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OAKHAM CASTLE, CASTLE LANE, OAKHAM, RUTLAND

TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

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SUMMARY
Analysis by dendrochronology of 69 samples from timbers within Oakham Castle has produced three dated site chronologies, indicating that timbers of at least four separate phases of felling are to be found in the hall, north aisle, and south aisle roofs.

The earliest phase is represented by a group of reused timbers with an estimated felling date of AD 1160–85 (although one timber might have been felled slightly earlier). It is very likely that these are remnants of the original roof and as such make Oakham the earliest hall of any English castle to survive so completely. The next phase of felling is represented by a further group of reused, though probably coeval, later sixteenth-century timbers, with an estimated felling date in the range AD 1568–93. As such these timbers denote a hitherto unsuspected felling phase. A third phase of felling is represented by another group of broadly coeval, early seventeenth-century timbers, these having an estimated felling date in the range AD 1621–44 representing an early alteration phase of the hall. The latest phase of felling is represented by a group of timbers which show no evidence for reuse and which almost certainly belong to the re-roofing of the hall. This group of timbers appears to have been felled in the mid-AD 1730s.

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INTRODUCTION

The earliest structures of Oakham Castle (Figs 1 and 2) are thought to date to the AD 1080s when a timber hall, defended by a keep with a motte and ditch, is first mentioned. Later, in AD 1340, the inner bailey of the castle is described as containing a building with four rooms, a chapel, a kitchen, gaol, stables, and barns. There was also an aisled stone hall, presumably a replacement for the earlier timber one. The site is further described at this time as being 'well walled', the stone curtain believed to have been built in the thirteenth century, and 'with a drawbridge' across a moat. Beyond the walls there were gardens and fishponds.

Almost all of these structures have since disappeared, with only parts of the curtain wall and the stone hall now remaining. It is this stone hall which is referred to as 'Oakham Castle'. On the basis of the stylistic evidence of the arcade capitals (almost identical to those of the choir at Canterbury Cathedral, begun in AD 1175) it is believed that the hall was built *c* AD 1180–90, almost certainly for Walkelin de Ferrers (died AD 1201), and if correct, Oakham would be the earliest hall of any English castle to survive so completely.

Internally a series of piers and arcades divide the body of the hall into four bays, whereas the present roof, which has traditionally been believed to be a later replacement, is of six bays formed by five king-post trusses and the two gable end walls (Fig 3). In addition to king-posts, tiebeams, and principal rafters, the trusses have collars and angled struts from the shouldered base of the king-post to the principal rafters. Also, in addition to the five trusses there are two lateral, intermediate beams at arcade top level, between trusses 1–2 and 4–5. These beams are supported by curved arch-braces which spring from short wall-posts.

A survey of Oakham Castle has recently been undertaken by Nick Hill (2013). This survey discovered that a number of timbers with early lap-joint type mortices have been incorporated in the present roof, which, given that this is thought to be a later replacement, are possibly reused from the original roof. Closer inspection of the timbers, afforded from a high-level scaffold tower, suggests that these potentially early timbers have probably been derived from what were once larger timbers by being split and cleft, and that such timbers are common and found in widespread locations throughout the roof.

SAMPLING

Tree-ring analysis of the timbers within Oakham Castle was requested by Nick Hill to provide dates for both the reused timbers, in the hope that this would establish the original construction date of the hall, and that of the replacement roof, itself a very interesting structure in that it is possibly a very early example of the king-post form, whose date is uncertain and importance has not yet been fully recognised. The dendrochronological brief requested analysis of timbers of both the main and intermediate truss types, as well as from the common rafters and main beams of the main and aisle roof structures.

A total of 69 samples was obtained by coring the extensive material available. Each sample was given the code OKM-C (for Oakham, site "C"), and numbered 01–69. An attempt was made to obtain samples from as wide a range of locations and elements within the roof as possible, from those which showed clear evidence for having been reused, or were thought possibly so, those which appeared primary to the present structure, and those whose place in the development of the roof was unknown. This approach, however, was slightly limited by the height of the uppermost parts of the roof (approximately 10 metres) which required the use of a mobile scaffold tower, and even then the positions of various beams and overhead light and sound fittings, and the fixtures and fittings at floor level presented difficulties. The location of all samples was noted at the time of coring and marked on survey drawings derived from those made and provided by Nick Hill. These are reproduced here as Figures 4a-k, with timbers colour coded in an attempt to indicate their likely phase of felling. The numbering system used in this report follows the apparent schema of the roof structure wherein the truss and bay numbers appear to run from west to east and individual timbers then being further identified on a north-south basis as appropriate. The positions of the common rafters are identified in relation to the double purlins of each pitch of the roof, these forming a lower, middle, and upper tier. Further details relating to the samples, in simple sample number order, can be found in Table 1a, with Table 1b listing the samples sorted by their likely phase of felling.

ANALYSIS

Each of the 69 samples obtained was prepared by sanding and polishing. It was seen at this time that two samples had fewer than the minimum of 45 rings deemed necessary for reliable dating, which were therefore rejected. The annual growth-ring widths of the remaining 67 samples were, however, measured, the data of these measurements being given at the end of this report.

The data of the 67 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing three separate groups to be formed at a minimum value of t=6.0. These three groups account for 64 measured samples, the samples of each group cross-matching with each other as shown in Figures 5–7. The cross-matching samples of each group were combined at their indicated offset positions to form site chronologies OKMCSQ01-SQ03.

Each of these three site chronologies was then compared to an extensive corpus of reference material for oak, this process resulting in the satisfactory dating of all three with each site chronology matching repeatedly and consistently with a large number of reference chronologies. Each of the three site chronologies was then compared with the three remaining measured, but ungrouped, single samples but there was no further satisfactory matching. The single remaining ungrouped samples were than compared individually with the full range of reference chronologies for oak, but again there was no satisfactory cross-matching, and the three samples remain undated. This analysis may be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
OKMCSQ01	21	231	923–1153
OKMCSQ02	23	238	1383–1620
OKMCSQ03	20	140	1598–1737
Ungrouped	3	---	undated
Unmeasured	2	---	---

INTERPRETATION AND DISCUSSION

Analysis by dendrochronology of the 67 measured samples from this building has produced three site chronologies, all of which can be dated. Interpretation of the sapwood on the dated samples would indicate the probability that, as intimated by the structural evidence, timbers of different phases of felling are to be found at this site.

Site chronology OKMCSQ01

The earliest dated material detected in this programme of analysis appears to be represented by the 21 samples of site chronology OKMCSQ01 (Fig 5) which are mostly timbers from the main hall roof with three from the south aisle roof and two from the north aisle roof. The majority of these timbers show clear evidence for reuse. None of the 21 samples in this site chronology retains complete sapwood and it is thus not possible to give a precise felling date for any of the timbers represented. Seven of these samples do, however, retain the heartwood/sapwood boundary at a relatively consistent position and date, this meaning that they are likely to represent a single, or fairly close-set, phase of felling. Within these seven samples the sapwood boundary varies by 15 years from AD 1138 (OKM-C11) to AD 1153 (OKM-C18), the average date of the boundary on the seven samples being AD 1145. Using a 95% confidence limit of 15–40 rings for the amount of sapwood these trees might have had would give the timbers represented an estimated felling date in the range AD 1160–85.

An eighth sample, OKM-C63, with seven sapwood rings, does have an earlier heartwood/sapwood boundary ring, this being dated to AD 1108. Using a 95% confidence limit of 15–40 rings for the amount of sapwood the tree represented by this sample might have had would give it an estimated felling date in the range AD 1123–48. Either this timber was indeed felled earlier than others represented by this group (which is a possibility given that it is a reused timber), or the tree had a higher number of sapwood rings than usual (again a possibility given that in a group of 69 samples we might expect to find several timbers with sapwood numbers outside the 95% probability interval).

Thirteen other dated samples in site chronology OKMCSQ01 do not have the heartwood/sapwood boundary and it is thus not possible to be completely certain that they too represent timbers cut as part of the same phase of felling. However, such is the level of cross-matching found overall between this entire group of samples that it is likely that all the trees represented were growing in the same copse or stand of woodland, and thus were probably all felled at about the same time.

Site chronology OKMCSQ02

Site chronology OKMCSQ02 would appear to represent two distinct phases of felling amongst its 23 constituent samples (Fig 6), an earlier sub-group and a slightly later sub-group. Again, none of the samples in this site chronology retains complete sapwood and it is not possible to give a precise felling date for any of the timbers.

Earlier-phase timbers

The earlier phase of felling appears to be represented by a sub-group of 13 samples, mainly from timbers of the hall but also three from the south aisle roof and one from the north aisle roof. Some of these timbers show clear evidence for reuse. The average date of the heartwood/sapwood boundary on the seven of these 13 samples that retain it is AD 1553. Using a 95% confidence limit of 15–40 rings for the amount of sapwood these trees might have had would give the timbers represented an estimated felling date in the range AD 1568–93.

The six other earlier phase timbers do not have the heartwood/sapwood boundary and it is thus not possible to be completely certain that they too represent timbers cut as part of the same phase of felling in the late-sixteenth century. However the overall cross-matching between the samples of this entire sub-group of earlier samples, including some timbers potentially derived from the same-tree (eg samples OKM-C22 and C40 cross-match with a value of t=12.6), suggests that this is a coherent group of timbers that are likely to have been cut during a single programme of felling. The heartwood/sapwood boundary date varies by 22 years and thus it is possible that these timbers represent a single short felling event or alternatively that they could represent a single felling period that perhaps spans a small number of years.

Later-phase timber

The later phase of felling seen in site chronology OKMCSQ02 appears to be represented by a further 10 samples, all of which are from the main hall and none of which show any clear evidence for reuse. In this instance the heartwood/sapwood boundary on the six samples varies by only five years, with the average boundary of the six being dated to AD 1604. Using the same 95% confidence limit for the amount of sapwood the trees might have had of 15–40 rings, and allowing that the latest sapwood ring on any sample (OKM-

C31) is dated to AD 1620, would give these timbers an estimated felling date in the range AD 1621–44.

Four other later-phase samples in site chronology OKMCSQ02 do not have the heartwood/sapwood boundary and it is thus not possible to be completely certain that they too represent timbers cut as part of an early seventeenth-century phase of felling. However, the overall level of cross-matching of these later samples again suggests that they represent a coherent group of timbers that are likely to have been cut as part of a single programme. This sub-group also contains some potential same-tree timbers represented, for example, by samples OKM-C29 and C31, which cross-match with a value of t=10.5, and OKM-C44 and C45, which cross-match with a value of t=11.7.

Site chronology OKMCSQ03

The latest episode of felling is represented by the 20 dated samples of site chronology OKMCSQ03 (Fig 7), which are predominantly from timbers of the hall roof, but also includes four north-aisle timbers and four south-aisle timbers. None of the sampled timbers show any evidence for reuse. Four of these samples, OKM-C01, C06, C10, and C59, retain complete sapwood, this meaning they have the last growth ring produced by the tree represented before they were cut down. Sample OKM-C10, from the hall, has a last complete sapwood ring date of AD 1734, and samples OAK-C01, C06, again from the hall, and C59, from the north aisle, have identical complete sapwood ring dates of AD 1737. These are thus the felling dates of the trees represented, there appearing to be no obvious difference in date between the hall and the north aisle.

Fourteen of the other 16 samples in this site chronology retain some sapwood or at least the heartwood/sapwood boundary, this varying by 25 years. As intimated by the known felling date of the four timbers discussed above, such a variation would suggest the possibility that these trees, rather than all having exactly the same felling date, were again felled over a short period of time in the mid-AD 1730s as part of a single programme of work. Such an interpretation is supported by the overall high level of cross-matching between all these samples, including the two without the heartwood/sapwood boundary, which again suggests a coherent group of timbers.

This group again includes some potential same-tree timbers. Examples of such may be represented by samples OKM-C01 and C09 (king-posts to trusses 1 and 3 respectively), which match with a value of t=11.4, samples OKM-C06 and C21 (south principal rafter truss 2 and king-post truss 5 respectively), which match with a value of t=11.1, and samples OKM-C07 and C08 (the struts to truss 2), which match with a value of t=11.8.

CONCLUSION

Analysis by dendrochronology of 69 samples from the timbers within Oakham Castle has produced three site chronologies, accounting for 64 samples, all of which have been successfully dated. Interpretation of the sapwood on the dated samples has identified four different main phases of felling.

The earliest phase of felling is represented by a group of reused timbers which have an estimated felling date in the range AD 1160–85. It is very likely that these represent the original roof of the building, which is believed to have been built in AD 1180–90 for Walkelin de Ferrers. As such this date makes Oakham Castle the earliest hall of any English castle to survive so completely. The majority of these timbers are reused as common rafters to the main roof of the hall, with a few being reused as struts to the trusses and a few as common rafters in the aisle roofs. Observations of the unsampled timbers of the roofs suggest the existence of a large number of other apparently reused timbers, suggesting the possibility that the roof contains a large quantity of original material.

A second-main phase of felling is represented by a further group of reused timbers which, while not necessarily all cut at exactly the same time in the later sixteenth century, appear to be basically coeval. As such these timbers represent a hitherto unsuspected phase of felling. Again, these timbers are reused as common rafters to the main or aisle roofs, with a few being reused as struts to the trusses.

A third phase of felling is represented by a group timbers, none of which showed any clear signs of reuse, used, apparently exclusively, in the intermediate trusses. These timbers have an estimated felling date in the range AD 1621–44, and are likely to represent an alteration phase to the building.

The latest and final phase of felling is represented by a group of timbers which show no evidence for reuse and are almost certainly primary to the present covering to the castle, representing a phase of re-roofing. One such timber was felled in AD 1734, with three others being felled in AD 1737. The remaining timbers are likely to have been felled at a very similar time. As such, this re-roofing phase is perhaps slightly later than had hitherto been believed. None of these eighteenth-century-phase timbers are used as common rafters in the main roof, the majority of them being utilised only in the principal trusses of the main range or the north and south aisles (although a few are used as common rafters in the aisles).

It would therefore appear possible that the original twelfth-century roof of the hall existed into the eighteenth century, the hall having undergone some works in the earlier seventeenth century when two intermediate trusses were inserted. As part of the eighteenth century works much of the original timber was reused along with some timbers which had been felled in the later sixteenth century.

It may be of interest to note the high levels of cross-matching seen between all three site chronologies created during this analysis, and the reference chronologies. As may be seen in Tables 2, 3, and 4, which list a small selection of the reference chronologies used to date the three site chronologies, the *t*-values are often high to very high.

One disadvantage of this widespread cross-matching is that it is difficult to make any reliable comment, as can occasionally be done, about the likely location of the source woodlands (eg Bridge 2000). It is unlikely however, particularly in the case of the original twelfth-century roof, that the timbers have come from very far. It is possible that the high levels of cross-matching seen in this analysis are due to the material used at Oakham Castle being derived from 'middle' England, which is highly representative of widespread 'overall' climatic trends.

A second item of note amongst some of these samples is the early date at which some of the trees represented might have begun to grow, and the age they might have reached at felling. For example, as may be seen from Table 1, the first extant ring on samples OKM-C11 and C24 is dated to AD 923 and AD 937 respectively. Although in both cases it is difficult to be certain how far these first extant rings are from the centre, or representative of first growth ring of the source trees, it is perhaps possible that these were laid down in the late-ninth century. If, as seems likely, these trees were felled in the later twelfth century, they would have been approximately 250 years of age. While such ages are relatively common amongst trees of this period, they are in contrast to the ages of trees seen in later periods, which are often very much younger when felled.

Three samples, OKM-C13, C53, and C60, remain ungrouped and undated. As again may be seen from Table 1, the first sample has only 51 rings, this being around the lower limit for tree-ring analysis and it is very likely that this contributes to its lack of grouping and dating. The other two ungrouped and undated samples are longer, with 80 and 60 rings respectively, and neither sample shows any problems such as distortion or compression of rings which may account for the lack of dating. It is common, however, in any programme of analysis to have some samples that cannot be dated and in this case, given that as few as three samples undated, it is noteworthy.

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TABLES

Table 1a: Details of samples from Oakham Castle, Oakham, Rutland, in sample number order

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
OKM-C01	King post, truss 1 (from west)	117	26C	1621	1711	1737
OKM-C02	Tiebeam, truss 1	94	h/s	1604	1697	1697
OKM-C03	North strut, truss 1	nm	---	------	------	------
OKM-C04	South horizontal beam, east side, beam 1A	nm	---	------	------	------
OKM-C05	Tiebeam, truss 2	113	17	1618	1713	1730
OKM-C06	South principal rafter, truss 2	103	24C	1635	1713	1737
OKM-C07	North strut, truss 2	112	h/s	1598	1709	1709
OKM-C08	South strut, truss 2	111	h/s	1599	1709	1709
OKM-C09	King post, truss 3	110	19	1614	1704	1723
OKM-C10	Tiebeam, truss 3	135	33C	1600	1701	1734
OKM-C11 ®	North strut, truss 3	216	h/s	923	1138	1138
OKM-C12 ®	South strut, truss 3	187	h/s	954	1140	1140
OKM-C13 ®	South common rafter 7, middle tier, bay 3	51	h/s	------	------	------
OKM-C14 ®	South common rafter 1, middle tier, bay 4	161	no h/s	956	------	1116
OKM-C15 ®	South common rafter 2, middle tier, bay 4	76	4	1077	1148	1152
OKM-C16 ®	South common rafter 2, lower tier, bay 4	78	h/s	1483	1560	1560
OKM-C17	South common rafter 6, middle tier, bay 4	70	no h/s	1433	------	1502
OKM-C18 ®	South common rafter 6, lower tier, bay 4	81	h/s	1073	1153	1153
OKM-C19	South common rafter 7, middle tier, bay 4	81	8	1475	1547	1555
OKM-C20 ®	South strut, truss 4	107	no h/s	1430	------	1536
OKM-C21	King post, truss 5	120	13	1609	1715	1728
OKM-C22 ®	North strut, truss 5	130	no h/s	1383	------	1512
OKM-C23 ®	South strut, truss 5	117	no h/s	951	------	1067
OKM-C24 ®	North common rafter 6, lower tier, bay 5	177	no h/s	937	------	1113
OKM-C25 ®	North common rafter 7, middle tier, bay 5	112	no h/s	991	------	1102
OKM-C26	South aisle plate, bay 6	79	h/s	1464	1542	1542
OKM-C27	South aisle rafter 2, bay 6	92	no h/s	1017	------	1108
OKM-C28	Tiebeam, truss 1A	75	4	1536	1606	1610
OKM-C29	North archbrace, truss 1A	91	h/s	1516	1606	1606
OKM-C30	South archbrace, truss 1A	78	h/s	1526	1603	1603
OKM-C31	South wall post, truss 3	104	18	1517	1602	1620
OKM-C32	South corbel, truss 3	58	no h/s	1529	------	1586
OKM-C33	North common rafter 2, middle tier, bay 3	115	no h/s	973	------	1087
OKM-C34	North common rafter 4, middle tier, bay 3	85	no h/s	964	------	1048
OKM-C35	North common rafter 5, middle tier, bay 3	70	no h/s	1010	------	1079
OKM-C36	North common rafter 3, lower tier, bay 3	60	no h/s	1479	------	1538
OKM-C37	South common rafter 1, middle tier, bay 3	55	20	1680	1714	1734
OKM-C38	South common rafter 2, middle tier, bay 3	70	no h/s	1629	---	1698
OKM-C39	South common rafter 4, middle tier, bay 3	48	16	1687	1718	1734
OKM-C40	South common rafter 1, lower tier, bay 3	92	h/s	1465	1556	1556
OKM-C41	South common rafter 5, lower tier, bay 3	66	h/s	1075	1140	1140
OKM-C42	Tiebeam, truss 4A	104	h/s	1498	1601	1601
OKM-C43	North wall post, truss 4A	57	no h/s	1539	------	1595
OKM-C44	North corbel, truss 4A	73	no h/s	1510	------	1582
OKM-C45	North archbrace, truss 4A	71	h/s	1534	1604	1604
OKM-C46	South archbrace, truss 4A	58	no h/s	1540	------	1597
OKM-C47	North common rafter 4, lower tier, bay 6	94	no h/s	1422	------	1515
OKM-C48	North common rafter 3, lower tier, bay 6	69	no h/s	1445	------	1513
OKM-C49	North common rafter 3, middle tier, bay 6	70	no h/s	1051	------	1120
OKM-C50	South common rafter 4, middle tier, bay 6	107	h/s	1040	1146	1146
OKM-C51	South common rafter 5, middle tier, bay 6	83	no h/s	1012	------	1094
OKM-C52	South common rafter 6, middle tier, bay 6	86	no h/s	1017	------	1102
OKM-C53	North aisle, bay 2, purlin	80	8	------	------	------
OKM-C54	North aisle, bay 3, upper common rafter 6	65	h/s	1492	1556	1556
OKM-C55	North aisle, bay 3, purlin	96	h/s	1621	1716	1716
OKM-C56	North aisle, principal rafter, truss 4	101	h/s	1614	1714	1714
OKM-C57	North aisle, bay 4, upper common rafter 3 ®	108	h/s	1045	1152	1152
OKM-C58	North aisle, bay 5, upper common rafter 1 ®	90	no h/s	1032	------	1121
OKM-C59	North aisle, bay 6, upper common rafter 2	79	22C	1659	1715	1737
OKM-C60	North aisle, bay 6, upper common rafter 3	60	no h/s	------	------	------

Table 1a: continued

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
OKM-C61	North aisle, bay 6, purlin	64	16	1672	1719	1735
OKM-C62	South aisle, bay 5, upper common rafter 1	80	18	1655	1716	1734
OKM-C63	South aisle, bay 5, lower common rafter 5 ®	89	7	1027	1108	1115
OKM-C64	South aisle, bay 5, lower common rafter 6	56	no h/s	1657	------	1712
OKM-C65	South aisle, principal rafter, truss 6	75	h/s	1648	1722	1722
OKM-C66	South aisle, bay 6, purlin	63	h/s	1655	1717	1717
OKM-C67	South aisle, bay 6, upper common rafter 2 ®	87	no h/s	1025	------	1111
OKM-C68	South aisle, bay 6, upper common rafter 4	65	h/s	1491	1555	1555
OKM-C69	South aisle, bay 6, upper common rafter 5	72	h/s	1482	1553	1553

*nm = not measured
**h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented
® = timber shows evidence of reuse

Table 1b: Details of samples from Oakham Castle, Oakham, Rutland, grouped by likely felling phase

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
	Twelfth century timbers					
OKM-C11 ®	North strut, truss 3	216	h/s	923	1138	1138
OKM-C12 ®	South strut, truss 3	187	h/s	954	1140	1140
OKM-C14 ®	South common rafter 1, middle tier, bay 4	161	no h/s	956	------	1116
OKM-C15 ®	South common rafter 2, middle tier, bay 4	76	4	1077	1148	1152
OKM-C18 ®	South common rafter 6, lower tier, bay 4	81	h/s	1073	1153	1153
OKM-C23 ®	South strut, truss 5	117	no h/s	951	------	1067
OKM-C24 ®	North common rafter 6, lower tier, bay 5	177	no h/s	937	------	1113
OKM-C25 ®	North common rafter 7, middle tier, bay 5	112	no h/s	991	------	1102
OKM-C27	South aisle rafter 2, bay 6	92	no h/s	1017	------	1108
OKM-C33	North common rafter 2, middle tier, bay 3	115	no h/s	973	------	1087
OKM-C34	North common rafter 4, middle tier, bay 3	85	no h/s	964	------	1048
OKM-C35	North common rafter 5, middle tier, bay 3	70	no h/s	1010	------	1079
OKM-C41	South common rafter 5, lower tier, bay 3	66	h/s	1075	1140	1140
OKM-C49	North common rafter 3, middle tier, bay 6	70	no h/s	1051	------	1120
OKM-C50	South common rafter 4, middle tier, bay 6	107	h/s	1040	1146	1146
OKM-C51	South common rafter 5, middle tier, bay 6	83	no h/s	1012	------	1094
OKM-C52	South common rafter 6, middle tier, bay 6	86	no h/s	1017	------	1102
OKM-C57 ®	North aisle, bay 4, upper common rafter 3	108	h/s	1045	1152	1152
OKM-C58 ®	North aisle, bay 5, upper common rafter 1	90	no h/s	1032	------	1121
OKM-C63 ®	South aisle, bay 5, lower common rafter 5	89	7	1027	1108	1115
OKM-C67 ®	South aisle, bay 6, upper common rafter 2	87	no h/s	1025	------	1111
	Sixteenth century timbers					
OKM-C16 ®	South common rafter 2, lower tier, bay 4	78	h/s	1483	1560	1560
OKM-C17	South common rafter 6, middle tier, bay 4	70	no h/s	1433	------	1502
OKM-C19	South common rafter 7, middle tier, bay 4	81	8	1475	1547	1555
OKM-C20 ®	South strut, truss 4	107	no h/s	1430	------	1536
OKM-C22 ®	North strut, truss 5	130	no h/s	1383	------	1512
OKM-C26	South aisle plate, bay 6	79	h/s	1464	1542	1542
OKM-C36	North common rafter 3, lower tier, bay 3	60	no h/s	1479	------	1538
OKM-C40	South common rafter 1, lower tier, bay 3	92	h/s	1465	1556	1556
OKM-C47	North common rafter 4, lower tier, bay 6	94	no h/s	1422	------	1515
OKM-C48	North common rafter 3, lower tier, bay 6	69	no h/s	1445	------	1513
OKM-C54	North aisle, bay 3, upper common rafter 6	65	h/s	1492	1556	1556
OKM-C68	South aisle, bay 6, upper common rafter 4	65	h/s	1491	1555	1555
OKM-C69	South aisle, bay 6, upper common rafter 5	72	h/s	1482	1553	1553
	Seventeenth century timbers					
OKM-C28	Tiebeam, truss 1A	75	4	1536	1606	1610
OKM-C29	North archbrace, truss 1A	91	h/s	1516	1606	1606
OKM-C30	South archbrace, truss 1A	78	h/s	1526	1603	1603
OKM-C31	South wall post, truss 3	104	18	1517	1602	1620
OKM-C32	South corbel, truss 3	58	no h/s	1529	------	1586
OKM-C42	Tiebeam, truss 4A	104	h/s	1498	1601	1601
OKM-C43	North wall post, truss 4A	57	no h/s	1539	------	1595
OKM-C44	North corbel, truss 4A	73	no h/s	1510	------	1582
OKM-C45	North archbrace, truss 4A	71	h/s	1534	1604	1604
OKM-C46	South archbrace, truss 4A	58	no h/s	1540	------	1597
	Eighteenth century timbers					
OKM-C01	King post, truss 1 (from west)	117	26C	1621	1711	1737
OKM-C02	Tiebeam, truss 1	94	h/s	1604	1697	1697
OKM-C05	Tiebeam, truss 2	113	17	1618	1713	1730
OKM-C06	South principal rafter, truss 2	103	24C	1635	1713	1737
OKM-C07	North strut, truss 2	112	h/s	1598	1709	1709
OKM-C08	South strut, truss 2	111	h/s	1599	1709	1709
OKM-C09	King post, truss 3	110	19	1614	1704	1723
OKM-C10	Tiebeam, truss 3	135	33C	1600	1701	1734
OKM-C21	King post, truss 5	120	13	1609	1715	1728
OKM-C37	South common rafter 1, middle tier, bay 3	55	20	1680	1714	1734
OKM-C38	South common rafter 2, middle tier, bay 3	70	no h/s	1629	---	1698
OKM-C39	South common rafter 4, middle tier, bay 3	47	16	1687	1718	1734
OKM-C55	North aisle, bay 3, purlin	96	h/s	1621	1716	1716
OKM-C56	North aisle, principal rafter, truss 4	101	h/s	1614	1714	1714
OKM-C59	North aisle, bay 6, upper common rafter 2	79	22C	1659	1715	1737
OKM-C61	North aisle, bay 6, purlin	64	16	1672	1719	1735
KM-C62	South aisle, bay 5, upper common rafter 1	80	18	1655	1716	1734

Table 1b: continued

OKM-C64	South aisle, bay 5, lower common rafter 6	56	no h/s	1657	------	1712
OKM-C65	South aisle, principal rafter, truss 6	75	h/s	1648	1722	1722
OKM-C66	South aisle, bay 6, purlin	63	h/s	1655	1717	1717

*nm = not measured
**h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented
® = timber shows evidence of reuse

Table 2: Results of the cross-matching of site chronology OKMCSQ01 and relevant reference chronologies when first ring date is AD 923 and last ring date is AD 1153

Reference chronology	Span of chronology	*t*-value	
Peterborough Cathedral nave structural, Cambridgeshire	AD 887–1225	15.6	(Tyers 1999a)
Barton coffins, North Lincolnshire	AD 785–1134	12.7	(Tyers 2001)
Whiston Manorial Barn, Rotherham, South Yorkshire	AD 899–1223	12.5	(Tyers 2002)
Eastgate, Beverley, East Yorkshire	AD 858–1310	11.4	(Groves 1992)
St Mary's Grove and Eastgate Street, Stafford, Staffordshire	AD 884–1189	10.3	(Groves 1987a; Groves 1987b)
Dyer Lane, Beverley, East Yorkshire	AD 903–1183	9.8	(Groves and Hillam 1985)
Peterborough Cathedral transepts, Cambridgeshire	AD 921–1194	9.4	(Tyers 2004)
Second Wood Street, Nantwich, Cheshire	AD 932–1509	9.3	(Tyers 2005)

Table 3: Results of the cross-matching of site chronology OKMCSQ02 and relevant reference chronologies when first ring date is AD 1383 and last ring date is AD 1620

Reference chronology	Span of chronology	*t*-value	
Flore's House, Oakham, Rutland	AD 1408–1591	11.4	(Hurford *et al* 2008)
Apethorpe Hall, Apethorpe, Northamptonshire	AD 1292–1740	11.1	(Arnold and Howard 2008)
Sinai Park, Burton on Trent, Staffordshire	AD 1227–1750	9.6	(Tyers 1997)
26 Westgate Street, Gloucester	AD 1399–1622	9.6	(Howard *et al* 1998a)
Black Ladies, Brewood, Staffordshire	AD 1372–1671	9.5	(Tyers 1999b)
Lodge Park, Aldsworth, Gloucestershire	AD 1324–1587	9.1	(Howard *et al* 1995)
Wakelyn Old Hall, Hilton, Derbyshire	AD 1415–1573	8.4	(Arnold *et al* 2008)
Kingsbury Hall, Kingsbury, Warwickshire	AD 1391–1564	8.2	(Arnold and Howard 2006)

Table 4: Results of the cross-matching of site chronology OKMCSQ03 and relevant reference chronologies when first ring date is AD 1598 and last ring date is AD 1737

Reference chronology	Span of chronology	*t*-value	
Kirby Hall, Deene Corby, Northamptonshire	AD 1509–1795	13.0	(Arnold and Howard forthcoming)
Apethorpe Hall, Apethorpe, Northamptonshire	AD 1292–1639	12.7	(Arnold and Howard 2008)
Worcester Cathedral, Worcester	AD 1484–1772	11.6	(Arnold *et al* 2003a)
De Grey Mausoleum, Flitton, Bedfordshire	AD 1510–1726	10.4	(Arnold *et al* 2003b)
Bay Hall, Bennington, Lincolnshire	AD 1591–1717	9.9	(Howard *et al* 1998b)
The Riding House, Bolsover Castle, Derbyshire	AD 1494–1744	9.5	(Howard *et al* 2005)
The post mill, Kibworth Harcourt, Leicestershire	AD 1582–1773	9.1	(Arnold *et al* 2004)
Old Clarendon Building, Oxford, Oxfordshire	AD 1539–1711	9.1	(Worthington and Miles 2006)

FIGURES

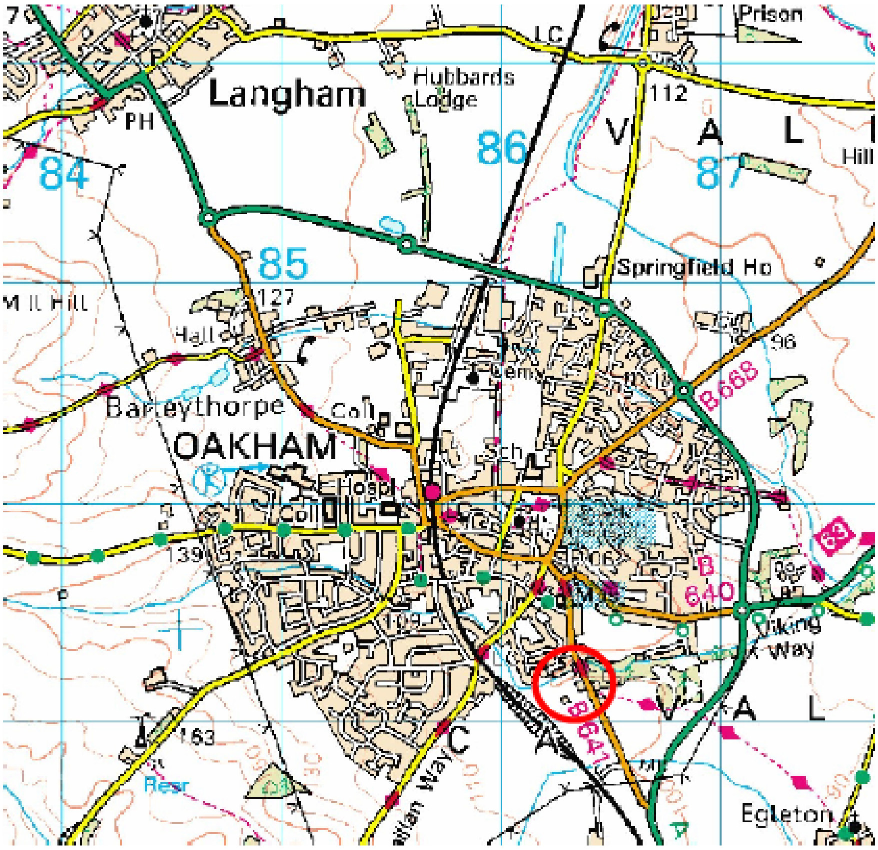


Figure 1: Map to show the location of Oakham Castle. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

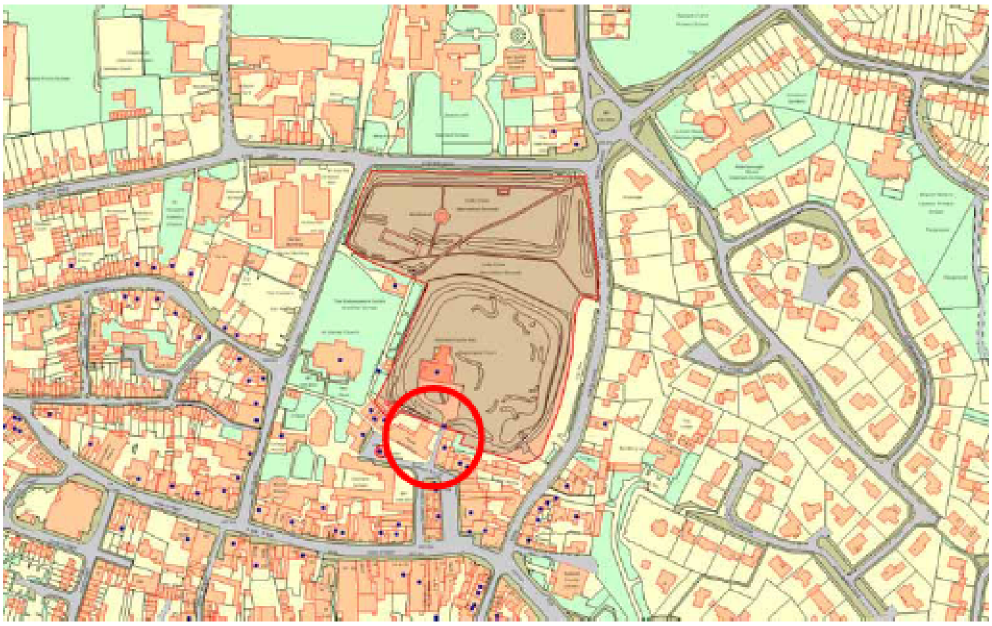


Figure 2: Map to show the location of Oakham Castle. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: General view of the Castle hall (photograph Robert Howard)

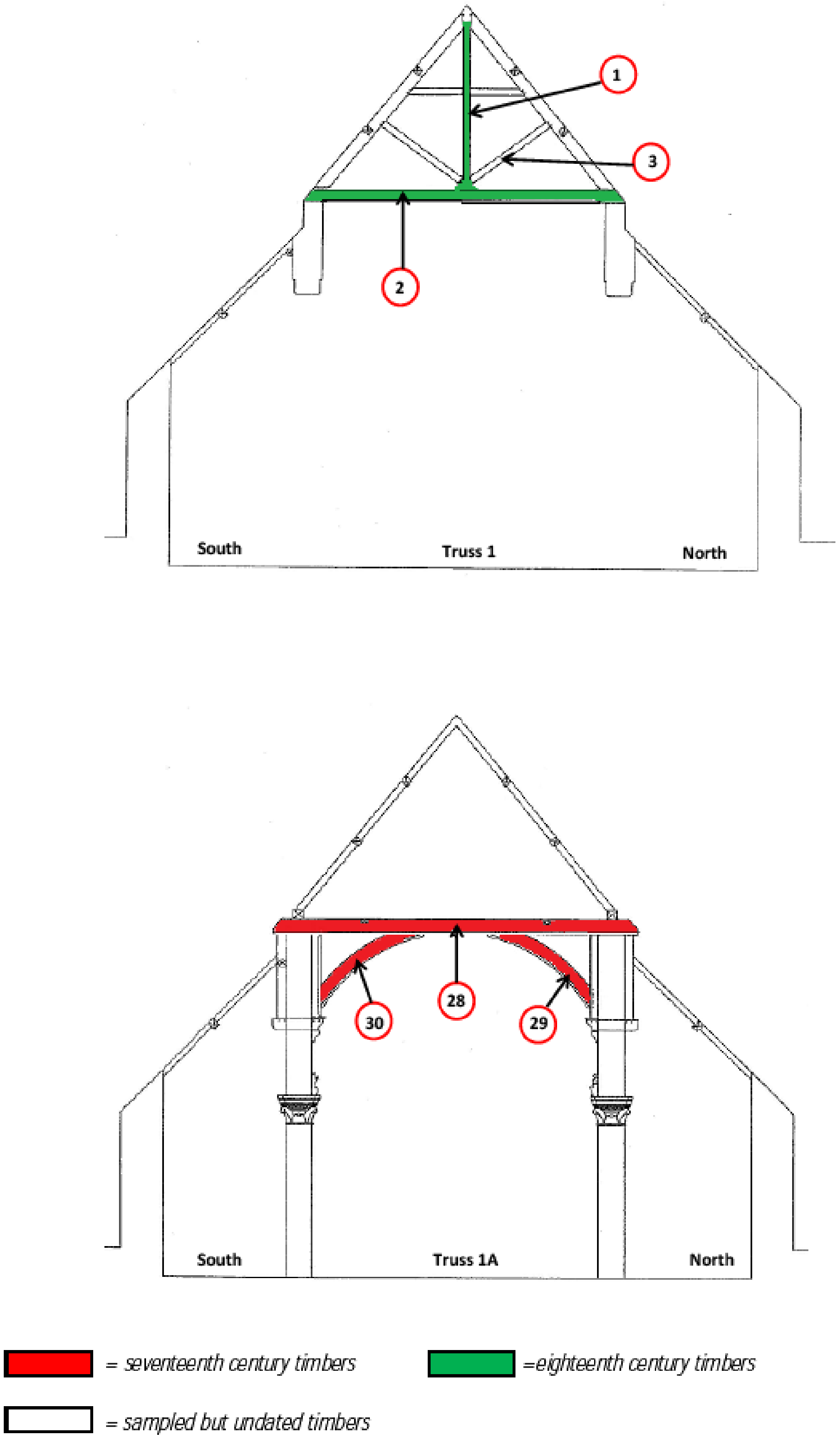
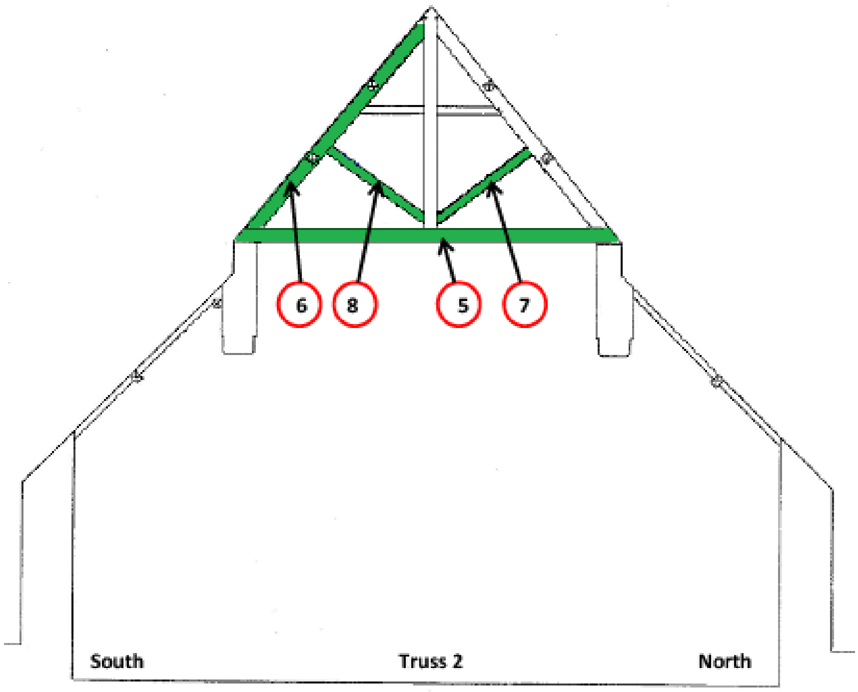


Figure 4a/b: Cross sections of the trusses to show sampled timbers (after Nick Hill)



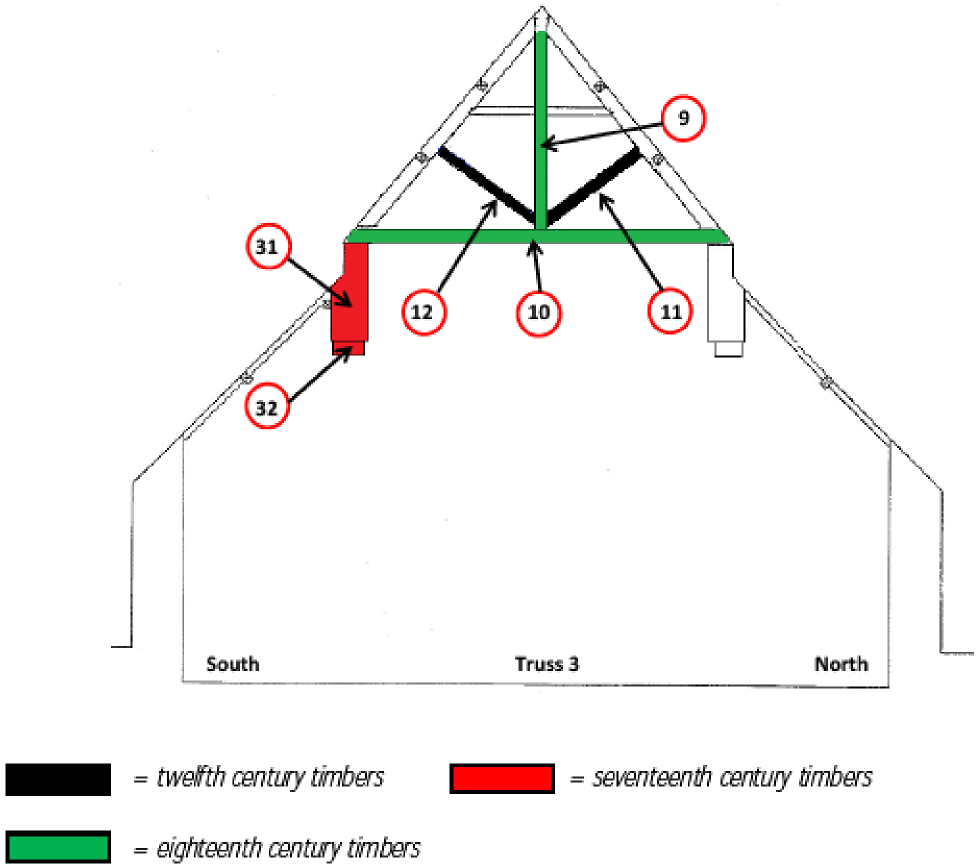
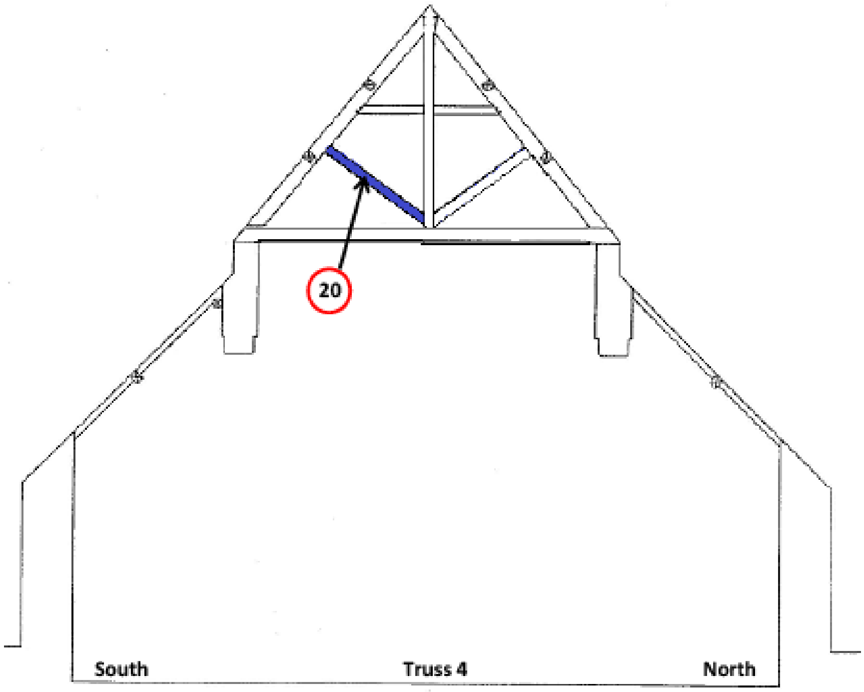


Figure 4c/d: Cross sections of the trusses to show sampled timbers (after Nick Hill)



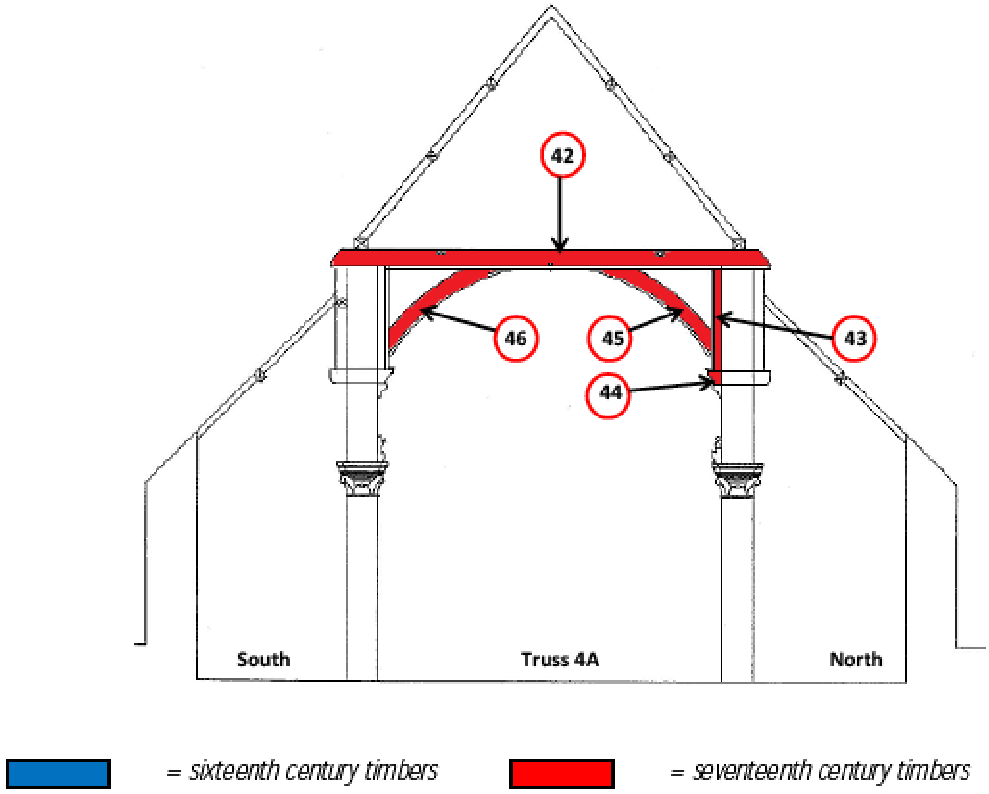
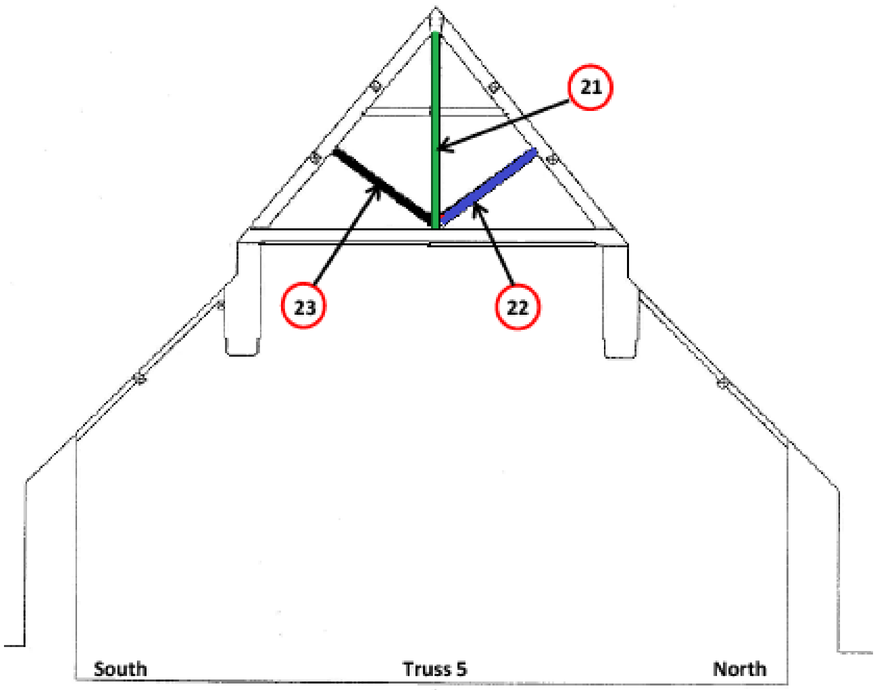


Figure 4e/f: Cross section of trusses to show sampled timbers (after Nick Hill)

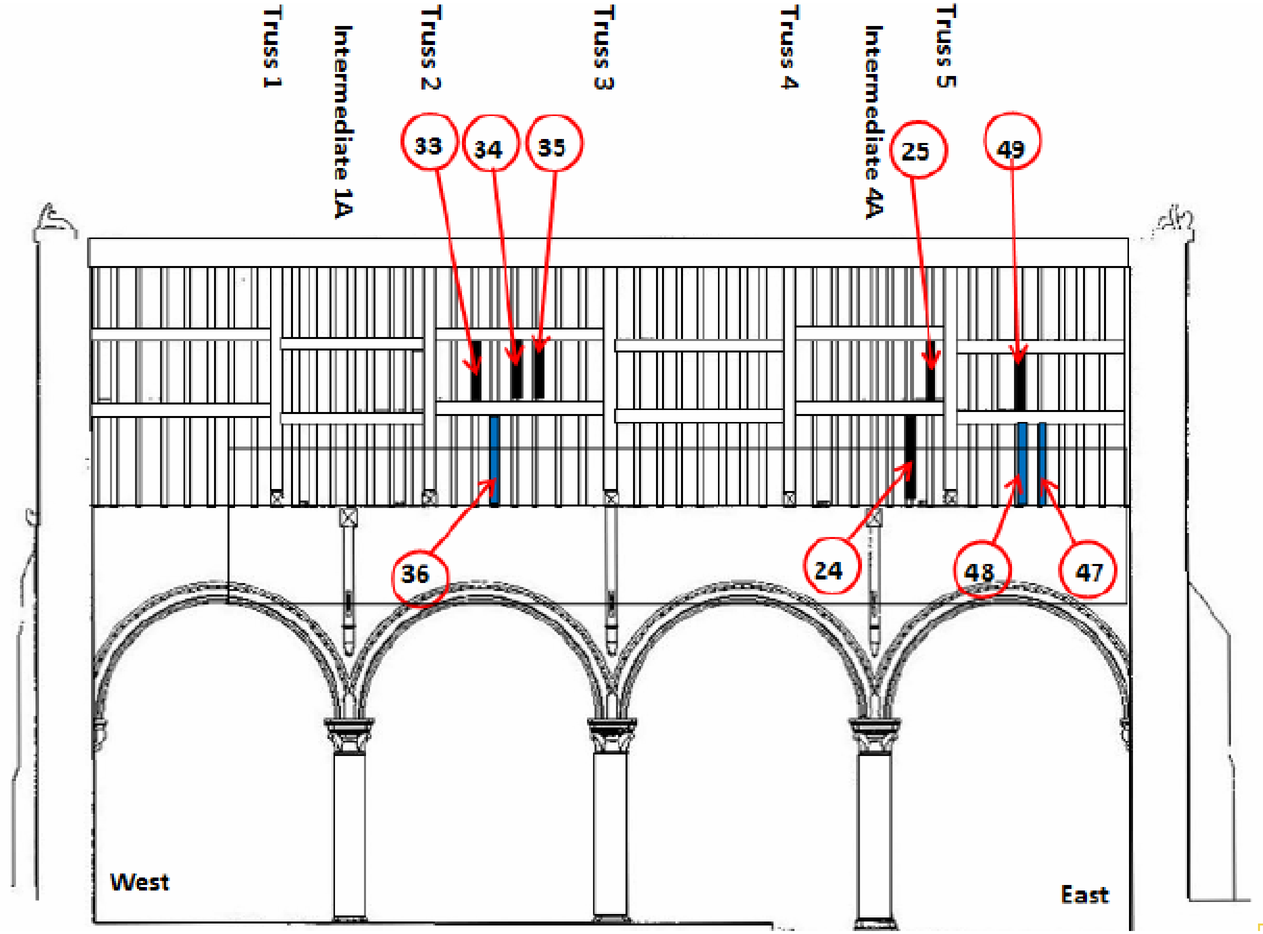


= *twelfth century timbers*

= *sixteenth century timbers*

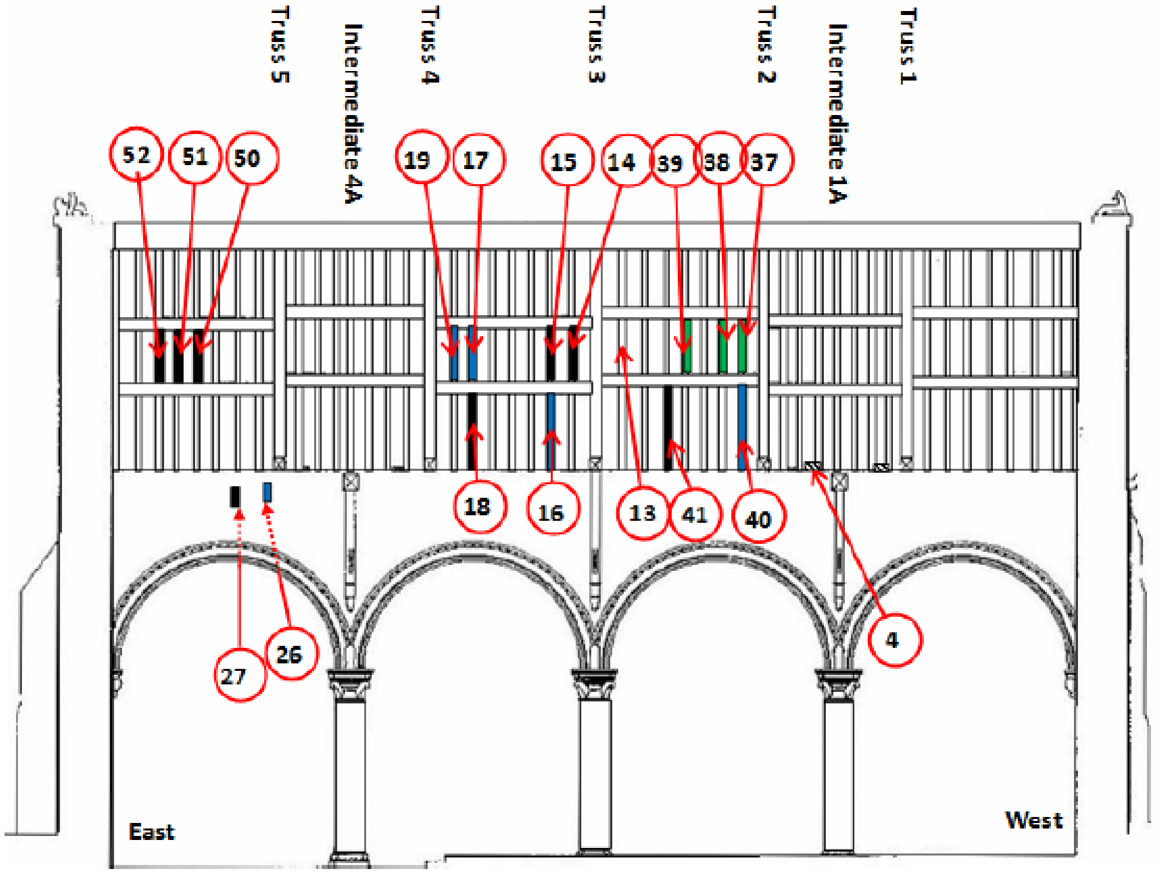
= *eighteenth century timbers*

Figure 4g: Cross section of trusses to show sampled timbers (after Nick Hill)



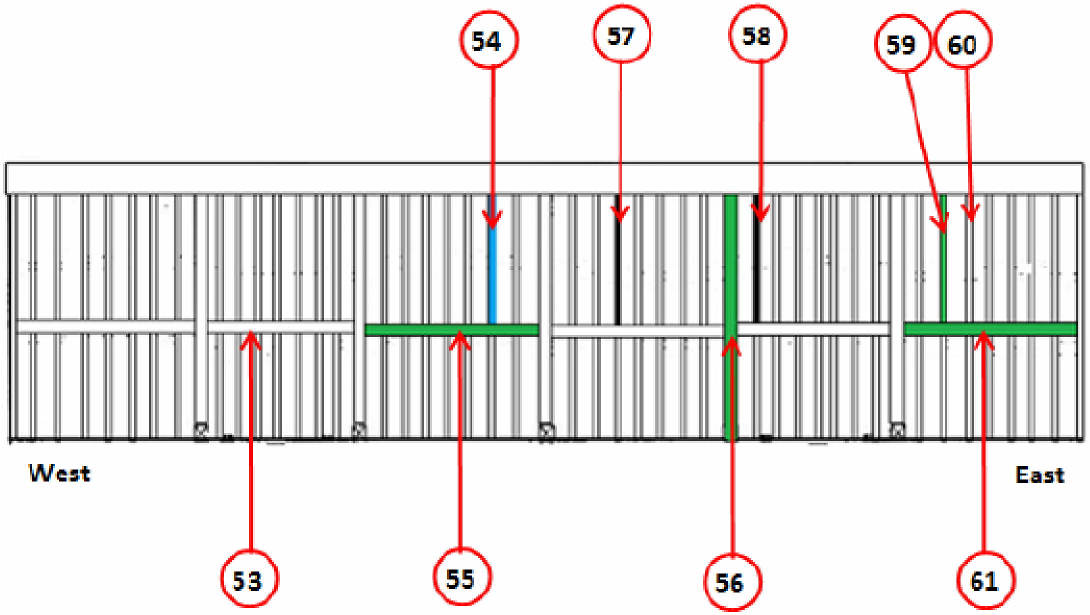
= twelfth century timbers   = sixteenth century timbers

Figure 4h: Long-section looking north to show sampled timbers (after Nick Hill)



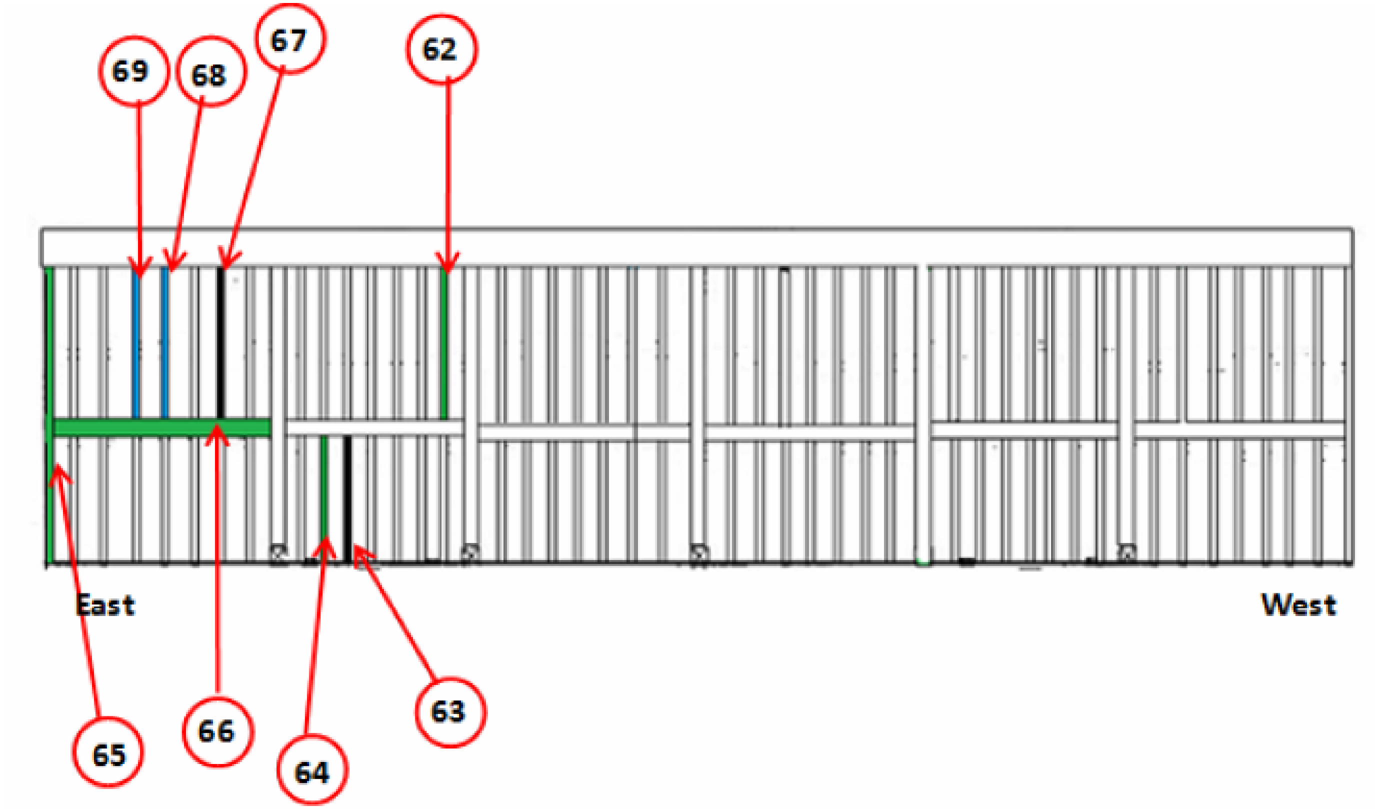
= *twelfth century timbers* = *sixteenth century timbers* = *eighteenth century timbers* = *sampled but undated timbers*

Figure 4i: Long-section looking south to show sampled timbers (after Nick Hill)



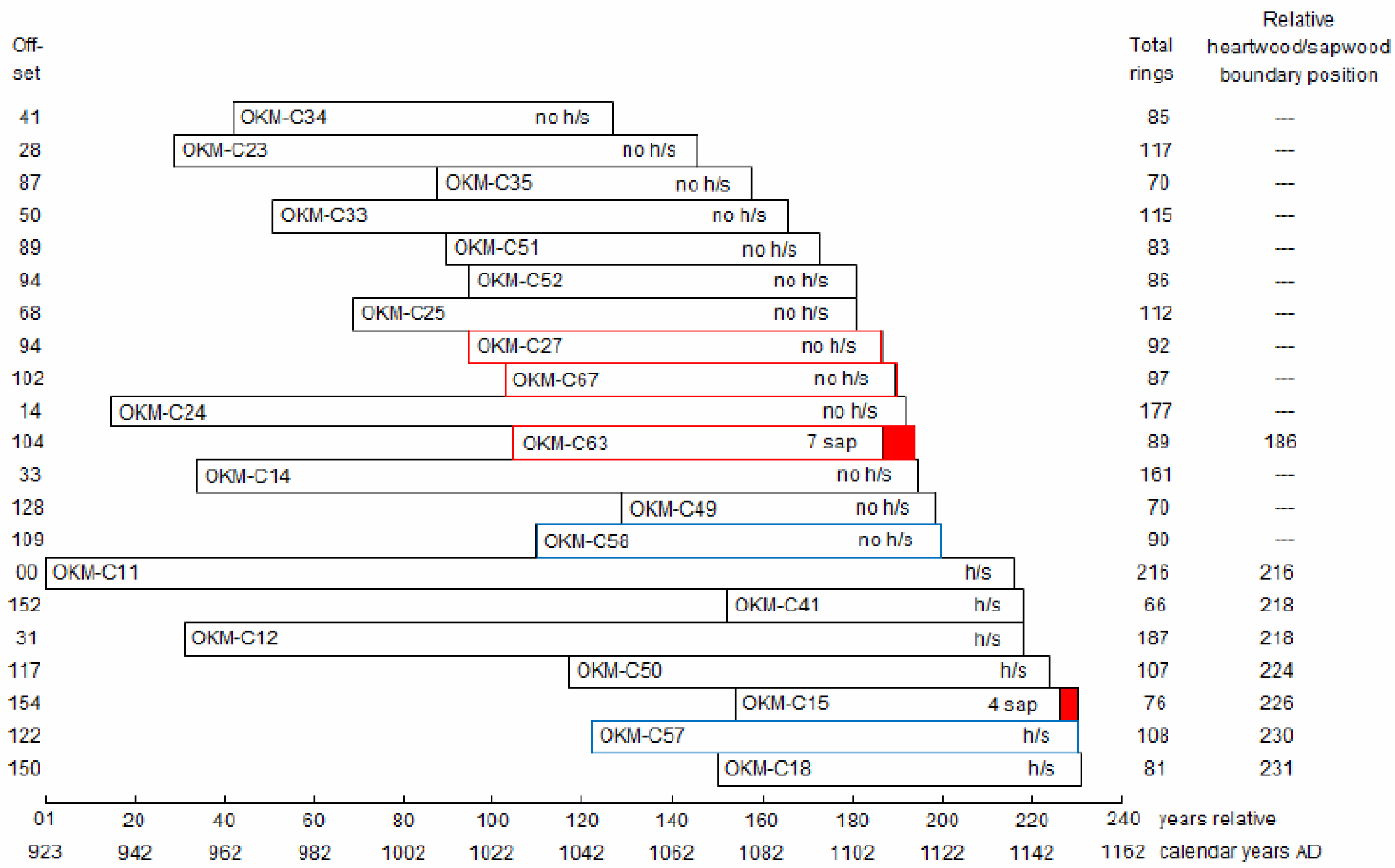
= twelfth century timbers = sixteenth century timbers = eighteenth century timbers = sampled but undated timbers

Figure 4j: North aisle roof to show sampled timbers (after Nick Hill)



= *twelfth century timbers* = *sixteenth century timbers* = *eighteenth century timbers*

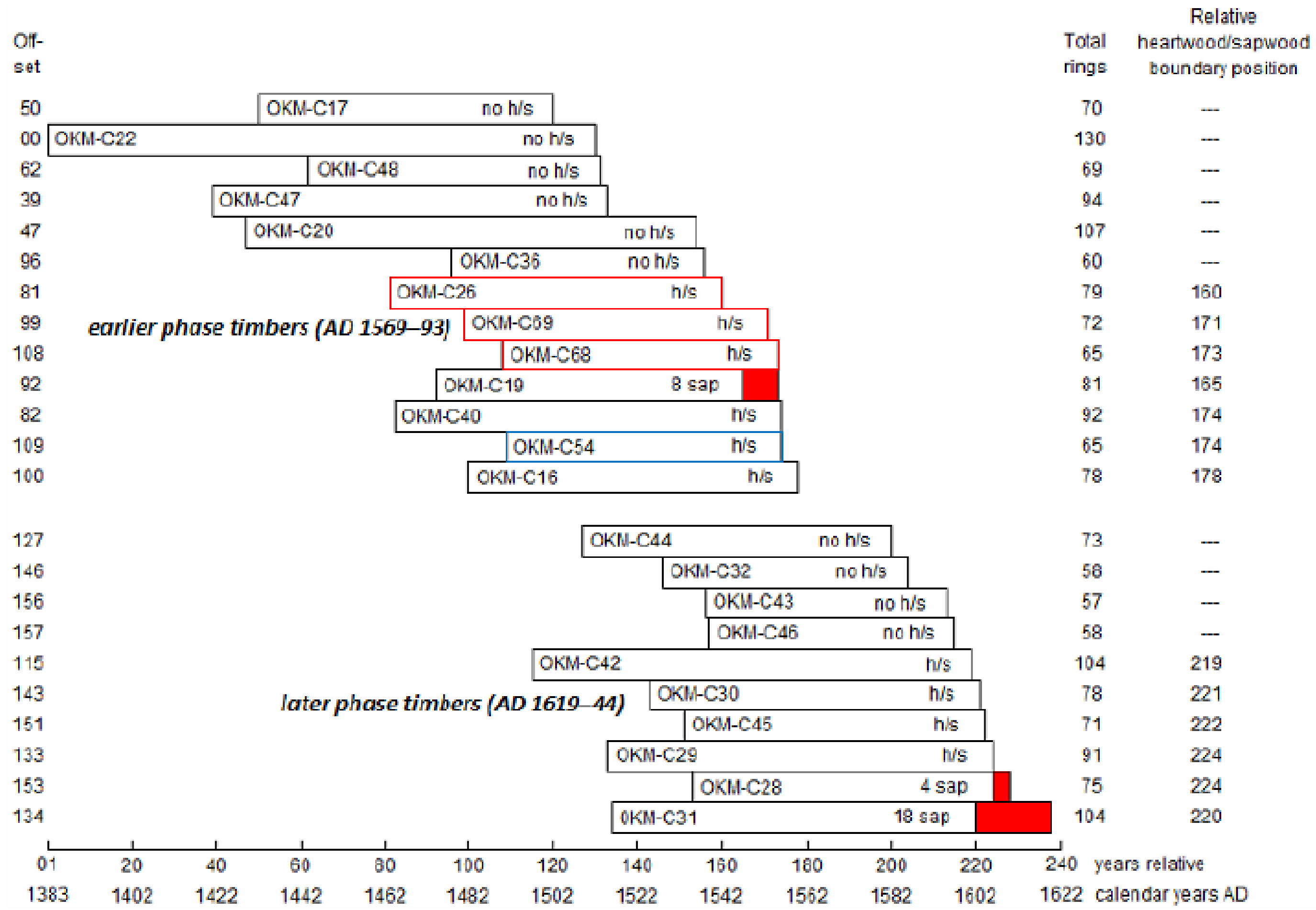
Figure 4k: South aisle roof to show sampled timbers (after Nick Hill)



White fill =heartwood rings; shaded fill = sapwood rings; h/s = the heartwood/sapwood ring is the last ring on the sample

Black outline [black box] = hall timbers, [blue box] = north aisle timbers, [red box] = south aisle timbers

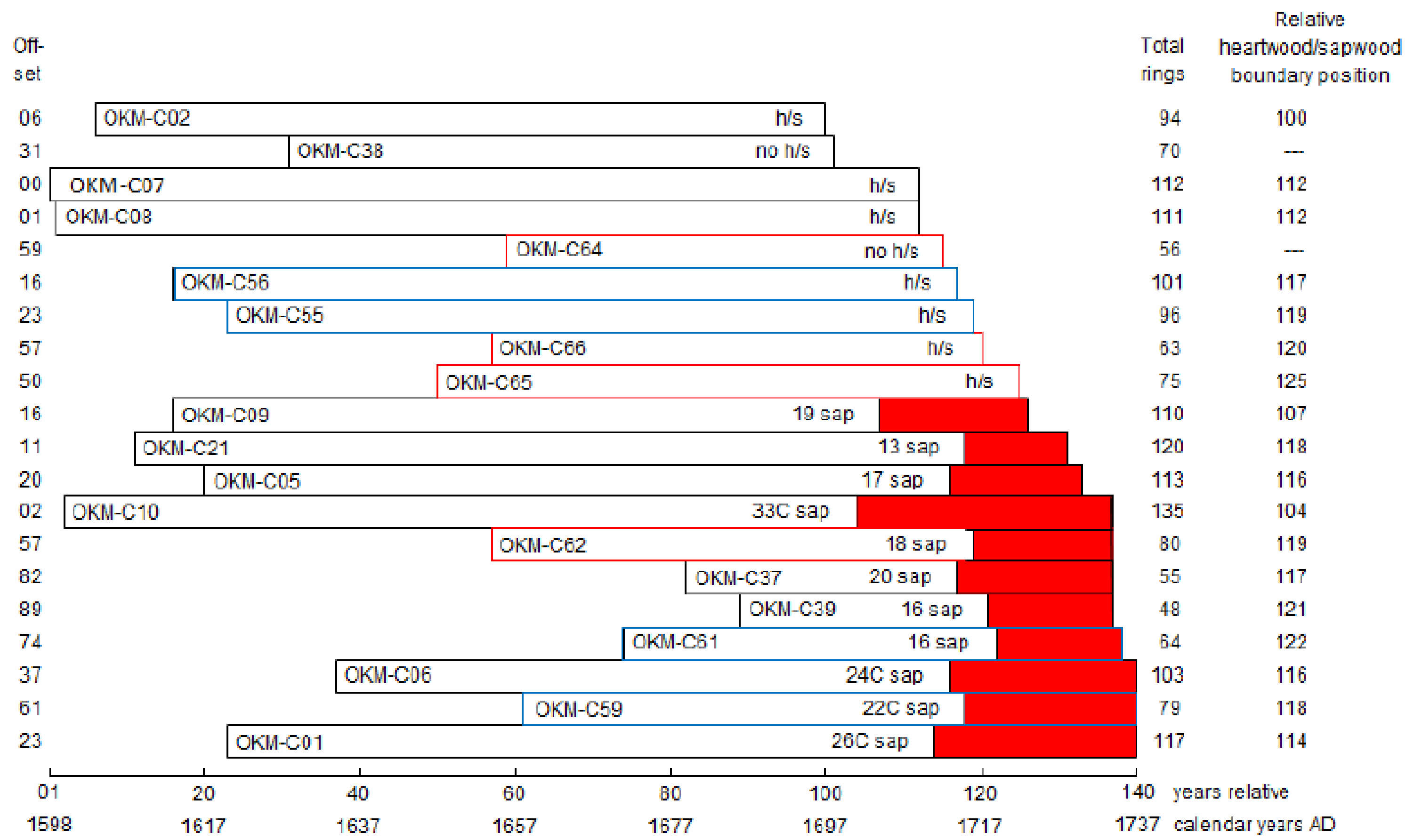
Figure 5: Bar diagram of the samples in site chronology OKMCSQ01



White fill =heartwood rings; shaded fill = sapwood rings; h/s = the heartwood/sapwood ring is the last ring on the sample

Black outline = hall timbers, = north aisle timbers, = south aisle timbers

Figure 6: Bar diagram of the samples in site chronology OKMCSQ02



White fill =heartwood rings; shaded fill = sapwood rings; h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented
Black outline [black box] = hall timbers, [blue box] = north aisle timbers, [red box] = south aisle timbers

Figure 7: Bar diagram of the samples in site chrsonology OKMCSQ03

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

OKM-C01A 117
501 488 446 435 496 369 362 478 411 243 310 335 416 312 297 361 226 364 248 351
288 272 269 323 289 377 279 293 246 261 199 132 78 102 185 155 151 179 185 220
151 154 199 198 139 106 154 179 145 144 178 173 192 176 87 95 139 160 165 192
145 160 133 128 108 171 138 126 107 103 128 111 112 107 114 142 132 111 91 91
110 99 146 120 97 112 90 157 171 118 138 122 129 94 131 123 124 80 91 147
158 121 70 138 143 143 172 101 108 151 92 122 77 132 109 146 95
OKM-C01B 117
488 488 445 436 491 375 355 477 417 244 306 343 402 303 304 358 231 347 265 351
292 264 267 328 284 372 282 297 238 260 199 127 84 111 173 157 151 182 188 209
150 159 202 205 132 105 168 171 145 145 188 172 193 165 92 95 137 161 167 187
147 163 132 118 115 176 137 128 102 108 125 116 110 107 117 140 132 109 94 89
104 104 143 126 92 107 102 144 170 121 141 130 126 96 121 123 136 75 77 157
163 117 73 135 137 164 151 95 118 144 97 121 81 146 99 147 92
OKM-C02A 94
527 343 389 461 490 368 466 396 306 333 357 318 258 150 180 182 118 122 190 160
127 77 58 178 150 211 120 149 186 235 142 187 109 168 270 243 330 331 244 239
148 147 329 237 339 174 137 277 220 121 93 120 219 237 253 179 170 140 139 138
177 178 161 170 230 259 160 173 147 109 78 63 61 104 140 215 245 134 151 158
137 127 211 176 236 144 82 91 85 129 126 98 70 127
OKM-C02B 94
508 360 368 459 477 374 481 402 305 319 358 324 256 161 189 171 112 123 185 169
120 72 66 185 148 203 122 149 179 245 141 186 106 170 262 250 318 343 238 249
143 140 307 236 341 180 138 287 223 120 91 119 219 213 259 179 168 136 135 129
178 178 160 167 234 263 162 170 147 105 78 62 65 99 144 217 242 139 152 152
147 114 218 171 212 144 78 80 101 127 122 97 75 128
OKM-C05A 113
387 346 423 398 407 384 280 277 209 297 339 372 218 210 214 221 186 227 221 289
360 294 345 254 266 204 126 102 225 239 286 171 143 184 202 168 123 203 269 222
259 144 160 114 79 109 135 135 127 167 198 224 193 162 185 150 84 90 94 175
204 195 229 166 221 155 120 139 255 150 188 109 80 53 72 74 78 71 55 124
130 95 97 71 63 61 45 65 53 66 63 77 47 37 41 47 39 59 52 44
50 51 50 66 59 45 42 44 43 53 31 45 49
OKM-C05B 113
392 345 409 409 409 385 290 266 227 290 354 373 219 211 186 211 185 224 202 295
363 291 342 273 271 198 140 95 225 226 288 170 148 189 198 162 126 235 249 230
259 143 150 115 80 102 136 149 119 149 212 225 194 155 184 158 89 84 96 163
199 193 224 172 227 145 126 144 259 144 194 110 75 55 79 70 75 64 56 127
129 97 98 78 68 61 51 54 55 61 66 80 42 40 47 46 40 56 50 49
46 53 56 61 47 52 42 46 46 39 32 42 48
OKM-C06A 103
476 192 134 206 197 233 218 165 121 134 157 270 150 184 148 115 116 93 70 67
108 104 116 100 93 129 111 90 102 74 105 54 89 91 103 99 122 153 133 118
114 65 140 166 146 138 93 162 129 143 103 147 121 171 91 95 99 108 125 126
137 134 176 183 120 126 127 160 194 187 164 179 140 233 199 109 179 189 176 172
158 167 166 140 111 156 195 202 116 168 149 194 262 232 190 125 115 105 95 119
157 166 183
OKM-C06B 103
473 201 134 201 199 225 227 161 128 127 169 260 150 178 157 118 111 98 71 64

106 103 125 98 101 134 92 96 92 89 97 61 78 101 93 112 110 141 148 117
108 70 136 167 148 138 106 157 145 133 103 139 123 175 87 94 92 112 133 123
127 127 183 187 119 125 133 160 195 191 163 179 137 227 192 111 188 181 182 142
159 166 172 131 122 149 193 206 129 169 150 184 263 243 193 120 112 120 79 117
164 153 183
OKM-C07A 112
410 373 305 287 389 406 398 319 377 363 304 256 252 223 188 161 167 176 175 189
180 158 218 209 239 231 220 153 116 178 208 233 143 170 142 151 91 166 133 148
179 98 128 144 101 78 58 65 95 120 166 97 90 105 124 111 90 144 163 130
154 111 125 88 74 85 117 131 92 113 152 161 128 116 112 93 67 75 75 128
136 110 135 108 134 99 67 63 146 121 98 59 52 46 44 52 53 41 45 53
74 62 54 50 44 42 33 37 52 52 47 67
OKM-C07B 112
385 377 304 270 387 377 396 320 366 385 305 257 243 214 178 163 168 176 173 210
183 153 214 217 235 235 220 153 112 179 213 235 135 173 142 155 80 143 139 140
179 103 128 150 99 75 65 56 99 121 166 103 89 106 130 111 75 156 161 131
159 96 122 84 65 82 105 123 104 104 122 152 140 109 109 104 63 81 84 132
145 122 129 116 130 100 58 73 137 99 100 65 49 45 46 48 59 41 41 63
65 59 57 48 48 44 34 36 47 59 53 72
OKM-C08A 111
412 273 245 116 130 205 265 389 357 281 186 174 193 165 168 199 187 172 221 179
164 247 243 261 303 276 162 118 204 221 223 130 137 116 134 65 155 111 174 192
106 131 141 123 66 60 69 135 141 135 90 72 101 104 81 77 120 145 101 168
81 102 68 48 68 88 114 90 93 124 151 115 103 108 83 61 59 72 109 122
114 118 87 113 93 56 51 81 82 98 66 40 45 45 55 64 39 47 90 95
62 44 43 42 44 31 40 46 64 57 76
OKM-C08B 111
400 276 250 126 145 207 245 377 358 280 194 172 192 172 166 191 181 171 221 175
190 239 236 274 307 269 161 116 205 217 216 139 134 111 130 69 154 113 177 188
111 126 149 114 62 63 72 129 140 130 98 69 91 114 71 79 122 146 105 162
95 100 66 47 68 99 116 84 93 117 153 116 105 104 85 58 65 67 105 125
138 120 92 114 70 66 52 86 83 93 70 39 42 51 51 62 45 47 86 103
57 44 44 46 41 25 43 43 69 56 78
OKM-C09A 110
325 357 421 321 270 252 579 363 314 395 304 376 321 378 381 372 209 223 279 282
234 251 228 195 309 270 273 274 235 252 268 297 412 303 347 285 325 232 119 95
83 162 147 147 170 169 210 170 189 221 171 146 102 145 143 139 135 161 130 170
148 90 77 120 136 133 117 114 131 114 98 117 144 112 129 99 80 103 90 89
86 107 109 121 99 101 97 112 106 127 117 98 112 101 122 116 74 89 111 84
67 116 77 87 65 51 62 76 76 82
OKM-C09B 110
312 406 437 316 238 292 558 354 324 394 315 389 357 382 355 355 212 224 289 274
240 241 233 204 302 278 268 279 223 272 264 301 410 286 352 287 342 228 127 95
92 151 144 151 177 173 194 166 178 206 170 135 103 138 136 131 129 147 135 164
143 93 80 130 152 136 120 116 126 110 100 101 158 111 138 92 81 99 97 86
95 102 104 129 104 93 99 112 102 130 119 101 111 97 136 98 83 88 105 79
66 121 85 82 73 43 48 75 40 87
OKM-C10A 135
296 309 357 282 332 161 248 285 400 444 443 434 312 421 315 295 312 271 280 294
285 219 243 229 184 91 87 131 143 168 128 108 144 145 105 142 103 154 198 196
285 183 148 108 100 97 196 191 225 132 134 122 157 130 108 172 158 190 135 106
136 101 75 80 76 84 102 98 104 128 118 112 87 88 72 75 68 90 122 95
121 81 94 92 78 66 113 84 98 69 53 64 70 78 62 62 51 68 59 54
44 48 50 46 49 39 42 40 46 49 53 40 44 45 46 39 40 51 43 34

35 27 29 39 38 36 36 24 28 27 33 28 28 18 28
OKM-C10B 135
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OKM-C13B 51
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OKM-C14A 161
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OKM-C17B 70
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OKM-C22A 130
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OKM-C24B 177
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OKM-C27B 92
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OKM-C28A 75
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OKM-C30A 78
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OKM-C46A 58
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454 233 348 262 364 381 236 306 278 306 346 379 385 284 299 358 260 283 235 235
387 291 331 160 100 177 133 127 137 165 117 181 135 150 195 202 158 178
OKM-C46B 58
447 515 426 387 394 474 435 245 477 586 303 503 344 333 349 656 281 373 589 386
439 247 358 279 347 386 240 299 269 307 352 382 363 284 321 349 258 289 240 240
394 289 329 166 103 180 134 116 143 162 122 176 124 151 192 215 168 192
OKM-C47A 94
127 156 105 118 107 149 149 106 102 67 96 57 95 115 132 77 64 72 93 123

146 211 170 130 127 119 121 143 143 147 149 130 158 149 139 118 150 138 168 167
168 149 139 133 130 124 127 79 60 69 76 76 86 126 105 95 98 132 128 157
125 103 93 91 105 135 112 102 105 115 94 95 99 96 137 94 67 83 119 91
78 70 95 84 88 61 74 89 105 78 87 79 81 76
OKM-C47B 94
112 167 110 109 106 160 154 103 102 69 107 74 95 156 126 88 58 82 87 132
132 204 155 117 101 126 122 145 144 144 152 151 161 141 133 122 155 147 166 134
169 156 125 142 123 134 123 91 65 75 85 61 105 126 98 108 99 133 135 154
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93 73 86 83 81 62 75 90 91 86 100 75 82 63
OKM-C48A 69
128 113 117 136 155 147 152 175 135 164 144 154 137 140 141 206 177 172 156 135
162 154 130 112 100 106 112 90 61 96 152 125 128 127 173 176 125 163 127 97
111 126 165 172 112 102 121 112 126 157 117 141 103 77 103 105 86 89 76 97
94 93 76 69 120 105 91 94 80
OKM-C48B 69
122 116 120 133 149 143 161 175 131 161 145 157 135 145 140 195 168 172 141 137
156 146 130 111 99 105 110 83 67 99 156 114 125 129 167 173 127 154 120 112
114 122 171 174 114 110 117 111 126 154 118 140 105 69 105 106 77 90 76 99
91 103 76 74 120 102 90 95 81
OKM-C49A 70
142 160 178 127 214 173 117 132 168 214 174 162 187 176 115 176 216 170 148 160
163 154 128 187 166 207 161 135 129 146 106 125 140 137 171 163 119 108 116 102
135 113 130 101 151 122 90 150 95 85 89 82 132 106 124 106 116 132 85 77
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OKM-C49B 70
120 166 168 137 212 172 119 152 154 210 184 151 179 173 118 187 220 179 140 153
170 156 140 189 169 204 163 137 123 144 102 119 160 130 150 155 113 93 124 120
122 110 126 103 145 115 106 136 112 82 80 81 136 93 121 111 117 130 72 77
73 75 94 109 113 153 133 127 89 128
OKM-C50A 107
180 182 174 165 117 140 172 147 140 166 136 141 146 195 117 194 171 124 169 146
181 174 123 116 139 100 153 141 162 110 117 115 123 145 136 153 155 140 113 134
143 100 146 126 113 139 124 99 97 105 111 97 115 125 112 138 98 94 120 95
85 97 104 135 109 118 134 120 138 84 85 91 94 113 111 133 129 119 145 108
135 92 143 143 127 101 105 74 99 103 111 136 110 110 112 135 123 92 129 138
179 158 124 94 89 115 132
OKM-C50B 107
184 181 180 160 116 146 161 156 146 178 130 140 151 186 141 183 161 151 155 161
183 163 113 131 136 104 138 157 165 116 113 128 124 136 141 157 158 130 124 136
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70 103 96 148 117 122 123 120 143 85 72 94 87 116 111 132 135 111 144 109
117 105 134 142 136 98 92 84 92 101 128 131 116 113 114 137 117 99 122 138
180 156 134 98 71 116 145
OKM-C51A 83
187 241 171 210 191 178 170 112 81 164 155 134 170 103 143 138 171 138 160 154
166 184 134 144 140 171 150 149 155 186 149 116 113 131 130 149 148 148 140 130
137 148 117 166 132 139 142 157 159 146 128 112 113 77 151 152 112 127 156 134
122 87 144 131 147 120 128 152 145 103 112 150 117 139 132 105 107 119 177 175
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OKM-C51B 83
206 232 197 218 182 171 160 117 83 167 148 148 158 110 138 131 161 138 170 153
135 179 143 166 128 163 162 147 149 178 175 116 95 153 140 151 147 153 139 139
168 134 109 184 139 129 156 162 144 166 148 111 113 81 140 132 121 131 156 125
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136 193 187
OKM-C52A 86
191 110 90 95 170 188 172 178 147 161 177 195 179 202 208 220 228 201 187 224
211 242 164 165 174 178 159 125 147 154 152 135 131 139 115 125 134 102 155 134

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127 134 141 143 99 125 153 143 170 137 108 130 114 115 145 110 116 150 195 120
118 145 106 97 125 128
OKM-C52B 86
179 108 93 94 171 181 171 180 140 168 173 200 180 199 209 212 235 201 195 216
207 245 172 170 168 183 159 128 143 151 154 129 135 138 113 118 125 103 162 127
91 117 131 136 138 138 138 125 96 132 124 142 118 116 119 128 129 148 141 169
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121 125 112 114 110 134
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239 146 189 228 203 156 126 275 278 317 271 201 192 107 107 165 187 273 242 226
314 181 229 103 164 160 214 185 82 195 85 214 123 106 86 130 121 114 58 105
114 129 176 141 153 175 142 118 92 206 163 185 140 187 200 221 228 145 84 179
OKM-C53B 80
226 196 269 400 367 268 275 167 155 262 101 289 386 256 264 309 189 157 199 175
255 129 189 234 192 145 133 241 269 308 271 195 192 100 107 163 186 279 237 226
339 167 221 107 175 154 218 185 82 192 90 200 128 96 89 135 105 122 60 106
107 121 172 146 164 171 142 120 85 212 156 184 140 193 200 216 231 149 83 178
OKM-C54A 65
149 141 176 170 205 150 128 160 170 131 125 105 116 98 141 87 87 130 128 100
92 155 96 110 151 124 89 121 75 151 226 186 203 119 166 206 279 172 155 200
132 128 128 252 198 202 204 209 220 212 190 191 199 218 167 131 191 290 151 187
155 159 173 185 207
OKM-C54B 65
151 148 179 163 211 150 115 164 177 141 124 100 112 98 130 95 78 121 134 89
87 140 105 99 151 125 94 131 89 157 242 179 205 141 174 216 278 173 154 190
135 121 135 266 213 195 209 206 218 210 189 184 194 228 162 132 176 289 153 179
153 153 160 185 192
OKM-C55A 96
267 194 179 163 126 88 161 172 180 138 336 304 259 139 171 107 112 176 157 246
214 185 143 184 180 254 162 187 160 128 105 137 107 165 283 225 211 163 129 192
130 137 229 168 106 93 106 130 137 115 180 172 248 151 137 75 209 282 203 280
150 215 132 103 117 164 107 170 82 87 90 96 131 117 110 156 150 220 118 135
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OKM-C55B 96
260 193 189 155 140 83 162 176 190 142 323 310 264 150 167 122 99 181 151 252
221 178 164 185 180 247 167 186 153 127 114 125 118 161 275 217 193 153 118 187
140 134 195 151 96 99 108 143 126 107 174 185 250 153 137 65 218 287 220 305
142 206 143 111 104 155 115 162 76 81 84 98 131 118 111 154 160 217 110 143
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OKM-C56A 101
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OKM-C56B 101
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OKM-C57A 108
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157 113 111 127 73 56 79 90 115 134 148 117 131 118 86 101 98 114 104 121
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OKM-C57B 108
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OKM-C58A 90
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OKM-C58B 90
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60 95 134 118 139 126 110 65 71 109
OKM-C59A 79
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OKM-C59B 79
164 190 163 119 196 160 137 132 170 209 142 142 164 153 216 144 110 69 115 107
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OKM-C60A 60
197 258 309 138 169 267 234 243 208 268 160 128 219 235 237 197 203 186 160 136
207 280 274 245 231 278 235 198 226 206 182 182 177 244 293 293 198 207 150 140
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OKM-C60B 60
204 249 318 142 181 284 237 257 246 268 151 139 215 232 244 206 208 190 154 140
190 272 277 253 228 284 248 190 228 204 175 182 181 254 278 330 181 223 148 132
104 96 93 115 159 207 169 132 178 171 190 151 143 168 157 176 129 201 168 275
OKM-C61A 64
249 263 274 215 167 311 263 188 271 190 293 216 167 106 247 214 207 129 103 214
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223 184 153 157 210 207 154 116 195 232 182 142 175 167 184 172 156 128 89 137
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OKM-C61B 64
244 269 264 194 209 240 215 225 265 216 269 197 182 116 275 221 200 132 104 216
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222 185 145 166 208 212 157 109 210 229 187 129 192 159 187 172 155 135 87 143
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OKM-C62A 80
249 331 260 269 204 304 228 212 266 201 182 132 166 312 242 233 287 301 395 278
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OKM-C62B 80
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OKM-C63A 89
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OKM-C63B 89
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OKM-C64A 56
235 193 120 140 111 125 189 161 172 166 242 167 171 198 276 214 295 203 186 126
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210 228 168 87 151 204 243 285 220 301 234 234 189 97 171 179
OKM-C64B 56
247 193 125 138 128 108 193 156 169 172 247 175 175 193 276 214 289 199 192 126
255 287 348 245 203 428 289 220 234 261 195 287 298 229 342 389 309 251 221 112
203 243 164 95 151 194 260 275 218 312 232 242 179 93 179 179
OKM-C65A 75
374 272 326 286 454 300 269 280 248 287 295 308 393 393 346 328 288 168 135 259
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417 381 150 206 263 292 277 403 228 258 171 169 312 342 232
OKM-C65B 75
395 279 322 280 435 301 265 275 257 282 296 301 407 399 332 321 285 173 140 262
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398 375 129 203 265 300 256 410 235 243 173 184 296 328 228
OKM-C66A 63
445 369 567 388 242 359 300 181 225 206 192 158 128 171 160 105 239 240 228 145
121 107 182 241 268 364 278 526 340 236 296 383 233 288 278 213 222 188 208 168
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OKM-C66B 63
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OKM-C67A 87
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OKM-C67B 87
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OKM-C68A 65
167 190 152 181 217 264 111 113 149 122 96 105 126 166 151 214 151 121 167 135
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OKM-C68B 65

167 199 150 192 214 266 127 89 135 134 98 100 126 183 148 230 148 108 154 131
112 108 125 118 107 98 72 45 92 67 92 144 123 119 91 97 117 135 106 122
151 92 105 128 168 134 126 204 223 235 221 168 179 232 240 242 185 275 356 176
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OKM-C69A 72
242 194 175 191 199 197 150 166 184 137 157 170 210 164 180 78 133 164 164 108
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OKM-C69B 72
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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 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6. **Master Chronological Sequences.** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a

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

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

t-value/offset Matrix

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

Bar Diagram

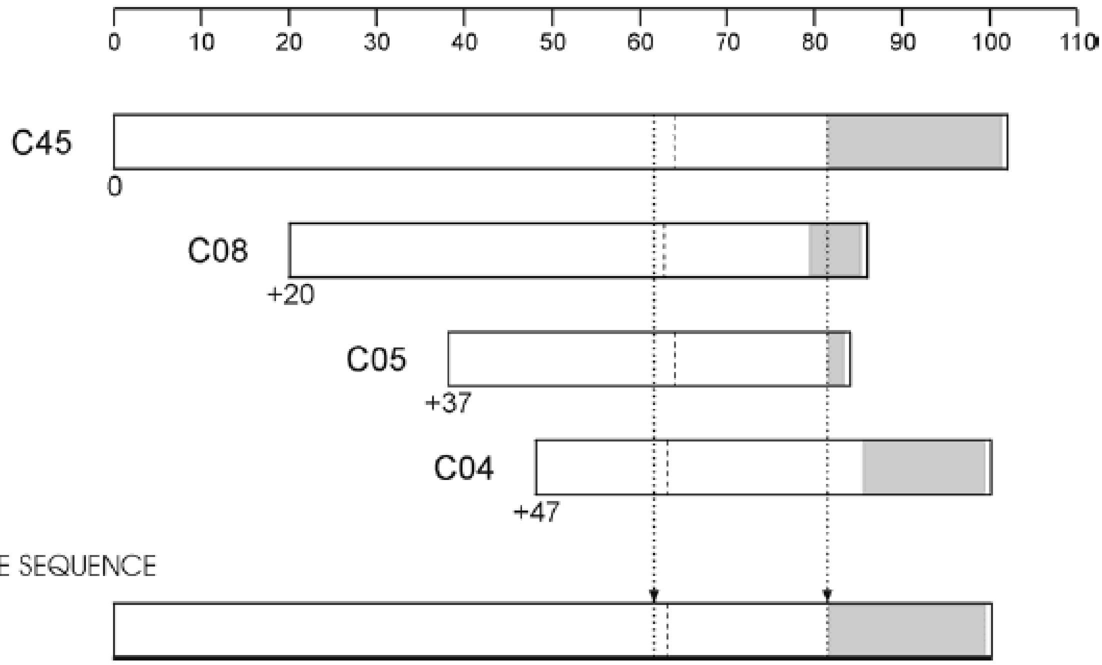


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

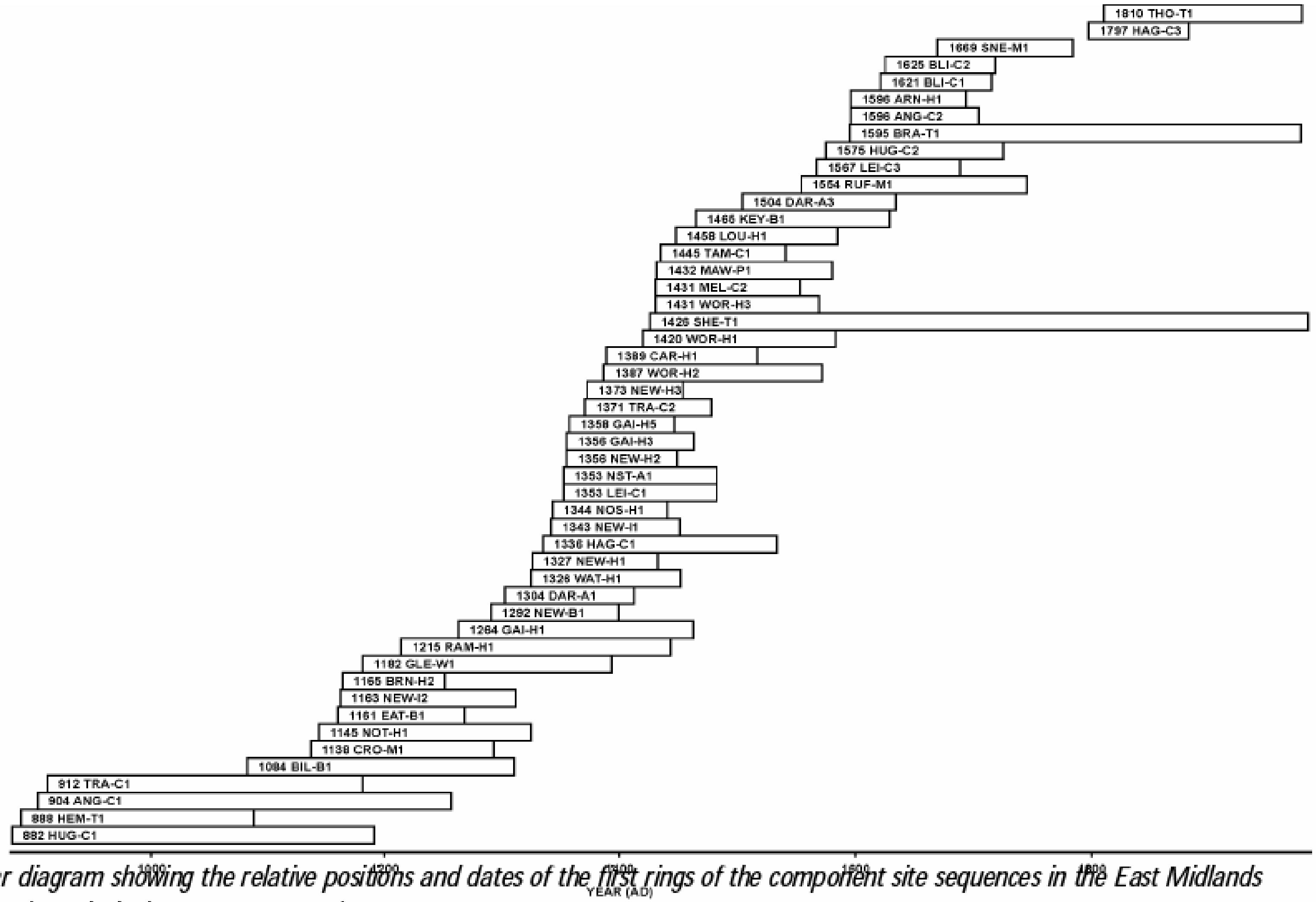
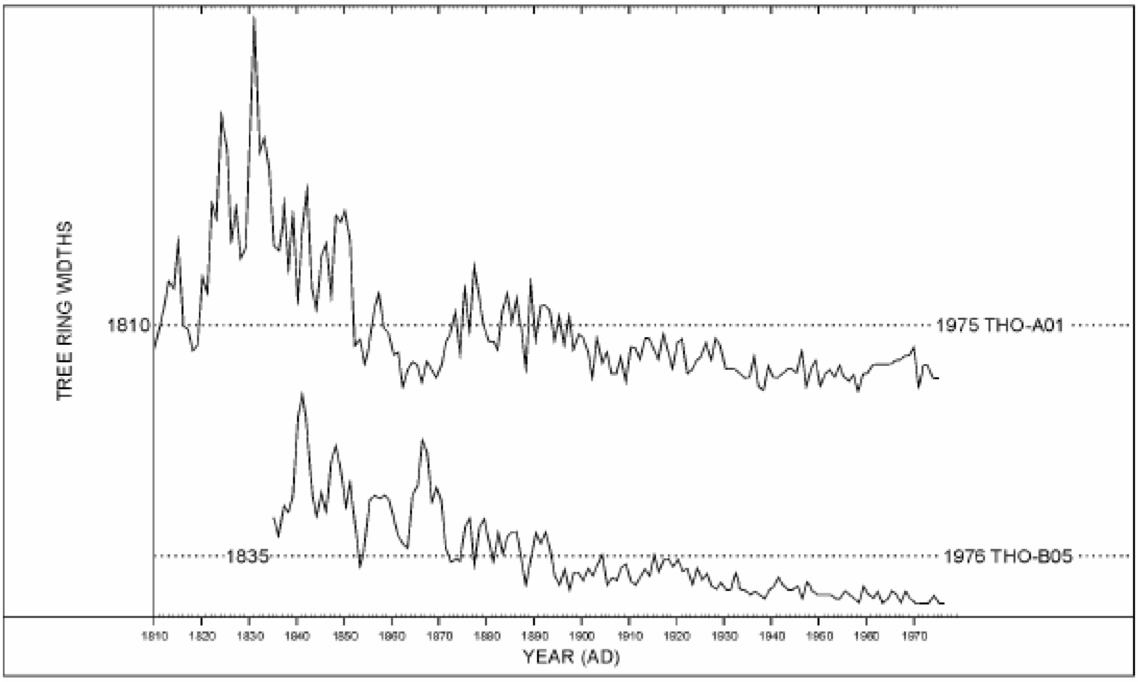


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

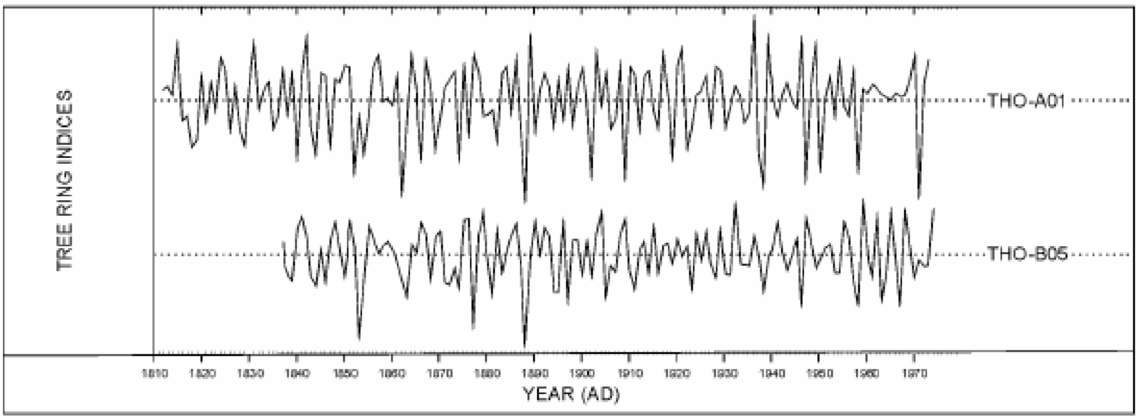


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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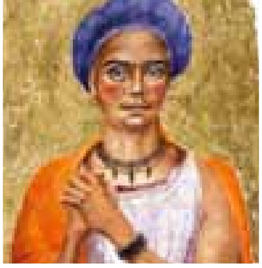


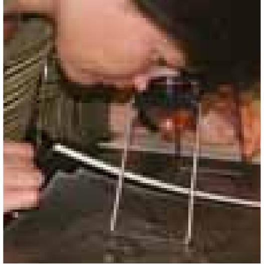


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