands Master Chronology	AD 882–1981	10.2	(Laxton and Litton 1988)
Nevill Holt, Leicestershire	AD 1274–1534	9.9	(Howard 2001 unpubl)
St Andrews Church, Wimpole, Cambridgeshire	AD 1469–1615	9.1	(Bridge 1998)
Kingsbury Hall, Kingsbury, Warwickshire	AD 1391–1564	9.6	(Arnold and Howard 2006)
Church of St Nicholas, Bringhurst, Leicestershire	AD 1502–1687	9.4	(Arnold *et al* 2005)
Sinai Park, Burton, Staffordshire	AD 1227–1750	9.2	(Tyers 1997)
St Stephen's Church, Sneinton, Nottingham	AD 1484–1654	8.8	(Arnold and Howard 2006 unpubl)
Lowdham Old Hall (barn), Lowdham, Nottinghamshire	AD 1422–1527	8.7	(Howard *et al* 1997)

Table 4: Results of the cross-matching of site chronology OKMASQ03 and relevant reference chronologies when first ring date is AD 1570 and last ring date is AD 1659

Reference chronology	Span of chronology	*t*-value	
England mid-west regional	AD 860–1790	5.9	(Tyers pers comm)
Lodge Farm, Staunton Harold, Leicestershire	AD 1533–1647	5.8	(Arnold and Howard 2007a unpubl)
15/17 St John's St, Wirksworth, Derbyshire	AD 1586–1676	5.7	(Howard et al 1995)
England mid-east regional	AD 947–1805	5.7	(Tyers pers comm)
Black Ladies, Brewood, Staffordshire	AD 1372–1671	5.4	(Tyers 1999a)
Bell Tower, Pembridge, Herefordshire	AD 1559–1668	5.4	(Tyers 1999b)
King's Manor, York, North Yorkshire	AD 1361–1667	5.2	(King pers comm)

FIGURES

Figure 1: Map to show general location of Flore's House (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

Figure 2: Map to show the location of Flore's House (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

Figure 3: Flore's House looking south west

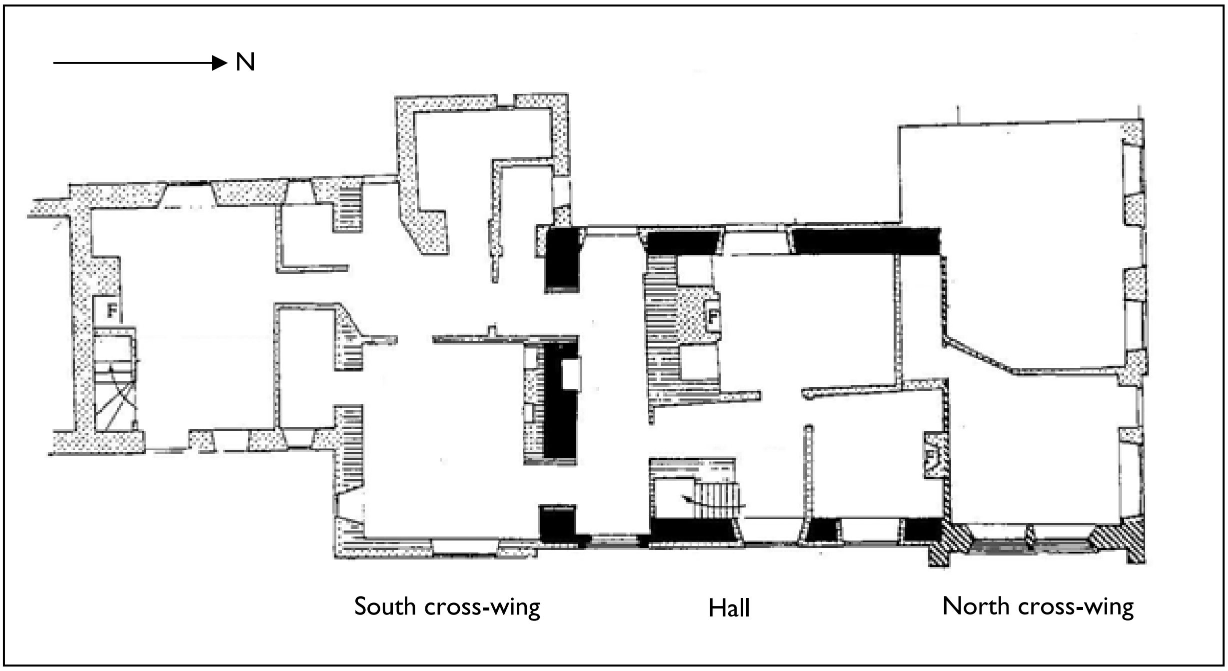

Figure 4: Flore's House ground floor plan (based on a drawing by M W Barley 1975)

Figure 5: The hall range roof truss B viewed from truss C looking north-west

Figure 6: General view of the cross passage looking east towards the front door

Figure 7: North cross-wing truss 7 viewed looking west

Figure 8: South cross-wing truss 2 looking south-east

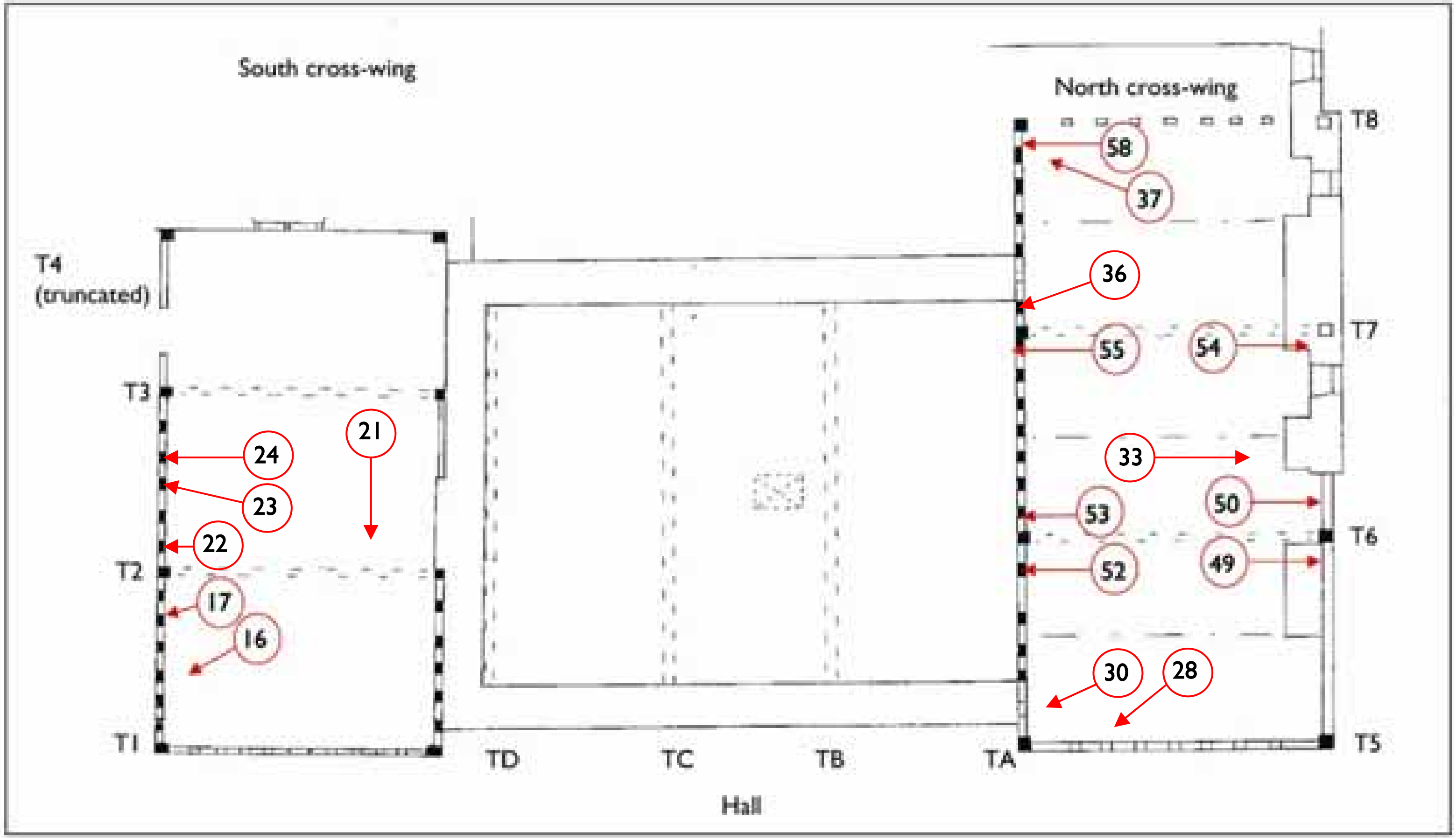

Figure 9: Upper floor plan showing location of samples not shown on the elevation and sections below (based on a drawing provided by N Hill)

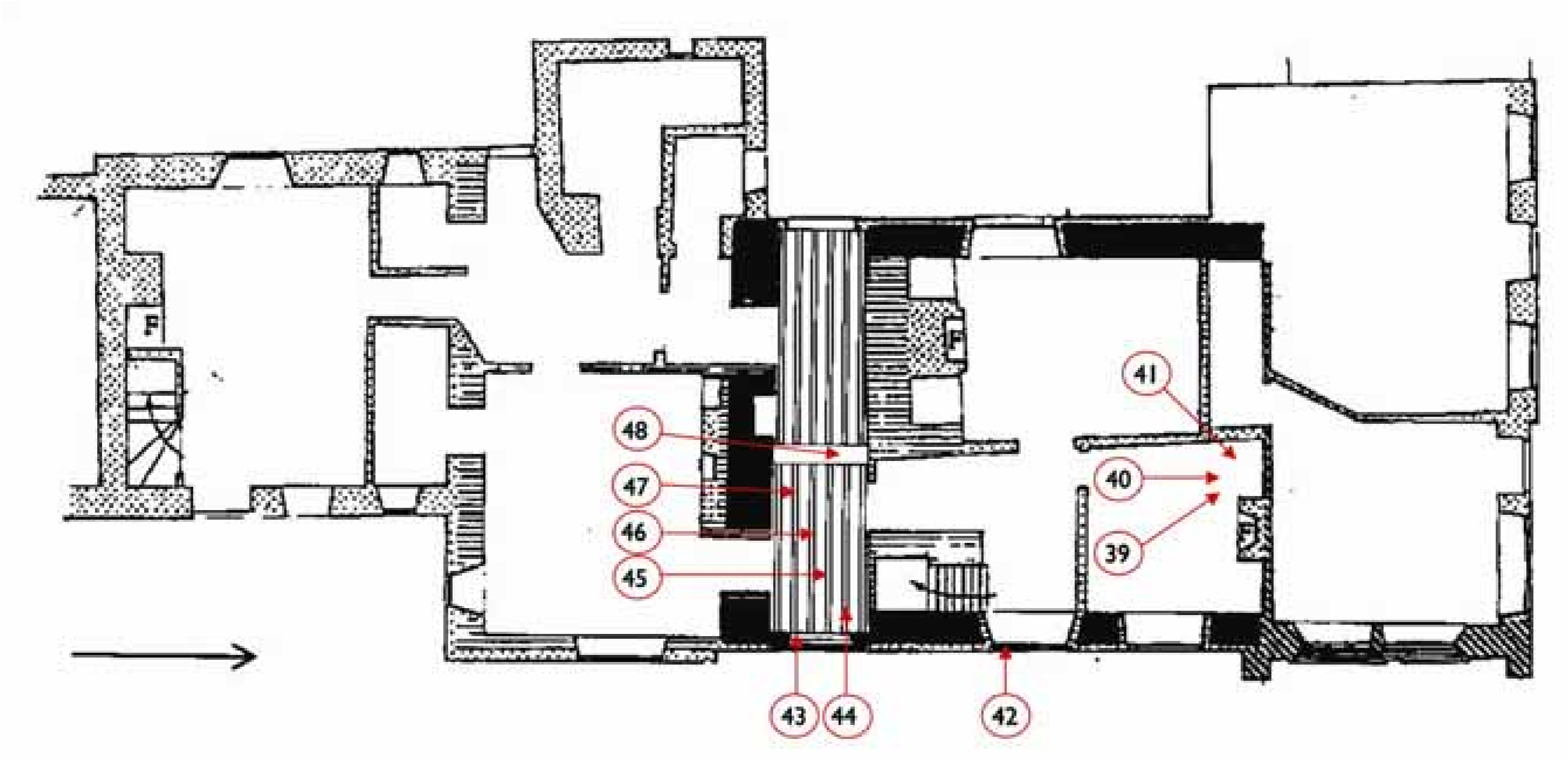

Figure 10: Ground floor plan showing sample locations (based on a drawing by M W Barley 1975)

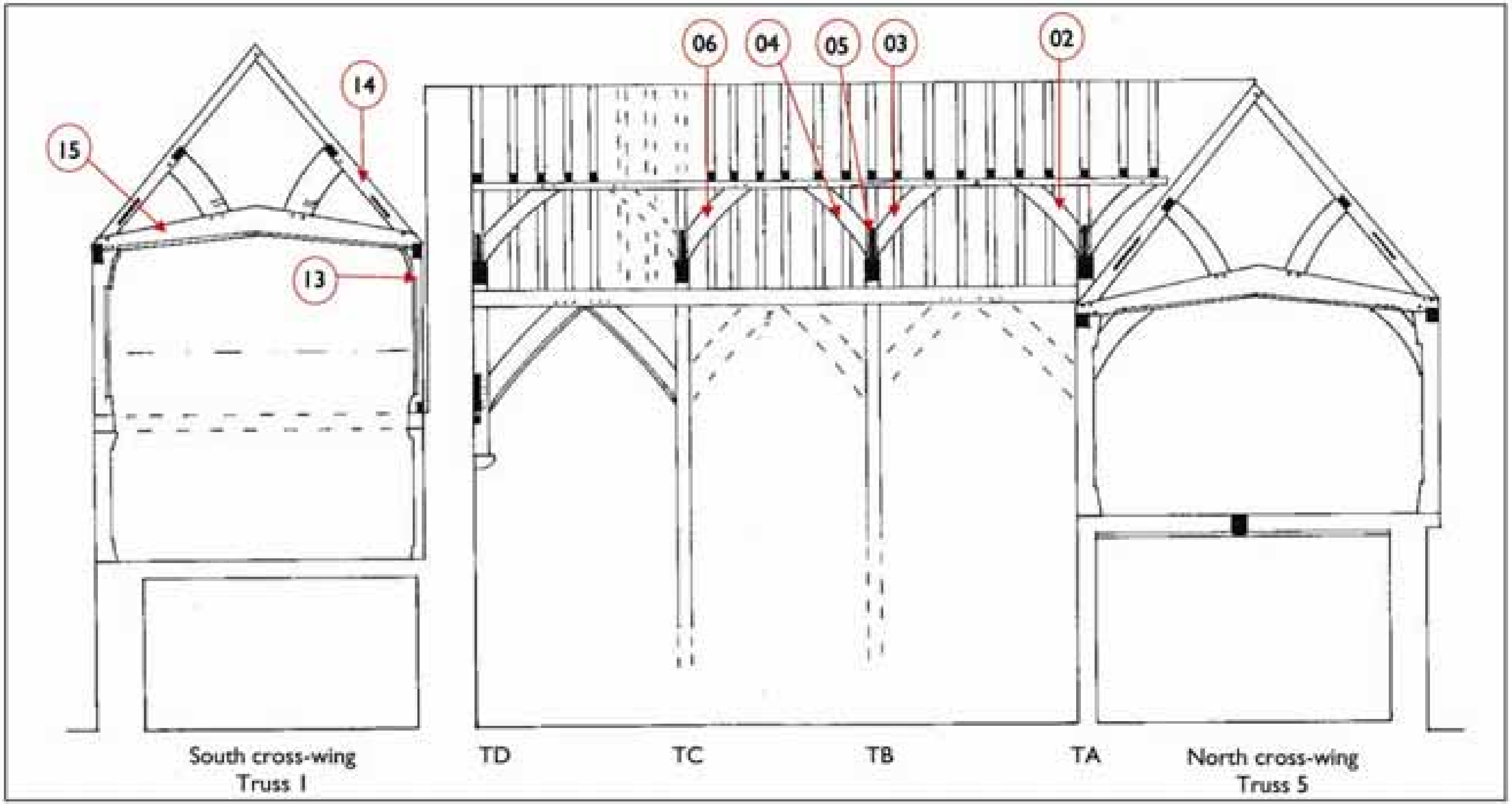

Figure 11: East elevation showing sample locations (based on a drawing provided by N Hill)

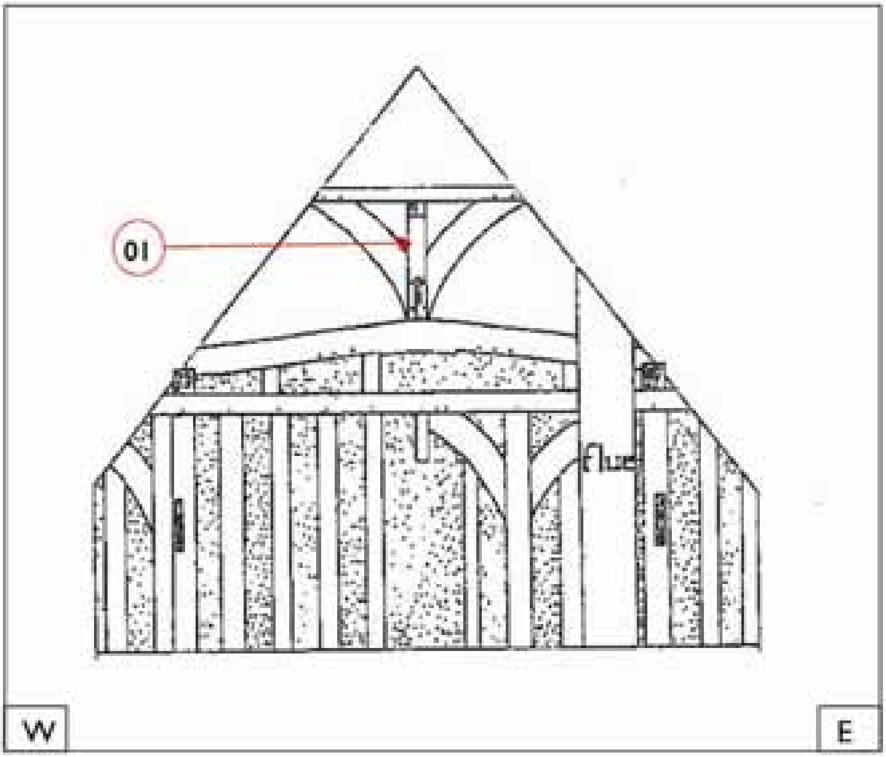

Figure 12: Hall range truss A showing sample location viewed from the south looking north (based on a drawing by M W Barley 1975)

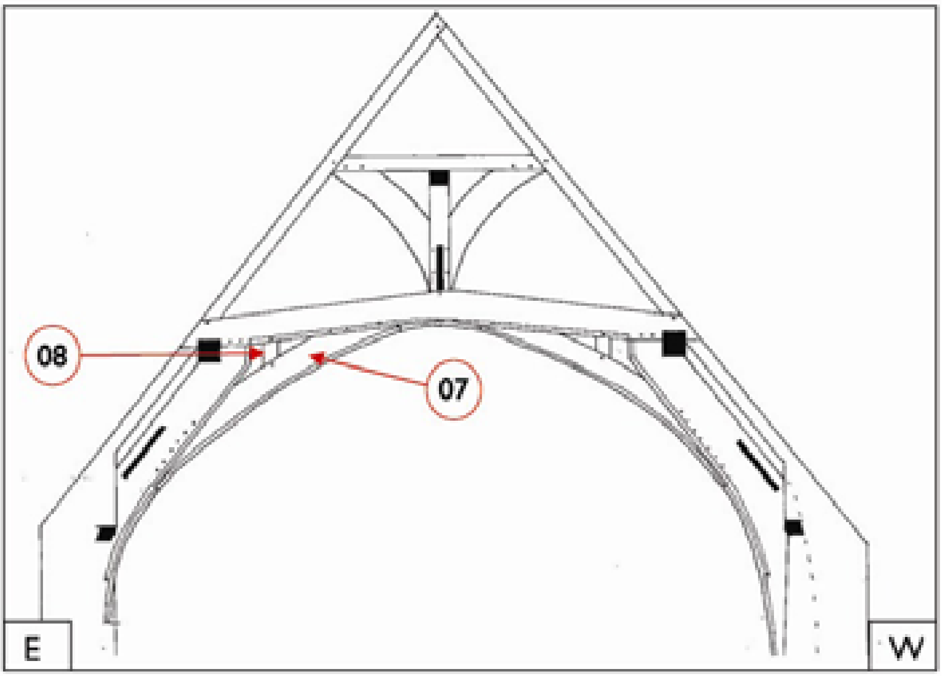

Figure 13: Hall range truss C showing sample locations viewed from the north looking south (based on a drawing provided by N Hill)

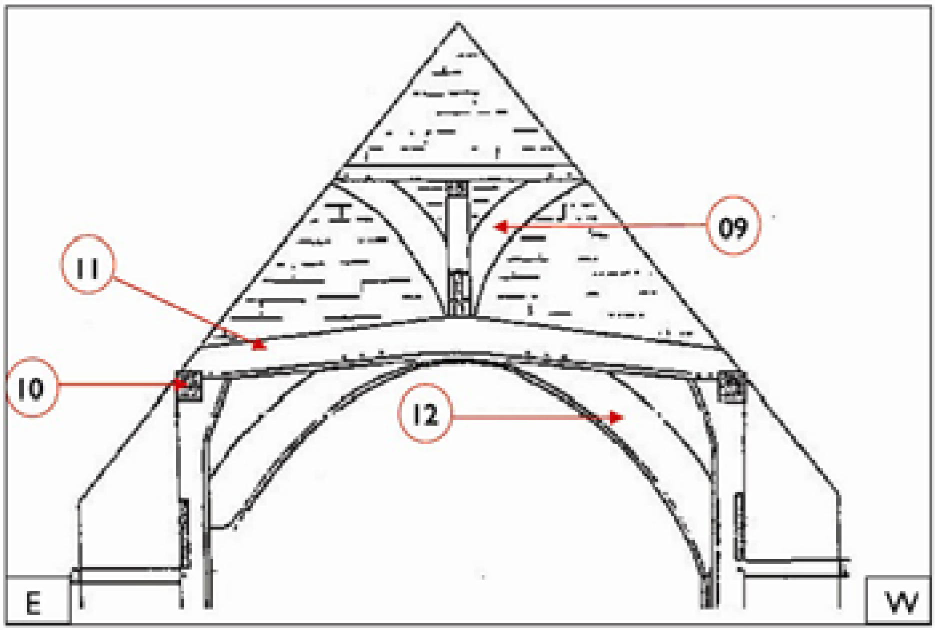

Figure 14: Hall range truss D showing sample locations, viewed looking north to south (based on a drawing by M W Barley 1975)

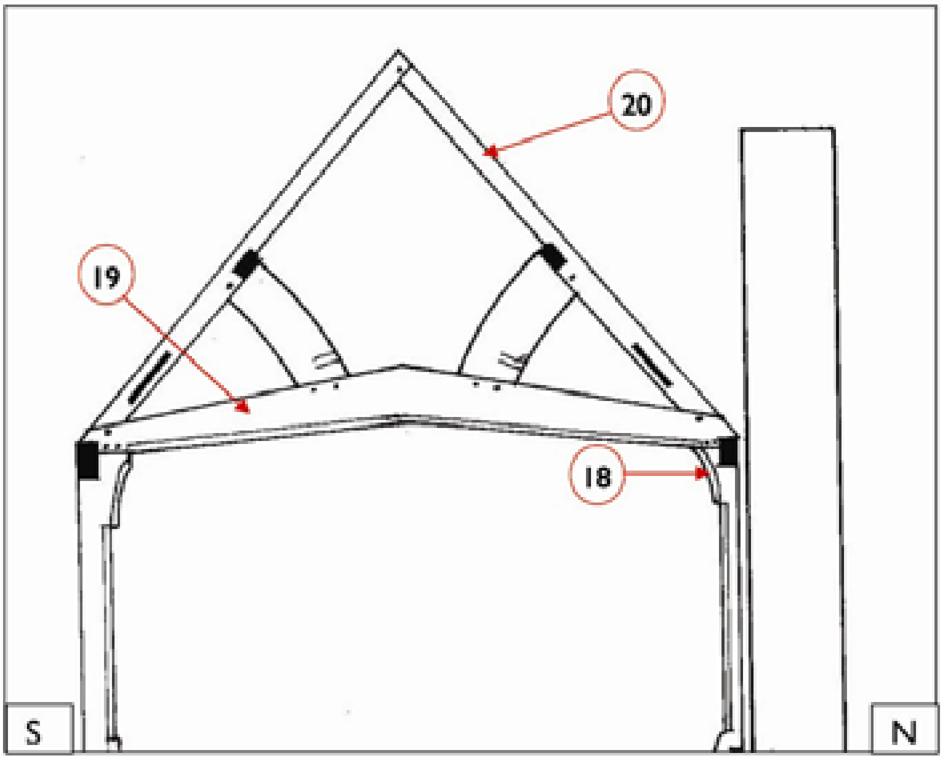

Figure 15: South cross-wing truss 2 showing sample locations, viewed from the east looking west (based on a drawing provided by N Hill)

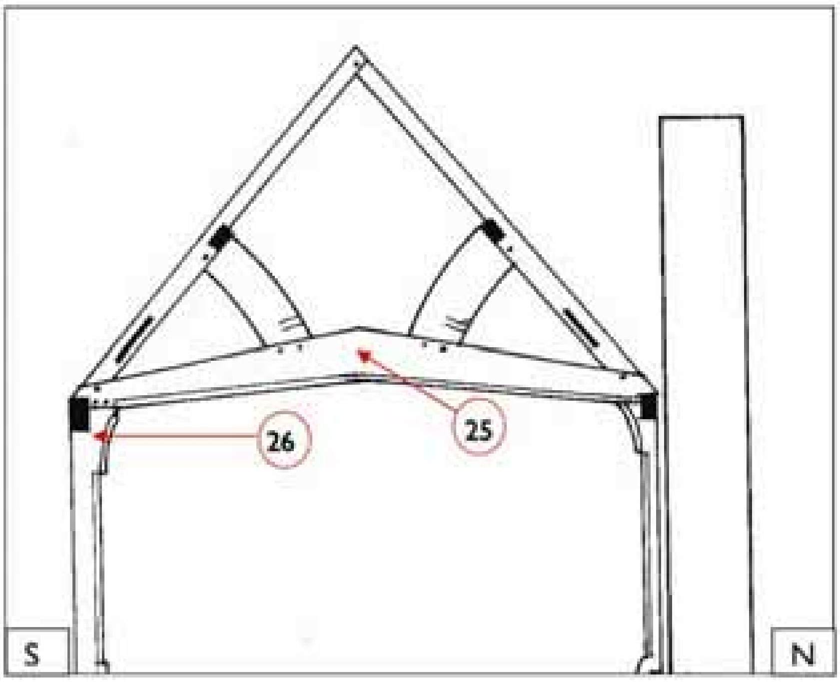

Figure 16: South cross-wing truss 3 showing sample locations, viewed from the east looking west (based on a drawing provided by N Hill)

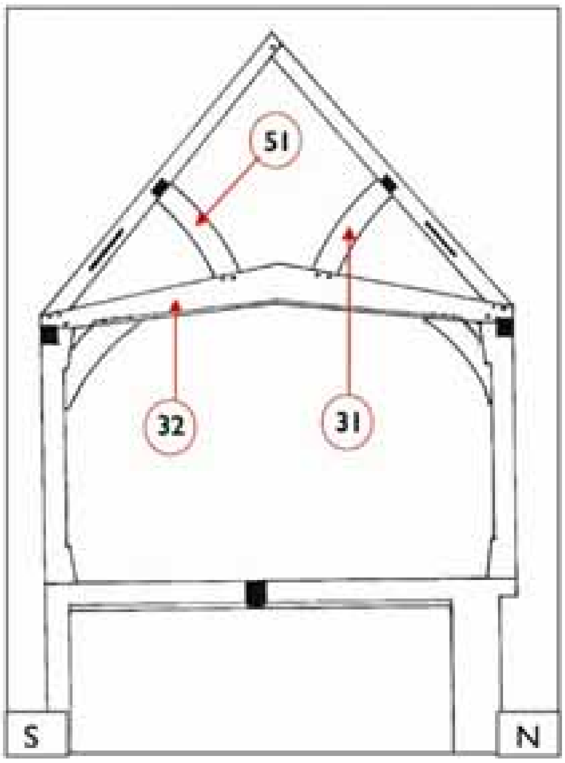

Figure 17: North cross-wing truss 6 showing sample locations, viewed from east looking west (based on drawings provided by N Hill)

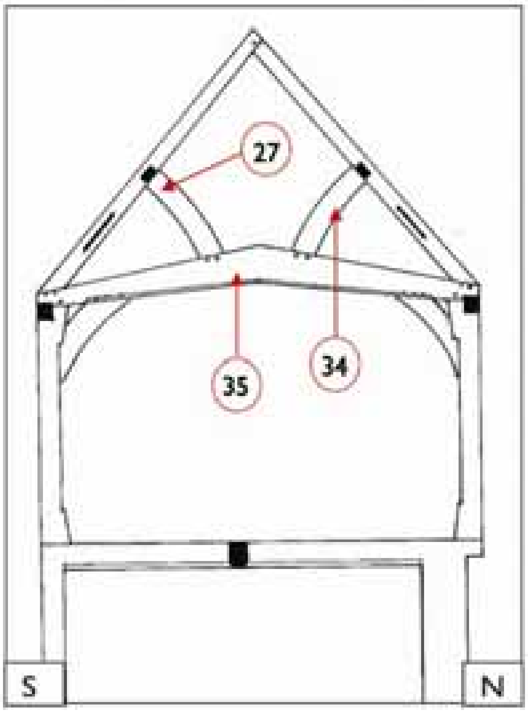

Figure 18: North cross-wing truss 7 showing sample locations, viewed from east looking west (based on drawings provided by N Hill)

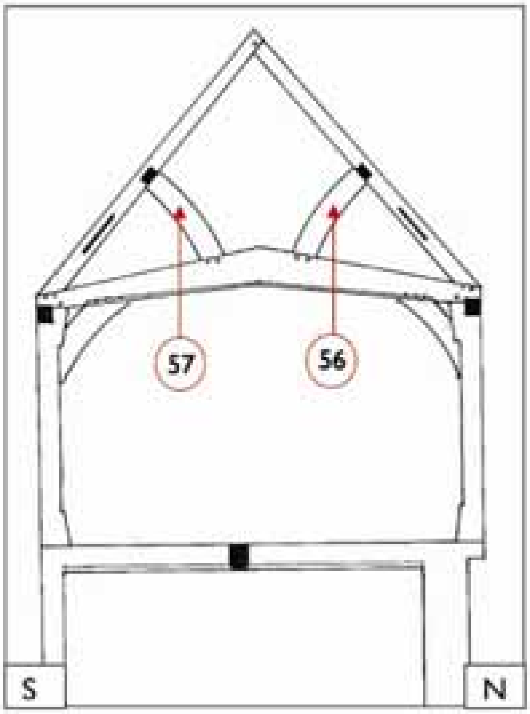

Figure 19: North cross-wing truss 8 showing sample locations, viewed from east looking west (based on drawings provided by N Hill)

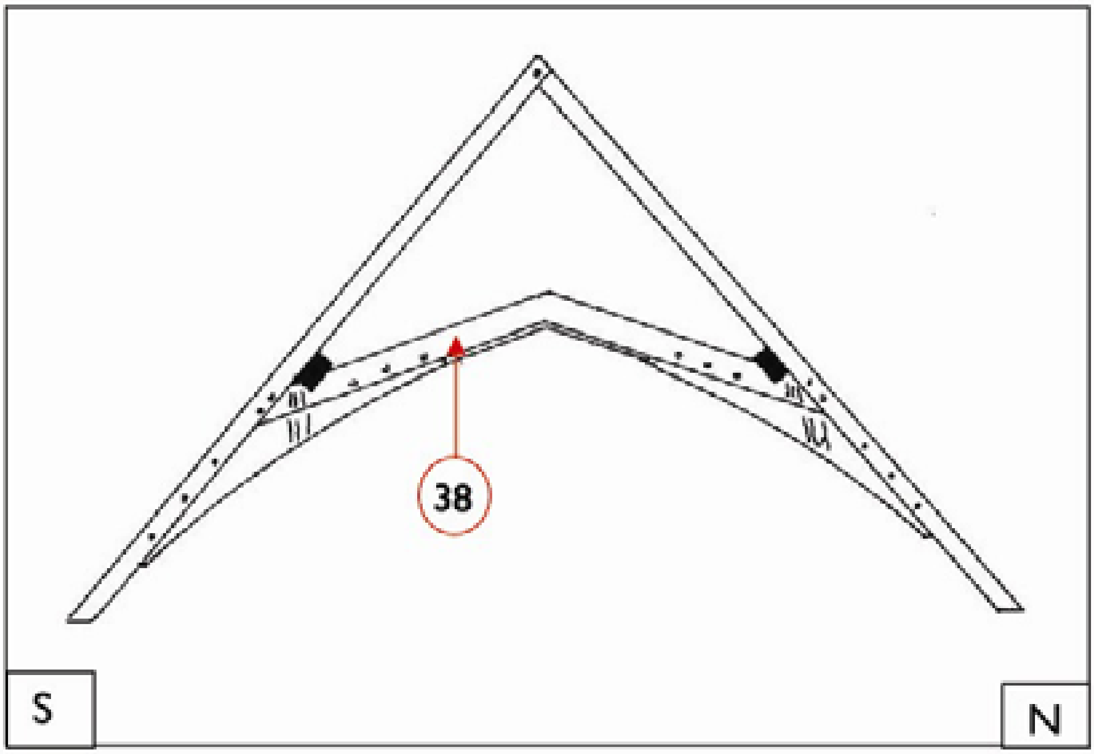

Figure 20: North cross-wing intermediate truss bay 3 showing sample location viewed from the east looking west (based on drawings provided by N Hill)

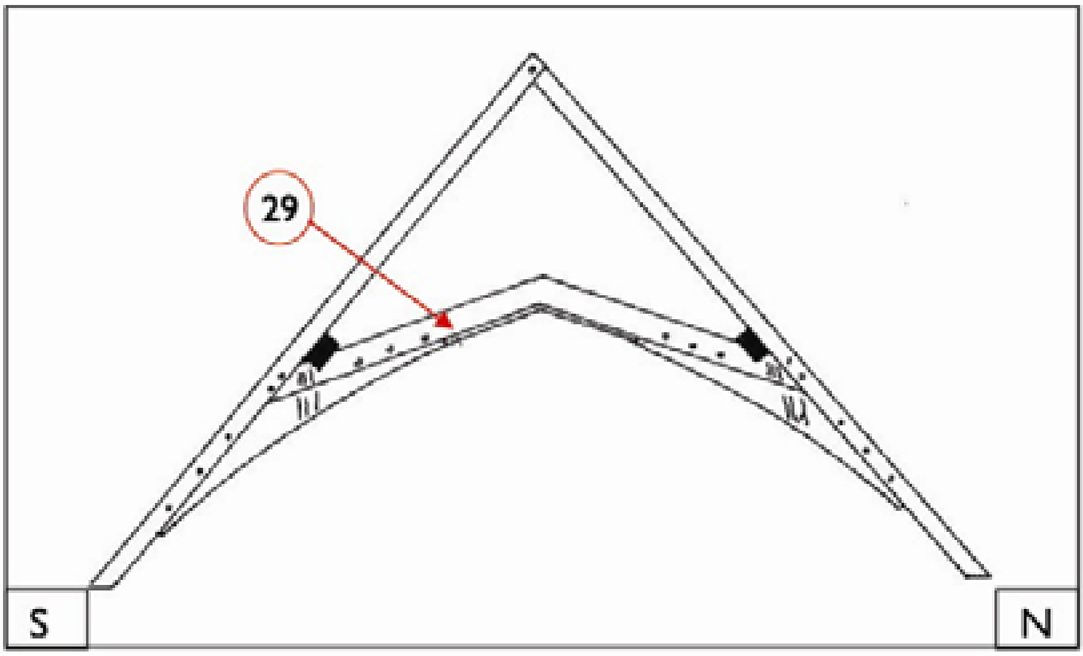

Figure 21: North cross-wing intermediate truss bay 1 showing sample location viewed from the east looking west (based on drawings provided by N Hill)

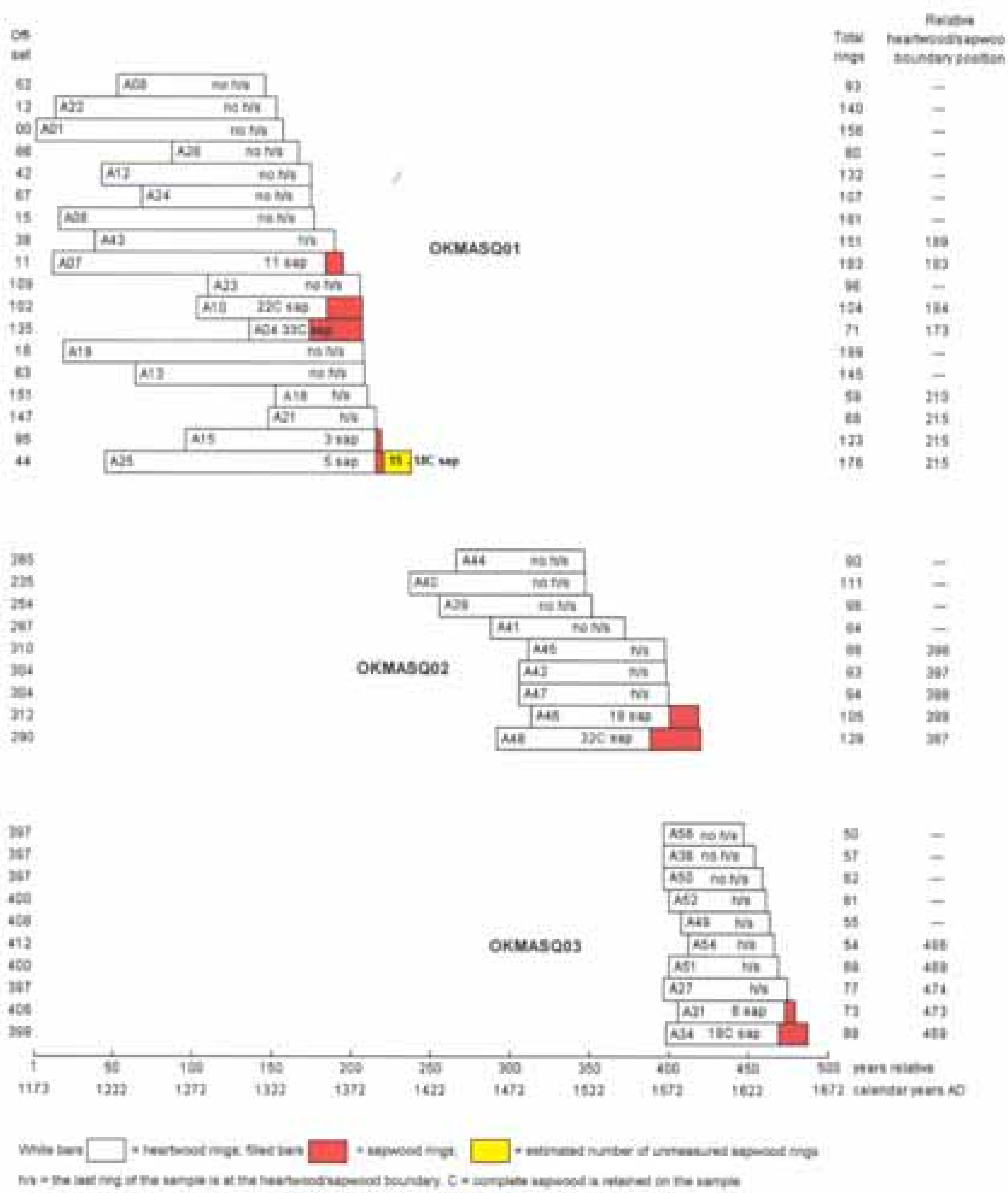

Figure 22: Bar diagram of the samples in site chronologies OKMASQ01, OKMASQ02 and OKMASQ03

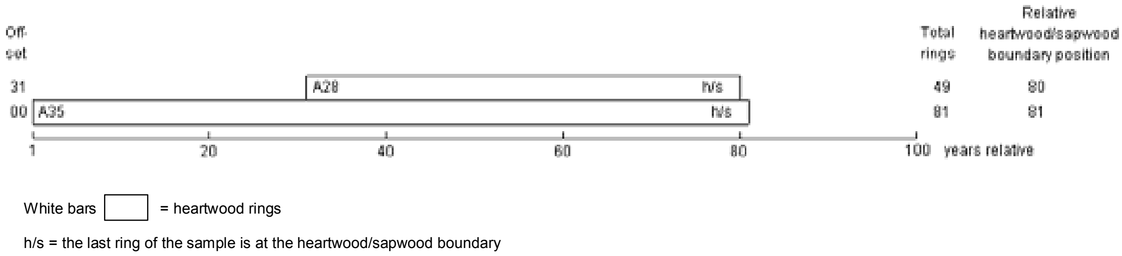

Figure 23: Bar diagram of the samples in site chronology OKMASQ04

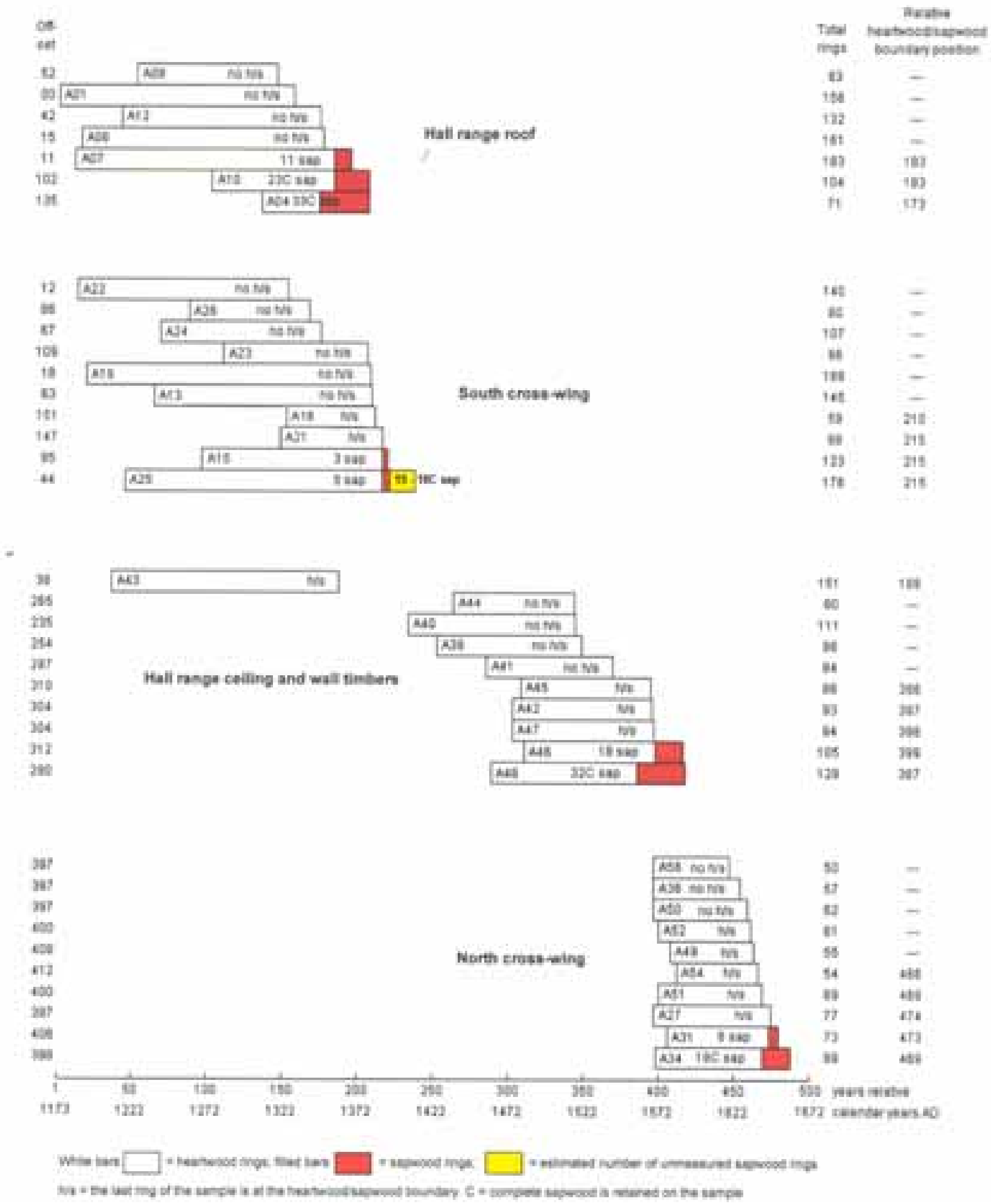

Figure 24: Bar diagrams sorted by area group

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

OKM-A01A 156
322 314 325 375 325 222 197 206 277 295 279 198 269 219 176 70 127 180 141 179
218 216 204 191 156 181 312 235 228 188 145 121 125 89 71 47 52 55 111 113
120 117 88 98 94 61 73 46 38 34 31 38 33 38 39 61 68 51 55 64
79 61 73 44 65 76 54 34 55 28 40 32 40 37 46 36 31 42 66 67
84 75 104 64 84 57 80 155 172 163 81 76 100 85 96 147 192 170 137 82
93 79 68 85 86 113 59 165 256 188 175 177 182 138 118 134 228 205 143 122
118 85 89 63 69 103 88 104 118 74 103 105 91 81 108 90 82 52 56 28
42 45 48 37 41 31 36 35 30 44 51 40 55 50 60 70
OKM-A01B 156
347 312 304 353 320 233 190 195 271 303 279 205 275 221 172 76 115 186 140 181
221 198 210 189 163 185 314 231 220 194 148 122 115 86 62 49 36 55 105 126
128 100 89 96 98 58 77 47 31 32 29 38 40 25 46 57 58 58 48 70
74 66 76 46 63 66 60 44 40 37 45 30 33 46 43 34 29 43 68 67
81 79 100 67 84 62 71 136 162 161 76 77 88 95 92 141 180 167 136 89
95 74 73 85 89 102 56 171 248 187 180 182 180 137 124 129 235 198 146 114
110 90 82 65 75 102 90 92 111 92 96 105 99 72 112 71 81 58 37 44
40 41 49 37 40 34 42 31 32 45 49 48 44 52 58 74
OKM-A02A 53
412 411 379 345 359 265 256 253 281 346 309 250 309 283 215 188 97 83 173 199
191 285 219 203 138 176 233 316 168 324 188 246 147 156 163 322 244 328 334
261 251 236 251 154 182 146 187 271 232 182 229 200 215
OKM-A02B 53
391 418 352 358 397 233 273 238 279 344 348 259 298 258 218 200 108 97 167 198
208 278 234 169 141 178 237 301 182 290 197 226 156 142 173 312 245 336 326
251 251 243 243 169 176 142 198 258 216 193 233 199 216
OKM-A03A 77
297 285 412 366 290 351 411 397 283 288 263 303 359 214 215 153 188 182 206
143 108 150 134 201 91 155 209 272 430 314 371 256 206 267 129 274 340 398 290
307 150 165 140 101 253 161 229 131 215 159 245 222 202 186 230 289 143 214 168
219 278 279 269 362 399 419 358 158 92 136 172 169 247 313 274 229 150
OKM-A03B 77
284 268 463 302 290 336 401 364 283 259 285 295 334 220 207 152 183 174 183
146 97 150 138 189 93 156 198 229 441 318 373 254 197 257 137 312 343 388 329
300 163 195 188 116 248 164 228 141 200 181 191 237 198 173 240 283 147 211 161
211 303 268 300 358 412 418 315 165 111 130 174 167 245 321 289 232 186
OKM-A04A 71
88 67 69 62 89 66 75 143 170 125 109 98 88 83 87 111 114 92 84 144
142 140 184 124 215 214 120 152 106 99 132 134 155 189 183 189 143 109 113 110
142 147 148 186 117 174 124 100 76 82 38 46 69 100 146 87 111 93 60 59

79 93 65 75 129 96 81 57 46 80 119
OKM-A04B 71
75 81 67 53 70 48 78 142 132 126 102 101 83 93 79 107 120 87 98 137
141 135 183 130 213 219 125 141 112 103 117 145 154 191 191 189 151 105 108
108 142 142 152 180 108 183 115 102 79 78 48 39 66 97 146 92 115 90 63 63
68 88 103 77 121 102 79 56 51 77 118
OKM-A06A 161
121 85 324 177 167 263 213 146 95 78 67 54 119 206 200 143 142 140 192 151
229 212 257 323 285 366 244 253 235 222 244 305 246 208 164 199 309 295 235
248 262 236 147 132 138 162 158 230 203 302 165 189 127 89 48 102 75 70 52
82 45 82 79 82 73 123 92 74 47 70 47 55 73 79 57 40 36 63 36 22
35 23 24 46 33 26 31 20 22 36 28 34 79 106 53 47 50 74 53 39
32 72 90 85 119 85 52 73 53 59 56 61 91 81 46 33 66 149 171 130
96 118 76 97 142 73 119 259 172 101 73 71 64 75 82 93 110 75 85 163
136 121 188 122 181 212 134 171 117 184 170 204 199 255 286 283 256 230 197
157 215
OKM-A06B 161
113 100 343 155 162 272 199 153 90 79 64 52 120 204 193 142 138 153 181 152
225 212 238 275 241 377 244 252 239 220 228 310 260 204 156 201 308 290 235
222 261 235 148 143 154 155 159 248 208 301 178 187 125 84 66 88 79 79 52
68 41 85 76 89 70 117 93 77 52 73 45 54 70 81 62 40 39 61 30 25
45 27 26 45 33 29 28 29 18 32 34 27 114 159 49 54 45 75 42 42
37 66 89 84 103 84 55 62 64 56 59 68 86 79 47 39 62 154 170 127
101 112 82 102 122 76 111 238 160 111 71 84 62 85 80 104 114 72 91 165
135 137 187 119 190 221 133 172 133 175 162 215 213 262 294 298 254 225 185
148 228
OKM-A07A 183
212 241 278 279 266 255 498 562 584 400 193 239 243 172 180 287 288 310 214
199 155 161 156 134 112 81 74 125 70 139 119 126 80 73 77 98 78 77 69 74
83 57 71 91 80 59 42 78 88 81 132 116 88 135 105 97 73 92 72 76
64 87 66 112 68 84 123 112 78 95 103 73 81 112 64 113 97 93 92 73
86 63 74 47 94 56 106 95 78 91 47 104 69 71 54 71 125 90 97 76
98 89 74 82 71 133 131 124 105 88 53 77 53 77 73 102 107 80 65 89
114 91 91 91 63 104 69 61 76 32 71 79 71 56 47 68 55 57 26 43
41 43 42 63 61 42 65 61 65 82 76 44 70 58 85 84 72 63 97 60
81 101 89 69 72 59 56 79 76 96 51 92 91 68 51 75 73 76 91 91
121 86 95
OKM-A07B 183
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202 157 162 171 129 105 78 72 112 85 136 120 125 75 81 70 98 77 83 69 64
82 60 74 90 83 53 48 81 77 84 130 122 96 137 90 91 70 87 66 83
60 87 66 102 75 81 134 101 96 87 105 72 74 125 64 124 91 88 91 84
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97 88 73 77 70 135 144 111 111 89 52 77 51 76 78 104 104 83 61 98

101 97 92 86 69 99 66 62 78 35 69 74 68 53 55 71 51 53 31 44
37 47 53 56 66 48 81 60 79 93 93 42 68 60 102 84 78 67 98 62
79 109 81 75 62 57 63 69 88 91 54 73 113 82 54 79 81 68 96 110
110 87 103
OKM-A08A 93
108 136 140 213 167 98 93 103 116 137 129 57 109 88 87 26 37 29 35 27
29 26 47 22 26 36 39 37 34 94 43 25 22 25 31 48 63 113 50 59
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175 124 109 121 239 214 252 174 187 148 138 119 129 146 157 141 163 104 137
167 146 109 124 104 104 69 110 91 111 98 116 69 80
OKM-A08B 93
94 88 93 140 152 84 91 112 138 134 123 64 108 89 80 38 37 31 36 28
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131 116 122 102 92 90 96 91 111 99 101 90 93
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332 481 576 524 450 303 361 465 462 432 533
OKM-A10A 104
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126 112 91 79 66 95 114 128 100 85 89 102 117 146 184 128 164 177 145 194
207 207 170 193 180 211 189 161 121 140 162 162 185 187 134 139 96 116 153 159
142 99 101 75 145 134 138 145 132 96 120 131 126 136 145 172 204 127 126 142
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115 112 125 99
OKM-A10B 104
202 166 189 154 136 193 268 245 231 177 174 249 143 170 230 213 154 156 148 116
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205 212 168 194 184 211 185 160 126 141 147 157 178 182 135 141 101 111 153 156
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117 101 132 137
OKM-A12A 132
235 253 201 137 205 122 125 110 125 165 172 152 217 191 215 137 142 140 150
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141 107 147 223 196 190 221 278 320 298 263 192
OKM-A13A 145
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219 217 244 182 239 326 275 236 159 165 195 160 117 103 193 219 235 205 190 97
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126 102 62 80 121 115 85 93 90 114 112 82 102 124 131 121 124 121 143 104
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86 135 145 147 135
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229 199 252 178 224 321 264 224 168 180 205 189 113 92 201 222 237 203 193 106
118 122 163 211 182 255 234 224 138 172 228 191 217 147 160 118 132 146 139 127
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78 91 118
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233 235 159 200
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90 85 77 58 72 45 68 45 65 47 45 67 46 37 45 35 35 34
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91 82 76 63 64 51 66 45 65 54 39 71 52 36 48 26 34 27
OKM-A18A 59
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288 264 189 155 155 257 304 349 248 304 262 132 241 209 185 172 103 128 198
225 216 169 160 125 89 106 103 93 132 97 118 83 43 77 82 84 110 100 110
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226 161 152 272 292 329 347 164 136 122 209 182 99 161 146 164 141 168 225 189
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OKM-A19A 189
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156 154 258 230 268 132 397 264 352 221 147 88 204 115 139 100 97 101 84 46
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76 59 83 38 52 48 58 55 38 57 42 28 24 17 18 23 27 30 62 93
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53 89 71 116 81 64 92 116 180
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148 157 229 242 257 139 405 264 355 218 123 87 206 120 127 100 100 99 68 61
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242 229 184 159 176 103 78 105 110 153 149 109 95 158
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268 306 323 311 254 268 205 157 127 95 119 135 216 122 150 134 100 122 145 95
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OKM-A22B 140
178 174 207 119 129 237 152 133 174 154 172 176 121 110 66 77 117 84 95 81
62 38 38 35 25 34 68 30 46 56 57 72 73 64 120 83 90 86 149 119
76 91 100 82 89 56 79 111 117 176 144 105 134 107 138 127 123 84 102 67

72 67 120 78 90 87 91 74 82 57 46 55 71 34 76 92 95 76 46 83
64 105 53 99 55 131 146 83 58 52 59 61 65 57 65 115 81 58 47 51
56 46 75 60 70 93 75 57 80 78 48 28 40 60 43 50 51 36 34 56
57 62 70 74 82 91 52 43 50 57 92 51 52 38 37 47 48 51 52 67
OKM-A23A 96
123 77 90 94 87 77 50 183 186 188 231 193 84 82 58 92 96 103 118 198
82 84 79 147 104 96 62 64 91 183 114 66 76 133 133 87 55 86 86 121
113 148 122 115 108 172 132 128 222 78 31 28 50 57 86 133 293 295 314 219
120 78 86 95 96 126 132 164 146 191 123 176 128 96 97 109 68 82 63 67
124 173 127 109 137 124 80 92 100 75 98 80 133 67 138 159
OKM-A23B 96
154 86 88 91 75 79 46 177 190 186 229 184 81 82 50 101 80 127 132 171
74 55 63 145 98 106 60 78 81 159 115 60 77 129 124 93 56 82 88 127
106 137 116 95 80 146 147 191 219 72 32 33 43 63 79 133 284 283 307 211
117 63 80 90 102 109 142 157 153 206 139 167 138 85 104 109 64 80 61 74
123 157 134 96 132 133 88 79 106 72 105 84 140 60 133 181
OKM-A24A 107
196 158 166 289 198 234 203 252 266 174 241 198 128 234 139 128 70 139 127 184
236 185 202 134 138 132 160 145 206 240 205 188 129 196 140 120 136 156 113
115 260 75 57 60 76 93 97 104 58 126 178 153 127 113 104 89 84 74 103 80
78 115 94 105 107 134 119 109 79 89 83 86 89 88 90 133 113 95 64 78
71 85 86 95 110 101 67 33 47 62 68 57 75 74 108 136 119 63 68 63
53 50 52 73 69 111 130
OKM-A24B 107
210 155 156 275 176 258 211 243 256 161 237 192 152 239 146 141 71 149 127 183
241 177 202 134 152 138 142 149 207 235 199 194 122 200 138 114 135 158 112
124 256 65 54 63 78 91 95 108 60 118 180 156 125 119 98 83 80 83 103 85
89 122 104 114 101 152 121 103 75 93 77 93 92 91 96 139 97 96 52 90
87 76 95 86 114 110 55 32 45 62 68 64 73 83 112 139 110 56 61 62
54 44 54 68 79 113 135
OKM-A25A 176
164 155 242 172 230 221 220 242 235 221 219 225 138 99 101 109 121 149 235 141
270 154 265 181 121 94 197 117 147 125 181 156 112 113 88 90 120 119 126 77
147 99 85 113 115 186 115 86 83 78 58 107 85 153 157 98 138 82 93 103
107 67 51 103 111 72 92 107 76 73 46 69 158 148 148 158 148 108 93 74
107 81 113 90 149 83 61 90 95 118 143 104 139 106 79 68 59 66 64 42
44 45 42 34 42 43 47 36 36 34 37 40 49 34 22 20 27 41 44 75
92 79 123 63 45 43 44 45 60 55 39 43 63 52 79 77 81 95 78 116
122 69 62 52 47 54 53 56 50 56 50 41 68 71 61 74 48 77 56 49
59 51 51 55 49 51 38 33 29 49 56 54 54 63 70 85
OKM-A25B 176
210 149 246 181 218 214 214 261 212 244 242 231 142 96 104 111 112 150 216 143
267 176 251 158 119 97 190 116 137 135 188 157 96 138 71 84 124 112 126 91
151 103 83 111 129 185 105 89 89 80 57 112 82 160 155 88 129 83 106 109

98 76 48 104 110 72 91 101 85 74 49 60 164 143 151 160 143 114 91 89
103 78 107 88 147 87 72 85 95 120 130 111 146 114 76 66 52 66 67 49
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71 70 140 63 44 54 45 43 61 50 44 56 67 47 72 63 93 84 75 123
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51 44 53 52 47 45 32 36 32 54 62 49 49 62 76 78
OKM-A26A 80
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97 204 265 232 235 223 220 150 105 63 110 183 235 294 290 156 93 60 77 84
190 207 186 94 144 116 173 157 189 131 155 73 79 73 96 114 80 79 75 59
80 57 87 58 86 77 74 75 53 89 84 113 100 148 193 195 98 91 125 146
OKM-A26B 80
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153 119 188 281 234 269 232 207 163 100 66 117 180 241 284 295 138 89 74 71
95 197 203 166 115 115 139 200 189 179 129 134 62 76 66 84 129 94 63 75 61
92 52 83 56 83 82 71 71 47 91 97 106 91 143 206 192 100 78 114 140
OKM-A27A 77
411 321 247 290 351 347 278 317 216 317 326 238 210 201 151 205 199 130 110
150 179 180 247 253 331 336 192 134 160 156 143 163 125 205 200 88 81 175 191
149 197 156 315 234 258 202 210 245 311 294 257 210 220 224 141 171 149 206 250
271 194 190 245 248 138 270 193 244 316 175 204 200 136 97 138 114 180
OKM-A27B 77
392 326 246 283 359 336 286 346 212 325 320 244 209 211 157 203 181 146 115
144 177 168 250 249 316 353 216 123 148 139 140 147 131 203 195 88 96 185 176
146 210 167 326 244 256 214 210 244 306 299 244 225 218 226 135 188 142 207 255
268 202 177 251 245 157 252 189 245 312 188 199 172 123 117 133 113 187
OKM-A28A 49
347 425 202 186 224 189 263 177 237 229 263 241 326 265 357 287 306 285 89 125
104 136 170 209 298 247 278 443 474 399 330 354 367 417 436 441 364 295 445
250 293 398 348 372 298 205 255 235 290
OKM-A28B 49
370 433 206 183 228 190 256 187 235 245 249 250 315 273 348 300 307 298 99 118
92 141 181 196 282 241 276 446 454 428 345 370 360 432 419 460 367 302 448 252
305 431 349 376 272 224 241 236 291
OKM-A29A 63
153 145 132 140 192 165 108 60 120 123 141 135 161 105 118 116 131 283 209 188
105 138 209 157 109 159 203 148 206 168 178 80 93 102 150 113 138 124 183 218
108 105 168 156 98 187 117 108 170 125 183 229 185 131 146 189 197 164 133 67
72 69 74
OKM-A29B 63
172 145 129 137 164 172 126 64 113 107 129 119 173 80 107 93 131 263 206 184
102 130 207 149 114 151 157 168 195 175 169 86 89 101 145 114 133 133 172 199
83 106 166 178 104 171 129 111 162 131 184 226 209 138 131 181 203 161 131 81
66 83 98

OKM-A31A 73
233 432 430 364 241 244 382 287 157 173 218 277 236 372 361 433 585 239 158
180 239 217 235 127 175 195 99 104 246 226 192 178 168 271 272 273 193 198 274
443 371 354 251 230 210 140 146 123 216 206 222 239 207 254 264 171 276 187 244
312 203 219 238 183 140 161 157 266 227 243 222 281 197
OKM-A31B 73
366 444 440 355 244 256 391 262 148 164 229 293 235 350 332 431 570 246 153
189 240 221 225 130 169 178 96 108 251 233 174 157 173 270 266 282 177 222 261
417 369 350 277 218 215 135 154 122 205 209 215 253 205 267 273 164 280 185 239
317 216 218 234 196 112 185 145 317 222 260 206 263 238
OKM-A32A 74
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230 323 394 392 267 173 175 248 234 143 165 141 153 199 133 146 170 222 225
242 167 239 233 192 169 224 191 99 146 164 193 221 199 148 190 165 158 143 103
106 89 105 150 157 199 230 262 176 244 200 208 194 103 184
OKM-A32B 74
692 566 453 130 79 91 100 115 93 113 102 166 169 178 81 88 167 225 173 182
206 316 394 397 288 167 178 235 232 162 153 145 159 186 135 158 172 218 230
249 161 233 228 196 168 224 183 115 136 153 208 214 197 159 182 175 153 137 124
94 88 107 156 160 190 197 250 171 260 197 204 190 91 204
OKM-A34A 89
349 114 174 255 373 365 476 309 390 217 274 210 154 254 258 223 156 137 217
244 215 307 257 183 156 69 66 122 108 81 87 119 146 117 41 77 126 132 133
147 131 204 188 205 121 149 207 266 221 154 125 156 181 75 109 83 150 148 106
131 107 108 89 89 156 123 152 173 105 122 161 122 92 146 151 117 157 162 140
193 168 205 185 142 158 101 79 91 127
OKM-A34B 89
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266 219 296 250 182 163 96 76 132 101 74 95 129 136 134 41 69 125 147 125
152 129 209 202 180 113 146 207 268 219 151 128 132 169 61 125 87 162 161 110
135 100 109 87 84 161 126 153 175 110 115 170 124 93 142 139 105 156 152 137
215 162 197 166 151 147 93 118 94 130
OKM-A35A 81
341 304 267 233 227 178 148 155 147 127 114 123 115 164 154 161 103 63 85 120
169 189 161 186 258 247 259 203 177 113 165 174 165 70 63 67 67 93 80 95
101 104 91 132 88 110 114 123 121 42 42 35 59 76 96 165 113 88 152 191
184 177 189 210 237 260 248 266 207 291 165 179 235 248 250 190 145 170 175
190 210
OKM-A35B 81
385 299 268 233 226 176 145 149 148 125 113 119 129 155 158 155 101 60 87 106
167 175 177 191 262 240 254 224 172 112 157 184 169 69 78 69 82 94 105 107
94 109 90 128 90 115 115 131 103 52 43 39 67 68 101 154 117 95 148 191
175 164 215 212 232 252 260 253 214 305 159 190 225 246 242 196 146 161 186
197 218

OKM-A36A 57
245 150 153 218 83 103 187 194 201 203 220 205 173 176 231 288 458 163 154 274
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129 134 168 202 257 274 269 230 239 280 252 201 177 275 213 163 194 218
OKM-A36B 57
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267 300 315 255 285 304 217 201 254 303 257 293 228 366 286 188 173 203 251
124 118 174 226 257 267 273 228 244 281 240 197 177 258 232 157 194 220
OKM-A39A 96
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82 112 170 211 287 189 156 198 168 213 137 147 142 144 100 91 91 69 113 118
80 76 105 127 120 98 78 143 177 110 131 112 198 152 156 131 116 107 146 119
134 187 139 106 83 76 91 134 97 149 114 74 72 127 110 107 94 90 92 108
134 93 130 172 154 153 140 122 101 96 77 116 157 84 89 187
OKM-A39B 96
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78 113 169 196 297 198 158 191 167 218 147 132 127 148 119 105 90 73 115 107
73 75 96 126 113 91 78 136 179 113 134 114 198 146 161 139 106 113 137 122
137 175 139 102 87 80 99 130 93 141 97 83 64 121 107 120 83 101 92 102
125 89 133 172 147 157 138 112 95 101 78 113 168 82 75 175
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202 243 268 277 289 146 265 374 357 298 187 156 229 189 180 178 108 75 56 46
61 125 167 213 173 168 357 231 246 157 177 191 211 154 123 107 91 125 125 92
132 125 217 127 163 134 306 401 212 233 184 246 186 166 144 83 87 133 80 135
179 134 144 84 76 65 85 67 102 80 58 71 124 88 56 74 64 66 78 68
67 105 137 162 168 145 106 71 56 44 89
OKM-A40B 111
113 101 74 156 310 99 128 157 166 180 237 144 299 209 101 276 159 155 137 214
191 244 260 273 278 158 280 371 352 273 205 164 223 189 181 174 110 69 57 41
66 124 154 203 182 168 377 223 253 185 194 207 228 144 129 95 101 123 118 85
124 124 209 134 160 143 281 390 209 234 191 241 174 181 134 88 89 133 80 135
181 127 134 74 80 67 91 55 106 72 65 75 119 92 52 73 64 59 76 73
74 102 142 168 163 146 108 68 59 61 74
OKM-A41A 84
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327 286 278 274 159 123 114 124 213 168 165 185 146 163 157 222 194 211 142 122
113 145 140 108 136 162 124 199 121 139 158 170 186 187 203 164 134 151 73 131
112 122 93 147 116 193 82 123 148 171 154 114 159 101 106 135 183 143 135 167
156 118 122 98 110
OKM-A41B 84
319 413 415 463 347 434 405 309 340 308 331 273 205 167 219 267 209 253 276
335 293 288 266 160 118 99 113 203 162 171 180 164 162 169 225 197 203 125 118
110 152 134 105 135 154 122 189 135 133 153 172 177 188 207 159 139 146 71 130

111 124 103 168 125 192 100 127 140 172 164 109 152 112 118 132 185 144 141 161
151 118 117 101 116
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140 190 202 161 215 239 135 127 149 123 139 176 187 265 243 232 197 226 274
254 152 138 89 94 120 87 131 148 89 153 103 84 143 157 163 165 152 155 125
149 69 114 75 81 89 131 125 171 90 152 109 149 143 124 103 74 64 65 79 59
83 69 94 62 72 53 64 61 89 89 58 106 101 72 71 74 88 89 102 82
74 109 96 87 102 102 113 76 74 77 97 113 115
OKM-A42B 93
198 189 212 174 218 232 134 120 138 117 154 179 207 253 238 218 208 240 254
262 154 141 90 98 111 95 133 147 82 159 95 89 141 150 163 163 148 158 128
149 64 116 78 77 89 124 133 158 98 150 110 154 143 122 93 84 60 68 69 55
90 75 82 62 63 57 69 60 83 81 59 109 115 79 69 80 94 89 113 86
72 104 97 87 91 109 119 72 81 78 94 108 137
OKM-A43A 151
79 80 131 95 105 118 165 160 191 159 154 118 136 170 147 120 119 130 144 95
109 81 140 126 115 76 154 107 122 149 123 128 188 146 142 161 188 133 118 85
82 83 182 129 188 175 171 115 175 159 148 212 164 133 158 153 121 102 126 147
148 109 94 128 130 87 103 113 108 150 98 88 77 74 81 74 67 55 122 100
121 109 145 104 87 81 87 80 106 117 96 101 74 95 73 100 107 98 121 98
81 121 104 111 82 102 86 74 79 86 79 88 78 76 70 66 93 82 84 94
61 75 111 87 117 85 90 121 137 101 104 74 82 120 143 96 113 87 90 79
86 92 130 111 110 114 128 115 115 117 122
OKM-A43B 151
114 66 124 106 105 106 162 166 194 156 156 122 146 160 135 142 122 121 131 98
109 90 140 119 118 88 150 100 114 146 129 141 181 147 155 166 185 124 117 98
79 89 183 131 186 172 175 106 175 153 154 201 169 132 163 142 122 108 133 150
113 82 98 135 119 91 106 105 115 141 97 81 80 65 101 75 62 65 113 109
115 108 142 106 73 93 86 75 112 107 110 96 76 81 87 93 102 95 117 90
82 117 103 101 92 111 82 72 78 91 97 70 78 80 68 74 94 71 82 92
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87 99 131 102 119 120 123 119 115 114 132
OKM-A44A 80
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222 184 222 213 224 189 186 150 176 169 141 217 193 250 174 165 137 161 173 142
139 150 161 161 183 206 104 108 132 134 191 172 182 205 145 163 166 190 190 148
100 67 65 104 81 58 85 81 46 88 58 98 103 133 151 132 154 126 143 165 107
OKM-A44B 80
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196 192 215 212 228 196 198 150 162 165 157 212 214 243 169 175 122 182 162 149
158 155 161 155 167 195 102 118 133 134 186 164 148 219 152 171 182 178 197 158
87 63 67 96 73 63 91 77 53 83 85 82 103 130 143 140 148 130 144 164 134
OKM-A45A 86

148 162 125 141 225 176 169 188 141 133 145 184 196 241 147 141 158 251 154
148 157 170 126 211 107 132 206 203 174 197 205 198 187 172 96 171 184 158 143
200 145 205 105 162 198 234 218 212 281 151 170 164 264 176 173 184 185 146 139
121 158 130 195 131 71 185 165 128 145 98 122 125 177 148 94 122 124 124 138
157 164 145 123 124 141 129

OKM-A45B 86

177 160 134 145 258 141 156 180 141 144 140 185 228 243 148 124 160 259 145
140 149 184 126 207 101 135 198 182 163 215 199 207 178 161 89 163 167 163 142
188 140 203 117 142 199 228 219 210 288 147 154 150 244 170 196 182 181 136 158
121 134 141 189 116 76 162 151 137 137 106 124 127 177 140 99 111 141 107 134
161 158 147 131 116 134 168

OKM-A46A 105

161 154 136 163 158 133 121 147 157 144 130 215 107 100 120 96 93 84 103 99
81 114 76 71 100 94 97 96 89 70 60 44 41 99 87 74 68 93 69 127
78 101 107 125 92 69 99 64 77 88 101 114 111 121 140 129 149 51 86 81
85 93 76 119 130 101 129 94 132 134 151 128 108 93 113 98 111 130 109 110
105 65 75 124 120 121 135 93 100 83 97 76 54 57 64 95 65 41 47 74
87 93 71 49 80

OKM-A46B 105

105 119 139 165 163 153 127 133 143 149 129 219 111 106 133 118 90 75 90 114
97 116 68 73 88 106 94 90 81 73 64 57 49 93 100 67 64 93 69 115
79 89 123 122 101 67 89 66 75 91 120 97 113 113 138 126 146 57 84 88
79 88 70 107 127 104 117 82 109 139 162 134 104 93 111 105 109 117 127 112
101 66 73 117 105 133 111 91 93 87 97 79 57 49 72 89 46 50 43 59
86 102 80 42 81

OKM-A47A 94

117 115 208 131 146 112 98 80 103 93 176 174 136 104 86 68 89 98 82 123
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53 112 86 68 76 150 133 121 50 97 129 92 88 70 155 64 56 56 109 64
71 67 67 51 94 46 86 75 79 55 34 95 120 47 102 64 91 104 216 74
46 61 81 156 81 159 112 108 111 72 98 92 143 159

OKM-A47B 94

148 123 195 123 155 115 92 90 93 99 162 178 133 96 78 71 84 105 76 127
82 76 77 121 75 72 69 73 86 102 98 84 122 157 192 161 131 81 76 59
48 108 95 65 82 143 131 123 46 104 121 99 85 82 149 69 69 50 135 72
63 66 68 48 85 51 92 69 78 65 40 82 118 47 93 65 85 103 233 71
51 67 106 156 81 155 112 101 96 73 97 101 142 155

OKM-A48A 129

348 270 240 136 103 113 130 153 164 137 128 151 184 214 182 200 248 286 255
231 187 108 122 145 206 163 196 241 152 175 166 181 195 246 140 152 125 197 166
189 170 171 120 179 119 142 164 181 174 173 152 130 139 144 66 92 140 115 100
112 110 161 78 111 112 101 127 104 143 82 90 102 111 85 71 91 76 66 78 67
100 86 98 82 60 87 90 58 80 66 56 57 76 63 44 48 52 42 62 63
47 49 44 40 30 45 59 48 46 30 45 30 32 48 51 50 62 81 57 67

46 80 84 101 91 86 98 59 95
OKM-A48B 129
306 268 169 134 98 117 136 162 164 130 130 150 182 209 189 219 233 263 257 253
170 112 125 139 211 155 198 249 172 187 152 181 189 229 144 153 120 205 170
183 171 163 122 175 118 152 163 168 169 179 150 127 139 143 72 95 139 120 97
112 112 158 81 110 113 103 122 104 136 87 99 93 114 83 69 94 76 66 71 74
100 80 95 92 49 92 85 58 81 62 71 49 78 60 49 56 59 39 60 62
54 47 51 35 39 40 51 45 48 29 35 31 37 49 59 44 62 70 65 65
50 77 93 99 80 92 83 66 98
OKM-A49A 55
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206 286 283 350 295 201 198 203 235 165 143 203 209 262 228 199 159 160 224 216
209 158 232 159 125 185 217 227 226 198 207 167 192 149 127 176
OKM-A49B 55
160 180 154 164 177 205 127 158 199 179 199 204 220 197 263 200 159 191 200
192 289 288 359 248 209 200 198 227 158 143 204 210 267 233 208 169 166 231 226
197 172 236 164 111 188 204 225 227 196 205 165 188 142 110 175
OKM-A50A 62
207 169 140 206 133 98 131 185 194 254 157 151 164 136 179 234 254 132 128 217
164 199 237 166 196 272 114 131 217 198 157 242 197 279 196 187 166 194 228
110 99 159 218 213 193 149 129 158 170 142 115 100 165 100 98 150 120 149 156
135 163 126
OKM-A50B 62
198 169 154 192 141 95 124 175 192 248 143 159 155 144 173 234 242 134 124 207
168 210 230 188 188 270 125 134 198 172 152 226 205 272 214 182 174 179 210
111 106 174 218 214 180 161 123 165 158 142 117 110 168 102 87 137 129 137 155
147 162 125
OKM-A51A 68
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330 359 396 535 351 256 214 223 179 217 144 239 231 88 118 251 226 154 188 131
268 231 269 143 136 162 288 238 218 175 177 237 131 107 72 157 168 190 182 126
136 103 101 142 110 169 170 80 145
OKM-A51B 69
482 438 464 371 417 346 498 511 541 461 300 302 326 271 164 146 246 269 251
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135 109 92 143 104 165 172 79 160 190
OKM-A52A 61
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224 327 345 211 187 247 213 234 343 287 368 356 217 244 265 270 198 139 204
251 255 238 231 240 267 297 285 260 208 235 206 147 176 163 172 203 244 202 177
216 173
OKM-A52B 61
195 81 90 115 122 168 177 170 210 251 221 299 202 279 168 135 185 198 238 261

205 333 317 192 182 241 204 221 349 286 354 360 211 254 256 268 198 138 210
249 246 242 239 227 262 320 280 260 208 244 186 141 165 183 172 213 234 208 177
201 155
OKM-A54A 53
255 380 109 108 158 173 166 198 172 291 361 192 205 244 237 225 273 265 343
229 122 184 224 210 125 135 151 206 186 166 134 151 163 194 144 129 107 207 174
115 147 157 283 199 217 163 117 134 124 103 185 159 236
OKM-A54B 54
254 332 130 111 170 157 169 213 159 242 358 191 210 263 258 192 273 273 347
264 131 191 231 219 107 133 138 211 185 156 135 133 153 190 156 129 117 202 188
117 153 177 253 218 241 172 128 138 130 110 177 178 217 250
OKM-A56A 49
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117 111 175 216 232 237 197 174 201 301
OKM-A56B 49
160 205 74 93 60 63 142 240 172 268 216 148 225 220 275 212 276 151 143 225
232 225 263 225 268 302 188 258 273 276 224 285 194 244 272 190 174 196 214
108 115 171 215 232 244 193 163 211 300 237

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

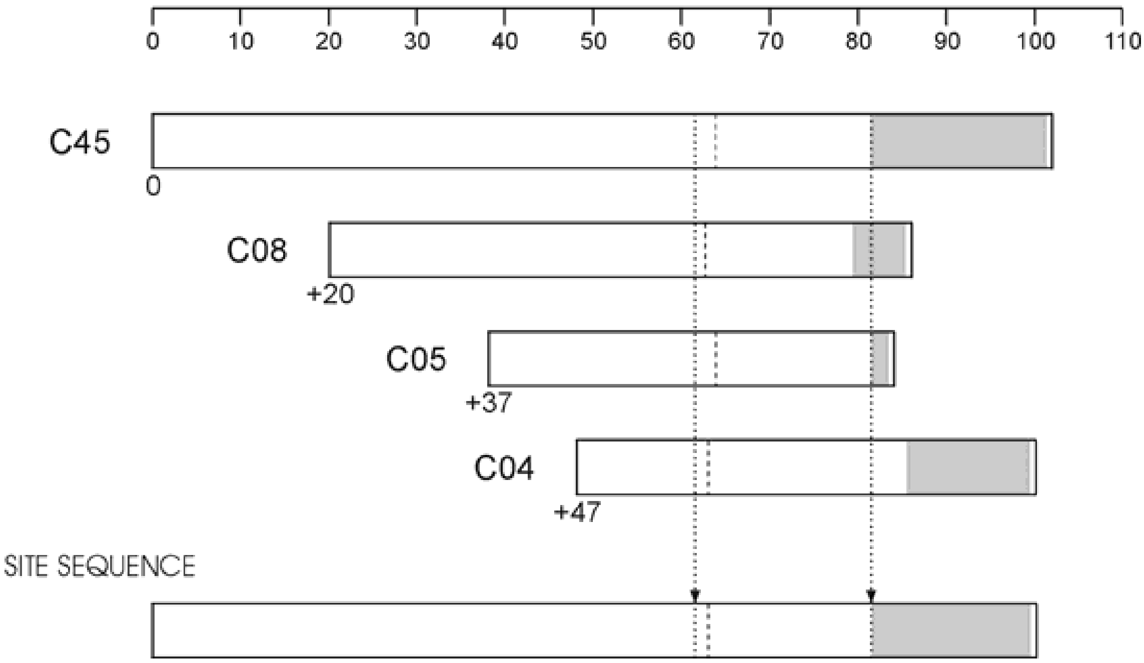


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

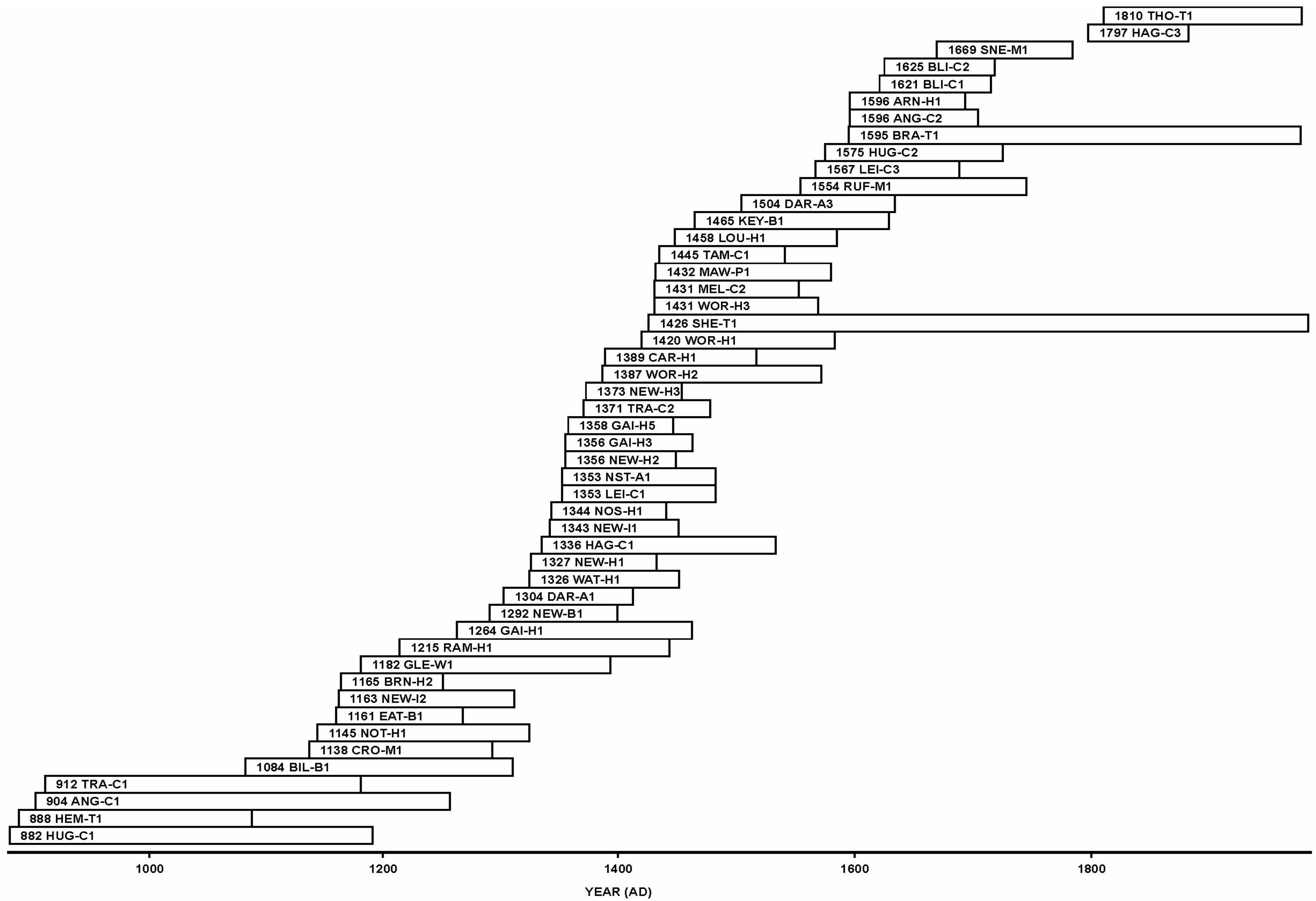
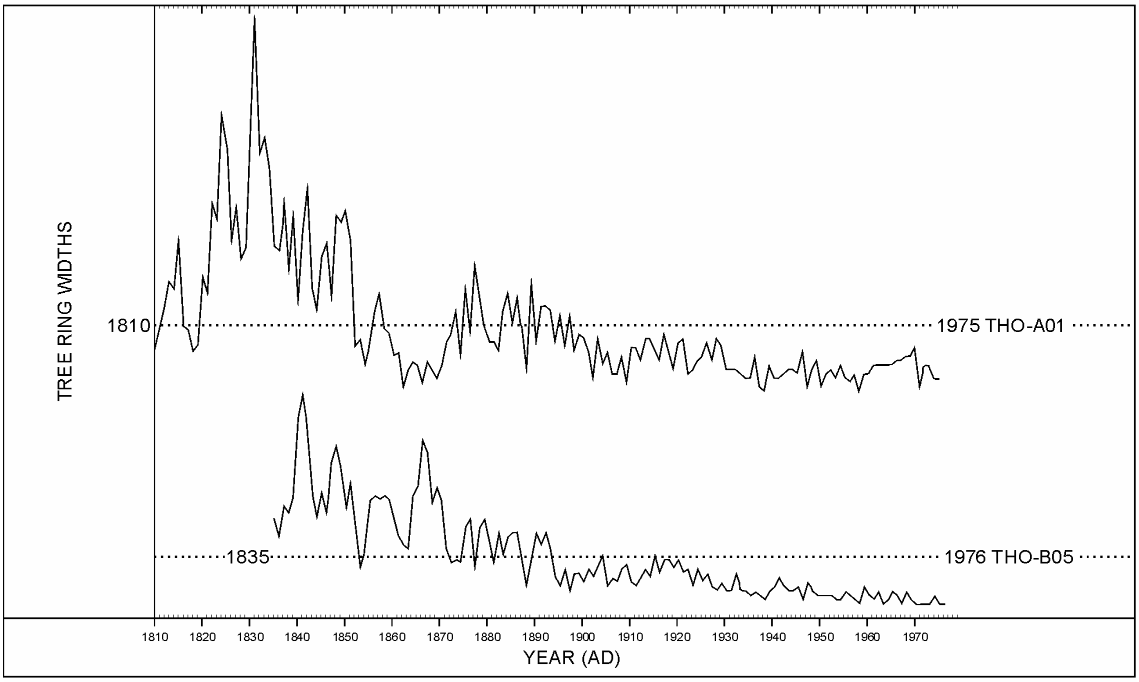


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

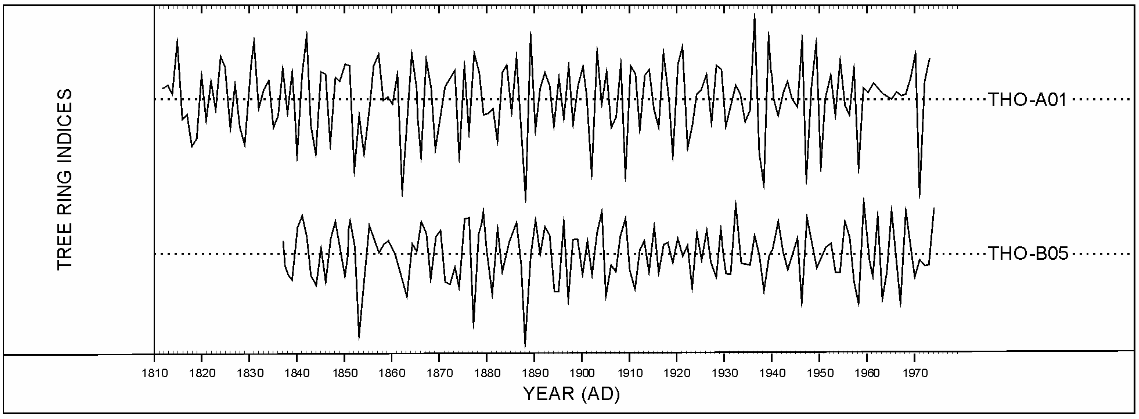


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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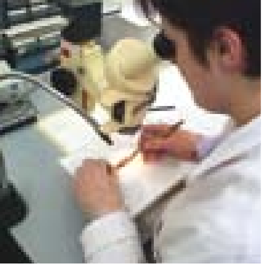
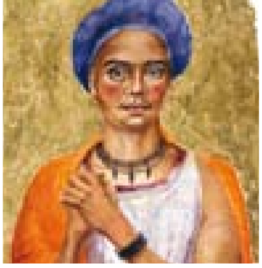



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