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The Commandery, Worcester
Tree-Ring Analysis of Timbers

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Summary

Core samples were obtained from 77 oak timbers within eight different parts of The Commandery, Worcester. Analysis of 73 of these (four samples having too few rings) produced four site chronologies, WORDSQ01–SQ04, comprising 47, 9, 2, and 3 samples, of overall length of 190, 101, 87, and 86 rings respectively. The first three of these site chronologies could be dated as spanning AD 1284–1473, AD 1608–1708, and AD 1569–1655, respectively.

Interpretation of the sapwood indicates that the majority of timbers used in this complex building, certainly those found in the Great Hall, the solar range (including a corridor partition wall), long chamber, and infirmary range, were felled over the period AD 1468–73, as building work proceeded.

The timbers used in the house on the street frontage could have been felled at this time too, but some timbers could have been felled slightly earlier and some slightly later. No post-medieval dates have been obtained from this building.

The roof of the ‘garden wing’ uses timber felled in AD 1708, this providing a date for the brick extension and refacing of the medieval building on the garden side.

The timbers of the infirmary addition cannot be reliably dated.

Keywords

Dendrochronology
Standing Building

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Introduction

Tradition maintains that The Commandery (SO 852 544; Figs 1 and 2) was founded by Saint Wulstan (b AD 1008), then Bishop of Worcester, *c* AD 1085, as a hospital. His reputation for religiosity led to miracles being reported at his tomb soon after his death aged 87 in AD 1094, and he was declared a Saint in AD 1203. Thus it may be significant that the first documentary references to the hospital are from the early thirteenth century, a more likely date for the hospital's foundation.

The earliest part of the standing buildings are some early-fourteenth century quatrefoil piers of three chapel nave columns, placed on the lawn outside.

Known as The Commandery because the masters of the hospital, from the late-thirteenth century, called themselves preceptors or commanders, the present timber-framed buildings are largely of late-fifteenth century date. These are centred on the great hall, which is impressive in size and detail, with arch braces to the hammer beams (filled in with tiebeams in the nineteenth century). The cross passage is defined by a spere truss with a seventeenth-century gallery above. There are long timber-framed ranges to the east and west, the solar range at the upper end and the infirmary range at the lower end respectively. A simple plan showing the different parts of the site is given in Figure 3, with views of the buildings being given in Figures 4a/b.

After the Dissolution of the monasteries, The Commandery was bought by Thomas Wylde in AD 1545, his family being one of the most prominent in Worcester, having become wealthy in the cloth trade. After his death in AD 1560, he was succeeded by his son Robert, who died in AD 1607.

Robert was succeeded by his son, Thomas Wylde II, who on his death three years later was succeeded by Robert Wylde II. This Robert Wylde was a barrister and a Royalist Officer who was among those responsible for surrendering the garrison at Worcester to Parliamentarian forces in AD 1646. He and his wife Ann had seven children; his eldest son, Thomas Wylde III inherited the estate in AD 1650. The Duke of Hamilton, a Royalist officer, died in The Commandery in AD 1652.

In AD 1695 Robert Wylde IV inherited an estate at Glazeley, Shropshire, which was to become the family's main residence in his son Thomas Wylde IV's lifetime. Thomas stood as MP for Worcester AD 1701–27, an expensive business which impoverished the family. The Commandery was therefore heavily mortgaged.

Following the Wylde family's move to Shropshire in AD 1695, their financial situation deteriorated until, in AD 1764, The Commandery was sold to the Dandridge family, who divided the building. They lived in one half of the east wing and leased out the remainder of the building as homes and businesses.

In AD 1805 The Commandery passed by marriage to Richard Mugg-Mence. He carried out many alterations and enlarged the living area into the whole eastern wing. The most notable alteration carried out was to form a carriageway through the Great Hall.

In AD 1905 The Commandery was bought by Joseph Littlebury, a printer, as a home and business. The Littlebury family themselves lived in the eastern wing of The Commandery, where Joseph Littlebury began to repair some of the damage done in previous years. The Littlebury family continued in residence until AD 1973 when the family business was closed. The Commandery was purchased by Worcester City Council in order to safeguard its future. On its purchase the building was extensively restored. The works, completed in AD 1977, touched on many areas of the building, in particular the west wing, where many of the makeshift buildings connected to the printing works were demolished. A further programme of restoration took place in AD 1988–90.

Today, as part of the City Council's Museum Service, The Commandery is being re-displayed with the benefit of a Heritage Lottery Fund grant.

Sampling

Sampling and analysis by tree-ring dating of eight different elements of The Commandery were commissioned by English Heritage. In particular, the sampling of timbers of the Great Hall was requested to refine, to an exact year if possible, the dates obtained for this element during a previous programme of tree-ring analysis undertaken in AD 1979 (Pilcher 1998). Sampling was also required from the solar range, the infirmary range and its addition, the house to the street frontage, the roof of the long chamber, the roof of the 'garden wing' and from an inserted partition within the solar range. The purpose of sampling and analysis was to inform a major programme of refurbishment. It was hoped that tree-ring dating would establish the date of the various element of The Commandery with greater reliability and accuracy and demonstrate any sequential development to the buildings. Photographs of some of these areas are given in Figures 5a/b.

From the extensive range of material available a total of 77 different oak timbers was sampled by coring. Each sample was given the code WOR-D (for Worcester, site 'D') and numbered 01–77. The positions of these samples are marked on plans made by Nicholas Molyneux and provided by English Heritage. These are reproduced here as Figure 6a–i. Details of the samples are given in Table 1. In this Table the trusses, frames, and other timbers have been located following the schema of the drawings provided, being further located on a north–south, or east–west, basis as appropriate.

The Laboratory would like to take this opportunity to thank Amanda Lunt and other staff of The Commandery Museum, who were at all times most cooperative and helpful, despite a certain amount of disruption during coring. We would also like to thank James Dinn, Worcester City Archaeologist, for his help in arranging access and for providing plans and background information on the possible phasing of The Commandery. Finally, we would like to thank Nicholas Molyneux, Team Leader at English Heritage's Birmingham Office, for the use of his drawings and for his contribution to the introduction above.

Analysis

Each of the 77 samples obtained was prepared by sanding and polishing. It was seen at this point that four samples, WOR-D16, D66, D72, and D73, had too few rings for reliable dating (less than 54) and these samples were rejected from this programme of analysis. The ring-widths of the remaining 73 samples were, however, measured, and were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum value of t=4.5 four groups of cross-matching samples could be formed, comprising 47, 9, 2, and 3 samples, of length 190, 101, 87, and 86 rings respectively. The relative positions of the cross-matching samples of each group are shown in the bar diagrams Figures 7–10. The cross-matching samples of each group were combined at their indicated offset positions to form site chronologies WORDSQ01–DSQ04.

Each of the four site sequences, and each of the 12 remaining measured but ungrouped samples, was then compared to a number of relevant reference chronologies for oak. This indicated cross-matches and dates for three of these site chronologies, and some individual samples. This analysis is summarised below.

Site chronology	Number of samples	Number of rings	Date span (where dated)
WORDSQ01	47	190	AD 1284–1473
WORDSQ02	9	101	AD 1608–1708
WORDSQ03	2	87	AD 1569–1655
WORDSQ04	3	86	------
ungrouped	12	---	------
unmeasured	4	---	------

Discussion of timbers / sources etc

Tree-ring dating would suggest that some timbers are derived from the same tree, probably as baulks split into two halves, or perhaps four quarters. Samples WOR-D19 and D24, for example, from the roof of the long chamber, cross-match with a value of *t*=12.4. Samples WOR-D49 and D54 cross-match at *t*=10.7, and WOR-D2 and D07 at *t*=10.2.

The analysis would further suggest the likelihood that a majority of the fifteenth-century timbers have come from the same general woodland source as each other. While there are indeed some lower, though still thoroughly acceptable, *t*-values, there are many values in excess of *t*=6.0 or 7.0, high enough to suggest that these samples represent several trees growing in the same district.

There is, however, a possible indication that some timbers within particular elements of The Commandery, the solar range for example, or the infirmary range, were growing together closer still, within the same copse or stand of trees. Amongst such groups of timbers values in excess of *t*=8.0 and 9.0 are seen. There is only one example of an especially close match between timbers from different elements of the site. This is found between samples WOR-D39 from the Great Hall and D55 from the infirmary range which cross-match with a value of *t*=10.3. These observations might suggest the possibility that while building went on over a period of time, some parts of The Commandery might have been built as distinct sub-phases of construction.

The early eighteenth-century timbers are likewise from trees growing, again, probably, in the same stand or copse as each other, with one or two trees perhaps coming from elsewhere in the same wood. It cannot be demonstrated that the same woodland has been used for both the earlier and later material.

Where exactly these woodland sources were cannot be precisely determined by tree-ring dating. It is likely, however, and probably not unexpectedly, that they were in the general area of Worcester, and certainly somewhere in the south-west. As will be seen from Table 2, which lists the reference chronologies by which site chronology WORDSQ01 has been dated, some of the best cross-matches are found against material from other sites in Worcestershire, Gloucestershire, and Oxfordshire. Site chronologies WORDSQ02 and SQ03 also show some tendency to match best with south-western sites.

Interpretation and conclusion

Analysis by dendrochronology of 74 measured oak samples from eight different areas of The Commandery at Worcester has produced four site chronologies, three of which, accounting for 58 samples, can be dated, with almost all areas producing cores with complete sapwood, denoted by 'C' in Table 1 and the bar diagrams. This means that each sample has the last ring produced by the tree or trees represented before they were felled and allows for the provision of very precise felling dates for the timbers.

The analysis shows that two periods of felling can be dated. Amongst the earlier majority group, represented by the dated samples in site chronology WORDSQ01, the earliest complete sapwood ring, dated to AD 1468, is found on sample WOR-D10, from a midrail in the solar range. The latest complete sapwood ring, dated AD 1473, is found on sample WOR-D22, from the roof of the long chamber. There are other samples with complete sapwood dated within this short time span to AD 1470, AD 1471, and AD 1472, from the long chamber roof, from the Great Hall, and the infirmary range. The relative position of the heartwood/sapwood boundaries, where it exists, on the other dated samples of this earlier period of felling is consistent with similar, if not identical, felling dates.

The only exceptions to this interpretation might be found amongst a few of the samples from the house on the street frontage, samples WOR-D69–D77. None of the samples from this area retains complete sapwood, so no precise felling date for any timber can be determined. Furthermore, the relative position of the heartwood/sapwood boundary on these samples, where it exists, is slightly more varied than that seen on other samples from The Commandery. Amongst those from the house on the street frontage the boundary varies by 24 years, from AD 1426, on sample WOR-D70, to AD 1450, on sample WOR-D76, with other sapwood boundary dates being spread out between these two. Given that this portion of The Commandery is known to have undergone extensive repairs, and appears to contain what might be reclaimed timbers, it is possible that timbers with different felling dates could be present. Thus, while it is possible that all the dated timbers from this range could have been felled *c* AD 1468–73, it is possible that some timbers could have been felled earlier, perhaps as early as AD 1441 (sample WOR-D70) or later, possibly as late as AD 1500 (sample WOR-D76).

The later period of felling is represented by the nine samples from the roof of the 'garden wing' in site chronology WORDSQ02 and the two samples from the same roof in site chronology WORDSQ03. Three samples from the roof, WOR-D29, D30, and D31, again all retain complete sapwood, with all three having the same last complete sapwood ring date, AD 1708. This is thus the felling date of the timbers represented. The relative position of the heartwood/sapwood boundaries, where it exists, on the other dated samples of this later period of felling is consistent with a single phase of felling.

It would thus appear that the a great majority of the timbers were felled towards the end of the fifteenth century, between about AD 1468 and AD 1473, and that despite the range of felling dates, albeit narrow, these timbers represent a single programme of construction dating to the first few years of the AD 1470s. Indeed, in the context of a large and complex building, it is perhaps to be expected that timbers with very slightly different felling dates, even within the same element of construction, may be found, eg samples WOR-D10 and D11, from the solar range, felled in AD 1468 and AD 1471 respectively, or WOR-D21 and D22 from the long chamber felled in AD 1471 and AD 1473 respectively. The different dating of these samples serves to illustrate the point that in a larger timber-framed building in particular there may be no one single 'felling date' but several, with timbers being cut over a short period of time as work progressed.

On the other hand, a much smaller element of the building, the roof of the 'garden wing' with its simple structure, does indeed appear to be made of timber cut in a single programme of felling. The timbers here date to AD 1708, and indicate when construction of the brick extension and refacing of the medieval building on the garden side was undertaken.

It is noticeable that no timbers from the infirmary addition have dated. This extension, thought to date to the seventeenth century, appears to have undergone some alteration or repair, with the timbers showing some variation in their size and patina. There is some variation too in the tooling marks on the surface of the timbers, with some being sawn and some appearing to have been adzed. It is quite possible that these timbers are of different dates and possibly from different sources. Samples from such mixed timbers are often more difficult to date.

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Table 1: Details of samples from The Commandery, Worcester

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Solar range					
WOR-D01	Lower west midrail, truss 24	70	no h/s	------	------	------
WOR-D02	Window sill, truss 24	127	no h/s	AD 1299	------	AD 1425
WOR-D03	West window jamb, truss 24	74	no h/s	AD 1316	------	AD 1389
WOR-D04	Central main stud post, truss 24	54	h/s	AD 1404	AD 1457	AD 1457
WOR-D05	East stud post, truss 24	80	13	AD 1380	AD 1446	AD 1459
WOR-D06	East window jamb, truss 24	69	h/s	------	------	------
WOR-D07	Stud post 1, party wall, trusses 23–4	81	no h/s	AD 1314	------	AD 1394
WOR-D08	Stud post 4, party wall, trusses 23–4	140	no h/s	AD 1284	------	AD 1423
WOR-D09	West main wall post, truss 22	54	h/s	AD 1393	AD 1441	AD 1441
WOR-D10	Midrail, truss 28	116	31C	AD 1353	AD 1437	AD 1468
WOR-D11	Upper west stud post, truss 28	70	30C	AD 1402	AD 1441	AD 1471
WOR-D12	Upper east stud post, truss 28	69	h/s	AD 1372	AD 1440	AD 1440
WOR-D13	Main central stud post, truss 28	114	2	AD 1347	AD 1458	AD 1460
	Corridor partition wall (trusses 27–8)					
WOR-D14	Cross rail	124	h/s	AD 1327	AD 1450	AD 1450
WOR-D15	Upper stud post	54	h/s	AD 1400	AD 1453	AD 1453
WOR-D16	Lower east stud post	nm	---	------	------	------
WOR-D17	Lower west stud post	77	h/s	AD 1372	AD 1448	AD 1448

Table 1: Continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Long chamber roof					
WOR-D18	Collar, truss 31	93	h/s	AD 1350	AD 1442	AD 1442
WOR-D19	South queen strut, truss 31	98	h/s	AD 1347	AD 1444	AD 1444
WOR-D20	South principal rafter, truss 32	96	h/s	AD 1345	AD 1440	AD 1440
WOR-D21	Tiebeam, truss 32	83	24C	AD 1389	AD 1446	AD 1471
WOR-D22	South principal rafter, truss 30	119	29C	AD 1355	AD 1444	AD 1473
WOR-D23	Tiebeam, truss 30	99	h/s	------	------	------
WOR-D24	South queen strut, truss 30	129	h/s	AD 1314	AD 1442	AD 1442
WOR-D25	North principal rafter, truss 30	98	23C	AD 1373	AD 1447	AD 1470
WOR-D26	Collar, truss 30	132	no h/s	AD 1300	------	AD 1431
	Garden wing roof					
WOR-D27	West principal rafter, truss 2	69	h/s	AD 1620	AD 1688	AD 1688
WOR-D28	East principal rafter, truss 2	74	13	AD 1624	AD 1684	AD 1697
WOR-D29	Diagonal rafter, truss 3	101	32C	AD 1608	AD 1676	AD 1708
WOR-D30	South purlin, trusses 3–4	96	30C	AD 1613	AD 1678	AD 1708
WOR-D31	South principal rafter, truss 4	97	26C	AD 1612	AD 1682	AD 1708
WOR-D32	North principal rafter, truss 4	83	23	AD 1621	AD 1680	AD 1703
WOR-D33	East diagonal rafter, truss 6	83	11	AD 1616	AD 1687	AD 1698
WOR-D34	East common rafter at truss 6	59	13	AD 1640	AD 1685	AD 1698
WOR-D35	West principal rafter, truss 7	85	no h/s	AD 1569	------	AD 1653
WOR-D36	East principal rafter, truss 7	84	no h/s	AD 1572	------	AD 1655
WOR-D37	East principal rafter, truss 8	89	23	AD 1618	AD 1683	AD 1706
WOR-D38	East queen strut, truss 8	68	h/s	------	------	------

Table 1: Continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Great Hall					
WOR-D39	South archbrace, truss 16	91	no h/s	AD 1342	------	AD 1432
WOR-D40	South spere post, truss 16	119	16	AD 1338	AD 1440	AD 1456
WOR-D41	South main wall post, truss 15	70	no h/s	AD 1362	------	AD 1431
WOR-D42	Main stud 9 (from north) truss 15	113	15	AD 1351	AD 1448	AD 1463
WOR-D43	North archbrace, truss 15	151	22	AD 1318	AD 1446	AD 1468
WOR-D44	North main wall post, truss 15	67	no h/s	AD 1369	------	AD 1435
WOR-D45	North wall plate, trusses 14–15	72	h/s	AD 1369	AD 1440	AD 1440
WOR-D46	South lower purlin, trusses 14–15	116	30C	AD 1357	AD 1442	AD 1472
	Infirmary range					
WOR-D47	West wall plate, trusses 4–5	54	h/s	AD 1387	AD 1440	AD 1440
WOR-D48	West main wall post, truss 4	99	h/s	AD 1355	AD 1453	AD 1453
WOR-D49	Tiebeam, truss 4	115	19C	AD 1356	AD 1451	AD 1470
WOR-D50	West stud post, bay 4 (window jamb)	81	20	AD 1388	AD 1448	AD 1468
WOR-D51	East wall plate, trusses 4–5	97	30C	AD 1374	AD 1440	AD 1470
WOR-D52	Tiebeam, truss 5	102	20	AD 1366	AD 1447	AD 1467
WOR-D53	West main wall post, truss 5	67	h/s	AD 1386	AD 1452	AD 1452
WOR-D54	East main stud, truss 5 (door jamb)	85	5	AD 1370	AD 1449	AD 1454
WOR-D55	West main stud post, truss 5	82	h/s	AD 1359	AD 1440	AD 1440
WOR-D56	West main stud post, truss 4	70	h/s	AD 1378	AD 1447	AD 1447
WOR-D57	Central mid-rail, truss 5	62	h/s	AD 1386	AD 1447	AD 1447

Table 1: Continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Infirmary addition					
WOR-D58	West wall plate, trusses 40–1	56	14	------	------	------
WOR-D59	East stud post, south of truss 41	77	no h/s	------	------	------
WOR-D60	East main wall post, truss 41	66	18C	------	------	------
WOR-D61	East principal rafter, truss 41	76	h/s	------	------	------
WOR-D62	Tiebeam, truss 41	66	16C	------	------	------
WOR-D63	Tiebeam, truss 42	56	10	------	------	------
WOR-D64	East main wall post, truss 43	79	19C	------	------	------
WOR-D65	East wall plate, trusses 1–43	55	15C	------	------	------
WOR-D66	West wall plate, trusses 1–43	nm	---	------	------	------
WOR-D67	West principal rafter, truss 41	80	h/s	------	------	------
WOR-D68	West main wall post, truss 43	54	no h/s	------	------	------
	House on street frontage					
WOR-D69	North queen strut, truss 37	72	8	AD 1369	AD 1432	AD 1440
WOR-D70	South queen strut, truss 37	72	12	AD 1367	AD 1426	AD 1438
WOR-D71	North west wall plate (trusses 37–8)	63	h/s	AD 1382	AD 1444	AD 1444
WOR-D72	North archbrace, truss 38	nm	---	------	------	------
WOR-D73	Main east – west ceiling joist	nm	---	------	------	------
WOR-D74	Ceiling joist 1 (from east)	79	h/s	AD 1369	AD 1447	AD 1447
WOR-D75	Ceiling joist 2	70	7	------	------	------
WOR-D76	Ceiling joist 5	68	10	AD 1393	AD 1450	AD 1460
WOR-D77	Ceiling joist 7	110	h/s	AD 1330	AD 1439	AD 1439

*h/s = the last ring on the sample is the heartwood/sapwood boundary
C = complete sapwood retained on the sample, the last measured ring date is the felling date of the timber

Table 2: Results of the cross-matching of site chronology WORDSQ01 and relevant reference chronologies when first ring date is AD 1284 and last ring date is AD 1473

Reference chronology	Span of chronology	*t*-value	
The Post Office, Oxhill, Warwicks	AD 1322–1447	9.9	(Alcock *et al* 1989)
England	AD 401–1981	9.8	(Baillie and Pilcher 1982 unpubl)
Worcester Cathedral, Worcester	AD 1286–1424	9.7	(Arnold *et al* 2003a)
26 Westgate Street, Gloucester	AD 1399–1622	9.5	(Howard *et al* 1998)
Anne Hathaways Cottage, Stratford on Avon, Warwicks	AD 1319–1462	9.3	(Alcock *et al* 1991)
England, London	AD 413–1728	8.7	(Tyers and Groves 1999 unpubl)
East Midlands	AD 882–1981	8.5	(Laxton and Litton 1988)
Southern England	AD 1083–1589	8.5	(Bridge 1988)

Table 3: Results of the cross-matching of site chronology WORDSQ02 and relevant reference chronologies when first ring date is AD 1608 and last ring date is AD 1708

Reference chronology	Span of chronology	*t*-value	
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1646–1813	6.9	(Howard *et al* 2000)
Worcester Cathedral, Worcester	AD 1484–1772	6.8	(Arnold *et al* 2003a)
Old Barn, Shottery, Stratford on Avon, Warwicks	AD 1591–1735	6.7	(Howard *et al* 1996)
East Midlands	AD 882–1981	6.6	(Laxton and Litton 1988)
De Grey Mausoleum, Flitton, Beds	AD 1510–1726	6.2	(Arnold *et al* 2003b)
Croome Court, Worcestershire	AD 1639–1753	6.2	(Arnold *et al* 2004)
England, London	AD 413–1728	5.9	(Tyers and Groves 1999 unpubl)
England	AD 401–1981	5.6	(Baillie and Pilcher 1982 unpubl)

Table 4: Results of the cross-matching of site chronology WORDSQ03 and relevant reference chronologies when first ring date is AD 1569 and last ring date is AD 1655

Reference chronology	Span of chronology	*t*-value	
Stoneleigh Abbey, Stoneleigh, Warwicks	AD 1398–1658	7.2	(Howard *et al* 2000)
Oak House Barn, West Bromwich	AD 1562–1655	5.9	(Howard *et al* 1991)
Hulme Hall, Allostock	AD 1574–1689	5.7	(Howard *et al* 2003)
England	AD 401–1981	5.7	(Baillie and Pilcher 1982 unpubl)
Sinai Farm, Burton on Trent, Staffs	AD 1445–1635	5.6	(Howard 2004 unpubl)
Worcester Cathedral, Worcester	AD 1484–1772	5.6	(Arnold *et al* 2003a)
10 High St, Stourbridge, W Mids	AD 1534–1661	5.0	(Howard *et al* 1993)
Wales and West Midlands	AD 1341–1636	4.6	(Siebenlist-Kerner 1978)

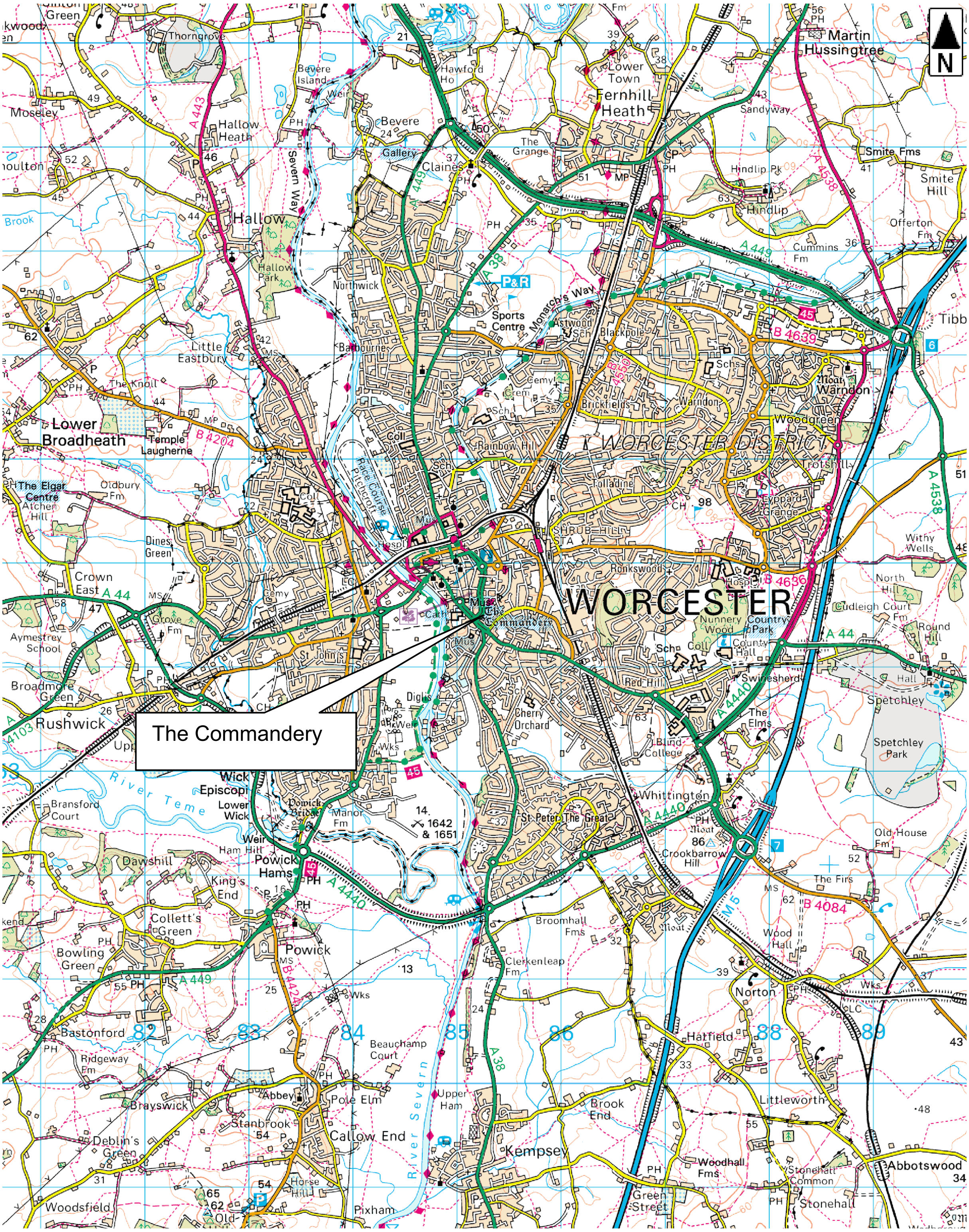


Figure 1: Map of Worcester, showing the location of The Commandery.

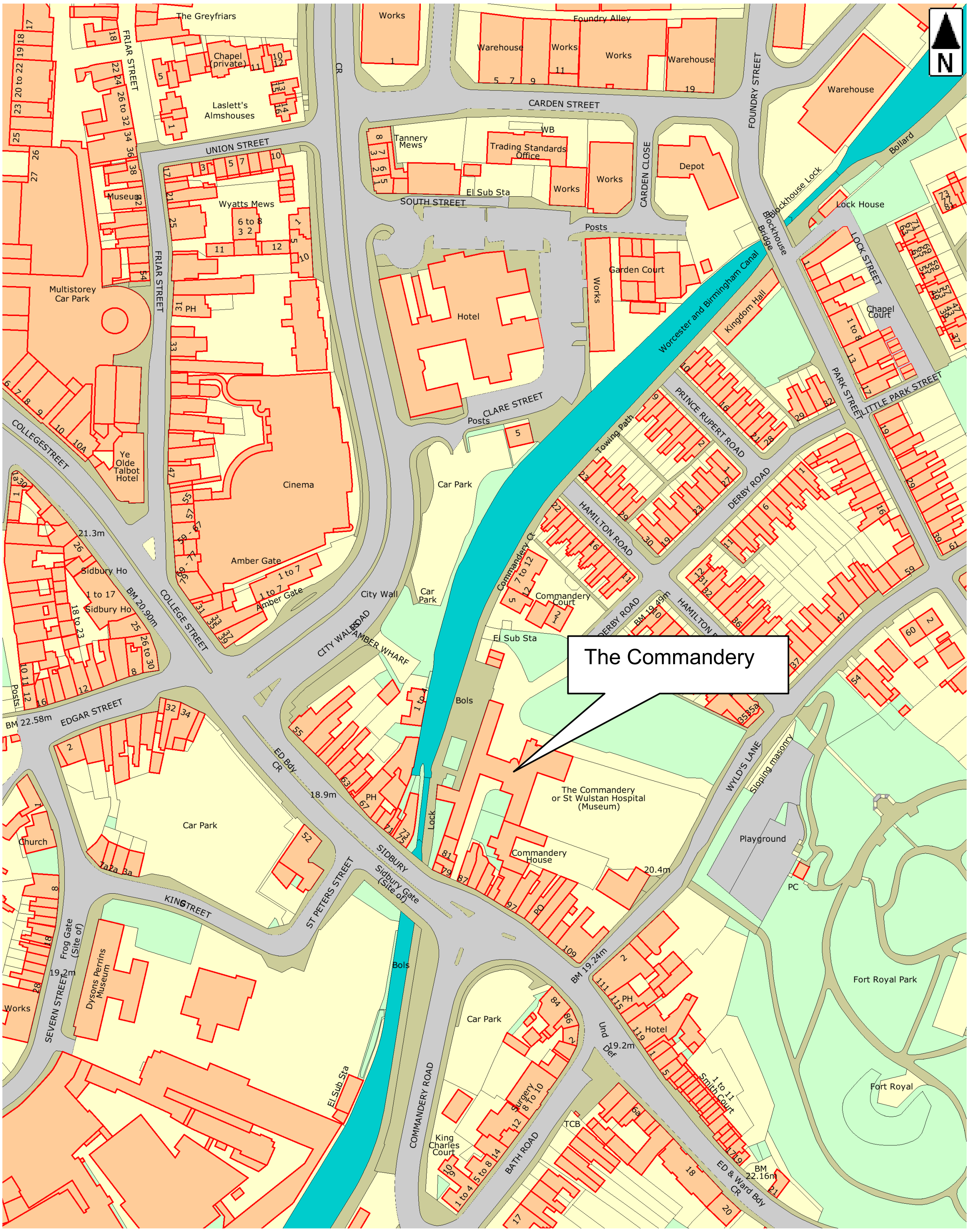


Figure 2: Map of Worcester, showing the location of The Commandery.

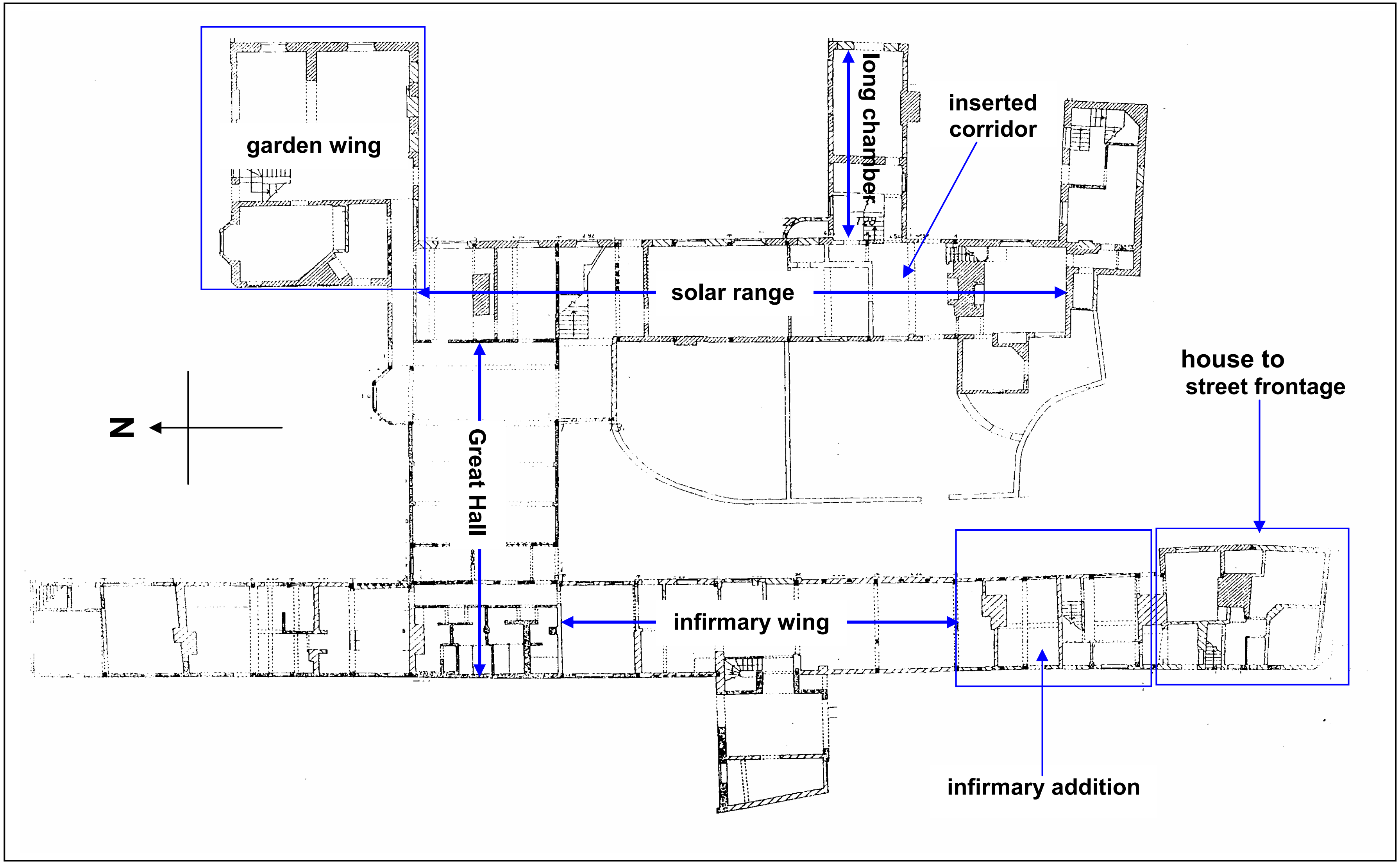


Figure 3: Simple plan of The Commandery

Figure 4a/b: East side of the infirmary wing and addition (above) and the south face of the Great Hall (below)

Figure 5a/b: View of the long chamber roof (above) and the infirmary addition (below)

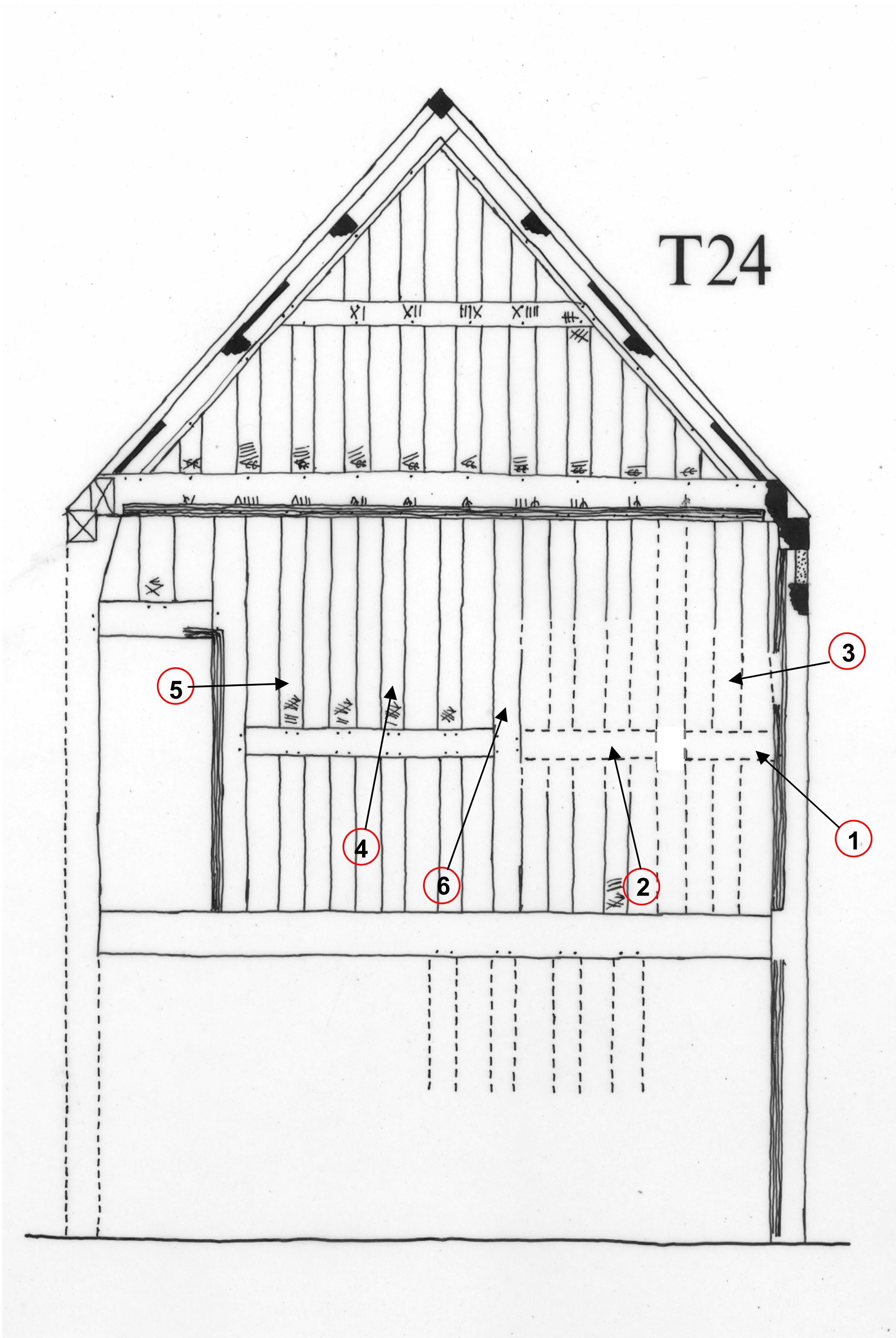


Figure 6a: Drawing of truss 24 from the solar range to show sample positions (viewed from the north looking south) (after Nicholas Molyneux)

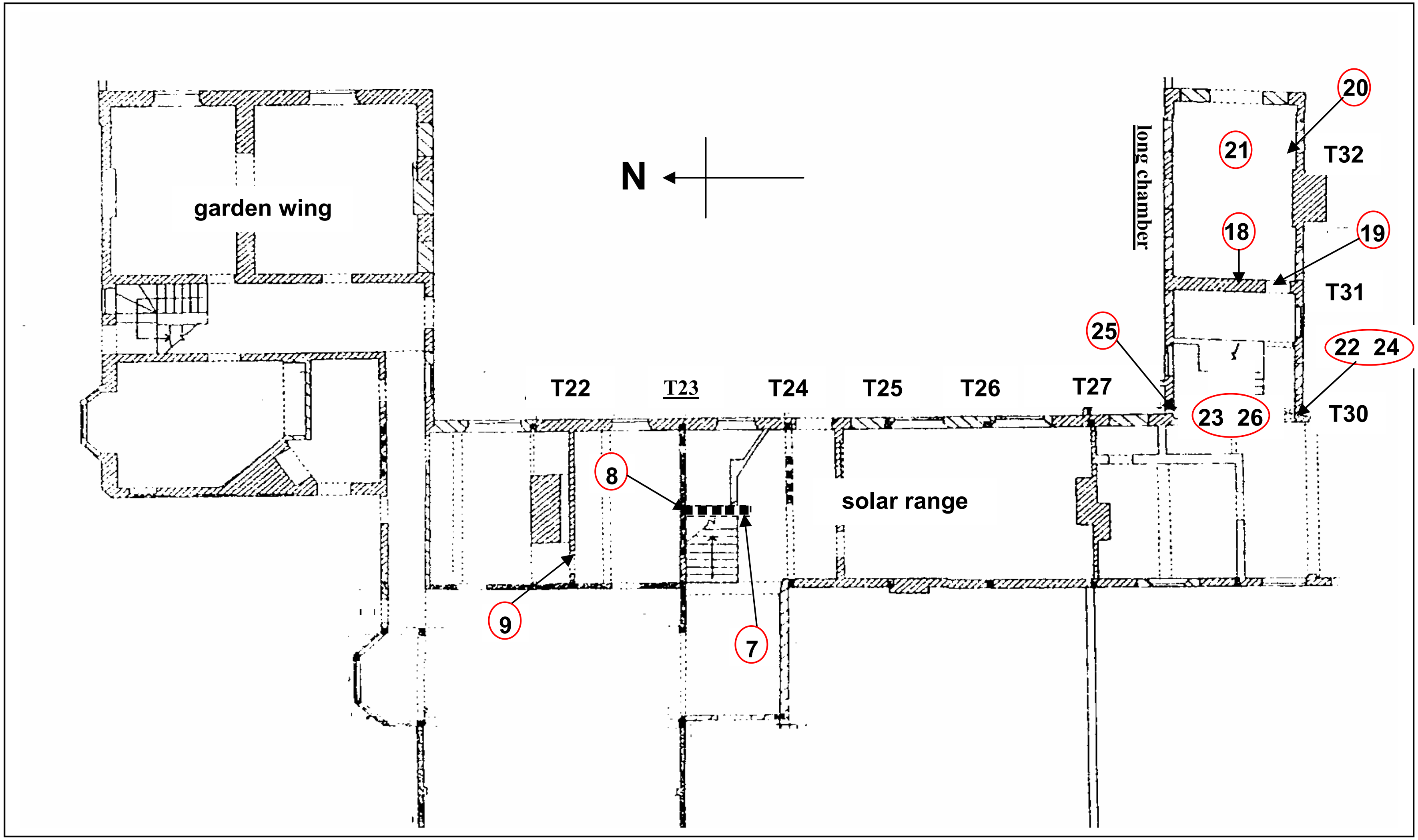


Figure 6b: Plan to show location of samples from the solar range and the roof of the long chamber (after Nicholas Molyneux)

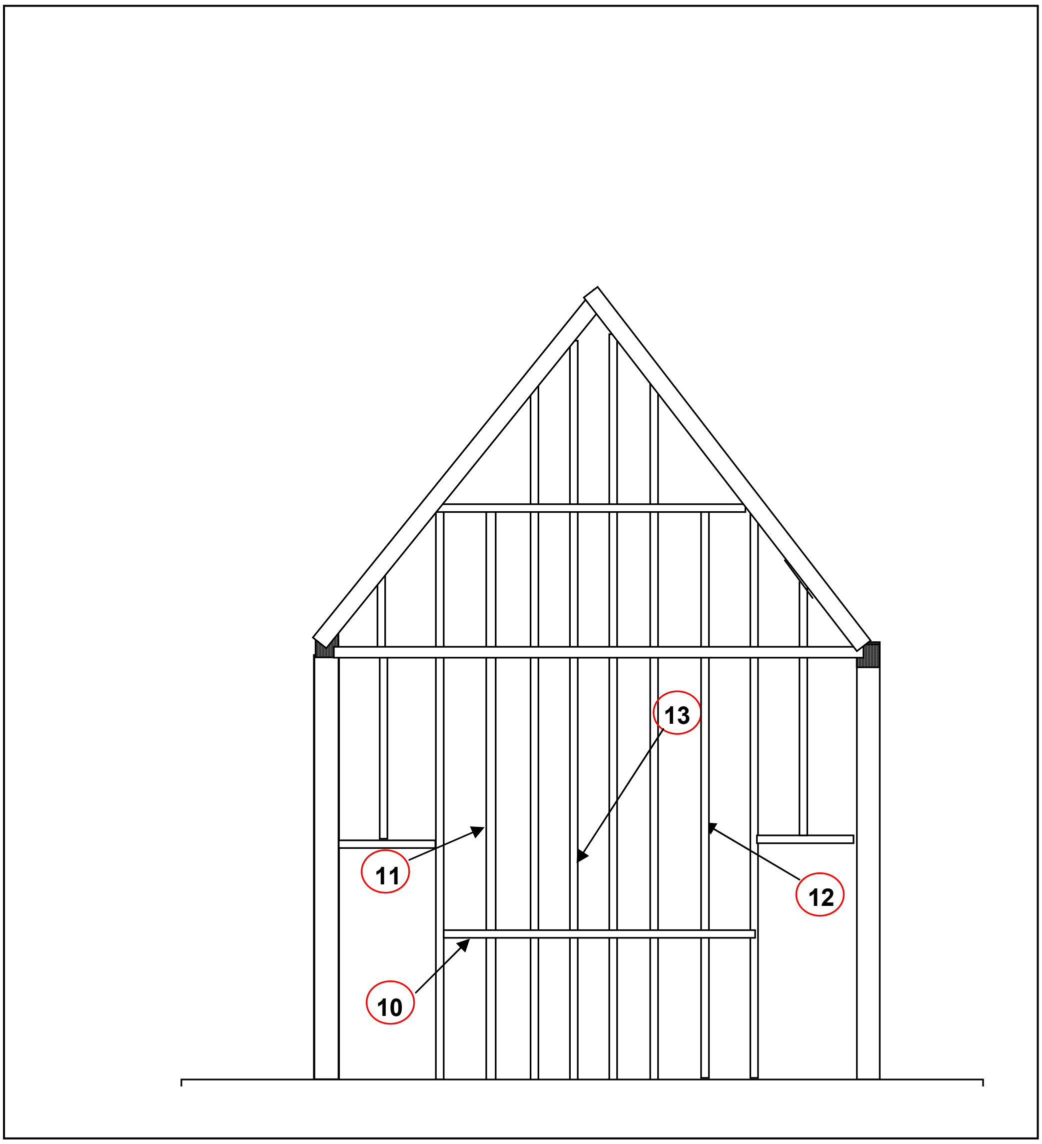


Figure 6c: Sketch drawing of truss 28, in the solar range, to show sample locations (viewed from the south looking north)

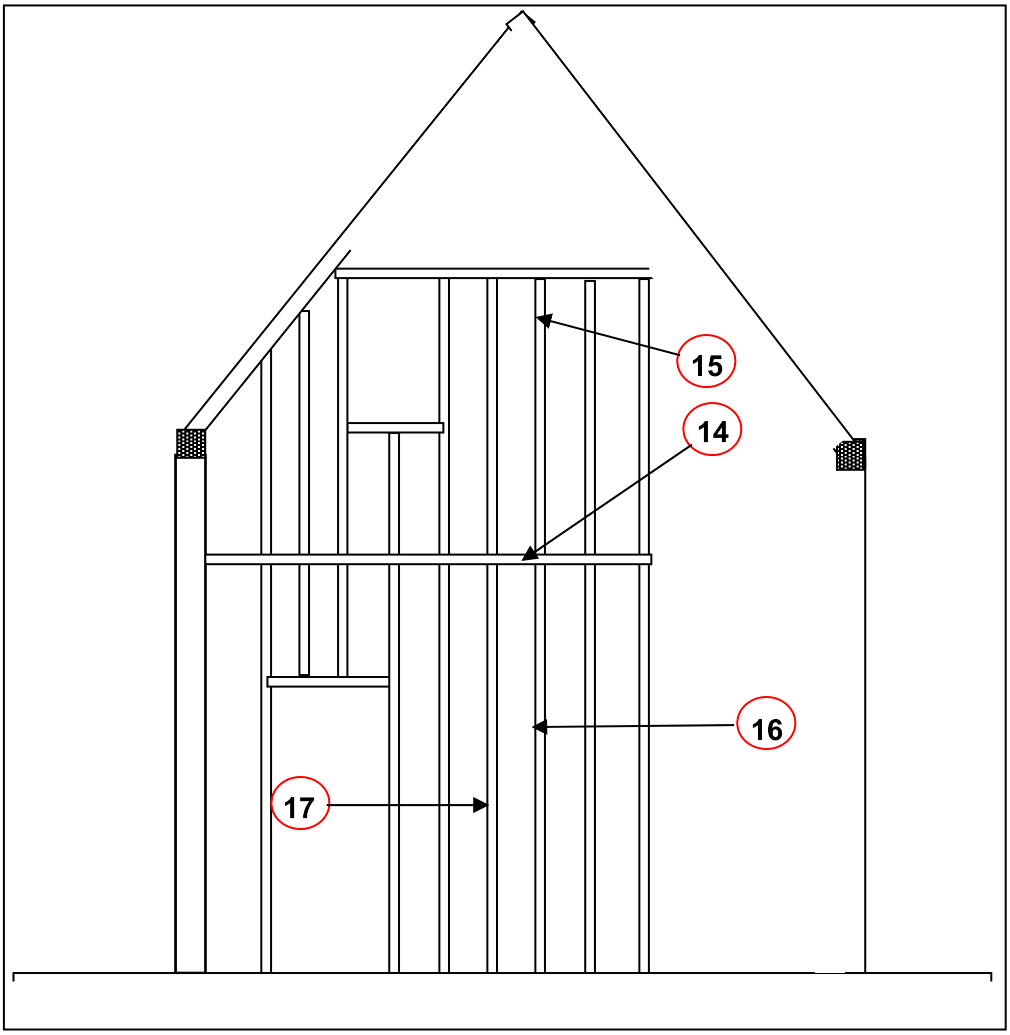
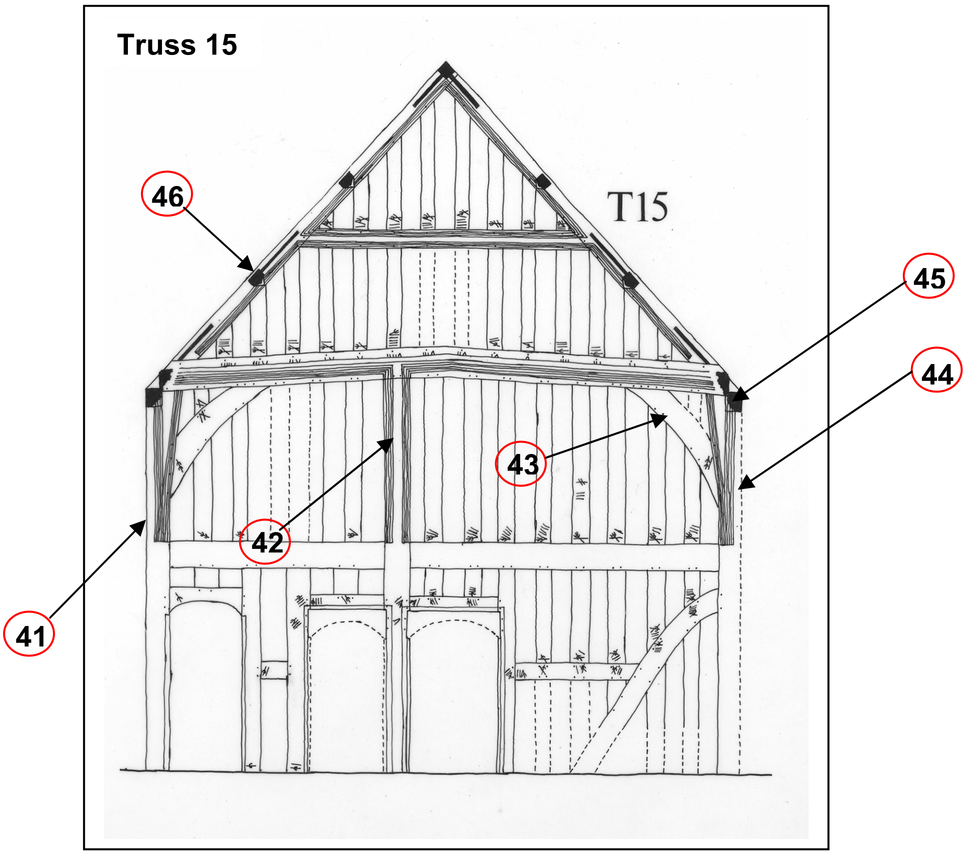


Figure 6d: Sketch drawing of the corridor partition wall in the solar range (trusses 27–8) to show sample locations (viewed from the south looking north)



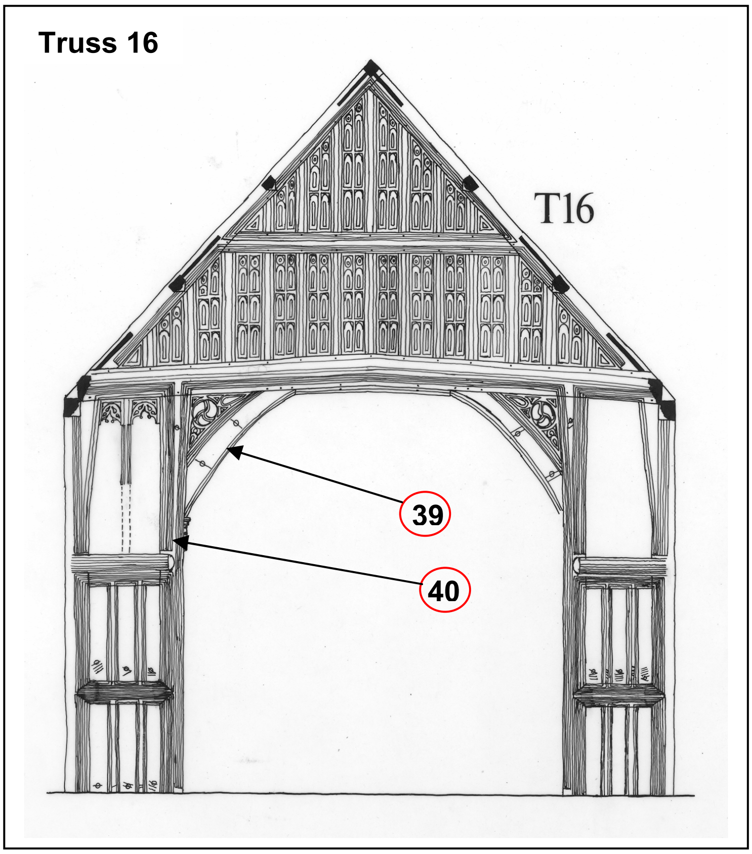


Figure 6f: Drawing to show position of samples from trusses 15 and 16 in the Great Hall (after Nicholas Molyneux) (viewed from the east looking west)

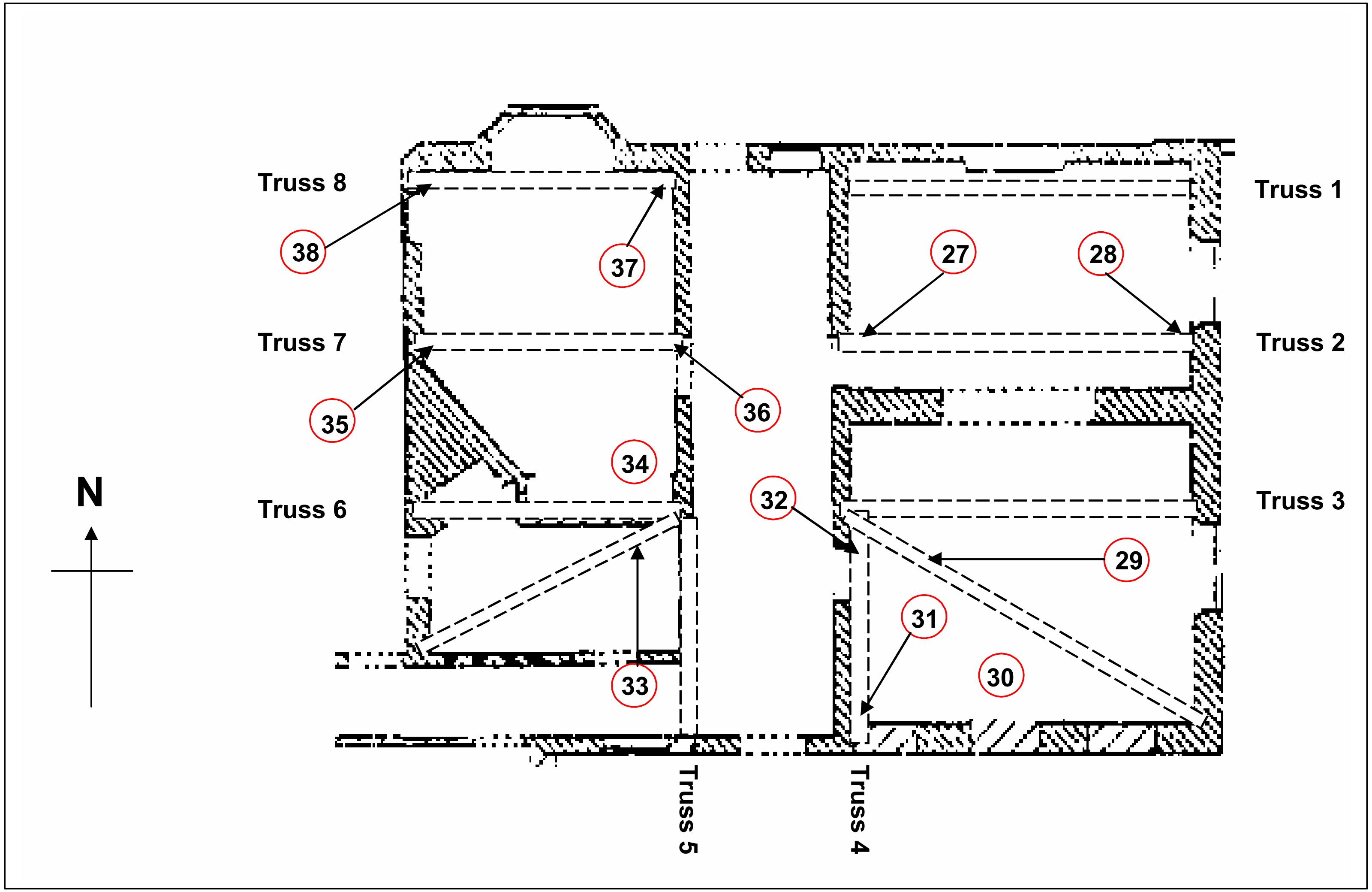


Figure 6e: Plan to show location of samples from the roof of the garden wing (after Nicholas Molyneux)

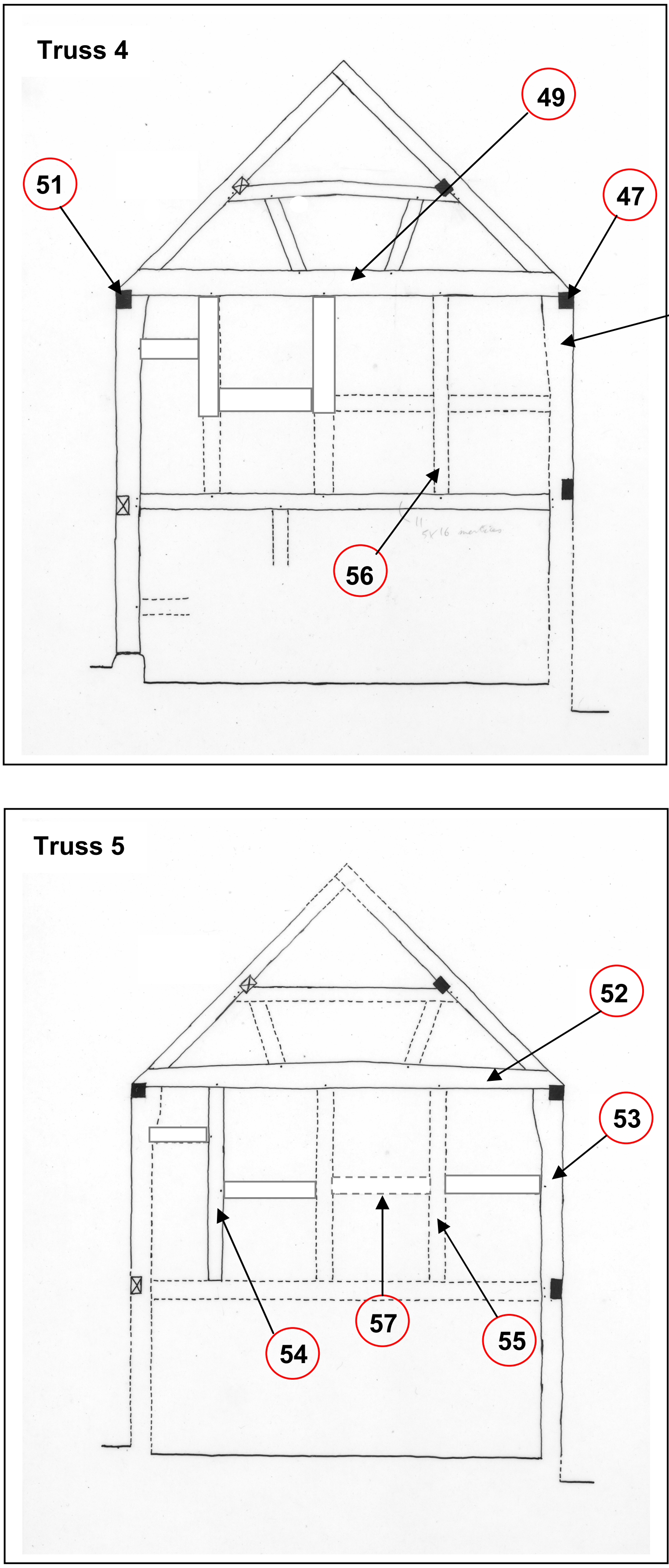


Figure 6g: Drawing to show position of samples from trusses 4 and 5 of the infirmary range (after Nicholas Molyneux) (viewed from the north looking south)

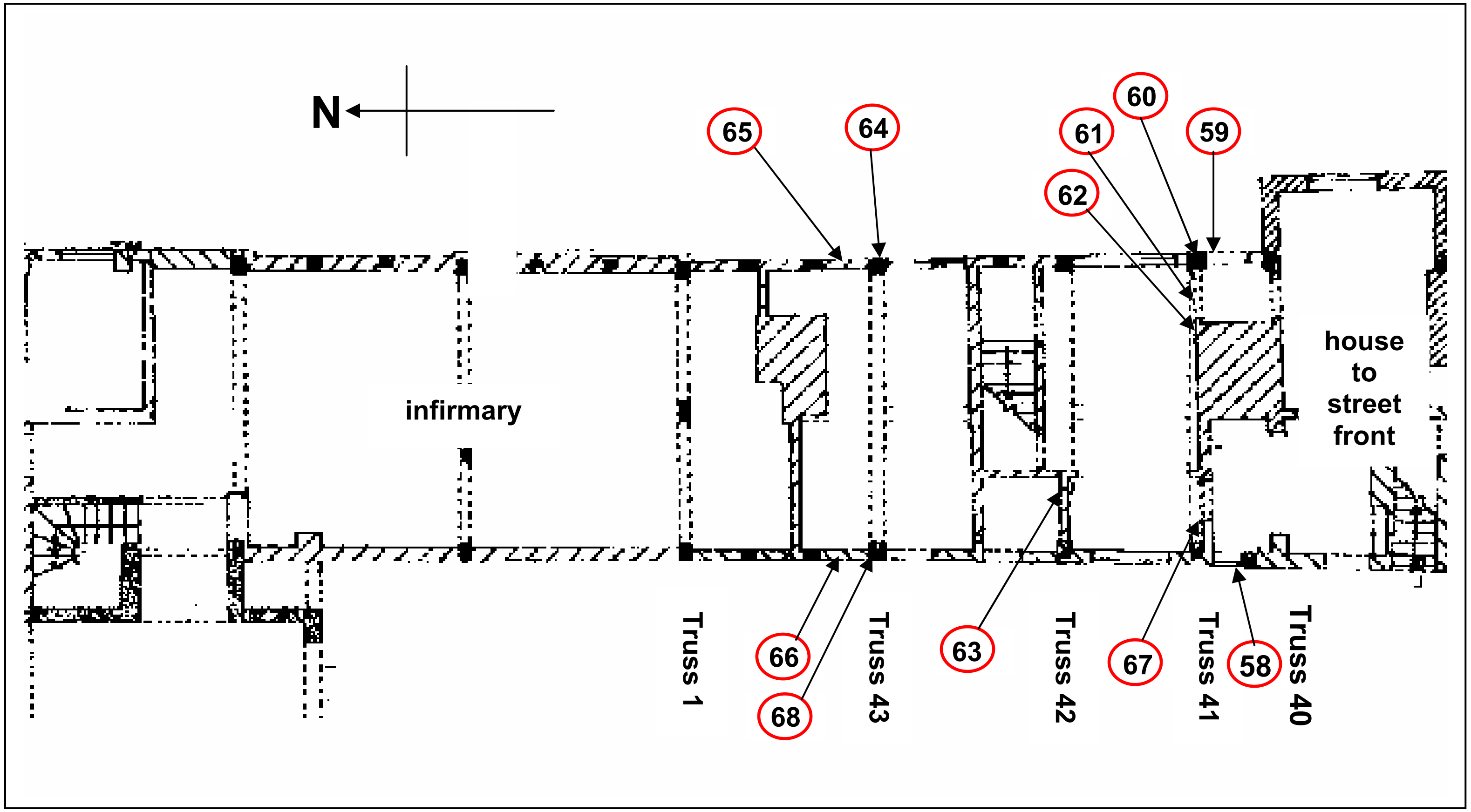


Figure 6h: Plan to show position of samples from the infirmary addition (after Nicholas Molyneux)

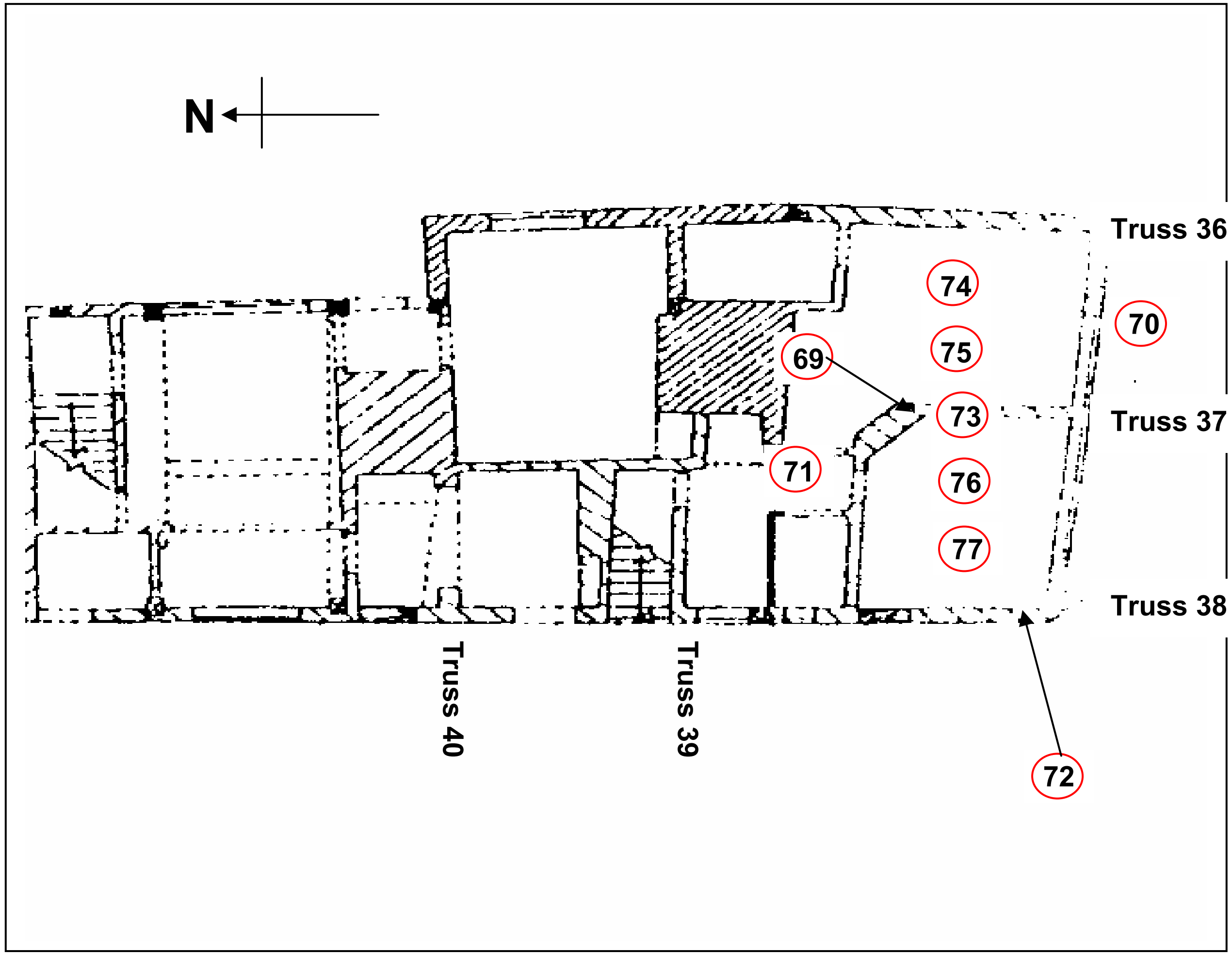
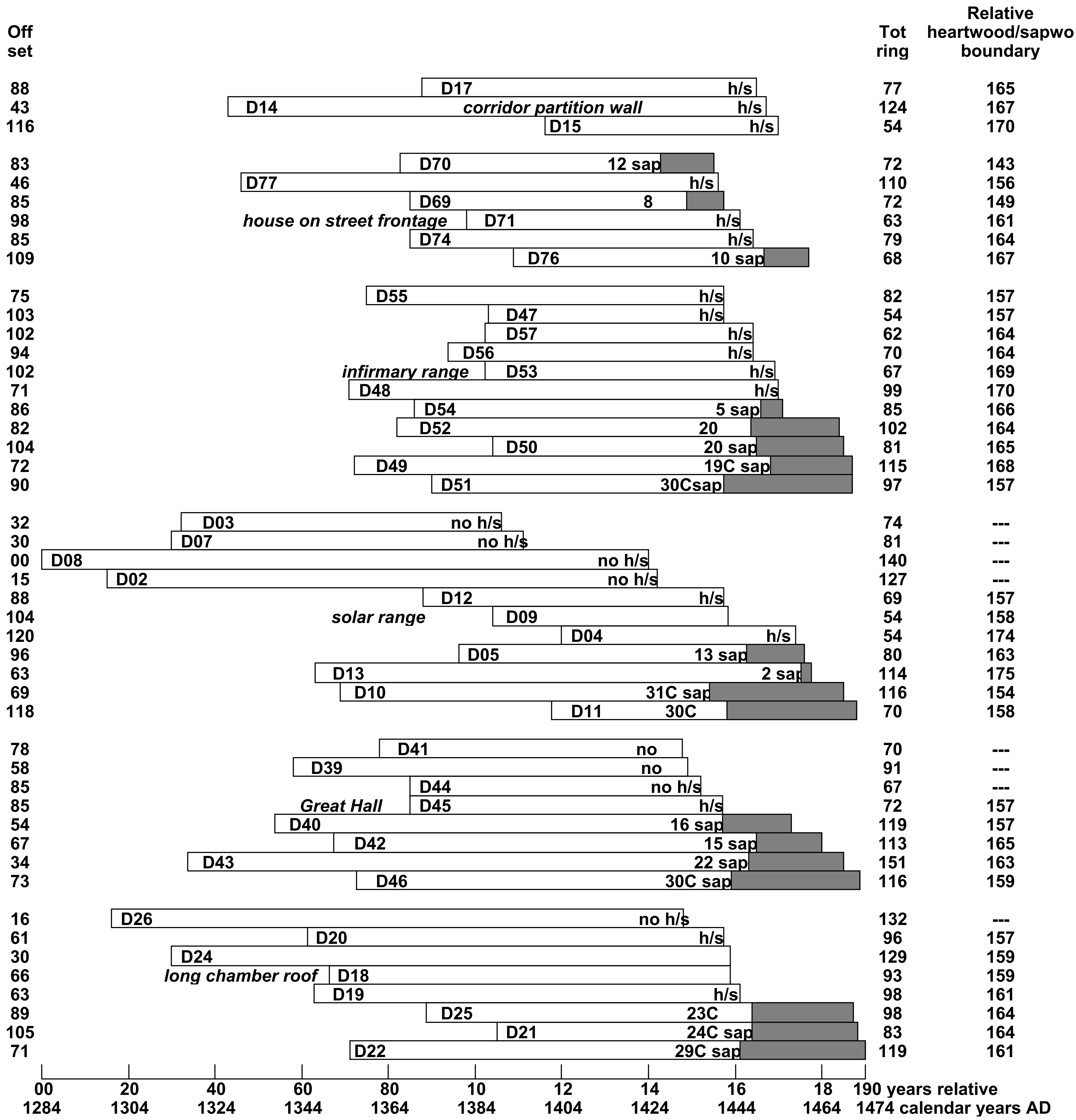


Figure 6i: Plan to show location of samples from the house on the street frontage (after Nicholas Molyneux)



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber

Figure 7: Bar diagram of the samples in site chronology WORDSQ01 sorted by sampling location in last measured ring position

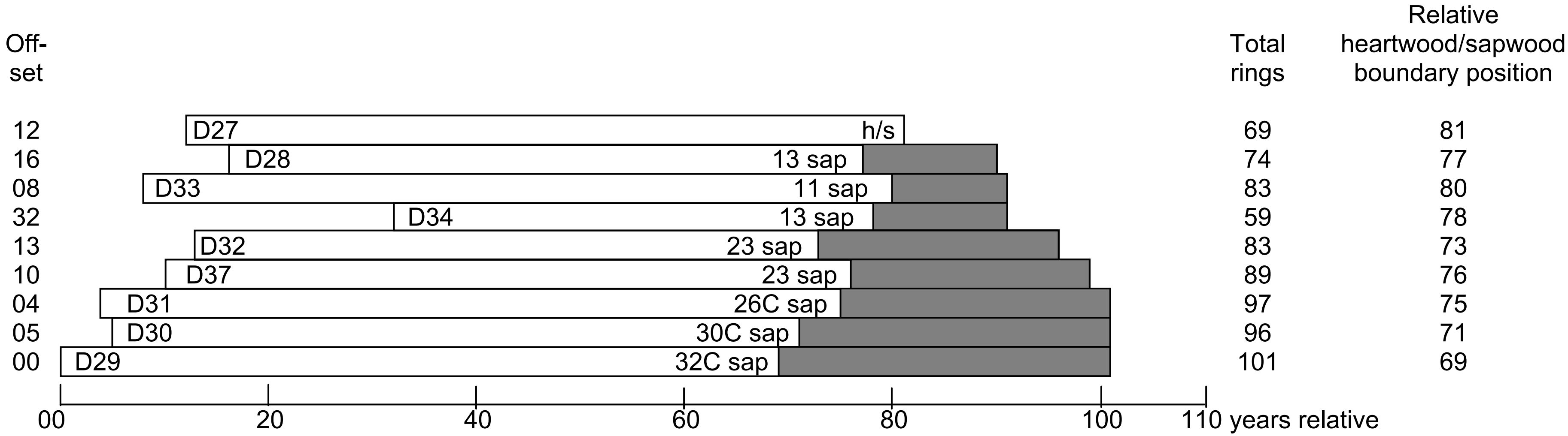


Figure 8: Bar diagram of the samples in site chronology WORDSQ02

white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample, the last measured ring date is the felling date of the timber

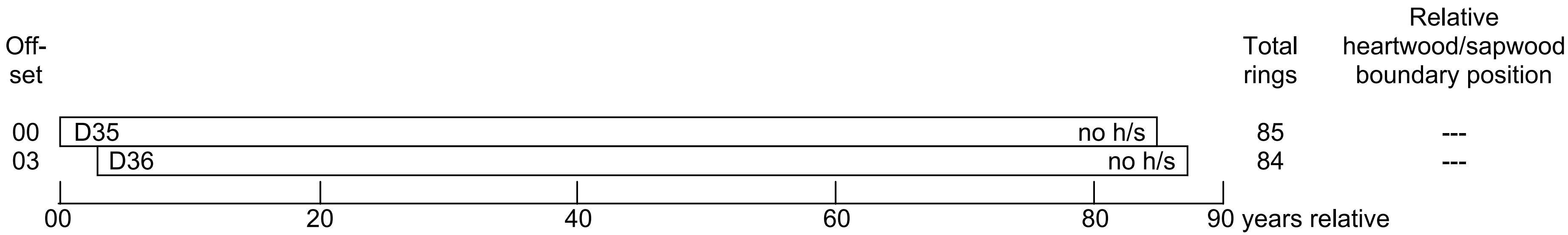


Figure 9: Bar diagram of the samples in site chronology WORDSQ03

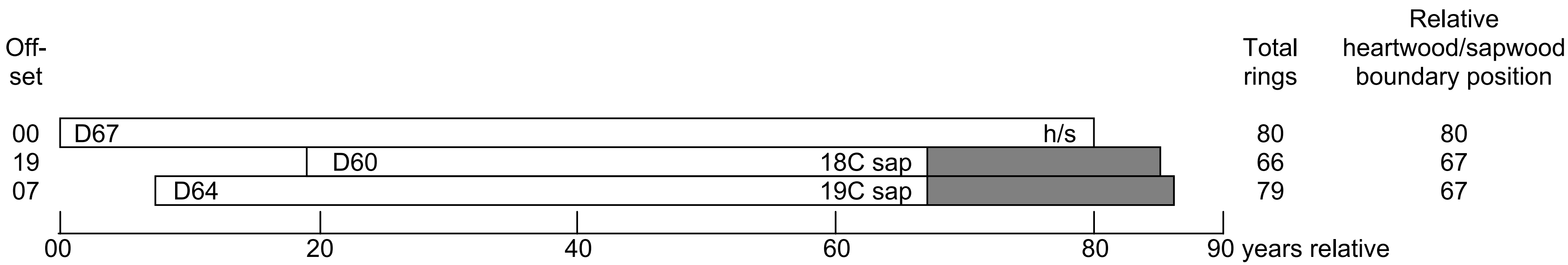


Figure 10: Bar diagram of the samples in site chronology WORDSQ04

white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample, the last measured ring date is the felling date of the timber

Data of measured samples – measurements in 0.01 mm units

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WOR-D01A 70
111 289 195 100 115 181 160 289 312 331 309 215 168 248 234 207 181 205 167 171
118 127 114 212 165 135 117 121 125 234 239 267 222 186 167 164 125 145 224 251
196 162 175 133 145 200 227 260 295 274 238 142 139 105 184 134 138 140 137 221
317 198 180 255 192 166 124 164 173 154
WOR-D01B 70
135 284 184 107 129 191 186 279 319 312 329 234 179 235 247 213 176 192 176 169
118 134 103 206 164 134 111 112 130 234 254 230 249 183 153 151 116 146 210 215
188 154 168 133 144 187 214 281 306 264 221 146 146 102 181 119 167 136 125 230
301 198 177 246 191 169 126 164 169 165
WOR-D02A 127
383 286 135 105 133 178 153 129 170 180 227 191 177 163 184 199 223 210 206 166
216 165 179 166 151 128  94  84 111 107 113 105 117 142 121 124 209 149 142 147
168 164 173 176 124 135 175 137 177 152 214 189 182 167 155 121  82  78 114 138
121 110  79 104 180 148 116 120 121 110 193 199 173 141 144 156 176 171 144 141
187 115 124 175 179 111 177 190 161 166 113 116  91  87  99  85 102 127 150 135
114 169 138 110 170 108  85 133 112 104 138 120 116 148 109  85 120  94 104 123
 75 111 160 137 144 162 175
WOR-D02B 127
358 220 151 131 111 147 143 121 155 197 244 198 199 110 150 218 232 190 198 172
194 161 186 169 154 112 105  96 109 127 113 115 139 148 119 103 193 149 145 161
161 162 182 178 137 132 168 153 163 156 201 200 174 166 161 126  91  77 123 132
127 103  80 121 185 169 108 124 117 129 198 193 173 133 149 153 172 165 138 163
173 117 128 170 182 108 190 198 154 165 130 103  89  82  96  92 102 124 160 118
129 177 140 108 149 118  94 119 105 106 139 118 114 136 106  92 121  95 106 110
 91 104 149 132 146 170 176
WOR-D03A 74
154 198 148 117 122 112 103 130 132  82  75  99 123 112 118  80 104 123 132 209
119 100 120 130 149 128 132 105 121 138 131 156 153 229 207 351 298 172  92  56
  65  65  63 137  84  65 105 166 233 183 237 197 158 222 179 196 223 180 164 249
206 135 128 255 147 156 184 155 108 166 177 145 171 196
WOR-D03B 74
153 196 135 112 131 113 102 136 128  94  71  98 127 111 115  83 104 115 141 205
118 103 117 122 153 124 132 105 126 151 128 158 176 245 204 361 316 162  86  67
 42  62  85 133  85  80 109 188 245 184 246 180 164 223 191 204 227 189 166 247
202 155 129 260 147 171 176 161 103 166 185 147 167 197
WOR-D04A 54
234 314 366 421 381 508 306 246 376 300 487 365 283 290 378 196 350 376 221 336
246 260 251 285 380 275 251 267 483 293 303 395 259 259 187 181 180 215 148 130
198 170 177 174 212 191 141 235 197 178 185 169 147 147
WOR-D04B 54
245 331 354 392 382 476 290 230 363 281 445 364 286 264 361 195 344 369 200 302
246 259 239 319 387 268 229 250 480 307 288 378 239 248 198 191 183 226 120 148
169 163 160 191 211 201 150 263 176 195 191 170 151 147
WOR-D05A 80
225 215 287 146 121  48 204 122 114 135 113 184 103  95 104 127 142  98 128 106
124 193  98  96  93  90 133 117 203 251 178 165 164 118 110 133  84  79 124  64
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 58  95  62  61 121  84  93  81  80  83  93 158  82  94  96  87 114 115 129 160
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127 187 104 104  87  96 137 113 200 249 186 156 153 113 120 131  81  92 106  67
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161
WOR-D07B 81
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174 218 225 167 169 204 166 168 179 188 100 153 185 166 169 134 154 120 104 142
156
WOR-D08A 140
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156 130 154 147 162 215 158 133 160 126 139 140 89 112 128 101 162 154 109 153
WOR-D08B 140
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127 169 211 174 187 166 183 161 132 157 103 122 154 145 132 189 225 185 148 196
171 139 144 133 164 222 150 129 160 131 135 127 106 116 130 116 160 157 112 153
WOR-D09A 54
137 191 170 270 142 248 230 260 326 295 247 270 429 412 330 468 284 244 240 228
307 276 245 194 171 181 186 177 140 140 150 106 162 159 142 177 173 138 130 113
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WOR-D09B 54
138 195 174 263 140 264 240 253 329 302 225 309 439 417 313 451 284 241 233 207
293 275 233 205 167 202 185 195 140 132 159 101 162 164 147 185 175 158 129 117
186 157 127 125 203 121 145 179 158 184 169 171 162 232
WOR-D10A 116
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WOR-D10B 116
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273 270 203 207 158 199 145 205 190 251 206 188 221 188 203 146 176 271 332 218
255 227 238 168 146 138 130 221 269 347 210 244 287 291 159 188 273
WOR-D60A 66
487 481 552 551 586 559 592 773 632 642 694 625 671 604 560 433 245 346 496 505
494 411 379 471 496 516 381 402 425 410 383 362 357 264 198 225 221 277 261 406
337 240 296 310 360 330 267 264 275 262 300 140 83 48 58 51 39 53 68 80
115 67 111 90 106 118
WOR-D60B 66
486 479 540 559 604 610 528 759 635 653 692 628 669 609 567 404 252 351 507 493
496 433 372 482 502 505 387 406 405 412 387 369 352 259 190 232 221 253 275 412
323 246 297 314 350 351 250 264 273 262 305 151 71 46 80 36 30 55 74 84
99 75 105 130 96 126
WOR-D61A 76
590 560 442 596 461 87 42 29 42 52 70 66 103 74 65 35 52 85 96 163
276 245 208 241 161 396 402 355 448 360 317 306 118 67 68 106 143 158 198 315
358 318 94 67 94 167 144 172 296 269 290 364 429 440 474 202 472 476 513 560
458 92 65 38 53 73 61 85 174 159 182 96 327 402 291 300
WOR-D61B 76
606 565 433 606 461 91 59 39 44 49 63 80 102 72 51 40 56 86 91 149
265 234 219 239 184 377 379 355 440 362 325 307 128 81 63 111 139 172 195 316
363 314 99 71 96 161 131 182 290 287 290 344 408 458 469 207 477 467 507 564
433 106 52 45 69 36 59 112 146 167 189 88 325 418 295 302
WOR-D62A 66
344 323 322 388 325 390 579 640 651 792 791 537 427 227 123 74 76 232 236 343
593 358 430 303 125 235 224 336 294 420 239 277 217 125 114 115 136 184 347 286
270 299 223 277 307 247 242 270 170 248 131 88 102 92 115 103 168 193 146 191
149 217 144 131 167 194
WOR-D62B 66
333 351 339 376 338 383 578 587 664 828 770 582 398 218 144 67 83 229 248 332
596 359 420 309 133 222 224 336 304 411 238 275 218 145 107 130 143 186 335 280
252 298 233 271 307 251 262 282 171 246 119 104 102 92 116 105 166 190 156 183
142 214 139 139 173 191
WOR-D63A 56
256 155 143 149 243 155 260 360 255 209 242 187 227 271 482 251 168 118 230 478
404 515 333 134 50 41 44 69 65 98 94 113 169 213 148 138 182 162 179 383
156 141 168 147 221 190 185 178 170 103 131 132 151 194 239 248
WOR-D63B 56
260 156 148 144 242 173 255 359 251 212 217 195 215 270 492 245 170 119 205 476
409 504 332 128 62 41 44 67 80 87 99 108 161 219 148 133 174 161 194 380
154 139 170 166 199 186 197 177 160 108 135 130 156 226 207 241
WOR-D64A 79
404 284 412 406 343 430 377 361 317 372 307 399 326 237 310 318 282 268 315 367
339 361 338 377 465 411 293 259 175 176 194 261 201 233 267 220 203 182 160 209
258 214 223 248 223 157 116 122 107 149 214 378 368 313 267 266 322 321 285 268
289 213 301 162 86 53 52 34 14 39 61 64 65 76 87 86 63 80 77
WOR-D64B 79
403 300 419 394 346 429 359 381 319 396 303 388 331 240 299 344 305 278 300 375
329 354 345 377 465 419 292 273 174 177 198 236 238 240 260 235 203 184 155 212
239 213 242 239 220 173 111 122 116 145 218 371 397 314 268 270 311 308 324 266
279 266 312 175 88 53 49 31 20 40 51 66 64 70 93 81 52 84 77
WOR-D65A 55
379 418 439 510 336 315 320 411 353 383 370 324 433 447 379 426 371 376 434 387
291 342 184 125 110 156 181 177 267 164 165 197 167 179 181 210 185 234 183 239
514 785 502 412 188 163 129 164 170 202 179 235 154 147 201
WOR-D65B 55
366 419 436 543 344 320 330 394 358 379 387 328 432 422 372 420 355 371 426 393
314 328 187 122 112 147 190 184 256 172 143 207 170 177 181 203 188 234 183 237
484 802 484 422 184 170 139 162 179 196 185 216 163 137 187
WOR-D67A 80
198 256 194 296 248 185 163 266 174 289 177 132 169 161 137 153 127 122 147 102
88 110 117 118 217 153 117 146 217 130 116 94 102 93 120 85 81 132 233 183
285 158 137 143 104 46 97 180 124 102 101 137 108 94 81 126 130 152 152 184
109 39 34 44 50 44 67 66 74 124 143 23 33 75 45 57 58 209 86 82

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WOR-D67B 80
200 195 197 290 234 183 174 273 177 269 179 135 179 171 122 157 118 126 129 118
 78 112 122 106 222 148 127 149 215 140  97  99  99  95 120  86  85 129 240 186
255 178 138 148 104  49  95 175 124 107 154 113 106  82 121 161 168 155 176 107
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WOR-D68A 54
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117  99 167 185 133 182 182 216 159 150 178 195 214 235 187 207 340 276 278 207
277 182 230 205 219 231 325 417 312  90  87 142  51  71
WOR-D68B 54
283 222 370 284 214 370 276 382 231 290 351 262 384 350 324 114 137 172 166  91
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276 181 237 200 206 240 329 411 320  89  83 149  53  72
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127 127  84  76  31  34  30  36  45  41  40  33  40  46  62  52  73  75  62  64
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WOR-D71A 63
217 221 304 237 352 298 319 358 231 392 180 198 182 219 282 211 259 294 327 388
207 284 247 228 268 210 238 187 114 118 114 103 107 146 144 142 129 116 118 154
149 176 172 125  89 100 166 118  91 128 154 148 142 168 113  91 126 117 107 125
104 104 121
WOR-D71B 63
223 247 303 242 366 296 313 341 247 395 184 190 190 225 273 218 268 292 325 392
220 284 240 220 271 210 234 173 137 109  94 124 106 131 151 141 140  90 121 169
146 177 180 125  97 104 159 101  95  97 148 156 155 158 101  98 131 107 114 127
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WOR-D74A 79
191 219 200 157 197 156 112 187 189 196 248 187 128 133  85  98 115 220 203 171
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WOR-D74B 79
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144 132 162  86 103  92  96 162 100  72 136 106 124  67  77  56  92  52  75  71
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WOR-D75A 70
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218 220 133 176 141 129 159 132 134 127  92  65  85  68  50  66  46  54  41  39
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WOR-D75B 70
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221 224 129 173 142 128 165 132 121 126  89  66  80  68  55  68  46  52  44  44
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WOR-D76A 68
132 144 134 229 144 188 211 172 199 116 177 110  93 126 117 129 154  88  89 103
102 128 146 107 106 123  80 124 196 155 245 216 189 122 110 178 142 161 202 241
146 167 157 136 121 152 102 136 191 115 165 168 123 111  86  84 104 120 216 179
189 174 227 176 179 183 153 197
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WOR-D76B 68
139 140 140 226 149 193 209 173 196 117 178 124  84 125 115 129 153  91  92 101
107 125 150 108 104 128  71 119 209 143 236 205 202 115 120 180 148 168 198 228
147 164 150 136 111 146 117 115 196 119 159 165 127 109  85  90  93 132 209 186
184 174 220 186 182 179 171 205
WOR-D77A 110
257 180 234 271 172 335 268 238 209 251 190 195 159 143 149 159 172 201 168 231
175 178 126 130 132  76  69 102 142 172 127 124 177 186 202 126 131 119  85 135
139  92  98 102  98  89 113 112 100 135 119  79 117  83 102  68  96  74  81  82
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 61  56  56  52  51  51  42  51  61  66
WOR-D77B 110
256 184 243 271 169 372 289 218 209 248 203 204 180 150 148 162 156 209 165 234
185 172 140 124 122  87  62 101 143 169 122 134 169 182 203 132 122 116  99 127
131 109  92  98  98  98 111 105 105 134 113  88 113  89  85  81  86  80  82  85
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 42  69  53  55  53  47  44  41  60  68
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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 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 1 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 1, 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 2 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 to 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 2; it is about 15cm long and 1cm 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 1: 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 2: Cross-section of a rafter showing the presence of sapwood rings in the left hand corner, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Figure 3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure 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 4: 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 2. 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 3).

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 4). 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 5 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 5. 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 5 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months 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 2, 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 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 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, 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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 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 Fig 6. 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 Fig 7. 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	

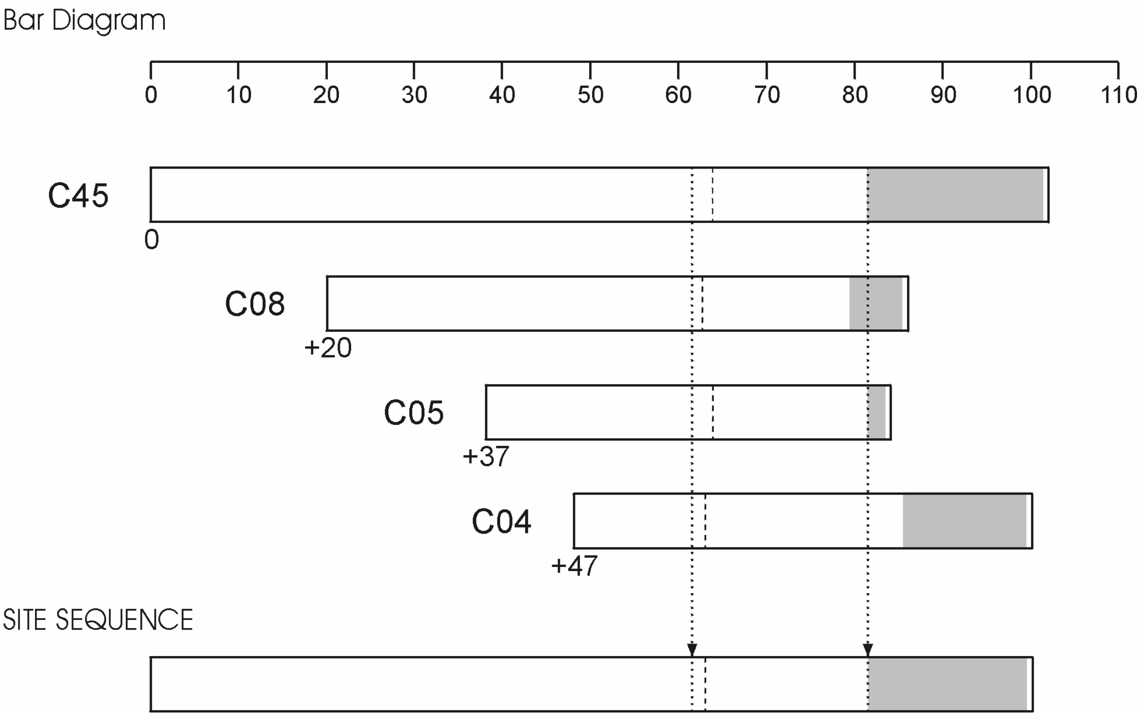


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

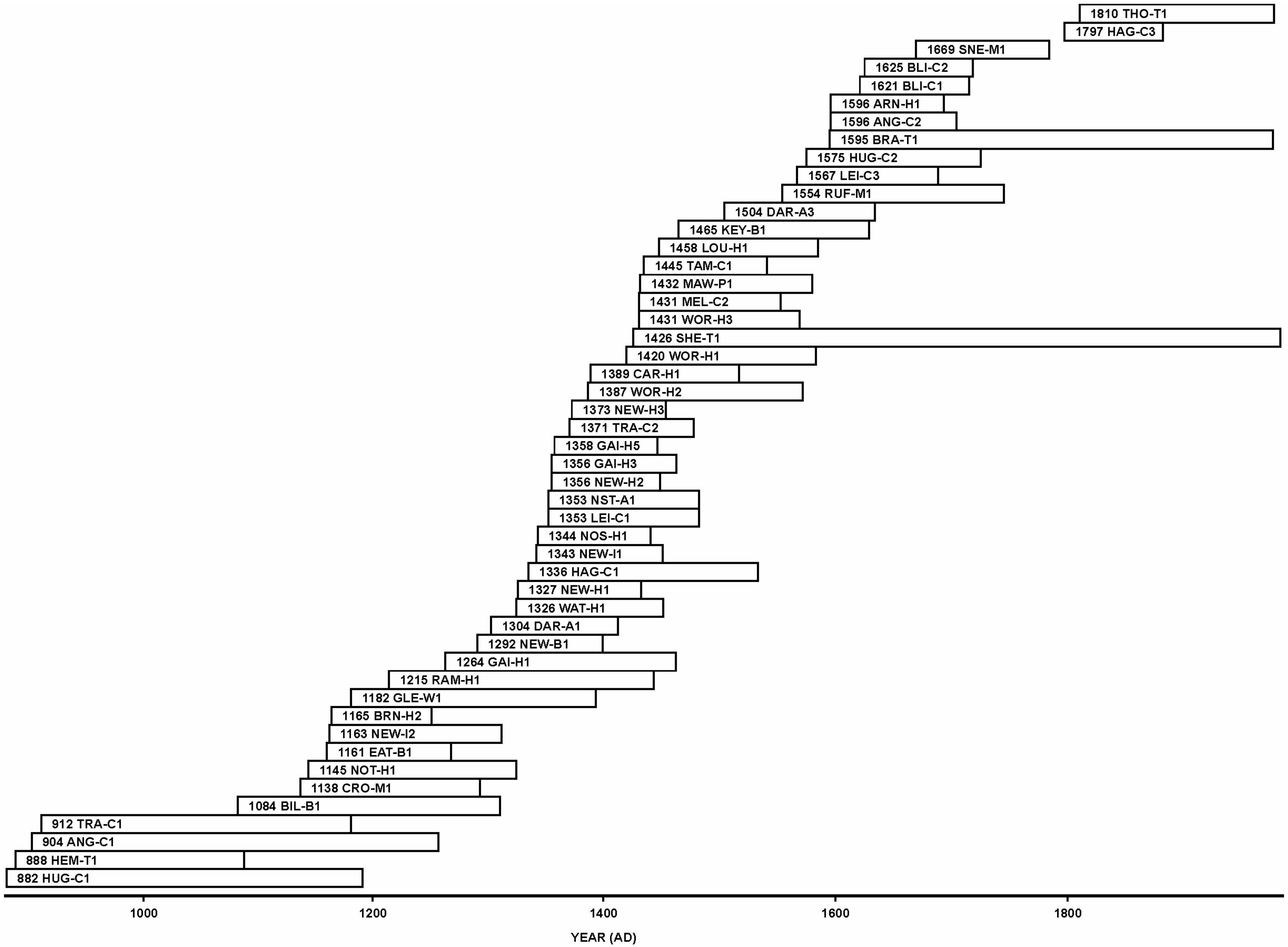
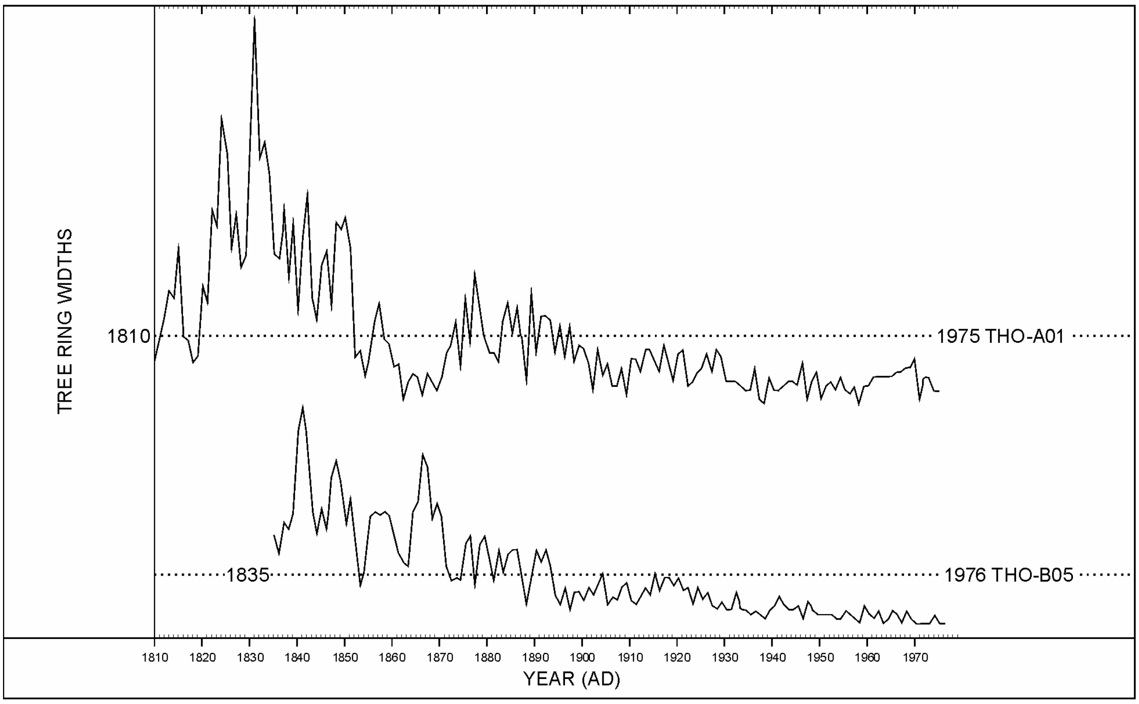


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

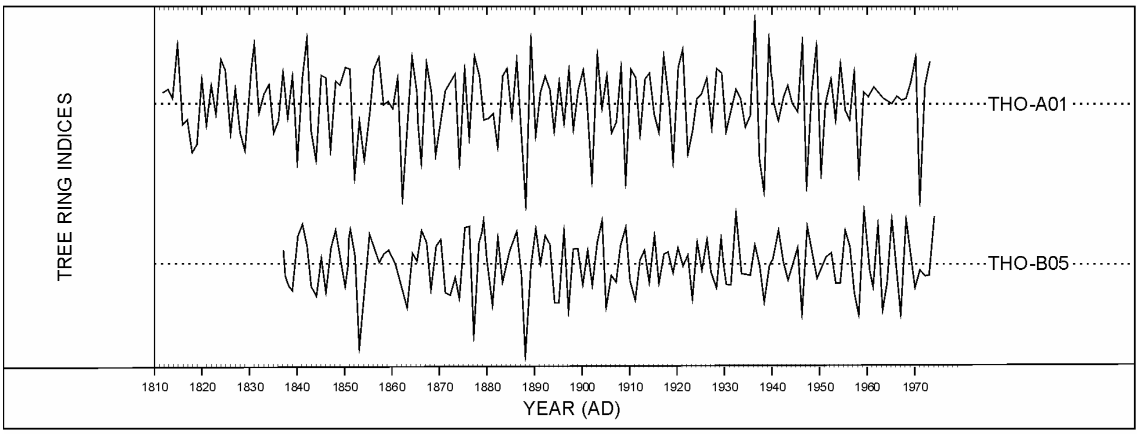


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Figure 7 (b): The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

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