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Summary

One hundred and five samples with a wide-ranging distribution within Hardwick Old Hall were obtained for tree-ring analysis. Ninety-one of these samples were measured of which eighty-six were analysed. This analysis produced six site sequences of which three were dated.

The main site chronology consists of thirty-nine samples with 216 rings spanning the period AD 1375 - AD 1590. The second chronology is made up of five samples, with ninety-eight rings spanning AD 1481 - AD 1578. A third site chronology has two samples with 103 rings spanning AD 1484 - AD 1586. Four individual samples were also dated. Three other site chronologies, accounting for 16 samples, remain undated. Twenty measured samples remain ungrouped and undated.

The majority of timbers sampled appear to have been felled over a short period in the late sixteenth-century especially for the construction of the Hall. Work appears to have proceeded in all areas simultaneously, there being no clear evidence on dendrochronological grounds for the separate phasing of different parts.

It is known from documentary sources that work on the Old Hall was begun in AD 1583 and was largely completed by the time construction was suspended in AD 1590 when work began on the New Hall. Tree-ring analysis appears to be entirely consistent with such an interpretation of the documents.

From the interpretation of the sapwood it would appear that some timbers used in the late sixteenth-century construction of the Old Hall were reused, having originally been felled in the very late fifteenth to very early sixteenth centuries. It is possible that these reused timbers were original to the earlier minor manor house, which is known to have existed on the site, and to have been incorporated into the Old Hall.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM HARDWICK OLD HALL, DOE LEA, NEAR CHESTERFIELD, DERBYSHIRE

Introduction

The ruined remains of Hardwick Old Hall present an impressive monument on the line of low hills rising to the east of the M1 motorway (SK462637; Figs 1and 2). This part of Derbyshire boasts in impressive collection of such sites with Chatsworth, Bolsover, and Sutton Scarsdale all being within a short distance of Hardwick and each other.

The history of the site is known from a wide range of documentary sources. The name most commonly associated with Hardwick, particularly with the elegant and refined "New Hall" (Fig 3) across the way from the Old Hall, is Bess. She was born at Hardwick, probably around AD 1520 (the exact date is not known), her father, John Hardwick, owning a minor manor there. Bess grew up here until she married her cousin Robert Barley. Upon Robert Barley's death in AD 1544 Bess married Sir William Cavendish, Treasurer of the Chamber to the King, a man with properties in five counties. Cavendish was persuaded to purchase the estate at Chatsworth and make Derbyshire his home county. The new house at Chatsworth was begun in AD 1552, signifying the beginning of Bess's mania for building palatial homes. Sir William died in AD 1557, followed by Bess's third husband, Sir William St Loe, in AD 1565. She married for the fourth time in AD 1568 to George Talbot, sixth Earl of Shrewsbury, but separated from him in AD 1583 (he died in AD 1590).

From the time of her separation from Talbot in AD 1583 Bess began converting the old manor house at Hardwick which she had inherited from her own family, generously enlarging it into a substantial mansion. It is this enlarged structure which became known as Hardwick Old Hall, and is the subject of this report.

It is likely that the Old Hall incorporated the earlier manor house, probably in the irregular gabled part. To this Bess added two wings at either end, each with a Great Chamber and each having state rooms on the top floors. These rooms had plasterwork by Abraham Smith, as well as having, for their time, unusually large windows. However, despite the lavish amounts expended upon it, the Old Hall was not built from the beginning to one design and the irregular planning of rooms and facades was the result of ad-hoc adjustments as the work progressed.

In AD 1590, seven years after work on the Old Hall had begun, Bess' husband, the Earl of Shrewsbury, died and she began another home, Hardwick New Hall. This was a far more ambitious undertaking on a clear plot of ground across the way from the Old Hall and built to a new and entirely up-to-date plan. Work on the New Hall was completed in short order and in AD 1597 Bess was able to move in. The Old Hall was then allowed to decay.

The sampling brief

Sampling and analysis by tree-ring dating was commissioned by English Heritage. The purpose of this was to establish possible phasing of the Old Hall in connection with the surviving accounts and to assess the significance of the site for its more accurate management in relation to its conservation. The English Heritage brief therefore called for the sampling of timbers in a number of different areas of the Hall. In particular it requested sampling of the timbers of the main staircase to establish whether or not it pre-dates that of the New Hall and whether or not it is later than the kitchen, pantry, larder, and other rooms below it. To determine this relationship the timbers of those rooms were to be sampled also. Where possible the timbers of the rooms above the kitchen and pantry, that is those of the first, second, and third floors were also to be sampled.

Sampling

Sampling first began in January 2001, with the timbers of the main staircase being cored first. Unfortunately work was brought to a halt by the outbreak of foot-and-mouth-disease, and sampling could not be resumed until October of that year. In the meantime a programme of conservation work on the Smith plasterwork was initiated calling for the setting up of scaffolding reaching to the parapets. A number of timbers that would otherwise have been out of reach were now accessible.

Thus, from the available timbers 105 core samples were obtained. Each sample was given the code HDW-A, (for Hardwick site "A") and numbered 1 – 105. Timbers were selected for sampling on the basis of their appearing to have sufficient rings for reliable dendrochronological analysis or having some sapwood, where it existed (or at least the heartwood/sapwood boundary), or both. Unfortunately, due to the ruined nature of the site and its long-term exposure to the elements, much of the softer parts of many timbers, that is the sapwood, and some of the heartwood too, was decayed.

Most of the timbers at the Hall consist of lintels of doorways or windows, or joists or main bridging beams of room floors and stairways. Many doorways and windows contain two lintels. In such cases the lintels are described by compass directions, as being either the north, south, east, or west lintel, as well as being as being noted as the inner or outer of the two where this might help with timber location. Where there are three lintels the term inner or middle lintel is used. Most other timbers, joists etc, are numbered and described from north to south, or from east to west as the case may be.

An attempt has been made to sample all rooms on a collective basis, so that each room is accounted for by a consecutive number of samples. Because of the nature of access and works in progress on site etc, this was not always possible, and some rooms have samples of non-consecutive numbers. However, the positions of all the samples have been located on plans and drawings provided by English Heritage, reproduced here as Figures 4 – 9. Using these drawings, and the sample descriptions in Table 1, it should be possible to find the position of each timber cored. One of the difficulties of these drawings is that they are intended to show the floor-plan of each level only, the timbers themselves are not shown. Sample numbers are placed on the plans at, or arrows point to, the approximate position of the timber concerned.

It might be noted at this point that many timbers have some evidence for reuse by way of apparently redundant mortices or peg holes etc. It is sometimes difficult to be certain about this redundancy because adjacent timbers, to which the remaining joints might have been related, may have been removed. Other older looking timbers, particularly window and door lintels, appear as if they might have been moved or at least reset. It is known that major conservation and repair works were undertaken at Hardwick Old Hall in the late AD 1950s and early AD 1960s, with the insertion of modern oak and the extensive use of concrete. This repair work may have added to the difficulty of finding timbers that are an original integral group.

The Laboratory would like to take this opportunity to thank a number of people who assisted wholeheartedly with this project. Firstly we would like to thank Lucy Worsley of English Heritage East Midlands Office in Northampton who toured the site prior to sampling to discuss the timbers. The Laboratory would also like to thank the English Heritage custodial and events coordination staff on site, in particular Christine Poulson for her unstinting help and hospitality during the cold early days of sampling in January and February. The Laboratory would also like to thank the staff of "Safe and Sound Scaffolding" of Chesterfield who provided such a steady platform close to the upper timbers for coring.

Analysis

Each of the 105 core samples was prepared by sanding and polishing. It was seen at this point that 14 samples had less than about 40 rings, too few rings for satisfactory analysis, and the annual growth rings of these were not measured. A further five samples with only 40 – 53 rings were, however, measured. Although strictly speaking such samples also have too few rings for satisfactory tree-ring analysis they were included in the hope that, having a large amount of data from the other samples, these shorter ones might cross-match and date too. In the event, however, it was decided not to include them in the analysis. The data of the remaining eighty-six measured samples with fifty-four rings or more were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). The data of all the ninety-one measured samples are given at the end of the report

At a minimum t-value of 4.5 six groups of cross-matching samples could be formed. The relative positions of the cross-matching samples in each of these groups is shown in the bar diagrams, Figures 10 – 15. The cross-matching samples of each group were then combined at their relative positions to form site chronologies. Each of these site chronologies was then compared with a series of relevant reference chronologies producing dates for three of them. The *t*-values for the dating site chronologies are given in Tables 2 – 4.

The six site chronologies were then compared with each other. There was, however, no further satisfactory cross-matching between them with acceptably high *t*-values, this despite three of them having overlapping date spans. Each of the six site chronologies was then compared with the twenty-four remaining ungrouped samples that had sufficient rings. Again there was no satisfactory cross-matching.

Each of the remaining twenty-four ungrouped samples with sufficient rings, ie in excess of 54, was then compared individually with a series of relevant reference chronologies for oak. This indicated dates for a further four samples, HDW-A14, A16, A17, and A26. The *t*-values for the dating of these four samples are given in Tables 5 – 8. Each of the component samples of the undated site chronologies, HDWASQ04, 05, and 06, was also compared individually with a series of reference chronologies in an attempt to date them separately. There was, however, no satisfactory cross-matching.

The analytical information discussed above can be summarised as below.

Site chronology	Number of samples	Number of rings	Date span (where dated)
HDWASQ01	**39**	**216**	**AD 1375 – AD 1590**
HDWASQ02	**5**	**98**	**AD 1481 – AD 1578**
HDWASQ03	**2**	**103**	**AD 1484 – AD 1586**
HDWASQ04	**10**	**142**	**undated**
HDWASQ05	**4**	**119**	**undated**
HDWASQ06	**2**	**88**	**undated**
HDW-A14	**1**	**58**	**AD 1517 – AD 1574**
HDW-A16	**1**	**64**	**AD 1502 – AD 1565**
HDW-A17	**1**	**86**	**AD 1477 – AD 1562**
HDW-A26	**1**	**91**	**AD 1375 – AD 1465**

Interpretation

Almost all of the six site chronologies created contain samples from different parts of the Hall. This is particularly so with site chronology HDWASQ01, which is made up of thirty-nine samples from almost all parts of the building. The exception to this observation might be the two samples from the kitchen pantry (HDW-A95 and A96) in the undated site chronology HDWASQ6, see Figure 15.

The dated site chronologies, and indeed the undated ones, show some variation in the relative positions of the heartwood/sapwood boundaries on their constituent samples. In site chronology HDWASQ01 for example the earliest heartwood/sapwood boundary is at relative position 101 (AD 1475) on sample HDW-A34 with the latest being at relative position 216 (AD 1590) on sample HDW-A19 (see Fig 10). These two samples are from timbers of the low larder and the closely adjacent kitchen ceiling respectively. Similarly in the undated site chronology HDWASQ04, sample HDW-A59 from the wall of the viewing platform has a heartwood/sapwood boundary of 96 relative while that of sample HDW-A68, from the third floor, is at relative position 142 (see Fig 13).

This can perhaps be further illustrated by grouping the dated samples by sampling area, as in Figure 16. It will be seen for example that samples from the low larder represent timbers that were probably felled in the very early sixteenth century, HDW-A34, as well as in the late-sixteenth century, HDW-A36. Similarly, the samples from the nursery include timbers felled in the late-fifteenth century, HDW-A87, and those felled later, as with that represented by sample HDW-A86.

This mixing of samples might suggest two things. Firstly, that older timber is being reused. Secondly that the timber felled later was felled as and when needed and distributed about the building during construction, and not felled for and used in discrete locations. It is possible that an on-site timber yard was established from which timber was taken. This of course supposes that not too much timber has been moved about the site during subsequent repairs and renovations.

This notion of continuous felling, rather than separate stages, can perhaps be illustrated if we take all the dated samples and simply present them by last ring order, as in Figure 17. Furthermore this appears to show that two basic periods of timber felling are represented. The earlier felling phase is represented by a small number of samples that have heartwood/sapwood ring dates in the late-fifteenth century ranging from AD 1465 for sample A26 to AD 1494 for sample A37. Using a 95% confidence limit of 15 - 40 rings for the amount of sapwood on mature oaks from this part of England, it is estimated that the trees represented were felled in the period AD 1480 – AD 1505 and AD 1509 – 34 respectively.

The later phase is represented by a larger group of samples that have heartwood/sapwood boundaries in the later sixteenth centuries, ranging from AD 1540 on sample A85, to AD 1578 on sample A86. Using the same confidence limits for the number of sapwood rings as above it is estimated that the trees represented were felled in the period AD 1555 – 80 and AD 1593 – AD 1618 respectively.

In this respect the timber represented by sample A19 is an anomaly. This sample has a heartwood/sapwood boundary date of AD 1590. The usual figure of 15 – 40 sapwood rings would give the timber an estimated felling date in the range AD 1605 – 30, somewhat later than all the others, and well after work is believed to have ceased on the Old Hall. Either the timber has fewer than 15 sapwood rings or it is indeed felled later and represents an inserted repair timber or a late continuation of work.

Conclusion

It is difficult to make a firm conclusion about the felling of the timbers sampled at Hardwick Hall. It would certainly appear that some of the timbers used here were felled sometime between the late-fifteenth century and the early sixteenth century. It is possible that these represent timbers felled for the construction of the earlier manor house owned by John Hardwick, Bess's father, and then reused in the Old Hall when that was built along with timbers felled especially for the purpose.

On the basis of the tree-ring dates obtained it is not possible to say that any one part of the Old Hall is distinctly younger or older than any other part of it. From the very gradual change in the relative position of the heartwood/sapwood boundary, from AD 1540 on sample A85 to AD 1578 on sample A86 (see Fig 17), it appears that building work probably took a relatively short time and finally stopped in AD 1590. Bess began work on the Old Hall in AD 1583 and it was largely completed when she began work on the New Hall in AD 1590.

Sixty-six of the 86 measured samples with sufficient rings, or over 82%, have been grouped into dated and undated site sequences, or dated individually. It is a feature of the analysis of this site that many of the samples, particularly those in site chronology HDWASQ01, cross match with each other with very high *t*-values, values of t=6 and 7 are common, with some 9s, 10s, and 11s also being seen. This suggests, as intimated by the documentary evidence, that many of the timbers do indeed come from the same local woodland source.

Twenty satisfactory measured samples remain ungrouped and undated. Most of these have sufficient rings for satisfactory analysis by dendrochronology, though some have low numbers of rings.

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Table 1: Details of samples from Hardwick Old Hall, Doe Lea, Derbyshire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Main east stair / passage screen					
HDW-A01	Central stud post, second-floor landing	40	h/s	------	------	------
HDW-A02	West cross-rail, second-floor landing	50	h/s	------	------	------
HDW-A03	Top rail, second-floor landing	79	h/s	------	------	------
HDW-A04	Cross-rail, first-floor landing	77	h/s	AD 1404	AD 1480	AD 1480
HDW-A05	Top cross-rail, first-floor landing	nm	--	------	------	------
HDW-A06	Middle cross-rail, first-floor landing	52	no h/s	------	------	------
HDW-A07	Stud post, first-floor landing	77	h/s	AD 1417	AD 1493	AD 1493
	Under-stair beams					
HDW-A08	Joist, first-floor landing	76	h/s	------	------	------
HDW-A09	Joist, first-floor landing	110	14	AD 1451	AD 1546	AD 1560
HDW-A10	Beam 1 (from bottom)	40	h/s	------	------	------
HDW-A11	Beam 6	54	17	------	------	------
HDW-A12	Beam 9	68	4	------	------	------
HDW-A13	Beam 12	60	h/s	------	------	------
HDW-A14	North-south spine beam 1 at base of stairs	58	10	AD 1517	AD 1564	AD 1574
HDW-A15	North-south spine beam 2 at base of stairs	117	h/s	AD 1434	AD 1550	AD 1550
HDW-A16	Foot of stairs east joist 9	64	h/s	AD 1502	AD 1565	AD 1565
HDW-A17	Foot of stairs west joist 5	86	5	AD 1477	AD 1557	AD 1562
HDW-A18	First landing, joist 18	109	h/s	AD 1460	AD 1568	AD 1568
HDW-A19	First landing, east cross-joist	73	h/s	AD 1518	AD 1590	AD 1590
HDW-A20	First landing, main bressummer beam	55	no h/s	AD 1438	------	AD 1492

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Kitchen ceiling beams					
HDW-A21	East-central north – south beam	82	18C	AD 1505	AD 1568	AD 1586
HDW-A22	East-most north – south beam	77	no h/s	AD 1428	------	AD 1504
HDW-A23	Common joist east 3	87	h/s	AD 1485	AD 1571	AD 1571
HDW-A24	Common joist west 1	75	h/s	AD 1490	AD 1564	AD 1564
HDW-A25	Common joist east 1	75	no h/s	------	------	------
HDW-A26	Common joist east 2	91	h/s	AD 1375	AD 1465	AD 1465
	Bakehouse					
HDW-A27	Central main east – west bridging beam	110	h/s	AD 1462	AD 1571	AD 1571
HDW-A28	Middle lintel, south window	71	h/s	AD 1481	AD 1551	AD 1551
HDW-A29	Outer lintel, south-east corner window	74	h/s	AD 1487	AD 1560	AD 1560
HDW-A30	Inner lintel, south-east corner window	69	h/s	AD 1500	AD 1568	AD 1568
HDW-A31	Middle lintel, south-east corner window	nm	--	------	------	------
HDW-A38	Inner lintel, south window	74	h/s	AD 1487	AD 1560	AD 1560
	Upper larder / low larder					
HDW-A32	Inner lintel to alcove in north wall	66	h/s	------	------	------
HDW-A33	Inner lintel to south window, low larder	69	h/s	------	------	------
HDW-A34	Middle lintel to south window, low larder	71	h/s	AD 1405	AD 1475	AD 1475
HDW-A35	Lintel to upper north door	78	h/s	------	------	------
HDW-A36	Outer lintel to south window, upper larder	110	h/s	AD 1461	AD 1570	AD 1570
HDW-A37	Inner lintel to south window, upper larder	89	h/s	AD 1406	AD 1494	AD 1494

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Main stairs – first-floor landing					
HDW-A39	East or inner lintel of hall to nursery	156	h/s	AD 1410	AD 1565	AD 1565
HDW-A40	West or inner lintel of hall to outer chamber	118	no h/s	AD 1420	------	AD 1537
HDW-A41	Inner lintel to south window to landing	92	30C	------	------	------
HDW-A42	West main joist at south end of landing	54	h/s	------	------	------
HDW-A43	East main joist at south end of landing.	66	h/s	------	------	------
HDW-A44	Common joist 1 from south, first flight	47	h/s	------	------	------
HDW-A45	Common joist 10 from south, first flight	57	11	------	------	------
HDW-A46	Common joist 12 from south, first flight	85	27C	AD 1488	AD 1545	AD 1572
HDW-A47	Common joist 4 from south, first flight	nm	--	------	------	------
HDW-A48	Common joist 2 from south, first flight	nm	--	------	------	------
HDW-A49	Main joist above second flight	nm	--	------	------	------
HDW-A50	West or outer lintel of hall to nursery	55	no h/s	------	------	------
HDW-A51	Outer lintel to north window to landing	105	h/s	AD 1381	AD 1486	AD 1486
HDW-A52	Inner lintel to north window to landing	nm	--	------	------	------
HDW-A53	Outer lintel to hall to bedrooms	54	h/s	AD 1502	AD 1567	AD 1564
	Viewing platform and second landing					
HDW-A54	East or inner lintel of door to platform	66	h/s	AD 1502	AD 1567	AD 1567
HDW-A55	West or outer lintel of door to platform	nm	--	------	------	------
HDW-A56	Putlock block in wall to east of platform	95	h/s	AD 1451	AD 1545	AD 1545
HDW-A57	Putlock block in wall to east of platform	54	no h/s	------	------	------
HDW-A58	Putlock block in wall to east of platform	62	h/s	------	------	------
HDW-A59	Putlock block in wall to east of platform	60	no h/s	------	------	------
HDW-A60	Putlock block in wall to north of platform	54	h/s	------	------	------
HDW-A61	East or outer lintel of door to gallery	nm	--	------	------	------
HDW-A62	Middle lintel of door to gallery	58	h/s	AD 1422	AD 1479	AD 1479
HDW-A63	West or inner lintel of door to gallery	56	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
	Gallery range, third – fourth-floor landing, and the upper part of the Great Chamber					
HDW-A64	Block 1 in west wall of gallery, third floor	54	no h/s	------	------	------
HDW-A65	Block 2 in west wall of gallery, third floor	56	no h/s	------	------	------
HDW-A66	Block 3 in west wall of gallery, third floor	54	no h/s	------	------	------
HDW-A67	Lintel of south window to gallery, third floor	96	no h/s	AD 1426	------	AD 1521
HDW-A68	Lintel of gallery/cross-passage door, third floor	59	h/s	------	------	------
HDW-A69	Lintel of window to "my Lady's Bedchamber"	132	h/s	AD 1428	AD 1559	AD 1559
HDW-A70	Lintel of door to "my Lady's Bedchamber"	58	h/s	------	------	------
HDW-A71	Inner lintel of south window to landing	68	h/s	AD 1502	AD 1569	AD 1569
HDW-A72	Inner lintel, north-west window of Great Chamber	nm	--	------	------	------
HDW-A73	Outer lintel, north-west window of Great Chamber	87	no h/s	------	------	------
HDW-A74	Floor joist, Great Hall second floor	113	h/s	------	------	------
HDW-A75	Block in east wall, Great Hall second floor	nm	--	------	------	------
	Former Great Hall (now largely removed)					
HDW-A76	South beam at first floor, west wall of Hall	128	no h/s	AD 1411	------	AD 1538
HDW-A77	Mid beam at first floor, west wall of Hall	98	h/s	AD 1452	AD 1549	AD 1549
HDW-A78	North beam at first floor, west wall of Hall	120	h/s	AD 1432	AD 1551	AD 1551
HDW-A79	Lintel to south window of Hall	88	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
	Mr Cavendish's room and inner room					
HDW-A80	Joist 4 from north in east wall	88	h/s	------	------	------
HDW-A81	Joist 3 from north in east wall	58	h/s	AD 1502	AD 1559	AD 1559
HDW-A82	Joist 2 from north in east wall	85	h/s	------	------	------
HDW-A83	Joist 1 from north in east wall	90	no h/s	------	------	------
HDW-A84	Inner lintel to south-east window	84	h/s	AD 1472	AD 1559	AD 1559
HDW-A85	Inner lintel to south-west window	81	h/s	AD 1460	AD 1540	AD 1540
	Nursery					
HDW-A86	Lintel 4 or south-most of nursery door	84	h/s	AD 1495	AD 1578	AD 1578
HDW-A87	Lintel 2 of nursery door	83	no h/s	AD 1375	------	AD 1457
HDW-A88	Inner lintel to blocked nursery window	89	h/s	AD 1484	AD 1572	AD 1572
HDW-A89	Outer lintel to blocked nursery window	nm	--	------	------	------
HDW-A90	Beam below viewing platform	nm	--	------	------	------
HDW-A91	Beam below top beam beneath platform	nm	--	------	------	------
	Kitchen pantry beams, ground-floor Great Chamber					
HDW-A92	West beam in kitchen pantry	95	h/s	AD 1472	AD 1566	AD 1566
HDW-A93	Middle beam in kitchen pantry	90	h/s	AD 1465	AD 1554	AD 1554
HDW-A94	Trimmer joist in kitchen pantry	117	h/s	AD 1438	AD 1554	AD 1554
HDW-A95	Southern lintel to pantry door	88	3	------	------	------
HDW-A96	Northern lintel to pantry door	54	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
	Ground-floor service rooms					
HDW-A97	Top block in south wall of north service room	114	no h/s	------	------	------
HDW-A98	Mid block in south wall of north service room	89	h/s	------	------	------
HDW-A99	Bottom block in south wall of north service room	71	7	------	------	------
HDW-A100	Inner lintel, south window, south service room	80	h/s	AD 1399	AD 1478	AD 1478
HDW-A101	South lintel service room door	97	h/s	AD 1477	AD 1573	AD 1573
HDW-A102	Middle lintel, service room door	117	h/s	------	------	------
HDW-A103	Joist 3 under stair above lobby / serving place	54	h/s	AD 1504	AD 1557	AD 1557
HDW-A104	Joist 7 under stair above lobby / serving place	nm	--	------	------	------
HDW-A105	Joist 6 under stair above lobby / serving place	99	h/s	AD 1460	AD 1558	AD 1558

nm = rings not measured
h/s = heartwood/sapwood boundary is last ring on sample
c = complete sapwood on timber, all or part lost in sampling
C = complete sapwood retained on sample

Table 2: Results of the cross-matching of site chronology HDWASQ01 and relevant reference chronologies when first ring date is AD 1375 and last ring date is AD 1590

Reference chronology	Span of chronology	t-value	
Mansfield Woodhouse, Notts	AD 1431 – 1538	8.5	(Howard *et al* 1997)
Thorpe in the Glebe, Notts	AD 1422 – 1521	7.9	(Esling *et al* 1989)
Whites Farm, South Leverton, Notts	AD 1399 – 1506	7.7	(Howard *et al* 1994a)
East Midlands	AD 882 – 1981	7.7	(Laxton and Litton 1988)
Ughill Manor, Bradfield, S Yorks	AD 1349 – 1504	7.6	(Howard *et al* 1994b)
England	AD 401 – 1981	6.4	(Baillie and Pilcher 1982 unpubl)
SFF-B01M	AD 1359 – 1591	5.7	(Morgan 1977)
Wales and West Midlands	AD 1341 – 1636	5.2	(Siebenlist-Kerner 1978)

Table 3: Results of the cross-matching of site chronology HDWASQ02 and relevant reference chronologies when first ring date is AD 1481 and last ring date is AD 1578

Reference chronology	Span of chronology	t-value	
Frith Hall, Brampton, Derbys	AD 1480 – 1602	5.2	(Howard *et al* 1993)
North Lees Hall, Outseats, Derbys	AD 1468 – 1578	4.8	(Howard *et al* 1994b)
Unthank Hall, Holmesfield, Derbys	AD 1359 – 1543	4.5	(Howard *et al* 1993)
Hoyles Farm, Bradfield, S Yorks	AD 1469 – 1613	4.4	(Howard *et al* 1994b)
Wales and West Midlands	AD 1341 – 1636	4.2	(Siebenlist-Kerner 1978)
England	AD 401 – 1981	4.1	(Baillie and Pilcher 1982 unpubl)
SFF-B01M	AD 1359 – 1591	3.7	(Morgan 1977)
East Midlands	AD 882 – 1981	3.6	(Laxton and Litton 1988)

Table 4: Results of the cross-matching of site chronology HDWASQ03 and relevant reference chronologies when first ring date is AD 1484 and last ring date is AD 1586

Reference chronology	Span of chronology	t-value	
Frith Hall, Brampton, Derbys	AD 1480 – 1602	6.8	(Howard *et al* 1993)
Sherwood Trees, Notts	AD 1426 – 1981	5.4	(Laxton and Litton 1988)
East Midlands	AD 882 – 1981	5.2	(Laxton and Litton 1988)
England	AD 401 – 1981	5.1	(Baillie and Pilcher 1982 unpubl)
Well Bank Farm, Midhope, S Yorks	AD 1392 – 1560	4.7	(Howard *et al* 1994b)
Hipper Hall, Holymorside, Derbys	AD 1454 – 1615	4.7	(Howard *et al* 1995)
Hill Top Farm, Heathcote, Derbys	AD 1425 – 1578	4.3	(Howard *et al* 1992)
Wales and West Midlands	AD 1341 – 1636	4.0	(Siebenlist-Kerner 1978)

Table 5: Results of the cross-matching of sample HDW-A14 and relevant reference chronologies when first ring date is AD 1517 and last ring date is AD 1574

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	8.2	(Laxton and Litton 1988)
White House, Blyth, Notts	AD 1453 – 1595	8.0	(Howard *et al* 1994a)
Unthank Hall, Holmesfield, Derbys	AD 1477 – 1589	7.3	(Howard *et al* 1993)
SFF-B01M	AD 1359 – 1591	7.2	(Morgan 1977)
England	AD 401 – 1981	6.8	(Baillie and Pilcher 1982 unpubl)
Mansfield Woodhouse, Notts	AD 1431 – 1538	6.4	(Howard *et al* 1997)
Wales and West Midlands	AD 1341 – 1636	5.4	(Siebenlist-Kerner 1978)
Offerton Hall, Offerton, Derbys	AD 1401 – 1592	5.4	(Howard *et al* 1995)

Table 6: Results of the cross-matching of sample HDW-A16 and relevant reference chronologies when first ring date is AD 1502 and last ring date is AD 1565

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	9.3	(Laxton and Litton 1988)
Wales and West Midlands	AD 1341 – 1636	8.2	(Siebenlist-Kerner 1978)
England	AD 401 – 1981	8.0	(Baillie and Pilcher 1982 unpubl)
White House, Blyth, Notts	AD 1453 – 1595	7.9	(Howard *et al* 1994a)
Dimple Farm, Matlock, Derbys	AD 1497 – 1593	6.6	(Howard *et al* 1996)
Offerton Hall, Offerton, Derbys	AD 1401 – 1592	6.5	(Howard *et al* 1995)
Church Street, Mansfield, Notts	AD 1439 – 1584	6.4	(Howard *et al* 1994a)
SFF-B01M	AD 1359 – 1591	5.9	(Morgan 1977)

Table 7: Results of the cross-matching of sample HDW-A17 and relevant reference chronologies when first ring date is AD 1477 and last ring date is AD 1562

Reference chronology	Span of chronology	t-value	
Sinai Park, Burton on Trent, Staffs	AD 1227 – 1750	5.7	(Tyers 1997)
East Midlands	AD 882 – 1981	5.2	(Laxton and Litton 1988)
England	AD 401 – 1981	4.9	(Baillie and Pilcher 1982 unpubl)
Great Wilne Farm, Shardlow, Derbys	AD 1489 – 1595	4.9	(Howard *et al* 1994b)
WOR-H3	AD 1431 – 1568	4.8	(Laxton and Litton 1988)
North Lees Hall, Outseats, Derbys	AD 1468 – 1578	4.7	(Howard *et al* 1994b)

Table 8: Results of the cross-matching of sample HDW-A26 and relevant reference chronologies when first ring date is AD 1375 and last ring date is AD 1465

Reference chronology	Span of chronology	t-value	
England	AD 401 – 1981	5.0	(Baillie and Pilcher 1982 unpubl)
The Old Rectory, Cossington, Leics	AD 1375 – 1526	4.9	(Howard *et al* 1992)
Ughill Manor, Bradfield, S Yorks	AD 1349 – 1504	4.9	(Howard *et al* 1994b)
Wales and West Midlands	AD 1341 – 1636	4.8	(Siebenlist-Kerner 1978)
23 Church Street, Eckington, Derbys	AD 1381 – 1474	4.5	(Esling *et al* 1989)
East Midlands	AD 882 – 1981	4.1	(Laxton and Litton 1988)

Figure 1: Map to show general location of Hardwick Hall

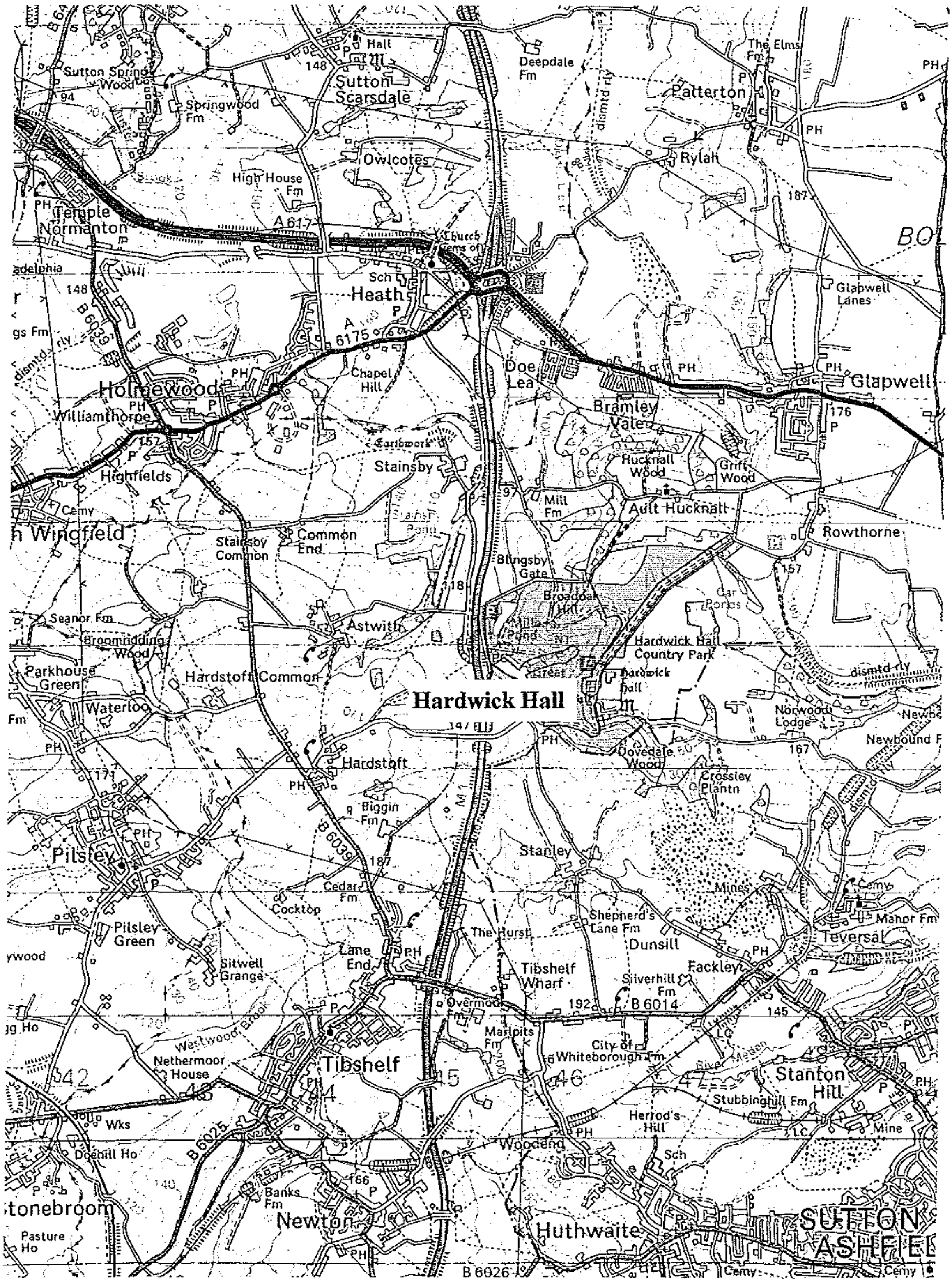

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Figure 2: Hardwick Old Hall to show general plan of the Hall, and the East and West Lodges

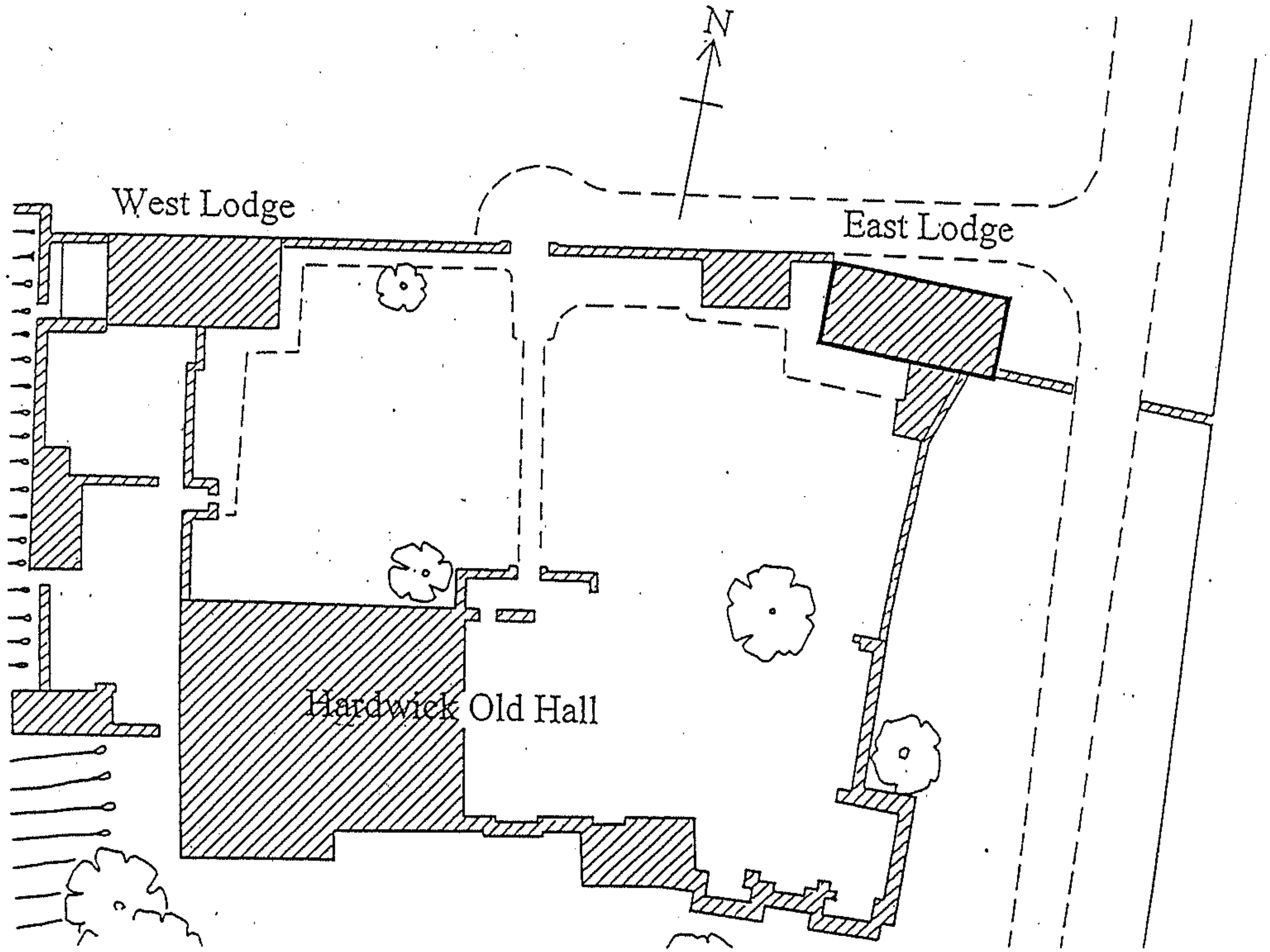


Figure 3: The New Hall at Hardwick, begun in AD 1590, as seen from the Old Hall

Figure 4: Plan of ground floor of Great chamber to show sample locations

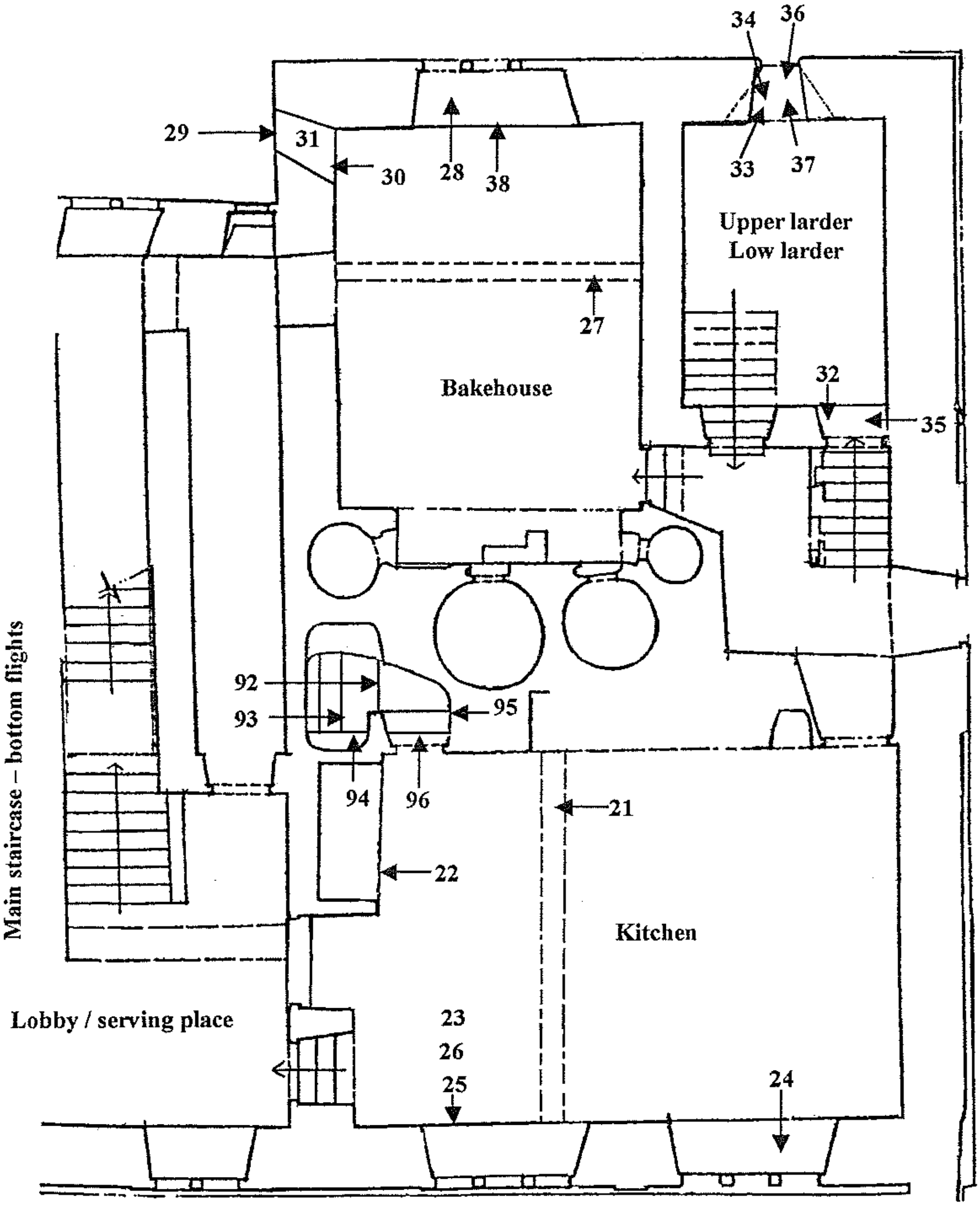


Figure 5: Plan of lower main staircase and ground floor service rooms to show sample locations

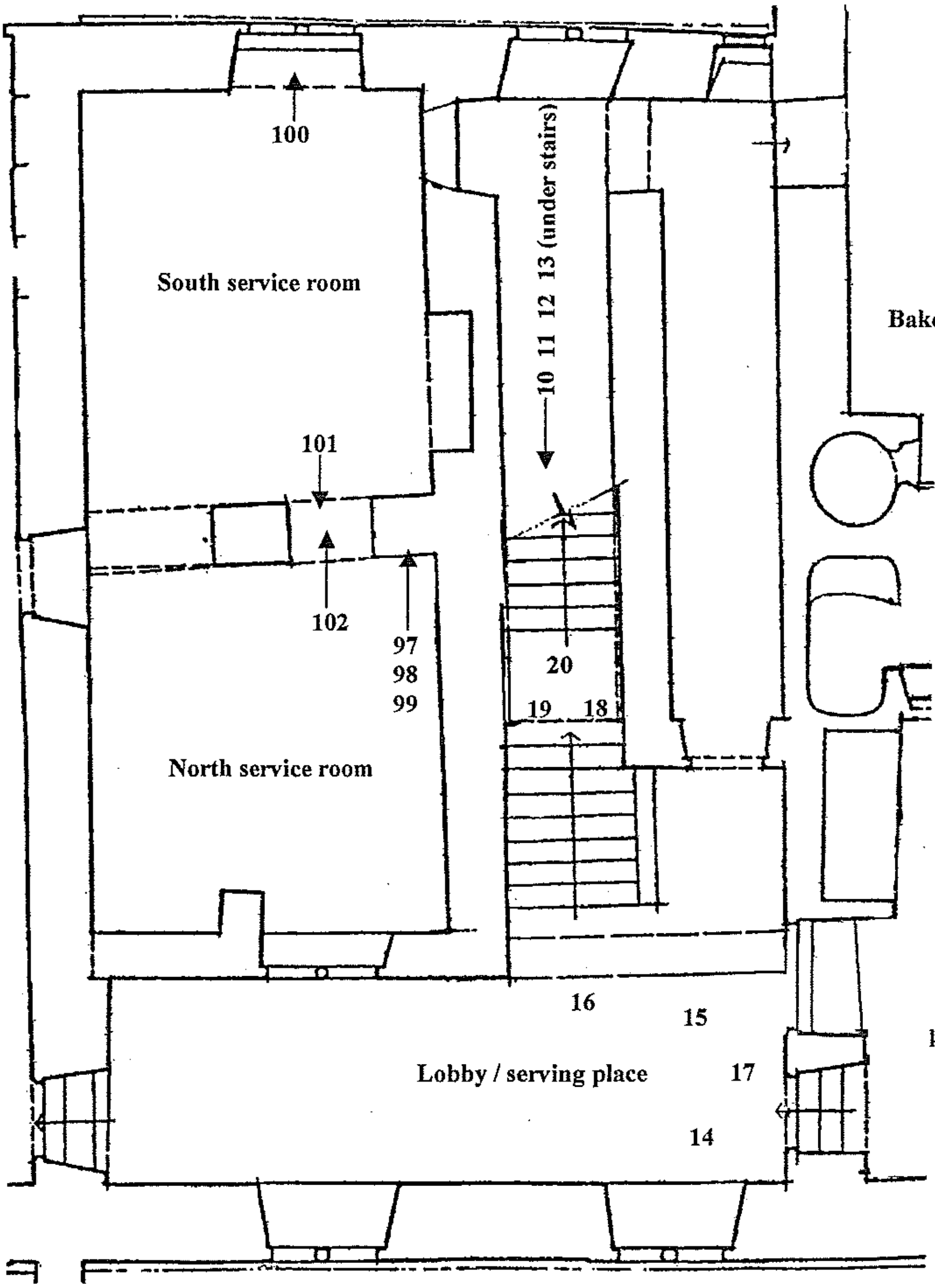


Figure 6: Plan of first floor to show sample locations

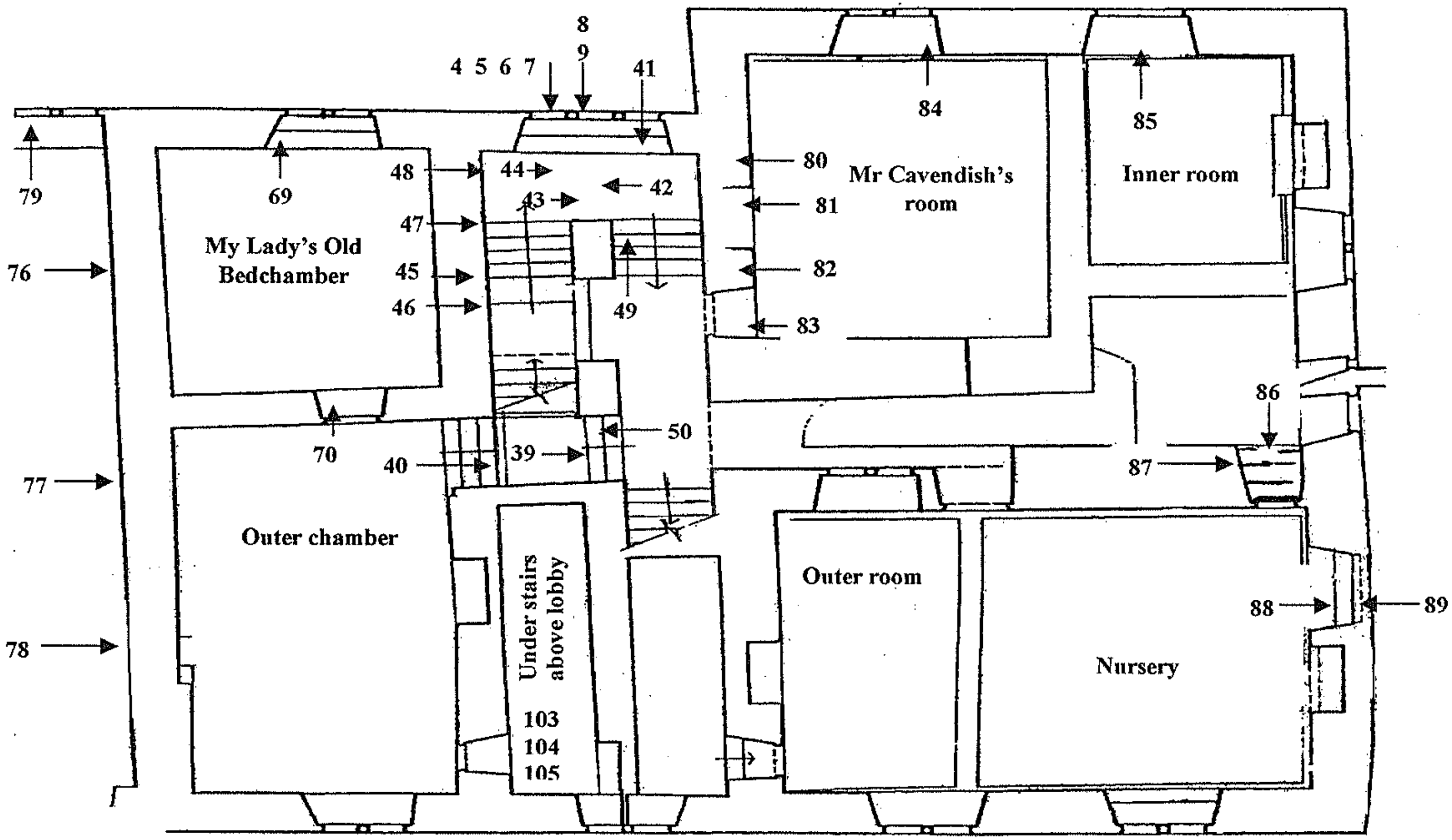


Figure 7: Plan of second floor to show sample locations

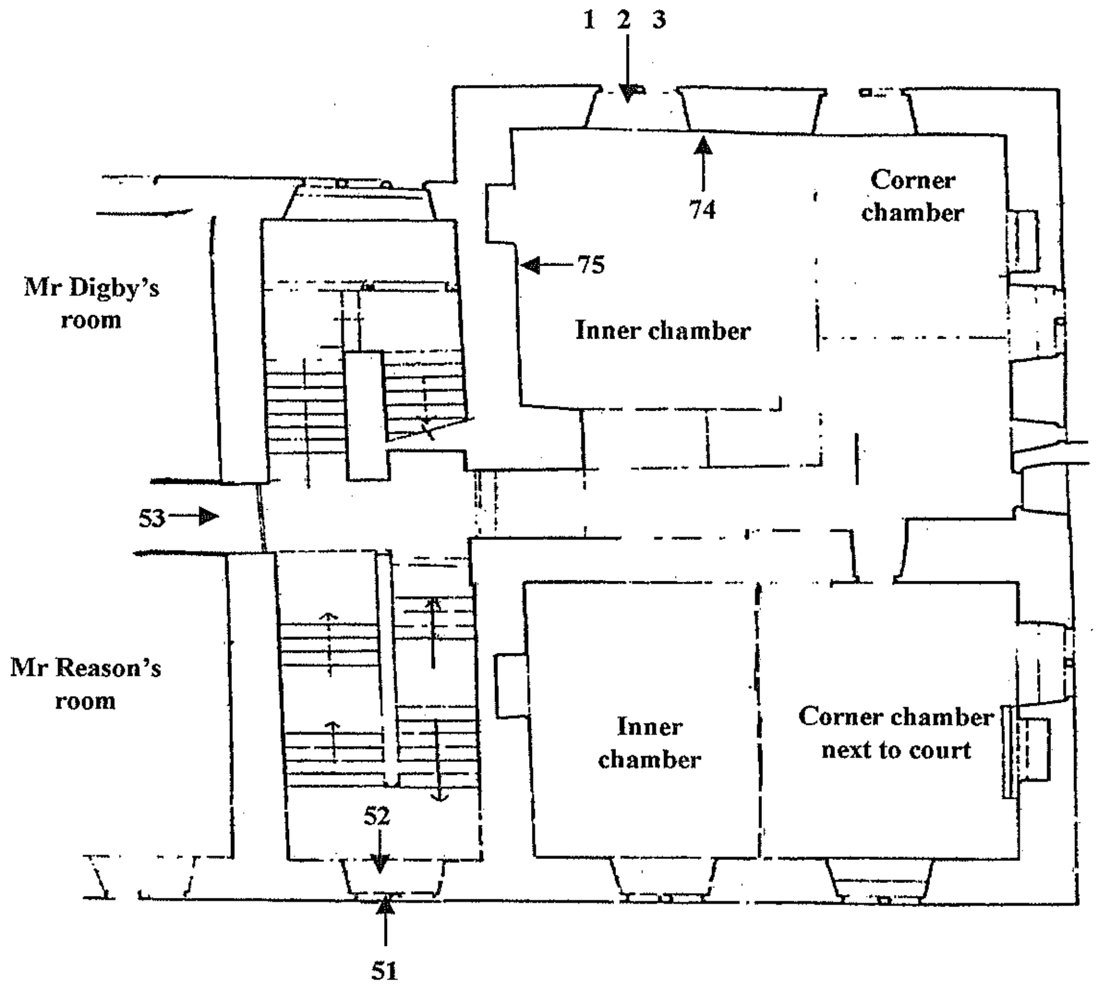


Figure 8: Third floor plan to show sample locations

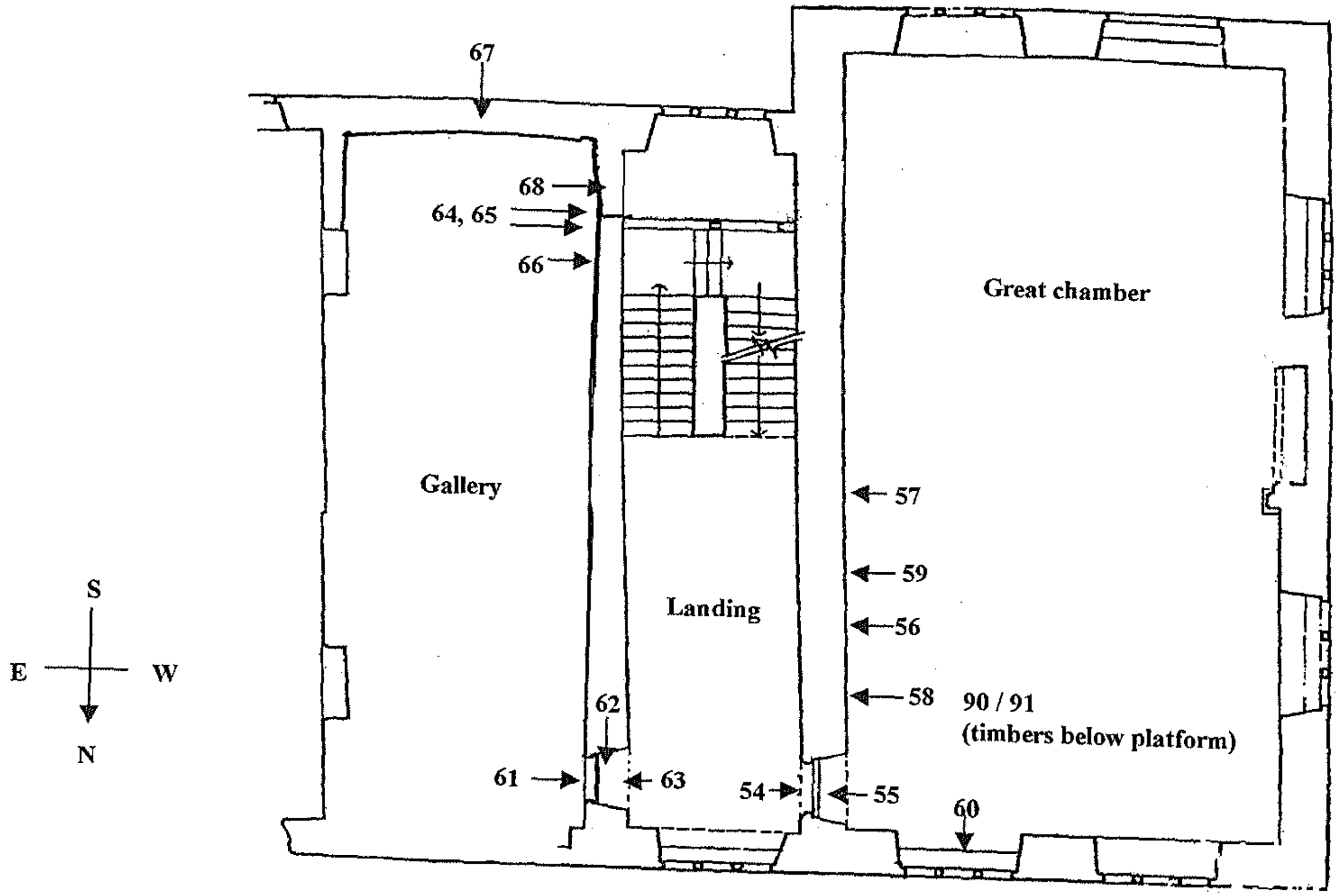


Figure 9: Plan of fourth floor to show sample locations

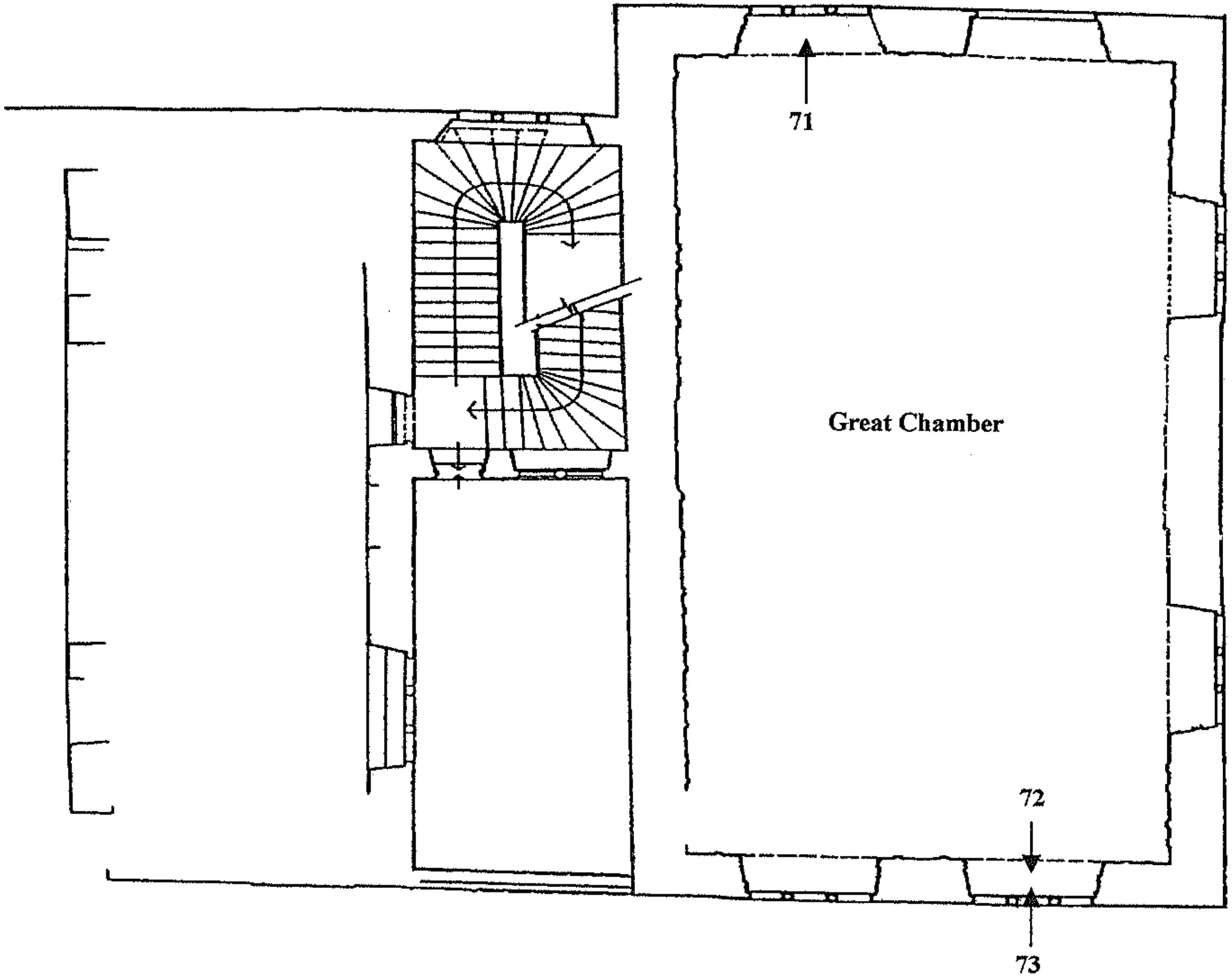
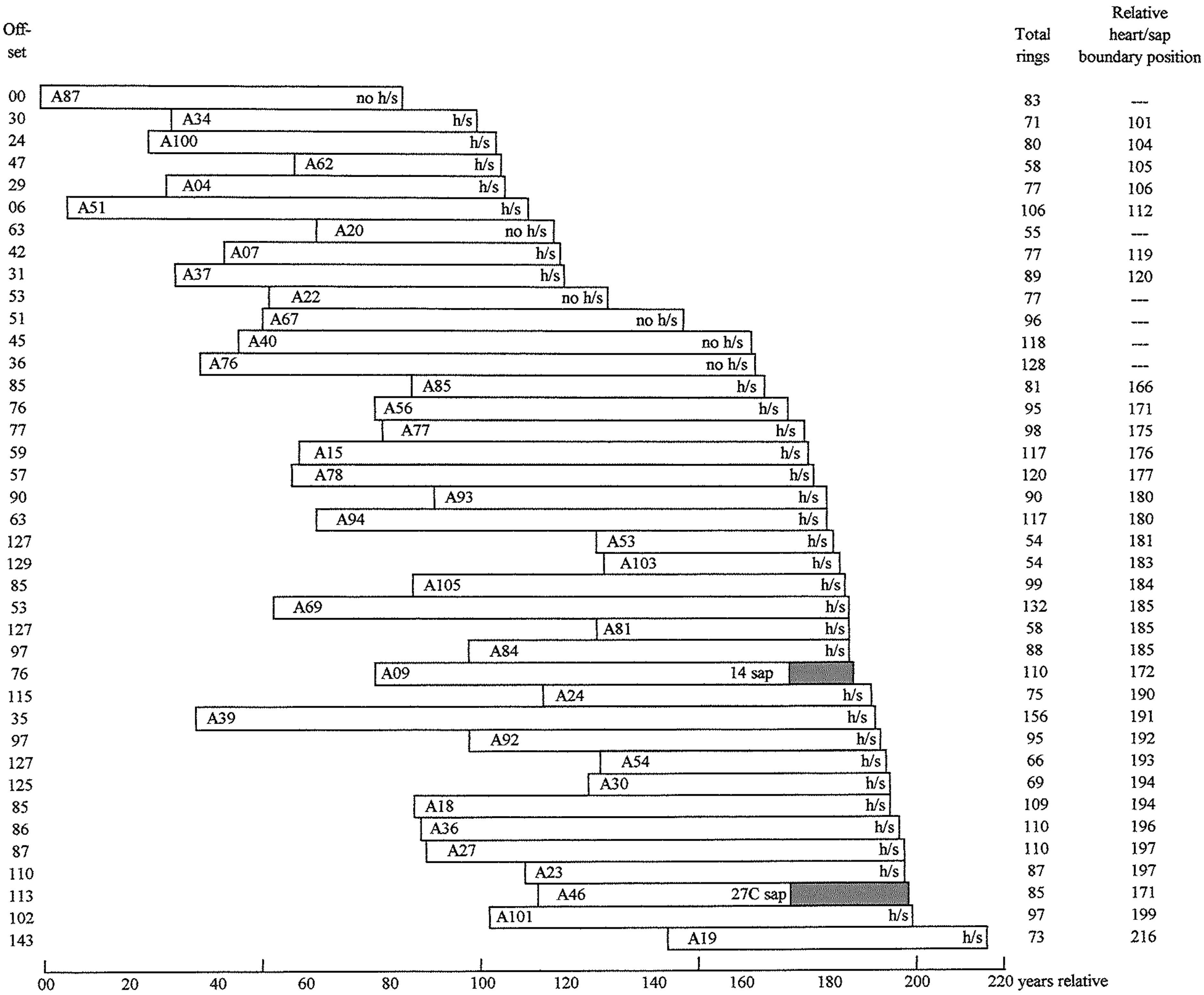


Figure 10: Bar diagram of samples in site chronology HDWASQ01



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 13: Bar diagram of samples in site chronology HDWASQ04

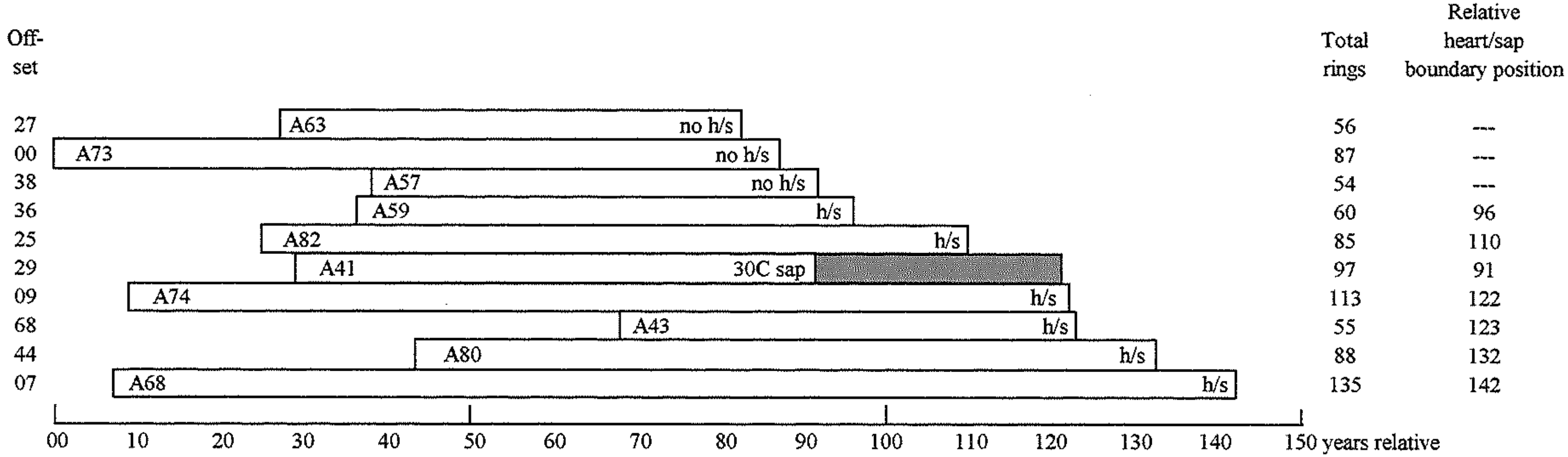


Figure 14: Bar diagram of samples in site chronology HDWASQ05

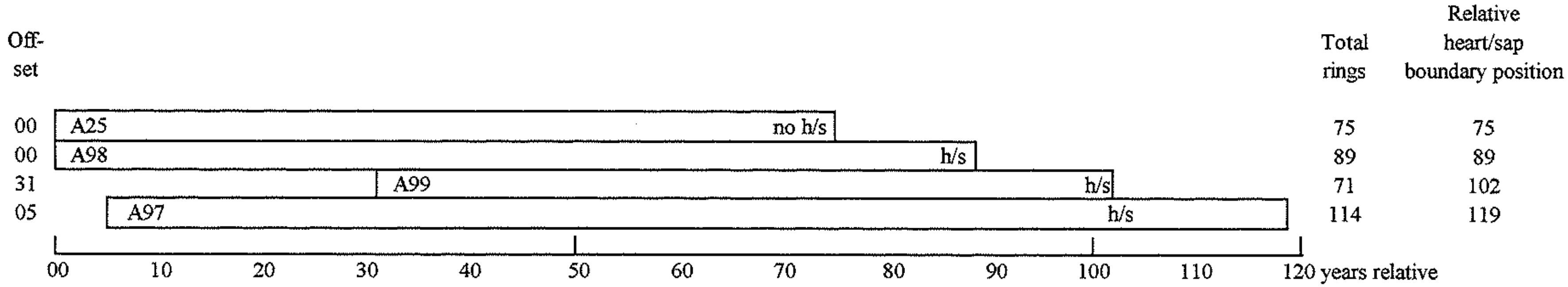
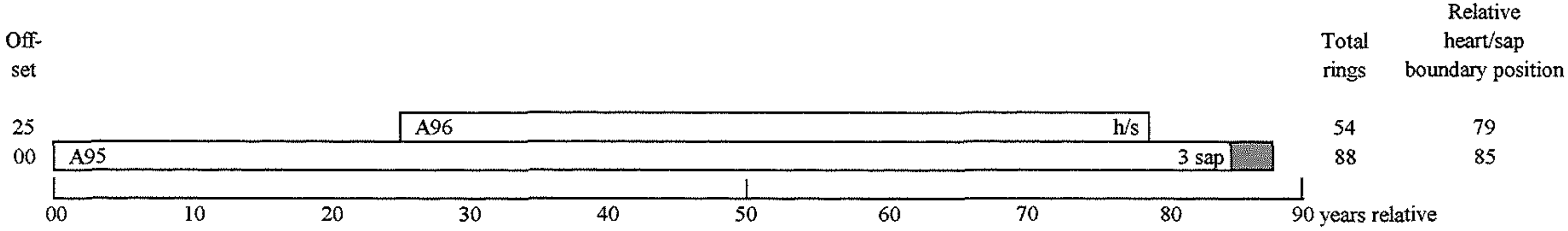
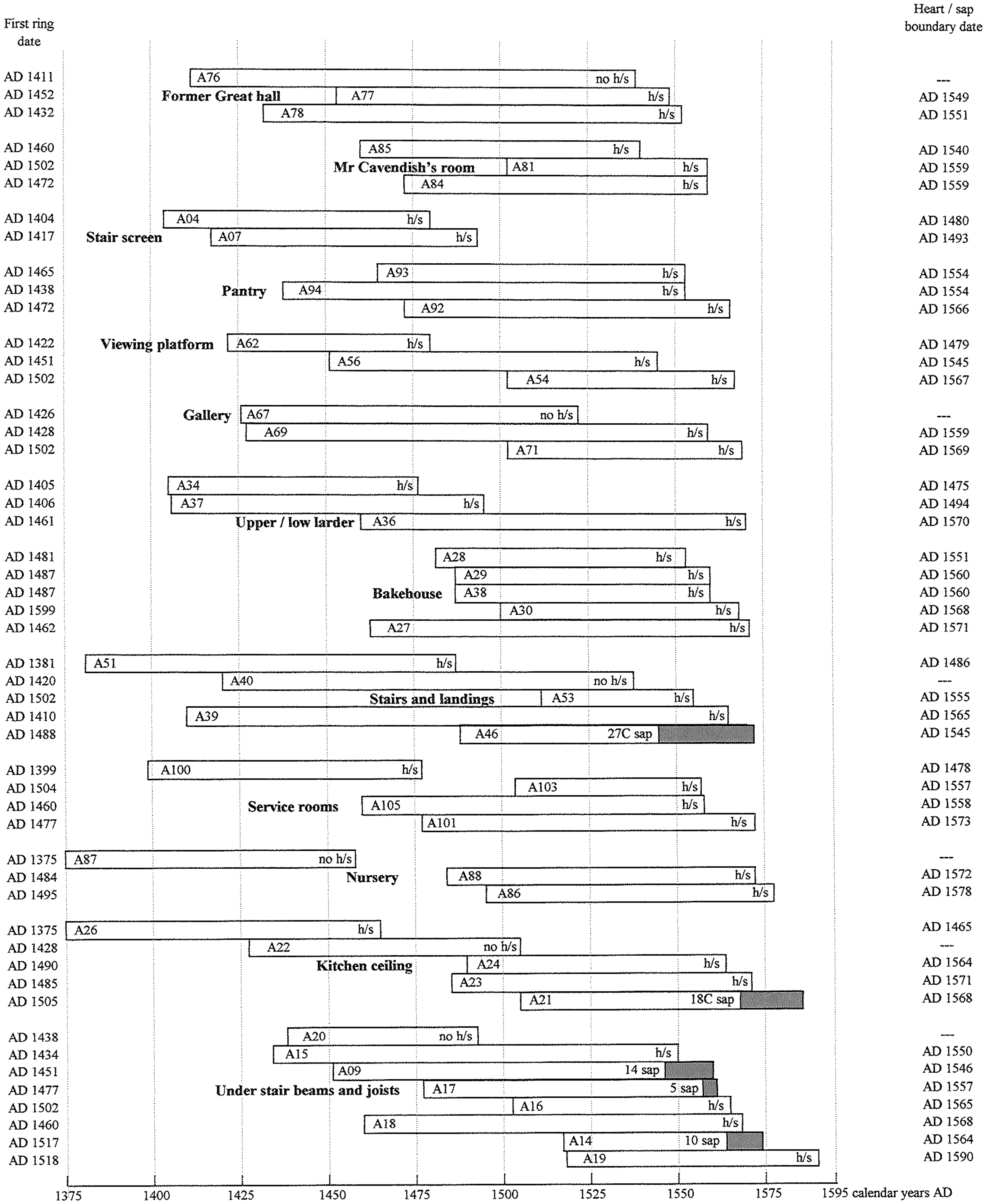


Figure 15: Bar diagram of samples in site chronology HDWASQ06



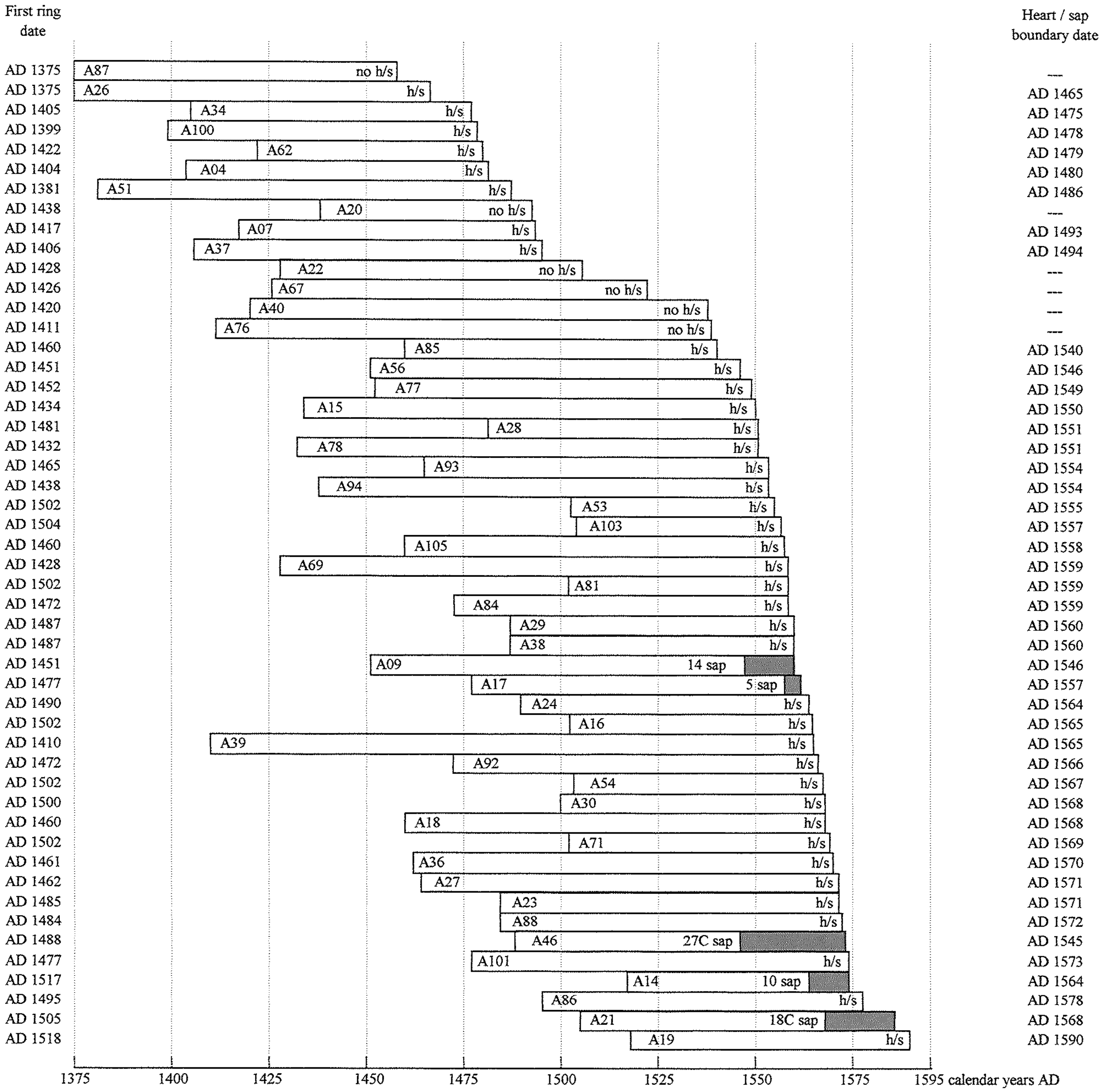
White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 16: Bar diagram of all dated samples by sampling areas in order of last ring date



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 17: Bar diagram of all dated samples in order of last ring date



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Data of measured samples – measurements in 0.01 mm units

HDW-A01A 40
493 448 472 522 394 276 339 493 512 435 557 474 611 695 464 466 343 375 422 560
610 497 505 373 333 396 404 390 478 513 563 482 429 374 285 280 262 236 332 462
HDW-A01B 40
490 454 477 516 373 285 336 499 498 430 551 503 608 670 469 450 339 360 443 566
611 481 502 380 319 416 386 403 470 550 579 476 405 401 305 283 264 238 325 429
HDW-A02A 50
315 289 390 450 430 377 325 532 537 466 603 508 526 586 601 608 663 423 379 380
356 390 438 166 121 126 125 161 162 282 231 213 150 198 189 194 187 192 216 231
282 212 214 254 292 228 301 449 367 298
HDW-A02B 50
339 292 402 428 426 387 327 524 551 477 621 501 523 599 616 601 619 420 370 380
366 389 437 175 109 121 122 169 166 281 237 216 162 184 200 192 194 192 211 219
286 202 218 246 266 252 298 419 397 256
HDW-A03A 79
165 113 135 115 108 97 87 178 226 164 154 188 153 117 121 151 198 236 202 112
188 170 116 215 81 64 48 50 70 90 128 102 118 131 121 146 127 108 84 138
115 95 72 86 111 89 103 98 138 157 203 162 195 149 115 153 145 149 114 140
208 182 169 123 171 186 105 111 183 124 128 189 192 189 134 189 129 111 169
HDW-A03B 79
161 119 142 104 112 96 97 163 229 169 162 174 159 91 106 158 169 217 197 131
193 166 146 202 63 76 63 51 84 110 136 115 115 132 122 138 132 89 93 151
117 96 62 86 114 87 113 84 148 148 221 162 189 156 115 143 151 147 107 144
206 173 163 124 185 172 106 123 169 120 131 211 172 202 124 178 146 116 153
HDW-A04A 77
602 450 665 520 599 793 704 546 688 550 612 454 514 229 247 176 374 391 245 397
321 398 304 248 394 325 349 520 530 379 301 310 228 174 173 313 301 325 240 474
336 212 75 42 47 48 67 95 98 120 130 119 153 115 137 156 180 162 166 250
230 253 319 410 376 353 339 276 254 266 407 396 255 180 172 198 260
HDW-A04B 77
645 462 636 497 598 784 815 512 664 549 615 483 516 215 231 171 437 387 249 399
322 405 305 244 386 338 335 508 553 401 311 310 228 178 159 315 308 321 256 474
344 211 68 37 53 44 68 96 110 110 136 111 154 119 136 163 179 152 174 251
237 255 317 398 381 361 326 286 257 273 401 400 250 188 168 208 249
HDW-A06A 52
473 498 399 399 600 571 516 465 560 403 370 460 379 308 118 133 249 180 203 155
149 183 165 217 182 174 143 209 206 200 179 116 119 137 133 123 107 124 159 146
185 171 254 219 229 167 209 161 220 191 266 242
HDW-A06B 52
421 485 399 381 599 572 519 465 554 414 373 451 384 313 109 141 239 174 209 160
151 196 159 219 187 170 154 206 211 214 188 109 125 133 129 125 108 127 154 164
192 168 248 226 230 173 206 169 218 201 240 270
HDW-A07A 110
163 164 165 217 170 171 140 152 129 128 170 174 170 118 147 180 173 180 236 197
197 133 144 143 262 176 150 156 135 137 124 56 48 50 50 66 82 72 84 99
82 115 100 124 155 110 55 58 54 72 94 132 140 138 180 128 91 93 126 110
82 48 43 53 45 64 45 76 78 63 82 137 134 202 146 219 170 158 126 122

66 39 45 53 75 86 98 97 80 107 77 71 117 123 177 128 137 136 127 168
157 158 169 130 124 73 66 82 118 122
HDW-A07B 110
185 155 159 223 169 171 154 140 127 135 172 144 150 122 134 156 170 190 240 197
187 159 122 134 249 185 144 156 136 134 109 59 40 53 50 72 80 66 67 89
90 106 104 128 163 110 55 59 57 65 91 126 128 137 185 132 88 98 114 110
71 55 46 50 50 61 57 67 77 62 84 133 137 201 142 227 169 148 128 125
63 37 50 51 75 78 106 102 77 110 74 67 129 114 198 123 132 149 130 152
150 167 164 138 129 76 62 60 94 124
HDW-A08A 76
97 114 155 178 189 173 256 232 197 265 384 365 361 278 190 192 154 160 124 88
68 86 78 114 152 176 149 133 116 105 128 127 52 36 43 40 67 87 71 63
56 89 99 96 89 83 113 88 126 118 94 76 89 131 168 116 86 54 95 119
90 125 131 144 142 149 150 118 267 256 218 211 245 424 479 361
HDW-A08B 76
93 119 158 168 200 172 262 230 199 263 394 364 362 262 191 191 148 154 118 88
76 81 72 117 153 172 154 140 117 99 113 131 54 42 40 43 59 82 79 73
51 86 94 110 82 91 107 90 119 116 100 71 94 126 166 116 83 58 105 110
86 128 127 145 138 152 147 120 263 253 214 219 248 419 490 361
HDW-A09A 77
123 58 84 134 132 129 200 147 139 103 104 116 131 160 164 215 151 153 107 117
86 136 126 174 172 152 131 213 146 111 116 111 125 138 157 107 103 93 132 210
165 129 107 123 134 107 125 79 94 47 53 72 43 63 68 68 70 114 111 116
96 86 118 103 124 128 134 104 183 113 180 142 128 98 104 122 124
HDW-A09B 77
114 58 85 129 137 128 188 146 137 109 100 115 136 162 155 212 159 148 116 113
86 138 123 178 173 148 128 222 149 104 120 108 129 140 153 140 95 114 123 199
175 129 104 124 135 114 119 88 85 54 59 64 45 66 66 68 66 115 123 109
96 86 117 106 114 134 132 116 191 119 177 150 130 96 99 114 131
HDW-A10A 40
122 217 217 244 153 154 208 254 240 274 256 274 175 265 64 48 36 58 41 50
54 125 199 132 104 91 71 48 66 57 108 44 51 60 83 98 84 75 92 106
HDW-A10B 40
127 211 229 241 147 150 203 249 241 260 260 271 171 269 67 54 31 64 40 50
56 128 201 128 104 92 68 49 59 72 103 49 51 61 79 91 87 72 94 111
HDW-A11A 54
216 241 282 221 272 263 450 317 323 360 372 292 286 271 332 352 286 364 184 209
175 192 140 159 168 134 119 92 99 92 101 98 90 92 113 122 156 123 150 157
144 130 128 152 178 150 192 177 166 177 194 221 214 197
HDW-A11B 54
253 242 268 235 261 264 447 329 312 363 378 295 277 265 330 353 292 362 172 218
170 178 155 158 173 129 115 93 94 91 97 97 96 92 107 115 161 124 149 157
143 131 131 155 167 157 177 187 169 176 198 219 203 205
HDW-A12A 67
168 108 159 132 213 186 216 252 99 123 101 108 135 135 156 156 173 183 111 70
158 137 173 227 168 161 108 126 116 107 143 185 243 215 150 148 111 179 135 191
228 297 262 214 143 110 94 188 235 212 177 172 112 67 103 201 193 163 105 140
138 115 133 98 177 171 100
HDW-A12B 68
143 106 147 170 205 192 234 228 94 131 85 109 141 127 155 172 160 180 112 63
169 129 181 214 171 161 128 114 117 113 128 201 237 205 150 145 115 178 143 185

236 302 263 212 150 122 91 181 252 208 183 168 113 63 105 209 192 160 90 145
128 116 124 105 178 170 139 83
HDW-A13A 60
253 243 288 192 262 261 175 240 245 215 84 79 127 101 142 150 178 149 135 182
269 172 231 172 279 215 203 156 224 277 256 206 203 113 126 242 218 187 201 206
121 98 131 104 126 188 211 213 224 225 216 163 149 223 212 125 157 150 156 212
HDW-A13B 60
271 248 296 201 248 257 167 243 241 209 77 75 126 108 144 164 165 160 124 188
264 173 253 177 266 205 197 154 206 284 254 202 213 104 137 223 228 169 174 213
131 94 122 101 134 186 203 238 210 223 211 179 134 220 220 115 168 145 134 235
HDW-A14A 58
299 431 388 273 418 462 419 480 293 403 388 434 343 354 393 229 292 244 331 322
315 320 265 335 297 272 233 259 249 191 163 297 404 286 287 216 206 261 281 171
138 145 275 251 219 238 208 174 182 159 194 199 199 186 189 156 131 194
HDW-A14B 58
345 428 385 285 416 467 405 484 291 407 395 441 336 357 399 230 293 230 332 331
297 322 265 351 284 261 241 246 260 187 166 307 397 290 300 211 215 264 289 168
132 154 257 243 227 231 211 169 195 149 179 216 199 182 192 161 147 157
HDW-A15A 117
120 136 217 169 108 150 148 169 155 163 194 163 84 141 148 239 159 210 142 192
240 197 273 249 245 163 189 201 205 183 166 213 229 229 192 246 220 232 177 173
144 184 180 198 182 143 168 165 119 175 185 139 143 181 126 107 102 75 97 124
144 138 167 133 118 135 147 174 131 170 151 171 133 106 69 73 84 97 105 106
122 122 123 116 96 117 125 163 134 126 109 72 92 88 109 109 112 140 138 128
119 129 103 136 149 156 195 145 128 111 138 124 120 121 134 125 148
HDW-A15B 117
120 131 224 169 104 143 157 172 151 167 199 161 88 136 146 237 163 217 141 178
246 211 275 249 257 156 180 190 201 193 149 210 219 235 196 237 211 227 190 166
127 195 183 205 157 162 161 158 128 180 191 152 130 175 120 112 102 85 90 119
151 135 171 126 112 139 151 156 144 172 145 177 132 118 76 81 71 99 111 109
120 120 122 117 93 132 126 154 153 110 113 69 90 85 110 111 109 139 145 133
125 112 114 140 146 157 186 159 125 122 128 123 123 129 131 119 155
HDW-A16A 64
415 333 329 511 433 395 235 271 226 293 342 322 301 317 288 212 332 308 228 273
342 330 331 191 323 306 300 270 241 362 214 218 165 271 244 218 258 209 266 252
191 178 230 235 182 155 237 308 237 261 202 203 235 284 184 127 153 184 189 172
223 203 159 194
HDW-A16B 64
393 346 330 515 440 374 247 268 223 299 321 317 293 340 305 214 335 308 232 274
350 342 351 210 332 309 307 260 246 357 216 209 166 275 248 217 250 211 274 235
211 177 229 235 179 163 234 297 248 262 205 197 230 281 185 124 157 186 185 168
230 216 175 189
HDW-A17A 86
107 79 93 116 165 193 190 188 224 205 270 158 126 96 84 88 108 116 122 205
120 112 117 119 139 155 159 183 106 106 113 77 121 126 124 164 139 120 119 203
162 216 195 177 182 228 186 205 132 168 147 213 291 266 337 239 175 138 229 228
382 389 404 435 403 308 334 252 439 260 248 241 353 288 227 182 222 214 144 139
92 95 174 143 114 180
HDW-A17B 86
109 83 81 121 172 186 193 179 240 233 258 145 125 105 81 96 115 100 119 215
123 119 112 133 146 145 172 180 106 117 102 74 129 139 125 164 111 133 134 214

164 206 209 172 180 219 184 207 102 183 168 212 295 243 357 251 186 142 235 244
370 408 398 442 393 297 349 284 468 253 240 251 338 305 236 181 216 225 142 142
99 95 162 136 127 176
HDW-A18A 109
155 138 123 141 100 123 167 117 181 142 168 172 153 153 190 217 171 145 112 150
139 155 139 155 170 157 122 212 161 118 96 112 117 109 114 179 171 157 121 109
135 94 83 158 158 166 141 112 109 188 123 154 133 103 99 123 120 77 120 134
110 200 120 96 186 109 89 99 66 73 70 86 92 82 105 115 102 102 118 147
130 76 81 81 84 116 109 88 97 109 125 141 140 114 90 91 48 61 86 105
122 104 89 122 148 60 92 88 102
HDW-A18B 109
137 140 126 129 101 123 175 127 173 151 162 168 153 150 200 226 176 146 114 147
133 159 139 157 166 147 126 201 156 110 102 112 123 100 129 174 164 155 121 111
137 76 85 158 165 169 137 108 117 189 145 149 127 108 101 114 123 80 125 135
101 196 123 86 185 115 91 94 74 73 68 75 96 89 94 118 98 108 114 147
127 84 83 83 83 118 101 96 97 109 135 124 157 120 79 87 48 64 89 108
112 98 101 125 156 77 90 86 104
HDW-A19A 73
243 235 262 290 265 305 337 315 294 293 342 287 253 255 306 324 263 263 230 266
193 223 215 126 73 72 77 86 66 83 82 97 95 101 107 145 145 137 139 172
139 108 108 146 137 181 150 185 140 180 175 149 152 122 167 144 145 153 186 207
229 139 100 58 65 51 74 80 77 93 74 105 121
HDW-A19B 73
218 241 267 290 251 303 330 309 285 300 307 266 252 248 317 288 253 275 231 270
193 209 202 118 74 62 73 74 80 72 76 99 90 89 109 146 145 141 124 148
148 108 115 138 141 201 172 180 139 148 187 150 149 123 167 148 137 153 194 211
222 173 97 61 67 42 75 77 73 102 75 108 128
HDW-A20A 54
308 255 335 273 247 289 325 262 250 139 101 128 132 141 159 151 195 210 265 259
242 239 311 332 260 307 287 262 323 317 256 250 265 291 240 218 302 366 276 255
203 247 223 276 202 150 91 60 54 71 51 52 68 78 97
HDW-A20B 55
312 259 343 272 240 296 314 271 245 138 107 128 141 154 164 182 217 227 264 241
248 242 340 312 282 265 274 270 318 334 238 225 257 308 263 228 306 355 263 259
223 267 209 293 232 146 85 62 59 57 59 61 62 80 94
HDW-A21A 82
272 277 271 359 330 423 487 475 328 235 193 286 114 127 137 89 86 95 107 142
107 140 143 129 180 188 328 322 140 68 45 39 64 63 111 111 130 70 115 124
137 149 134 171 136 188 196 186 228 182 178 130 182 232 226 246 191 209 176 201
151 135 120 155 181 184 171 159 149 138 104 88 130 121 123 156 184 136 167 206
208 265
HDW-A21B 82
271 280 269 356 335 424 489 474 373 224 195 280 130 127 132 83 98 90 106 150
99 143 138 139 179 187 323 331 135 68 48 46 59 63 108 113 122 73 142 106
128 151 156 169 152 172 196 172 227 184 173 124 189 234 220 248 194 205 176 204
151 134 120 154 176 187 171 158 154 135 108 88 127 122 131 148 191 130 157 216
210 269
HDW-A22A 77
82 89 146 125 107 45 38 37 38 73 90 74 121 141 117 108 119 109 97 248
337 305 292 522 529 331 363 400 433 376 313 181 315 274 367 403 241 243 391 451
438 421 206 110 100 91 79 179 288 184 141 156 112 179 87 51 59 50 76 136

161 166 213 239 298 214 206 275 568 323 324 354 211 135 172 185 155
HDW-A22B 77
94 91 146 135 101 50 37 35 37 77 90 71 119 139 121 99 124 104 104 237
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416 410 220 118 104 93 80 209 290 189 128 163 116 173 97 48 54 49 73 136
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173 171 209 158 188 153 186 228
HDW-A76B 128
307 323 315 306 289 287 287 294 244 263 210 165 169 203 194 161 164 152 168 117
102 143 118 168 156 110 88 74 82 195 158 150 142 181 198 118 122 119 219 138
160 126 122 185 152 223 168 114 100 122 155 153 154 129 123 161 197 200 209 239
221 136 132 118 174 172 167 136 182 188 208 177 195 224 187 257 323 176 146 149
88 121 205 197 215 224 214 144 148 207 230 210 161 175 195 259 161 112 147 173
171 197 143 159 169 151 118 123 150 158 187 179 109 122 85 93 111 194 160 194
168 175 205 158 190 151 186 229
HDW-A77A 98
155 171 214 171 196 201 253 241 259 242 229 217 202 216 206 196 177 244 242 215
196 202 166 203 195 197 159 146 159 182 141 180 198 175 185 239 146 125 133 113
127 145 162 153 150 145 103 129 140 152 159 155 144 181 169 161 89 101 99 128
128 155 124 129 184 132 150 152 135 197 168 136 170 119 82 122 168 137 143 178
176 174 119 143 134 173 160 165 165 138 130 119 129 110 112 67 98 163
HDW-A77B 98
147 168 227 166 198 209 253 245 271 245 215 222 202 193 219 202 176 240 240 220
186 199 169 204 198 189 162 145 163 181 140 178 197 175 184 250 139 124 136 114
118 148 166 163 143 142 104 113 155 147 166 153 138 188 172 154 96 101 95 132
123 151 123 136 171 139 152 147 133 210 164 137 164 111 85 96 177 132 147 170
183 172 123 139 135 179 146 172 165 151 120 114 128 111 115 68 100 131
HDW-A78A 120
201 115 142 131 116 113 116 132 242 151 134 212 251 253 101 113 143 183 126 227
344 251 240 279 289 239 195 143 165 149 152 166 147 118 142 237 201 182 162 207
124 128 97 143 210 205 135 205 136 202 144 129 144 125 137 236 279 227 157 99
118 146 204 168 195 191 110 149 194 196 189 176 127 211 215 222 113 142 292 256
209 188 157 164 111 97 143 211 129 166 178 95 120 103 142 169 226 168 178 186
184 154 163 185 208 163 160 180 225 212 166 237 189 182 131 135 202 243 153 210
HDW-A78B 120
201 119 147 132 112 112 131 127 238 164 152 215 259 242 102 118 141 186 102 245
306 216 232 249 273 252 211 144 173 158 140 156 179 117 144 188 205 201 183 206
125 142 99 139 190 184 139 213 147 208 151 120 144 134 132 238 274 228 157 86
112 141 198 171 196 183 110 150 196 173 205 171 129 212 205 223 102 158 293 246
223 186 154 168 112 94 138 215 135 161 185 87 120 103 140 163 234 165 187 193
181 147 167 179 188 177 161 179 207 231 174 218 200 179 137 138 203 226 152 204
HDW-A79A 88
174 159 267 287 255 181 194 159 143 164 152 195 187 127 130 207 216 178 176 176
179 206 172 165 199 217 143 221 181 114 149 116 109 139 189 137 129 147 120 106
89 63 55 53 88 64 93 94 95 101 79 97 98 99 114 69 81 68 70 88
58 43 56 80 80 93 68 72 62 80 72 54 57 59 74 53 63 56 67 55
76 103 79 79 85 72 79 71
HDW-A79B 88
151 158 284 292 251 183 190 160 142 171 153 190 196 123 133 203 214 191 152 185
177 215 169 161 196 215 153 218 180 115 144 124 111 139 188 135 124 131 113 113
92 61 48 64 83 76 84 95 81 96 86 85 101 101 116 66 78 75 72 80
73 39 69 73 79 99 78 69 62 78 77 55 53 58 75 53 62 57 69 48
84 102 74 78 84 77 75 67
HDW-A80A 88
247 229 230 252 268 259 344 296 243 277 232 202 216 188 244 315 260 210 234 204
195 220 226 81 64 61 48 92 53 77 84 72 88 92 118 125 137 102 104 152

138 127 126 162 185 134 169 138 153 119 143 162 150 73 43 31 59 70 80 73
100 109 128 108 113 124 141 126 111 109 53 34 55 61 50 48 53 77 85 82
138 91 66 116 133 126 78 100

HDW-A80B 88

243 243 237 232 277 279 335 301 224 270 234 206 217 190 247 318 268 216 230 204
203 217 226 80 56 67 63 91 50 69 81 81 88 89 123 125 131 104 102 148
136 128 126 149 189 138 177 142 145 116 146 167 141 69 49 37 61 68 79 71
97 121 121 117 110 107 149 125 111 105 57 46 50 55 49 50 58 67 86 85
142 92 68 113 139 127 78 99

HDW-A81A 58

173 248 234 192 212 150 142 124 138 276 191 123 92 82 148 138 210 136 172 230
169 159 212 178 185 257 228 161 104 47 45 91 90 70 63 94 112 166 214 197
162 249 276 307 148 123 179 185 228 287 207 230 143 211 129 133 144 237

HDW-A81B 58

180 248 237 196 208 158 154 124 146 270 186 117 94 95 138 126 210 148 166 218
190 155 210 169 201 257 243 171 107 54 43 84 101 72 68 98 114 174 210 196
157 248 265 298 145 109 182 196 215 268 238 220 147 203 135 126 139 213

HDW-A82A 85

132 164 219 214 129 122 136 133 156 202 252 191 169 120 144 180 120 64 46 64
114 101 191 143 171 242 264 242 286 320 288 353 255 192 240 209 190 170 243 263
360 213 102 70 114 106 108 115 139 117 165 124 164 262 178 293 255 210 224 137
143 108 109 99 50 32 21 32 44 51 76 117 113 112 176 205 96 159 154 175
146 186 214 244 321

HDW-A82B 85

124 152 228 213 130 130 129 136 151 201 248 193 163 120 155 164 120 49 42 60
101 99 199 144 156 243 236 245 291 343 298 376 259 196 257 217 191 167 241 264
362 230 110 63 154 110 95 120 136 120 144 133 176 259 175 294 264 208 228 147
148 112 118 112 43 36 31 27 46 58 81 114 113 118 173 204 98 158 149 177
143 186 204 249 321

HDW-A83A 90

397 477 633 543 207 169 128 155 114 154 140 173 197 263 179 356 229 342 247 213
238 292 402 304 231 316 262 371 302 400 183 76 70 106 160 126 136 169 141 183
195 171 173 224 182 126 203 231 150 204 212 230 192 205 236 158 80 113 229 243
227 146 83 84 104 147 168 131 119 228 207 172 239 198 273 236 193 201 145 144
136 118 88 54 124 164 162 183 144 168

HDW-A83B 90

414 481 633 539 230 171 128 156 124 154 182 202 210 259 175 370 220 320 259 213
256 293 410 292 239 341 253 371 307 379 183 93 57 109 158 132 130 171 152 182
187 172 174 224 183 136 214 237 144 218 233 233 206 214 236 161 87 117 234 264
234 167 83 70 101 145 145 149 120 207 231 154 222 192 253 231 193 190 139 139
136 117 88 75 105 157 170 197 150 158

HDW-A84A 88

130 139 118 173 171 160 159 135 125 137 74 124 83 47 61 77 71 58 73 78
100 99 87 98 112 135 107 103 69 80 78 88 77 81 104 92 96 90 106 99
116 83 91 105 123 104 123 117 91 115 59 55 51 49 52 63 53 54 46 68
70 86 69 103 79 86 92 122 166 134 80 100 102 135 108 79 124 98 162 142
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111 144 117 170 168 165 157 131 134 127 83 122 88 50 66 74 71 62 68 77
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106 87 91 106 123 93 116 126 88 122 58 55 55 51 47 57 56 55 48 64

69 77 79 99 80 81 93 135 157 120 86 98 104 140 108 74 130 103 159 135
147 130 92 117 73 69 41 63
HDW-A85A 81
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73 75 80 94 64 89 92 98 94 101 92 94 119 103 110 104 133 105 112 112
116 146 58 53 49 48 43 48 49 59 50 69 77 77 82 111 81 103 96 111
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HDW-A85B 81
148 156 121 175 145 146 152 202 173 196 232 199 133 151 143 238 216 208 188 194
183 185 159 195 97 76 85 101 92 68 104 99 119 117 89 107 128 130 102 86
82 77 77 92 64 92 93 91 100 101 95 96 114 99 112 115 123 100 112 132
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HDW-A86A 84
429 381 318 233 380 128 54 91 155 86 74 57 91 178 331 420 563 335 119 108
140 156 168 146 260 277 361 261 211 236 316 328 356 373 338 315 352 370 169 116
76 62 72 86 84 81 78 67 58 87 98 31 29 26 26 42 61 95 92 95
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95 89 95 135
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134 151 167 147 261 275 363 244 219 227 302 295 346 377 330 303 357 362 163 110
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100 117 71 149 138 190 195 177 193 206 208 71 44 60 65 55 60 69 81 100
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125 122 95 104 114 132 128 114 134 150 152 113 116 123 158 122 126 129 111 148
105 88 92 105 91 143 147 126 147 169 118 104 95 95 148 122 132 142 129 138
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86 98 184 191 160 118 135 183 161 145 136 186 230 211 217 228 271 215 173 135
147 168 182 192 198 210 227 191 203 170 146 144 142 126 150 113 99 110 128 126
114 127 103 96 121 129 124 125 143 144 165 113 125 128 173 122 128 145 118 138
114 96 87 91 105 156 133 126 145 168 122 99 94 86 141 130 133 136 143 120
159 225 210
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312 262 228 168 149 144 182 300 387 371 378 298 284 137 57 53 49 76 82 85
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305 185 190 268 219 264 328 454 362
HDW-A88B 89
669 521 358 632 310 257 248 210 223 192 183 275 416 223 192 215 252 226 172 185
293 262 228 171 138 153 189 296 363 376 386 298 286 142 59 53 47 77 86 89
121 144 116 127 119 146 88 218 183 67 35 28 34 48 45 90 128 125 71 111
115 113 136 204 215 245 238 222 223 276 239 196 202 194 254 312 326 352 331 327
311 178 189 268 234 268 319 458 358

HDW-A92A 95
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138 139 140 164 219 197 135 144 157 94 118 130 115 194 84 76 87 91 70 99
118 96 94 107 108 121 198 163 142 179 165 120 165 119 151 162 147 100 37 38
33 42 27 38 54 62 75 90 110 113 82 122 110 115 143 131 180 193 159 185
160 178 118 111 70 92 126 131 116 116 161 171 216 153 107
HDW-A92B 95
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121 88 98 99 107 126 197 153 146 197 170 115 160 124 153 157 149 98 41 39
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65 87 74 97 102 103 110 98 113 95
HDW-A93B 90
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HDW-A96A 54
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199 165 317 162 150 166 163 212 163 279 244 233 208 203
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175 190 202 290 209 245 192 168 108 174 176 183 149 179 181 182 248 204 209 225
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127 115 71 163 144 133 172 107 90 98 54 60 74 70 95 91 102 80 52 58
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HDW-A99B 71
333 570 526 425 315 373 343 490 311 327 294 382 229 180 205 204 265 325 264 219
192 184 136 200 200 227 169 207 135 328 441 273 292 224 172 161 168 226 145 118
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HDWA102B 117
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81 106 82 74 84 122 128 126 132 169 137 198 144 75 62 78 66 94 103 152
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158 110 147 125 148 135 145 129 113 100 70 60 83 116 124 121 110
HDWA103A 54
284 279 284 243 199 217 268 348 362 269 188 306 220 168 193 227 208 272 158 285
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HDWA105B 99
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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 Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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. 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 University of Nottingham Tree-Ring dating Laboratory

1. ***Inspecting the Building and Sampling the Timbers.*** Together with a building historian we inspect the timbers in a building 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. Similarly the core has just over 100 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.

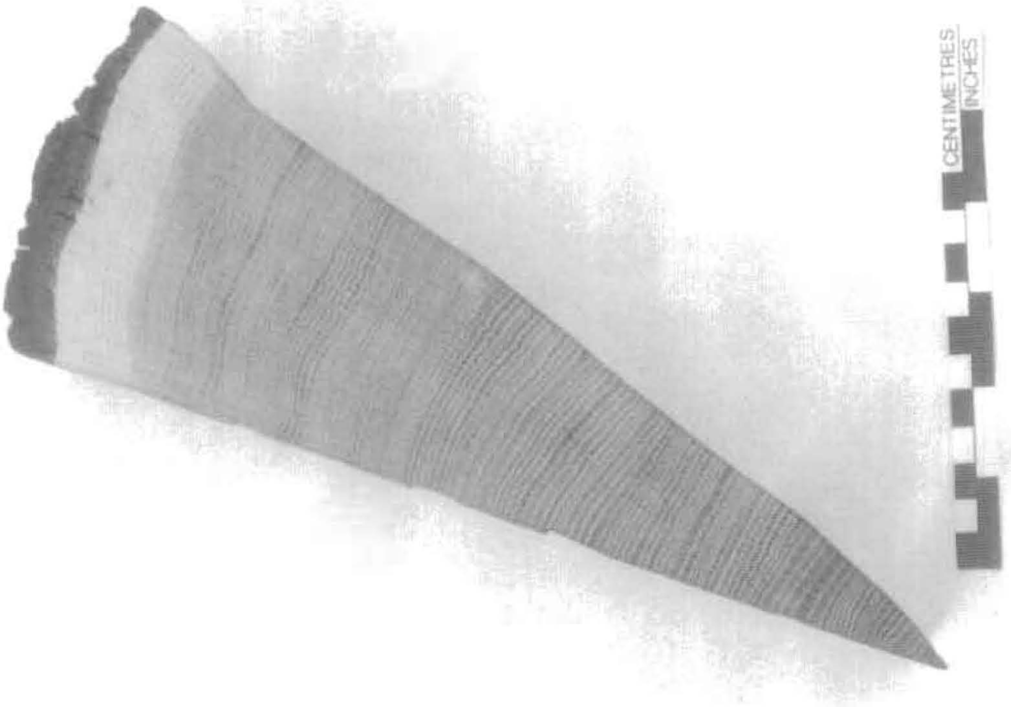

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

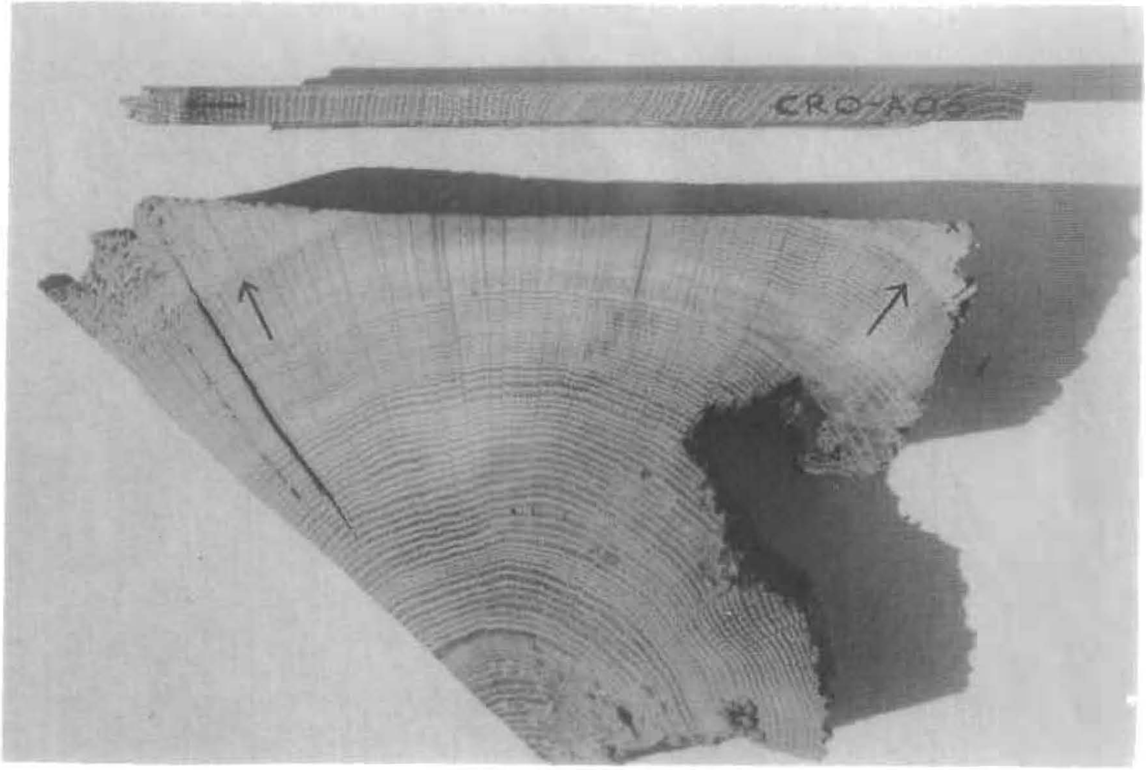

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig 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 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.

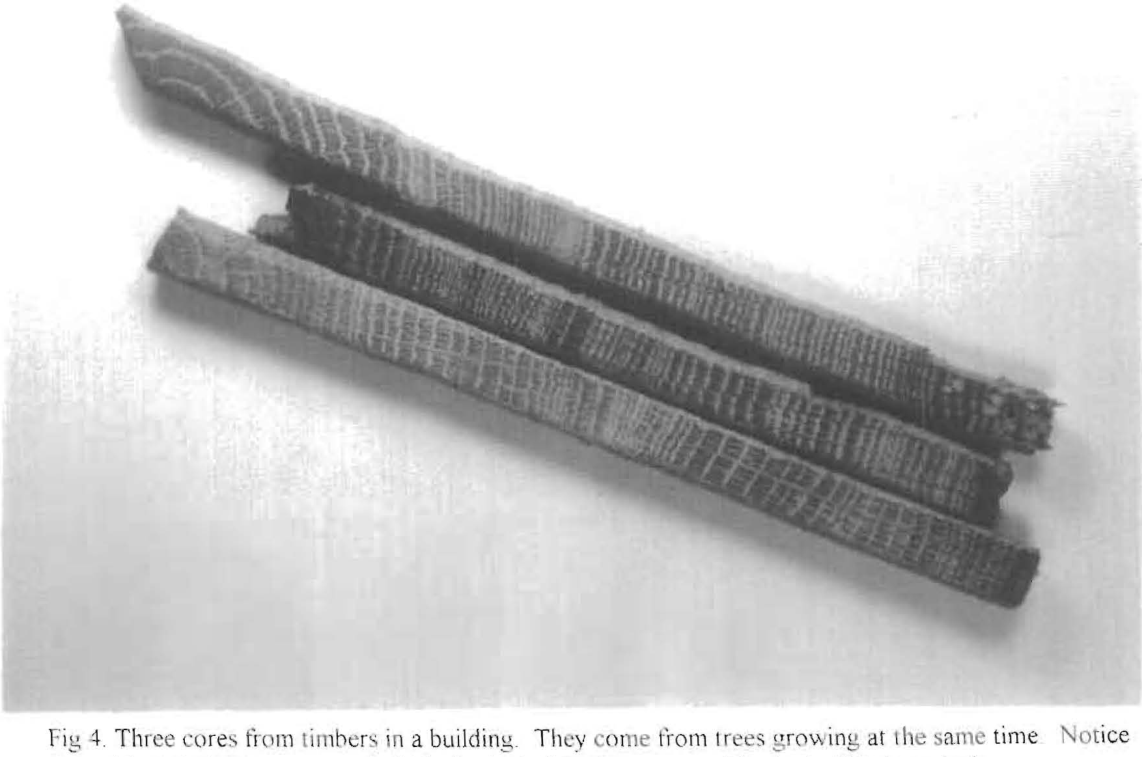

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 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 inspecton 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 is insured with the CBA.

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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

   This is illustrated in Fig 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, 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 between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the 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 Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

   Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

   Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

   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. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

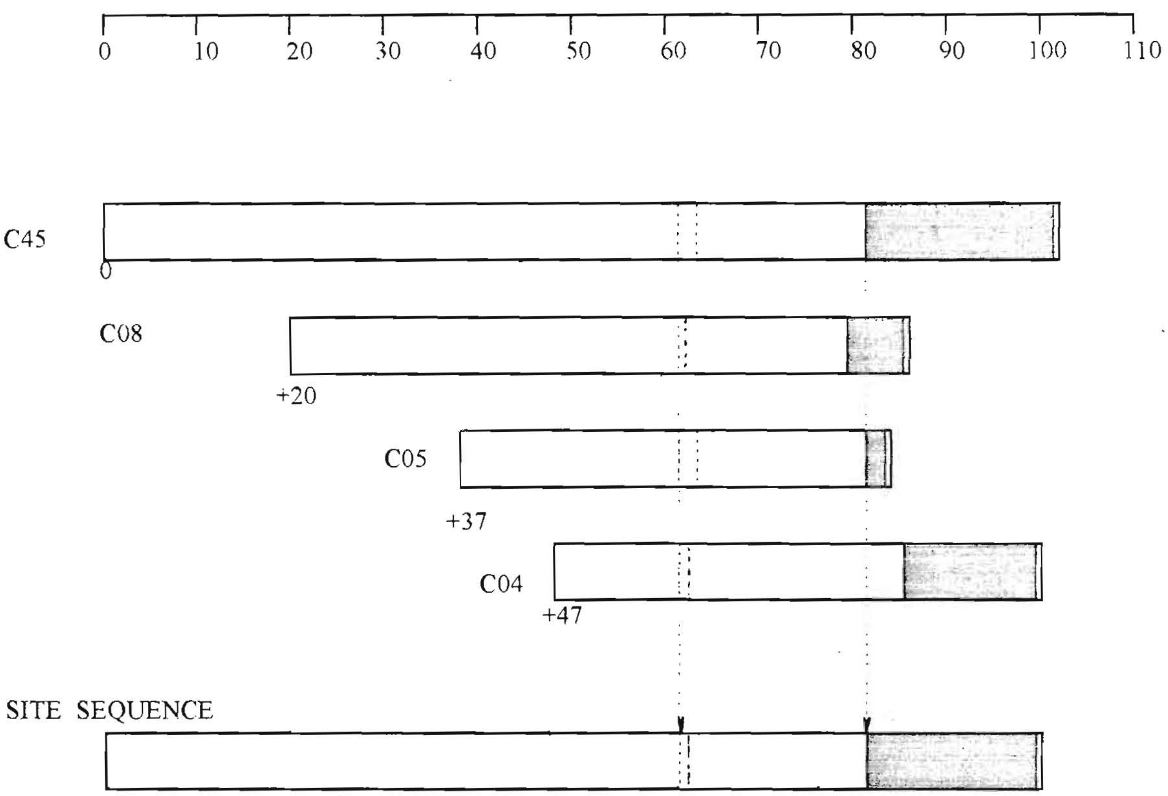

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction***. There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ*, and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 1988b, 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* 1988a). 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 (1988b) 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 (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

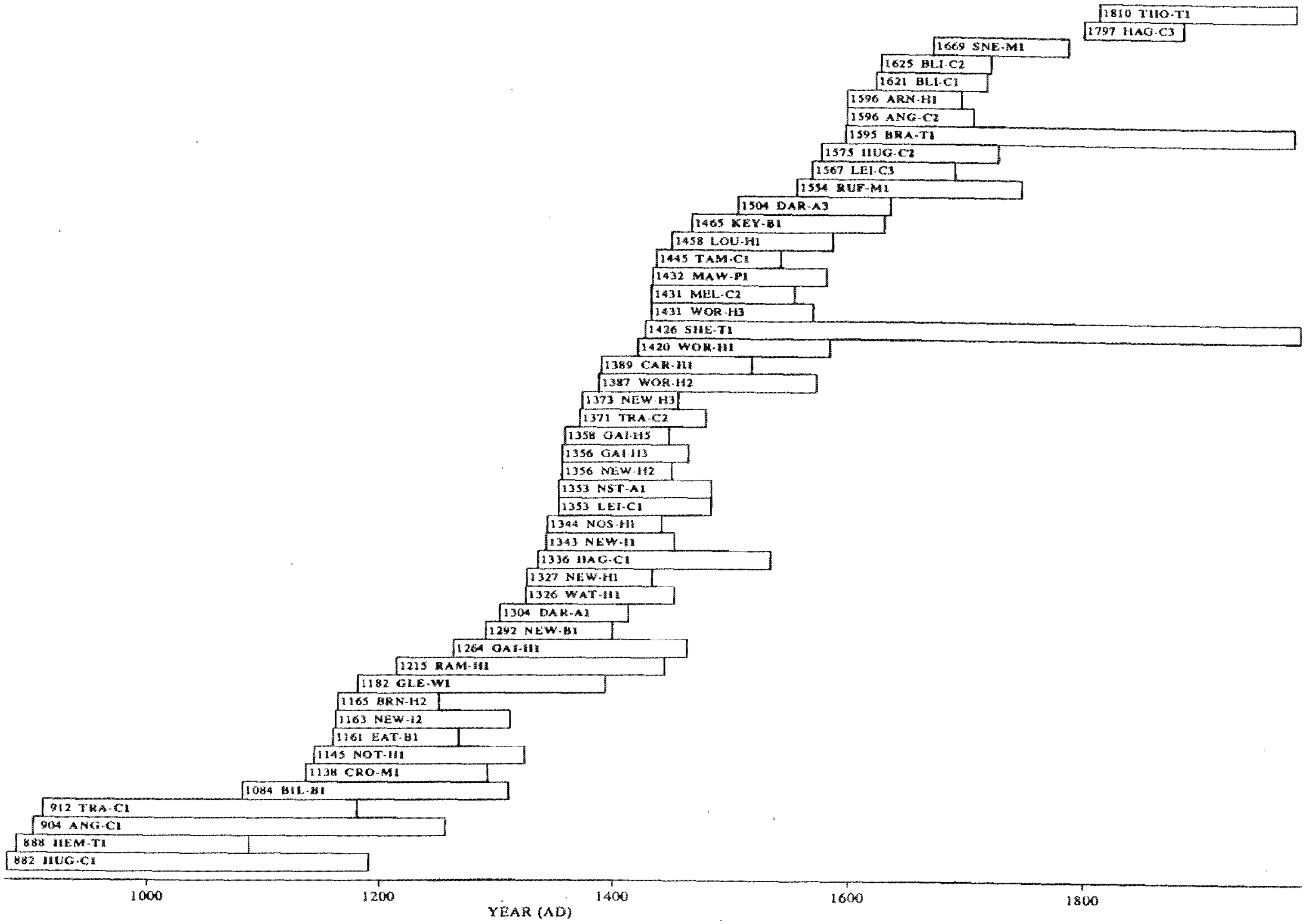

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

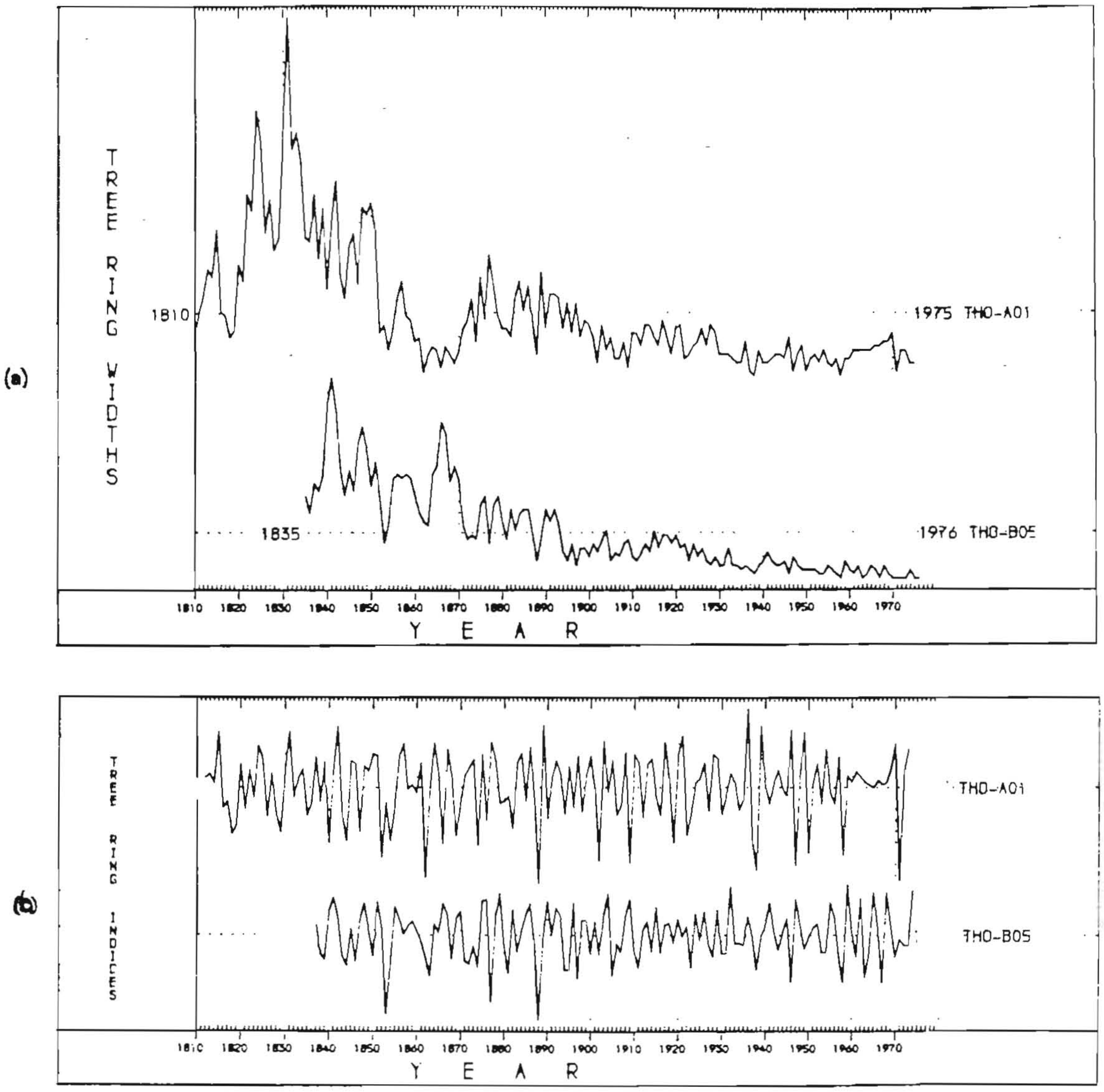

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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