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TREE-RING ANALYSIS OF TIMBERS FROM HEADSTONE MANOR HOUSE, PINNER VIEW, HARROW, LONDON

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Summary

Ninety-nine samples from the Manor house were analysed by tree-ring dating. This analysis produced seven site chronologies, two of which date. The first dated site chronology consists of nine samples from a wide range of locations within the building. This site chronology has 107 rings that span the period AD 1439 to AD 1545. Interpretation of the sapwood, and the relative positions of the heartwood/sapwood boundaries on the dated samples, suggests that the timbers represented have an estimated felling date in the range AD 1554-84.

Given the wide range of locations of the samples in this site chronology it is perhaps not appropriate to infer a felling date range for timbers from specific locations nor a sequential development for the Manor house. Its dating does, however, suggest that a certain amount of work was undertaken at the site in the mid- to late-sixteenth century.

A second dated site chronology consists of eight samples, all from the open hall and cross-wing range of the Manor house. Interpretation of the sapwood, and the relative positions of the heartwood/sapwood boundaries on the dated samples in this second site chronology, suggests that the timbers represented have an estimated felling date in the range AD 1310-15.

A third, undated, site chronology contains seven samples and has 88 rings. The other four undated site chronologies consist of two samples each and range in length from 57 to 66 rings.

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Introduction

Headstone Manor (TQ 141897; Figs 1 and 2) is a grade I listed timber-framed aisled hall house with a cross-wing. Both parts are believed to be contemporary and to date from the fourteenth century. The Manor of Harrow was amongst the estates owned by the see of Canterbury, Archbishop John Stratford purchasing the surrounding land in AD 1344. Standing on a moated site adjacent to a tythe barn, the Manor is believed to have been partially demolished and then extended in the sixteenth century, these works affecting the great hall and high end in particular. Upon the Dissolution in AD 1546 the site was sold to Sir Edward North (later Lord North).

In AD 1631 the house was owned by the Rewse family who paneled the remains of the great hall and built an extension to the rear. Francis Rewse fought on the Royalist side in the Civil War, the debts incurred for this necessitating the sale of the house to William Williams in AD 1649. Williams built a substantial new wing, with cellars, pantry, and bedrooms. Subsequent owners built another wing in the AD 1770s, and gave the front a brick façade. The building was converted to a farmhouse in the seventeenth or eighteenth century and now serves partly as a local museum.

The Manor was the subject of a small programme of analysis by dendrochronology, undertaken by the Nottingham University Tree-ring Dating Laboratory in December 1995. This earlier tree-ring dating concentrated on sampling timbers from what is believed to be the earliest extant part of the present building, the open hall and cross-wing (Howard *et al* 1996).

The current programme of sampling and analysis by tree-ring dating was commissioned by English Heritage in conjunction with archaeological recording and analysis by David and Barbara Martin of the Institute of Archaeology, London. The purpose of the tree-ring analysis was to assist with the dating and the phasing of the building. The aim of the present programme of work is to would help inform the conservation process and assist in the drafting of repair proposals for the building. For the purposes of this report the samples obtained in AD 1995 were re-analysed in conjunction with those obtained under the current programme. More recently the tythe barn at Headstone Manor has also been analysed by dendrochronology (Howard *et al* forthcoming).

Establishing dates for the various parts of the Manor would provide information on the medieval development of this site, plus its post-medieval expansion during the fifteenth to seventeenth centuries. These changes are evidenced by structural alterations made to the Manor house during this time. It was hoped that it might be possible to link the changes at the house to the historical phases.

The Laboratory would like to take this opportunity to thank David and Barbara Martin for their help in interpreting the building, their assistance with sampling, and for providing drawings. The Laboratory would also like to thank Harrow Council for allowing sampling and in particular Jan Strode, David Whorlow, curators of the Centre, and the staff for their help, cooperation, and hospitality during sampling.

The building

A considerable amount of reconstruction has taken place at Headstone Manor, with a substantial number of timbers showing evidence of reuse. Given the suggested age of the site and the history of extension and alteration, Headstone Manor presents a complicated building sequence. A schematic outline plan of the site is provided in Figure 3. The original fourteenth-century high-end accommodation and part of the original hall towards the south end of the site have long since been demolished; only a portion of the original hall survives. Attached to the north side of what remains of the hall is the original cross-wing.

To the north of the cross-wing stand two additions, a west wing (running north – south) and an east wing (running east – west). It is believed that the west wing may be the earliest addition to the original fourteenth-century building, possibly having been built to replace the original kitchen in the mid-sixteenth century. The north gable shows that this phase was built with exposed close-studding and it may have been jettied along its west side. It is believed that some time later, probably in the mid-seventeenth century, the southern part of the west wing was rebuilt. It is thought probable, therefore, that the west wing contains timbers of two phases.

The east wing (also to the north of the cross-wing) is a two-and-a-half bay, two-storey structure with a tenoned purlin roof, probably of seventeenth-century date. This roof appears to be of a single phase of construction.

At the east end of the hall lies the "tower", which contains timbers believed to represent four, or more, elements or phases of construction. At the lower level these timbers consist of phase I walls plus floor frames which may also be phase I, but may be phase II; for the purposes of sampling they are treated as two separate elements. Phase III of the tower consists of upper wall-frames and rafters associated with the heightening of this part of the building, possibly in the eighteenth century. The fourth phase here consists of a single roof truss to the south gable. It is believed that this was originally the north gable of a now missing structure formerly standing to the south of the tower. When this lost portion was demolished the roof truss was retained, becoming fossilized in the roof of the tower. The dating of all these phases is uncertain.

In addition to these phases the English Heritage brief requested samples from an enclosed outshut structure, attached to the south wall of the east wing. The basement walls here are of brick and flint of seventeenth-century character and they incorporate a seventeenth-century type brick mullion window. The roof itself is of the same tenoned purlin type as that over the north range. However, constructional details show that it must be later than the north range.

To the south side of this outshut is a timber-framed porch structure to the rear, or east end, of the hall cross-passage. Sampling of this area was requested to clarify the dating and phasing of the doorway.

Finally, samples were requested from the window, framing, and sub-structure of the west wall of the remains of the original hall.

Sampling

After discussion with David and Barbara Martin on the possible phasing of the Manor buildings and of the timbers available, and in conjunction with the brief provided by English Heritage, a total of ninety-nine core samples was obtained from the twelve phases/areas requested. Sampling was made particularly problematic by the quantity of reused timber. Each sample was given the code HED-M (for Headstone, site "M") and numbered 01 – 99. Details of the samples are given in Table 1. In this table the timbers sampled are described by type (stud-post, tiebeam, etc), and identified by their unique timber-code number, where given, taken from the drawings provided.

The locations of the samples were also recorded on these drawings, reproduced here as Figures 4a-j. The sample numbers and their general locations are summarised below.

Sampling location	Sample numbers	Sampling location	Sample numbers
Tower wall frames – phase I	HED-M01 – 08	Hall range – west wall	HED-M49 – 56
Tower first-floor frames – phase I/II	HED-M09 – 16	East-wing roof	HED-M57 – 64
Tower roof – phase III	HED-M17 – 24	Porch	HED-M65 – 72
Tower – south gable truss	HED-M25 – 32	Outshut roof	HED-M73 – 80
West wing – north end	HED-M33 – 40	Cross-wing	HED-M81 – 88
West wing – south end	HED-M41 – 48	Open hall	HED-M89 – 99

Analysis

Each of the ninety-nine samples was prepared by sanding and polishing, and the growth-ring widths measured; the data of these measurements are given at the end of the report. The growth-ring widths of all the samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a minimum *t*-value of 4.5 seven groups of samples formed, the relative off-set positions of the samples in each of these groups being illustrated in the bar diagrams of Figures 5 – 11. In these bar diagrams the samples are annotated to show its general location. It will be seen that some of the groups include samples from a wide range of locations within the building.

The growth-ring widths of the samples in each of the seven groups were combined at the indicated relative off-set positions to form site chronologies HEDMSQ01 – HEDMSQ07. Each of the seven site chronologies was then compared with a series of relevant reference chronologies for oak. This indicated dates for only two site chronologies, the *t*-values for these being given in Tables 2 and 3. This analysis is summarised below.

Site chronology	Number of samples	Number of rings	Date span (where dated)
HEDMSQ01	9	107	AD 1439 – AD 1545
HEDMSQ02	7	88	Undated
HEDMSQ03	2	57	Undated
HEDMSQ04	2	56	Undated
HEDMSQ05	2	66	Undated
HEDMSQ06	2	57	Undated
HEDMSQ07	8	72	AD 1234 – AD 1305

Each site chronology was compared with the other six and with the remaining ungrouped samples but there was no further, satisfactory, cross-matching. Each of the remaining ungrouped samples with more than 55 rings was then compared individually with a full range of relevant reference chronologies for oak but, again, there was no further satisfactory cross-matching.

Interpretation

The relative positions of the heartwood/sapwood boundaries on the samples within site chronology HEDMSQ01 lie within fairly narrow limits, having a sixteen year difference, 91 years relative on sample HED-M04 and 107 years relative on sample HED-M58 (see Fig 5). It is thus probable, that the timbers represented have the same, or at least a very similar, felling date. The provenance of the samples in site chronology HEDMSQ01 does vary, however, with the tower phase I, west wing (north end), west wing (south end), west wall, and the east-wing roof being represented.

The average last heartwood ring date of the samples in site chronology HEDMSQ01 is AD 1539. Applying the usual 95% confidence limit for the amount of sapwood on mature oaks from southern England of 15 – 45 rings would give the timbers represented an estimated felling date in the range AD 1554 – 84.

It is possible, though much less probable, that the timbers represented in site chronology HEDMSQ02 have the same (though unknown) felling date. This is because the relative positions of the heartwood/sapwood boundaries on the samples within site HEDMSQ02 chronology HEDMSQ02 have wide limits, ranging from 50, on sample HED-M18, to 88 on sample HED-M09, a difference of 38 years (see Fig 6).

Indeed, it appears more likely that two phases of felling are represented by this site chronology. Samples HED-M18, M41, and M59 may represent one phase of felling because the relative positions of their heartwood/sapwood boundaries are similar to each other. Samples HED-M09, M13, M45, and M46, which also have relative heartwood/sapwood boundaries similar to each other, may represent a different, later, phase of felling. The timbers sampled again have different provenances with the tower phases I and II, west wing (south end) and east-wing roof being represented. Given that the chronology itself is undated, it is not possible to calculate an estimated felling date range.

Only the eight samples in site chronology HEDMSQ07 appear to represent a single phase of timber felling from a distinct area of the Manor house, what may be the original open hall and cross-wing. The relative positions of the heartwood/sapwood boundaries on the eight samples lie within narrower limits, 43 years relative on sample HED-M86 and 61 years relative on sample HED-M90, a range of eighteen rings. The timbers in this area shows little obvious signs of reuse.

One of the samples in site chronology HEDMSQ07 (HED-M84) comes from a timber which had complete sapwood. Unfortunately about 5mm of sapwood was lost in coring, such a loss probably representing about 5 missing sapwood rings. Given that sample HED-M84 has a last measured sapwood ring date of AD 1305 this would suggest a felling date for the timber represented of *c* AD 1310, certainly no later that AD 1315. It is thought likely that this is the felling date for all the dated timbers from the open hall and cross-wing.

For the most part, the timbers represented by the samples in the other, undated, site chronologies appear to represent single fellings. This is because the relative positions of the heartwood/sapwood boundaries on the samples is very similar. It will be seen in Figure 7 for example, that the relative positions of the heartwood/sapwood boundaries on the two samples in site chronology HEDMSQ03 varies by only one year. The relative position of the two samples in site chronology HEDMSQ04, Figure 8, is the same. However, judging by their degree of cross-matching, it is likely that these pairs of samples represent single trees. Samples HED-M17 and M19, and HED-M26 and M27, for example, cross-match with each other with values in excess of t=12.0 .

Conclusion

Analysis by dendrochronology has been able to provide only a rather crude estimate of the date of a modest number of samples. Some of the samples are from what is believed on stylistic and structural evidence to be the earliest extant portions of the manor house, the open hall and cross-wing. The dated timbers from this area suggest a felling date of AD 1310 – 15. This is generally in keeping with the fourteenth-century date expected for this part of the structure, though it is perhaps very slightly earlier than expected. Prior to tree-ring analysis of the hall and cross-wing it was generally assumed the original aisled hall was built *c* AD 1350. This was based on documents linking the site to the Archbishops of Canterbury, who owned it at this time. The tree-ring dates therefore have important implications for the early history of the site.

Other timbers from a wide ranges of locations are dated as being felled in the later-sixteenth century, having an estimated felling date range of AD 1554 – 84. Such samples are from a wide range of areas within the Manor house. This, and the fact that there is evidence of widespread reuse of timber, makes it difficult to reliably infer precise construction dates for the various phases or an evolutionary development. Nevertheless, the evidence for sixteenth-century fellings obtained by dendrochronology does support the conclusion that much reconstruction work took place around this time, based on fabric evidence.

Nearly all the samples have very short growth-ring sequences, many of them having only the minimum number of rings, 55, statistically acceptable. Below this number of rings less certainty can be placed on cross-matches because the amount of overlap between samples and between samples and reference chronologies becomes too small to be meaningful.

Several samples show wide and complacent growth rings with little variation in ring-width from year to year. The lack of a varied and distinct climatic signal in the growth rings may in part also account for the lack of cross-matching and dating. Other samples show bands of very narrow or distorted rings and this too can make cross-matching and dating difficult. Despite these possible problems it was felt that attempting some analysis was worthwhile, given the importance of the site and the necessity of obtaining some understanding of its development.

This programme of analysis at Headstone Manor highlights the difficulties of providing reliable results and meaningful interpretation from a complex multi-phase building with quantities of reused timbers that produce poor samples. This work thus reinforces the argument for using a wide range of research and analytical methods at such sites.

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Table 1: Details of samples from Headstone Manor House, Headstone, Middlesex

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Tower wall frames – phase I					
HED-M01	1002 Stud	55	h/s	------	------	------
HED-M02	1003 Stud	54	h/s	------	------	------
HED-M03	1013 Brace	59	h/s	------	------	------
HED-M04	1019 Tiebeam	71	h/s	AD 1459	AD 1529	AD 1529
HED-M05	1101 Sill beam	67	h/s	------	------	------
HED-M06	1106 Stud	54	h/s	------	------	------
HED-M07	1110 Stud	52	h/s	------	------	------
HED-M08	1120 Wall plate	63	h/s	------	------	------
	Tower first-floor frames – phase I					
HED-M09	1015 Sill beam	59	h/s	------	------	------
HED-M10	1016 Door jamb	57	h/s	------	------	------
HED-M11	1017 Top beam	40	h/s	------	------	------
HED-M12	1018 Door jamb	37	no h/s	------	------	------
HED-M13	1402 Floor joist	56	3	------	------	------
HED-M14	1404 Floor joist	53	h/s	------	------	------
HED-M15	1405 Floor joist	57	h/s	------	------	------
HED-M16	1406 Floor joist	58	h/s	------	------	------
	Tower – phase II					
HED-M17	1123 Brace	66	no h/s	------	------	------
HED-M18	1129 Stud	54	10	------	------	------
HED-M19	1131 Stud	56	no h/s	------	------	------
HED-M20	1132 Window sill	48	h/s	------	------	------
HED-M21	1611 Common rafter	59	h/s	------	------	------
HED-M22	1613 Common rafter	56	h/s	------	------	------
HED-M23	1614 Common rafter	64	h/s	------	------	------
HED-M24	1602 Common rafter	69	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
	Tower – south gable truss					
HED-M25	1041 Tiebeam	56	9	------	------	------
HED-M26	1051 East principal rafter	54	8	------	------	------
HED-M27	1052 West principal rafter	57	8	------	------	------
HED-M28	1053 East stud	57	7	------	------	------
HED-M29	1054 East queen brace	54	h/s	------	------	------
HED-M30	1055 East central stud	55	no h/s	------	------	------
HED-M31	1056 West central stud	54	no h/s	------	------	------
HED-M32	1057 West queen brace	55	h/s	------	------	------
	West wing (north end)					
HED-M33	Collar	71	h/s	------	------	------
HED-M34	East stud/queen post	58	no h/s	------	------	------
HED-M35	East brace, purlin to principal rafter	52	h/s	AD 1492	AD 1543	AD 1543
HED-M36	Central upper stud	68	no h/s	------	------	------
HED-M37	West stud/queen post	56	h/s	------	------	------
HED-M38	West brace, purlin to principal rafter	66	h/s	AD 1475	AD 1540	AD 1540
HED-M39	Lower east central stud	69	no h/s	AD 1439	------	AD 1507
HED-M40	Lower west central stud	77	no h/s	AD 1449	------	AD 1525
	West wing (south end)					
HED-M41	East inner rafter	75	20	------	------	------
HED-M42	Collar	55	h/s	------	------	------
HED-M43	West brace to central frame/truss	81	h/s	AD 1462	AD 1542	AD 1542
HED-M44	East brace to central frame/truss	54	h/s	------	------	------
HED-M45	West common rafter 8 from north end	57	h/s	------	------	------
HED-M46	West common rafter 9 from north end	54	h/s	------	------	------
HED-M47	West common rafter 12 from north end	55	h/s	------	------	------
HED-M48	East common rafter 11 from north end	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
	West wall					
HED-M49	602 North window jamb	50	no h/s	------	------	------
HED-M50	607 Window head-beam	57	no h/s	------	------	------
HED-M51	614 South stud block	55	no h/s	------	------	------
HED-M52	615 Central stud block	57	no h/s	------	------	------
HED-M53	616 North stud block	54	no h/s	------	------	------
HED-M54	618 Wall plate	46	h/s	------	------	------
HED-M55	625 Wall stud	57	14	AD 1488	AD 1530	AD 1544
HED-M56	626 Wall stud	56	h/s	------	------	------
	East-wing roof					
HED-M57	South queen strut, east gable	95	h/s	AD 1441	AD 1535	AD 1535
HED-M58	North queen strut, east gable	66	h/s	AD 1480	AD 1545	AD 1545
HED-M59	North principal rafter, truss 2 (middle)	81	23	------	------	------
HED-M60	South principal rafter, truss 2	79	h/s	------	------	------
HED-M61	South principal rafter, west truss	55	h/s	------	------	------
HED-M62	Sill of east gable window	54	h/s	------	------	------
HED-M63	North principal rafter, west truss	55	h/s	------	------	------
HED-M64	North principal rafter, east gable	58	h/s	------	------	------
	Porch					
HED-M65	1801 South door-jamb		h/s	------	------	------
HED-M66	1807 North door-jamb		no h/s	------	------	------
HED-M67	1810 Short rail		h/s	------	------	------
HED-M68	1811 Wall post		no h/s	------	------	------
HED-M69	1813 Top rail		no h/s	------	------	------
HED-M70	1815 Cross-rail		h/s	------	------	------
HED-M71	1816 Cross-rail		h/s	------	------	------
HED-M72	1803 North spandrell		no 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
	Outshut roof					
HED-M73	Brace, east wall	57	h/s	------	------	------
HED-M74	West principal rafter	58	h/s	------	------	------
HED-M75	Upper rafter 7 from east end	56	h/s	------	------	------
HED-M76	Upper rafter 6 from east end	56	h/s	------	------	------
HED-M77	Upper rafter 4 from east end	57	h/s	------	------	------
HED-M78	Lower rafter 4 from east end	54	no h/s	------	------	------
HED-M79	Upper rafter 2 from east end	53	h/s	------	------	------
HED-M80	East principal rafter	58	no h/s	------	------	------
	Cross-wing					
HED-M81	West brace, west crown-post to collar purlin	59	h/s	------	------	------
HED-M82	West brace, east crown-post to collar purlin	80	13	------	------	------
HED-M83	East brace, east crown-post to collar purlin	47	9	AD 1255	AD 1292	AD 1301
HED-M84	Collar, frame 2 from east	41	20c	AD 1265	AD 1285	AD 1305
HED-M85	South common rafter, frame 13 from east	63	8	------	------	------
HED-M86	South common rafter, frame 11 from east	38	h/s	AD 1239	AD 1276	AD 1276
HED-M87	South common rafter, frame 9 from east	42	5	AD 1254	AD 1290	AD 1295
HED-M88	South common rafter, frame 4 from east	18	12C	------	------	------

Table 1: continued

Sample number	Sample location	Total Rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Open hall					
HED-M89	004 Crown-post, south truss	51	h/s	AD 1239	AD 1289	AD 1289
HED-M90	003 Tie-beam, south truss	63	2	AD 1234	AD 1294	AD 1296
HED-M91	West arcade plate	29	h/s	------	------	------
HED-M92	East arcade plate	60	3	AD 1237	AD 1293	AD 1296
HED-M93	Window jamb in east wall of aisle	33	h/s	------	------	------
HED-M94	Wall plate to east aisle	39	h/s	AD 1245	AD 1283	AD 1283
HED-M95	001 South east corner post	23	h/s	------	------	------
HED-M96	002 South west corner post	39	no h/s	------	------	------
HED-M97	Timber reused as tie-beam above wall plate, east aisle	35	11	------	------	------
HED-M98	102 Cross-beam at north end of open hall	35	h/s	------	------	------
HED-M99	Stairway door jamb in service partition / cross-passage wall	66	h/s	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber, all or part lost in coring
C = complete sapwood is retained on sample, last measured ring date is felling date of timber

Table 2: Results of the cross-matching of site chronology HEDMSQ01 with relevant reference chronologies when first ring date is AD 1439 and last ring date is AD 1545

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	5.6	(Laxton and Litton 1988)
England	AD 401 – 1981	3.9	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	4.5	(Bridge 1988)
Kent-88	AD 1158 – 1540	5.6	(Laxton and Litton 1989)
England London	AD 413 – 1728	7.2	(Tyers and Groves 1999 unpubl)
MC10---H	AD 1386 – 1585	5.1	(Fletcher 1978)
Sinai Park, Staffs	AD 1227 – 1750	4.7	(Tyers 1997)
Chicksands Priory, Beds	AD 1200 – 1541	5.1	(Howard *et al* 1998)
Lacock Abbey, Wilts	AD 1395 – 1546	6.0	(Esling *et al* 1990)
26 Westgate Street, Gloucester	AD 1399 – 1622	4.8	(Howard *et al* forthcoming)

Table 3: Results of the cross-matching of site chronology HEDMSQ07 with relevant reference chronologies when first ring date is AD 1234 and last ring date is AD 1305

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	5.6	(Laxton and Litton 1988)
England	AD 401 – 1981	5.7	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	4.6	(Bridge 1988)
Kent-88	AD 1158 – 1540	5.9	(Laxton and Litton 1989)
Cubbington, Warwicks	AD 1170 – 1312	8.8	(Howard *et al* 1988 unpubl)
Chichester Cathedral	AD 1173 – 1295	8.4	(Howard *et al* 1992)
Thame Park House, Oxon	AD 1234 – 1319	6.3	(Howard *et al* 1993)
Reading	AD 1160 – 1407	8.2	(Groves *et al* 1997)

Figure 1: Map to show general location of Headstone

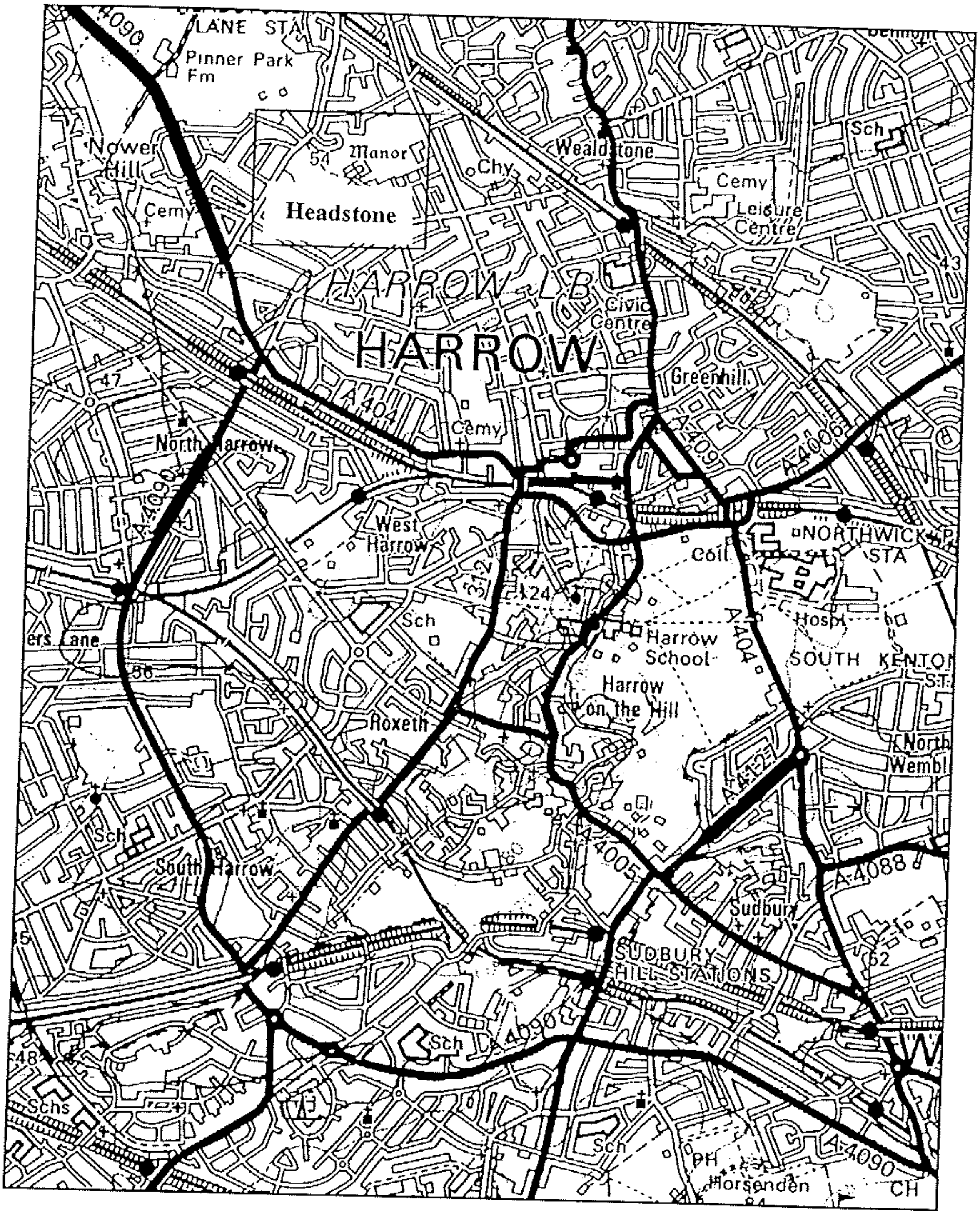
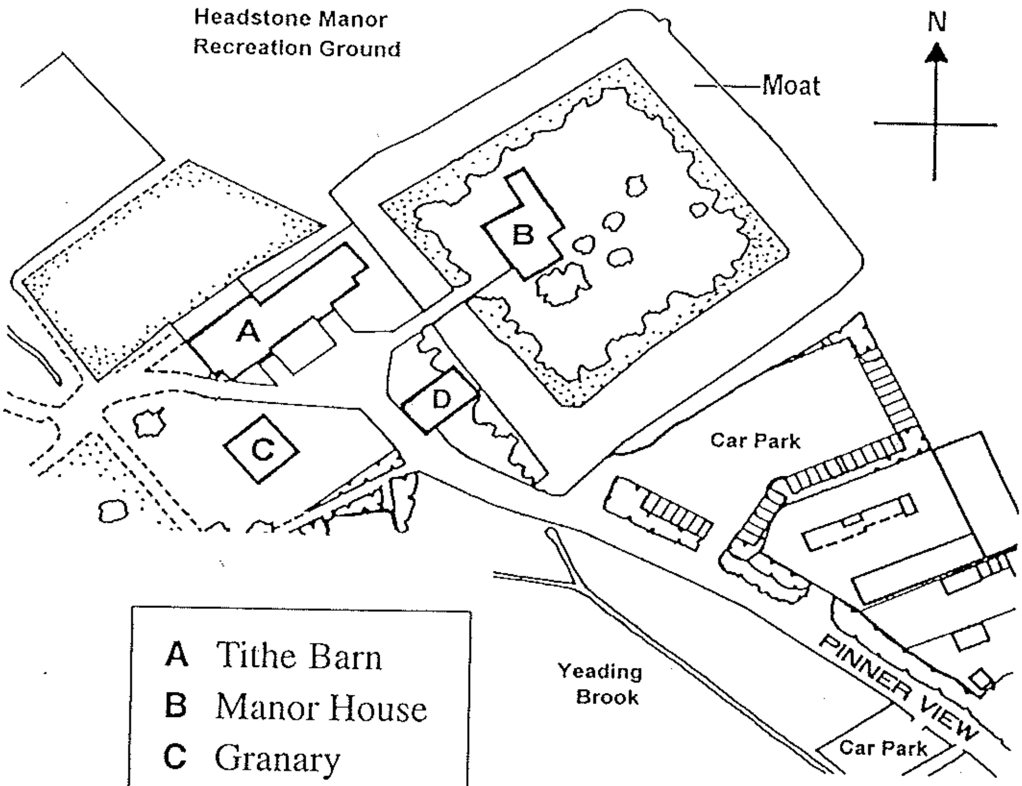


Figure 2: Map to show position of buildings at Headstone Manor



A	Tithe Barn
B	Manor House
C	Granary
D	Small Barn

Figure 3: Schematic plan of Headstone Manor

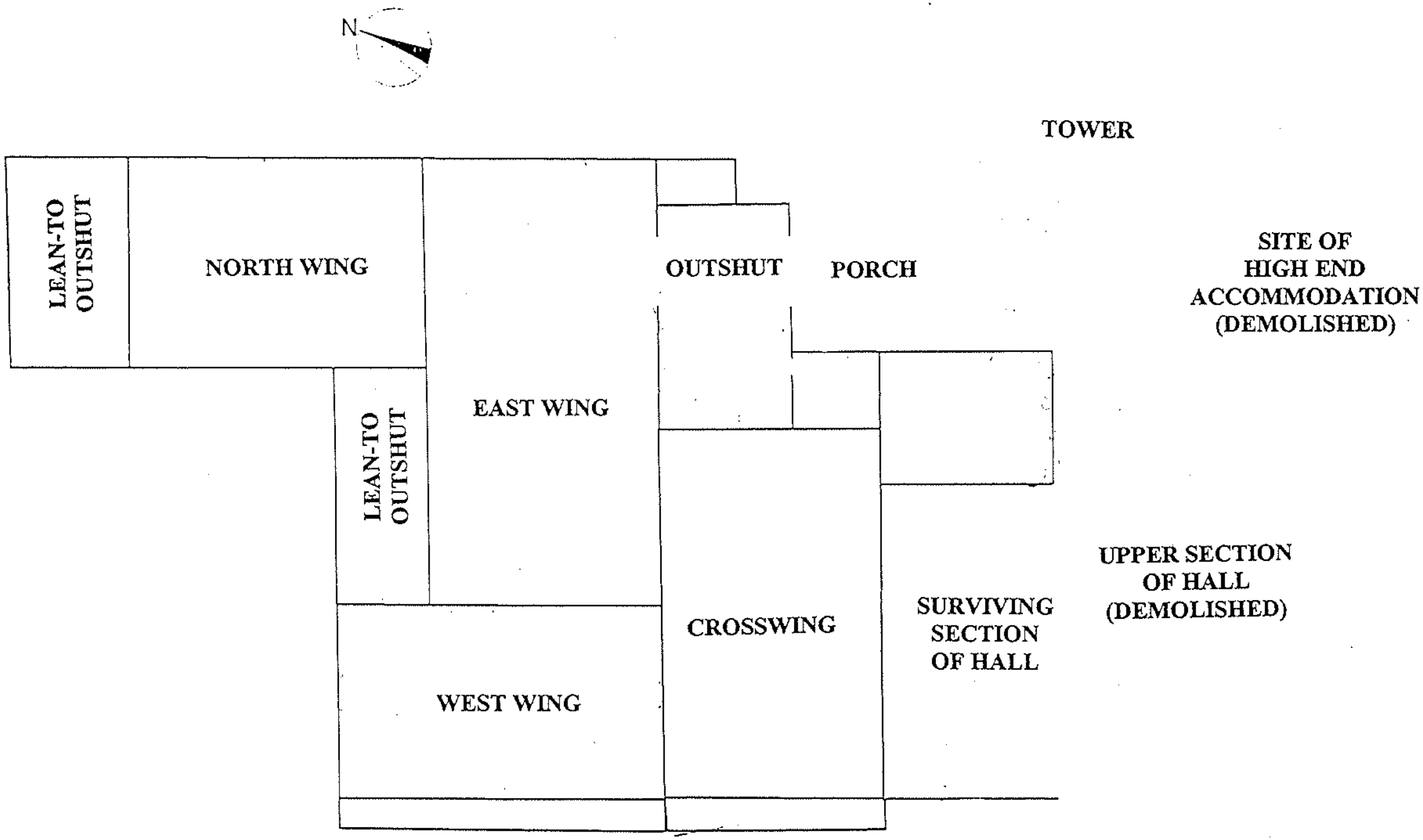


Figure 4a: South wall-frame of the tower (viewed from the south) to show timbers sampled (drawn by David and Barbara Martin)

Figure 4b: Tower first-floor frame to show timbers sampled (drawn by David and Barbara Martin)

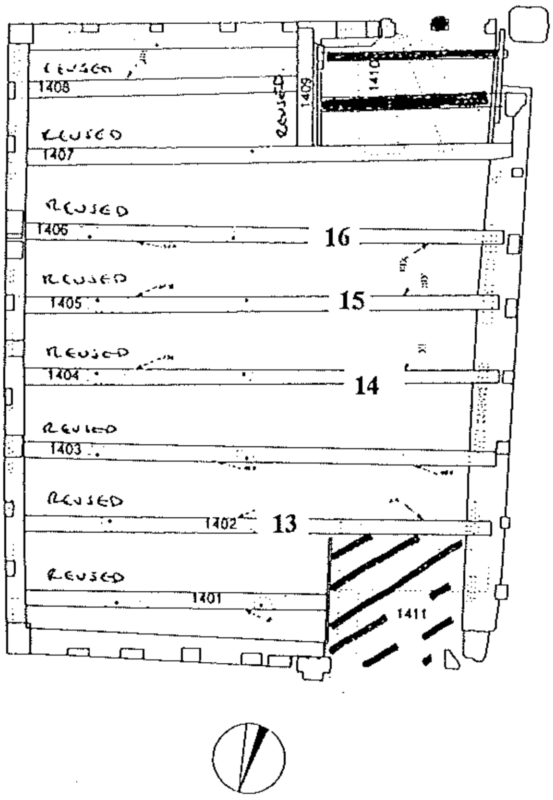


Figure 4c: East elevation of the tower (viewed from the east) to show timbers sampled (drawn by David and Barbara Martin)

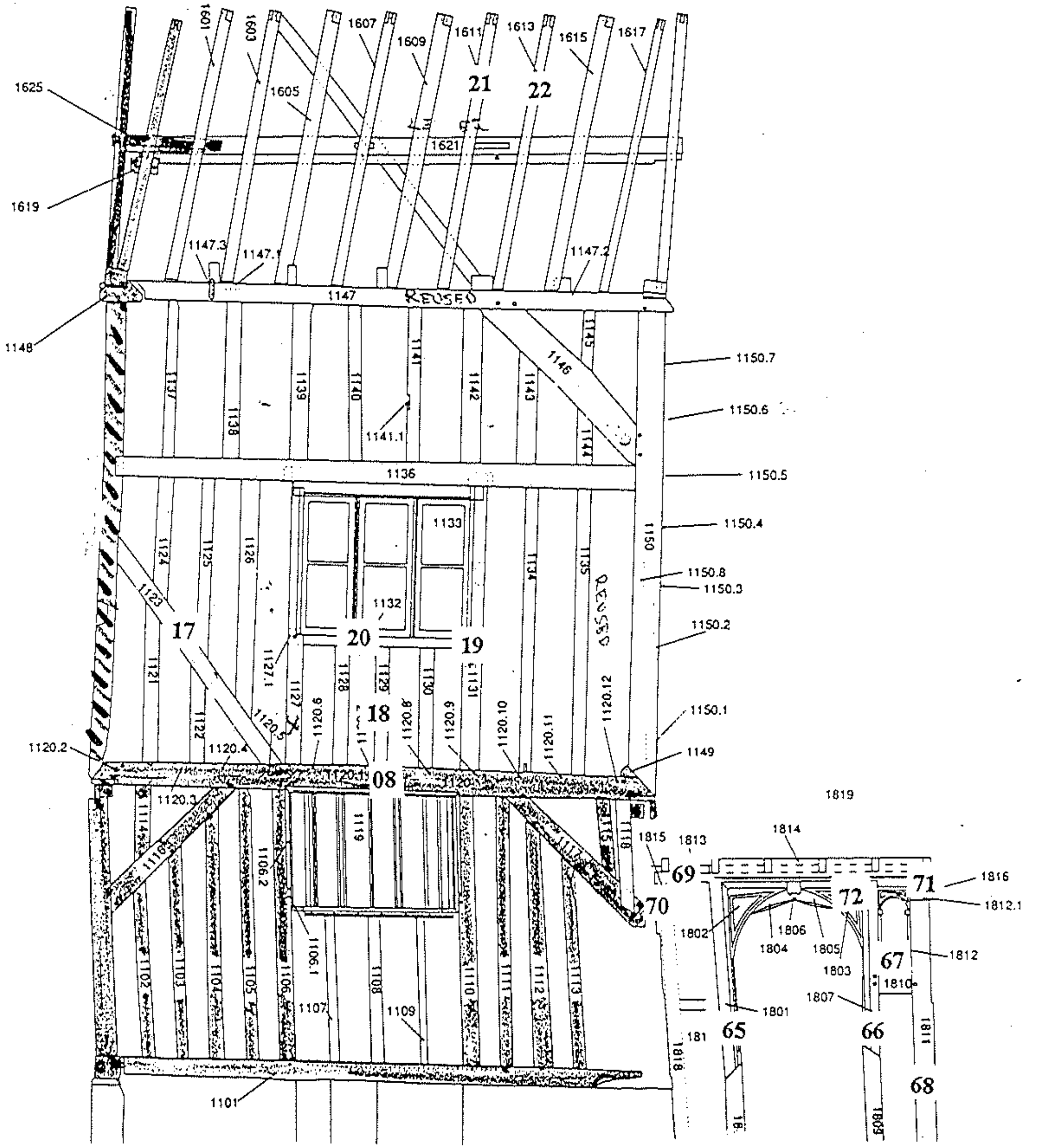


Figure 4d: West elevation of the roof of the tower (viewed from the east) to show timbers sampled (drawn by David and Barbara Martin)

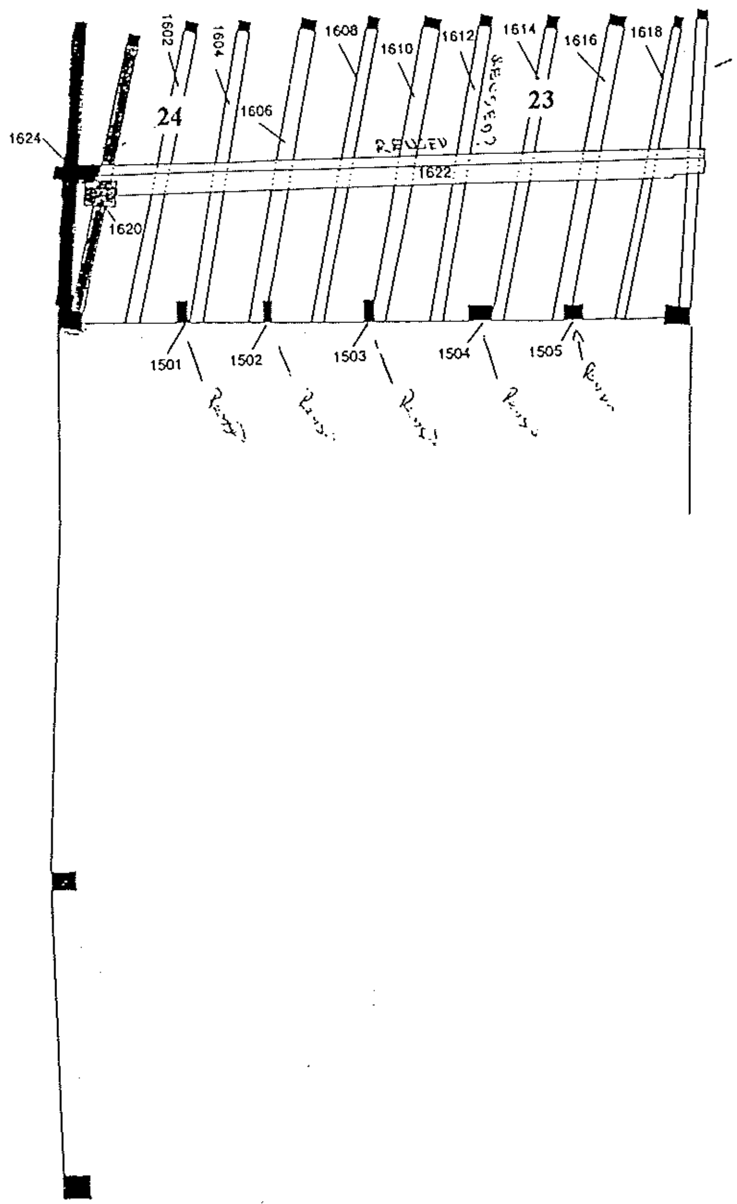


Figure 4e: Hall truss (viewed from the north) to show timbers sampled (drawn by David and Barbara Martin)

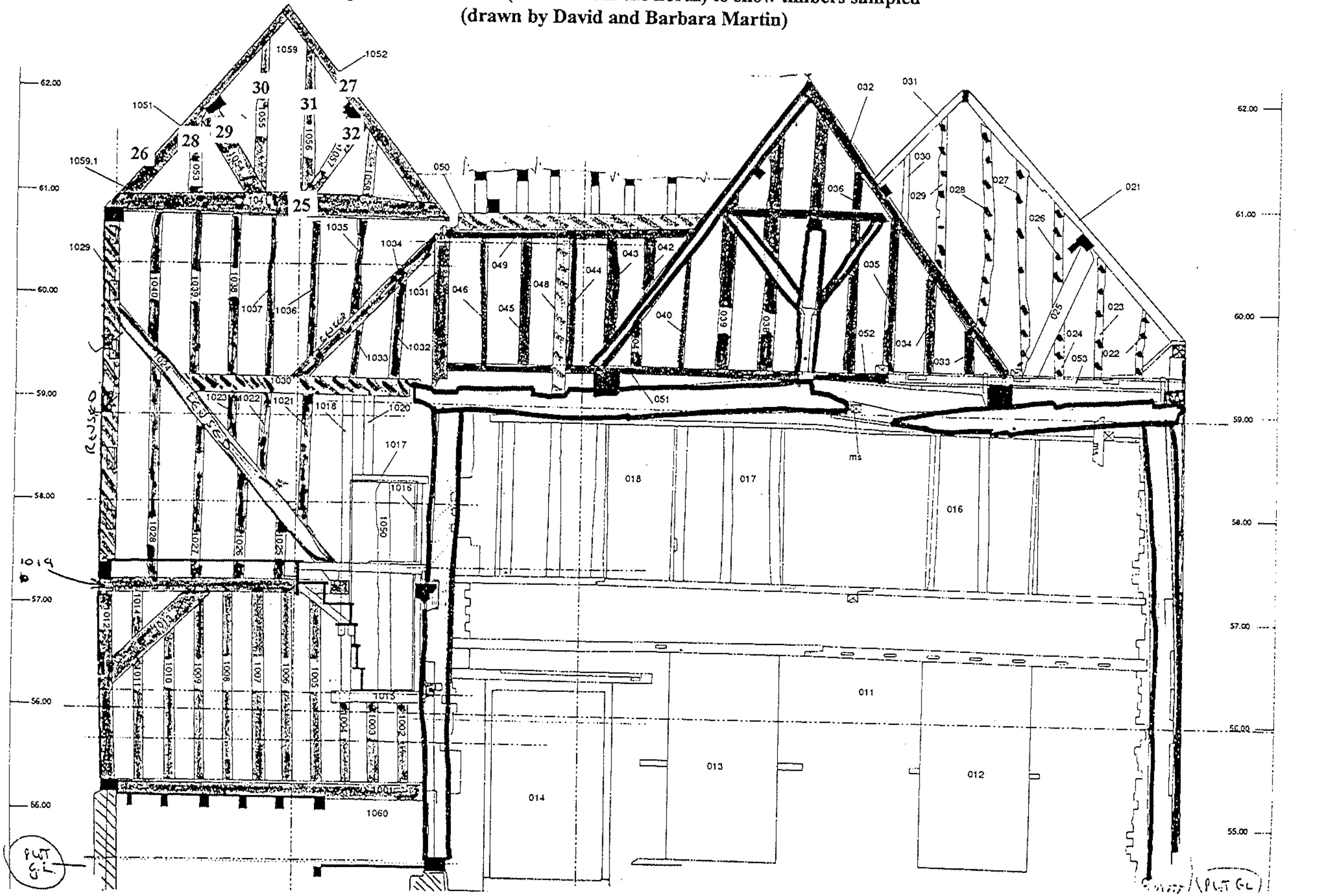


Figure 4f: West wall (viewed from the east) to show timbers sampled (drawn by David and Barbara Martin)

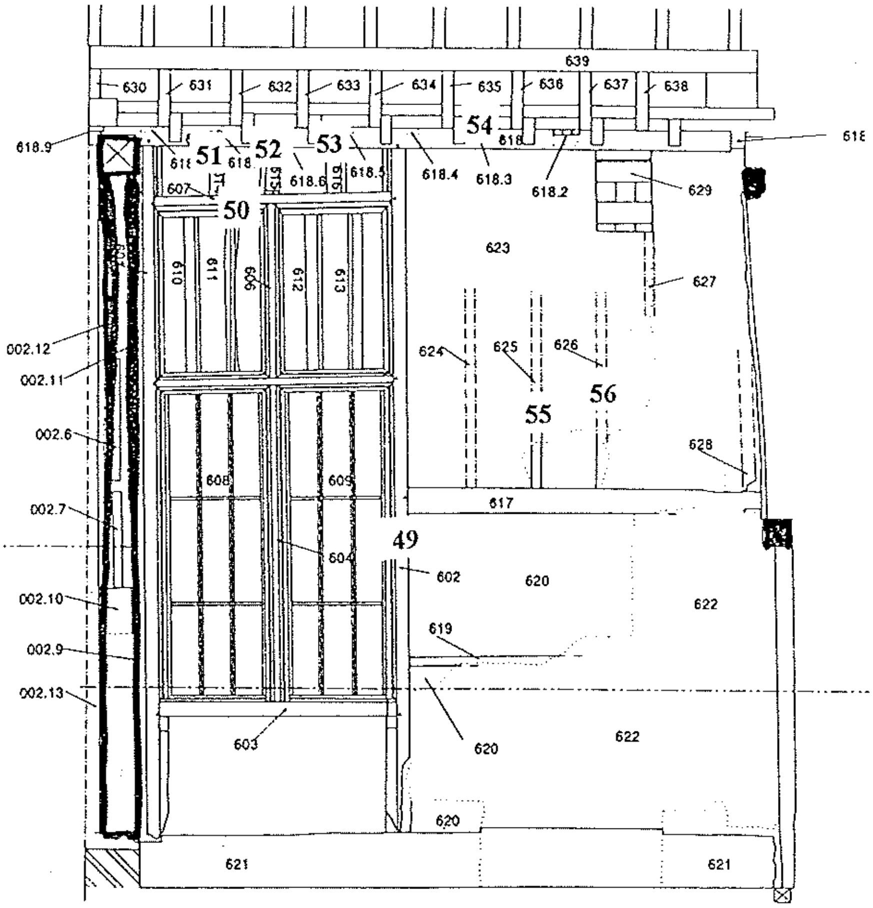


Figure 4g. Plan to show location of samples from the west wing roof (drawn by Richard Harris)

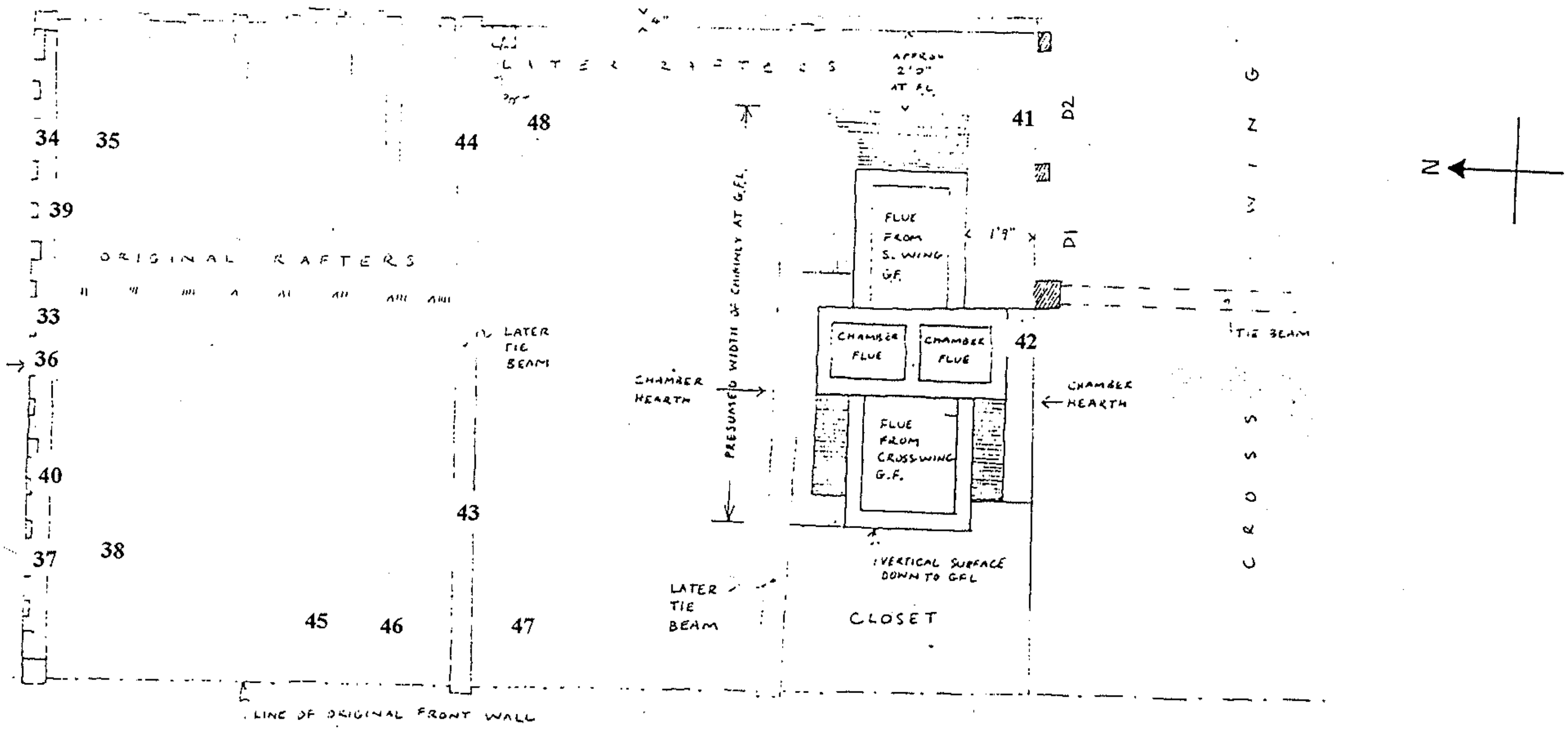


Figure 4h: Plan to show location of samples from the east wing roof (drawn by Richard Harris)

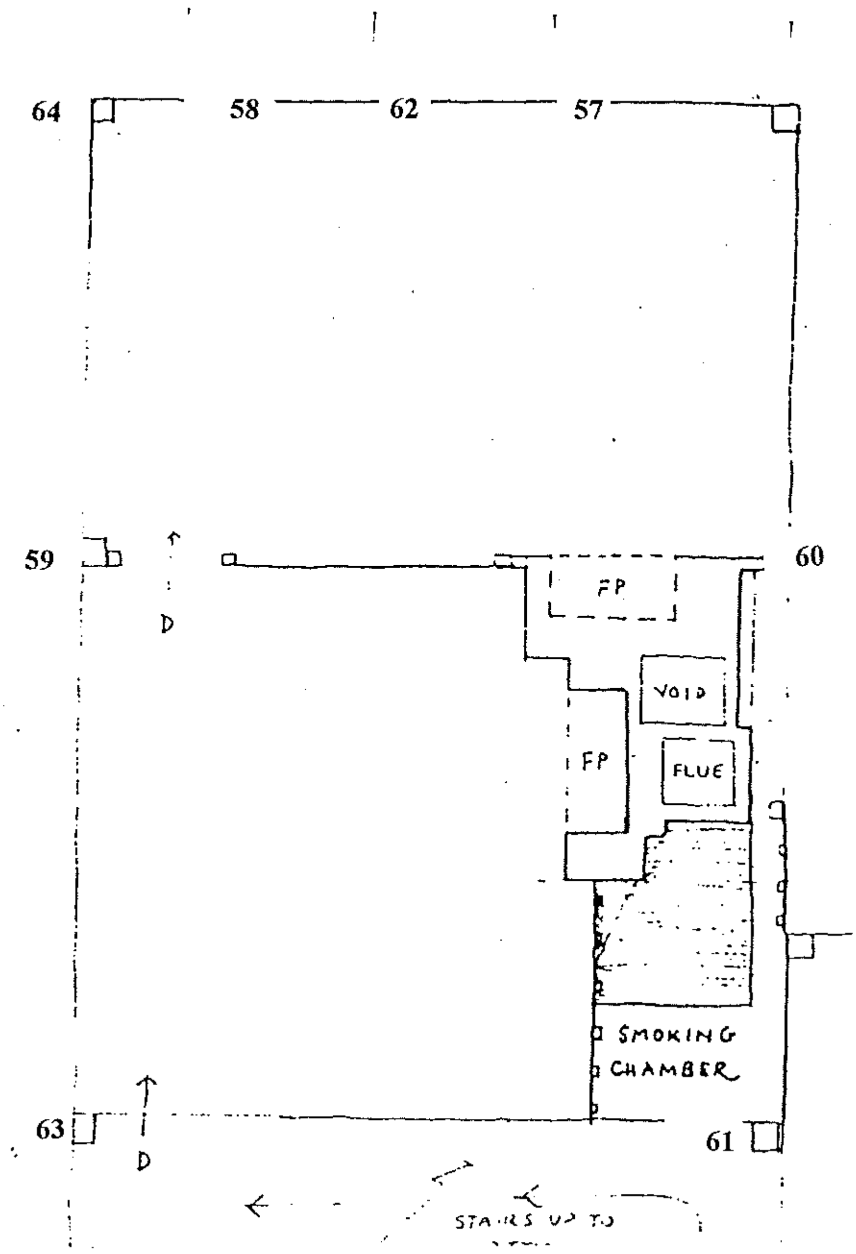


Figure 4i: Plan to show location of samples from the outshot roof (drawn by Richard Harris)

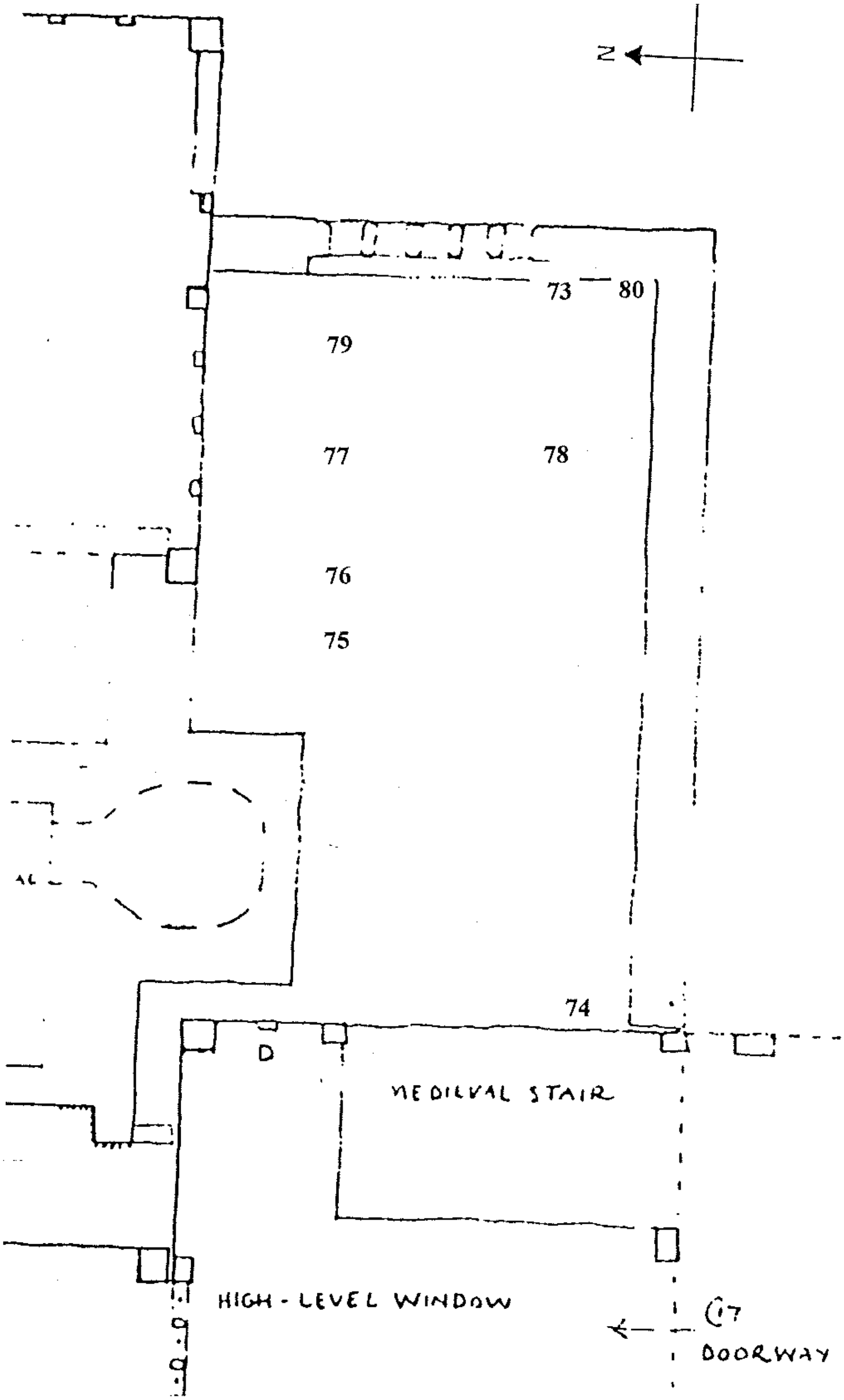


Figure 4j: Plan to show location of samples from the open hall and cross-wing (drawn by Richard Harris)

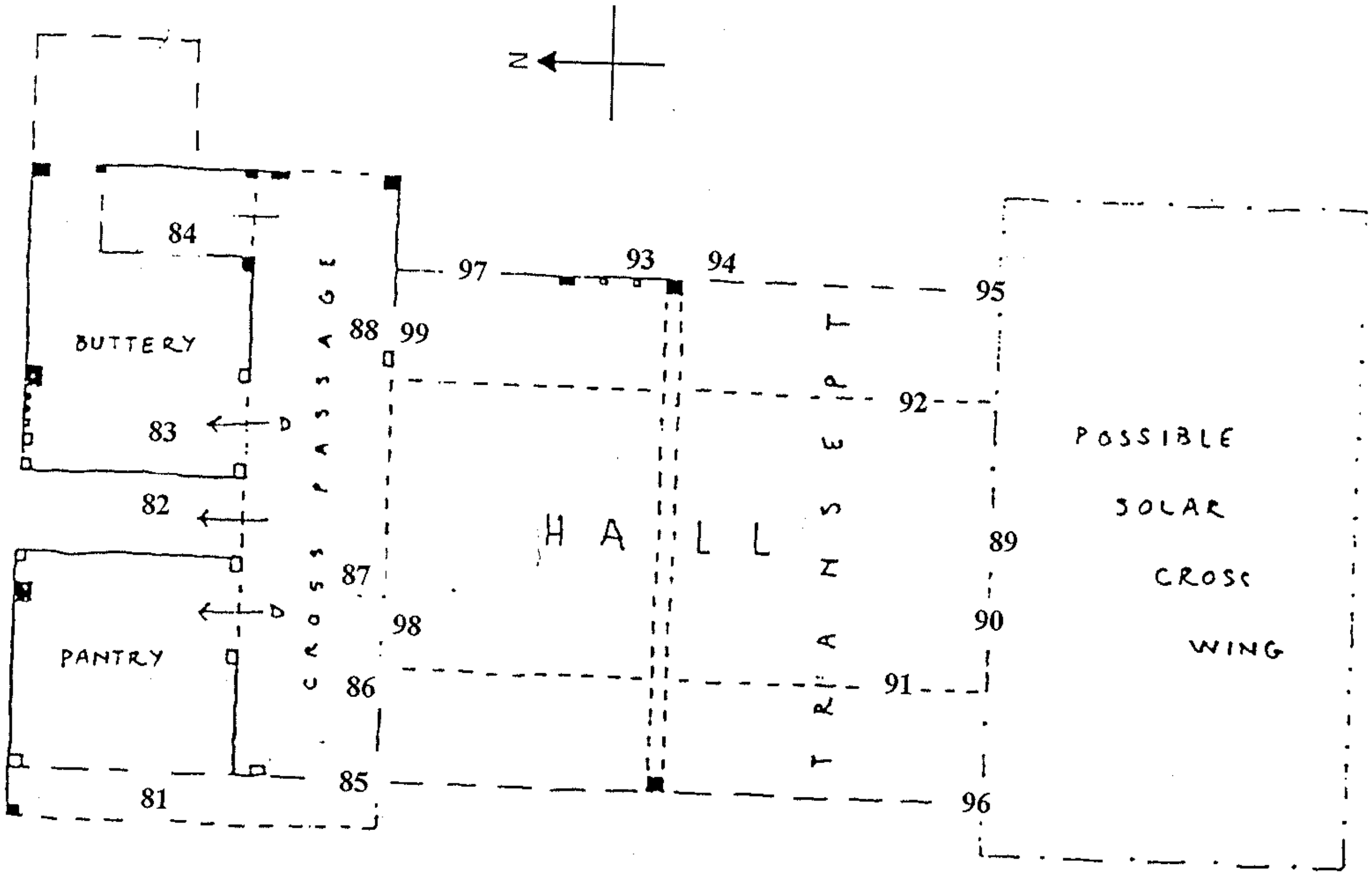


Figure 5: Bar diagram of samples in site chronology HEDMSQ01

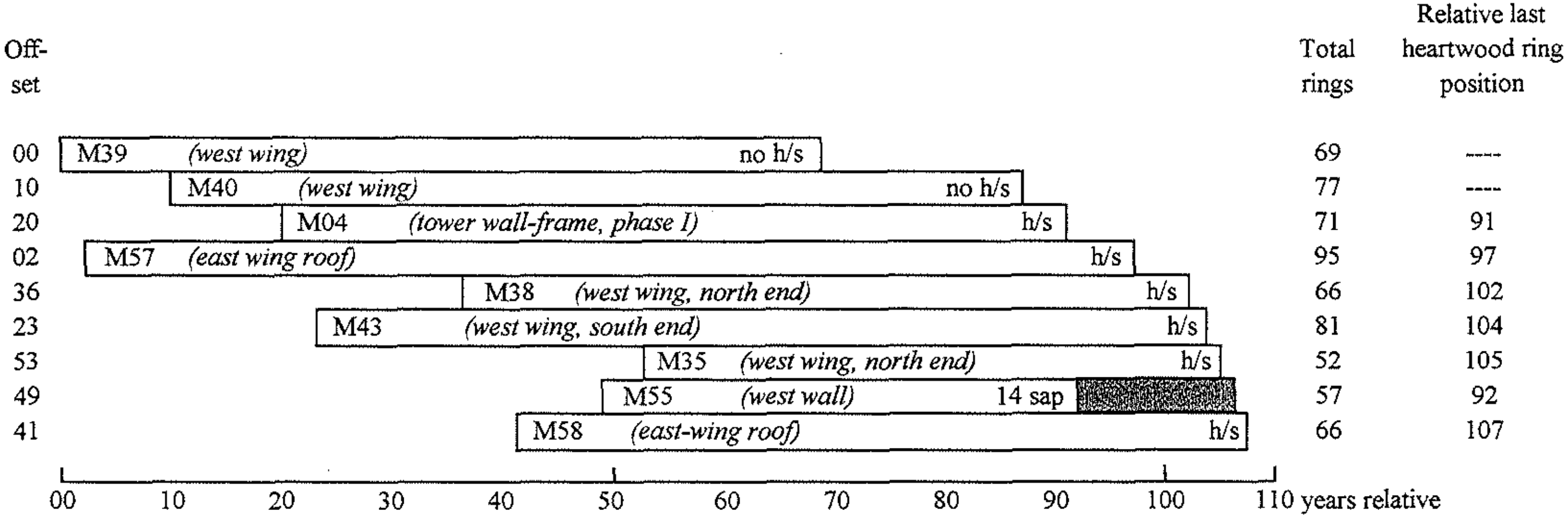


Figure 6: Bar diagram of samples in site chronology HEDMSQ02

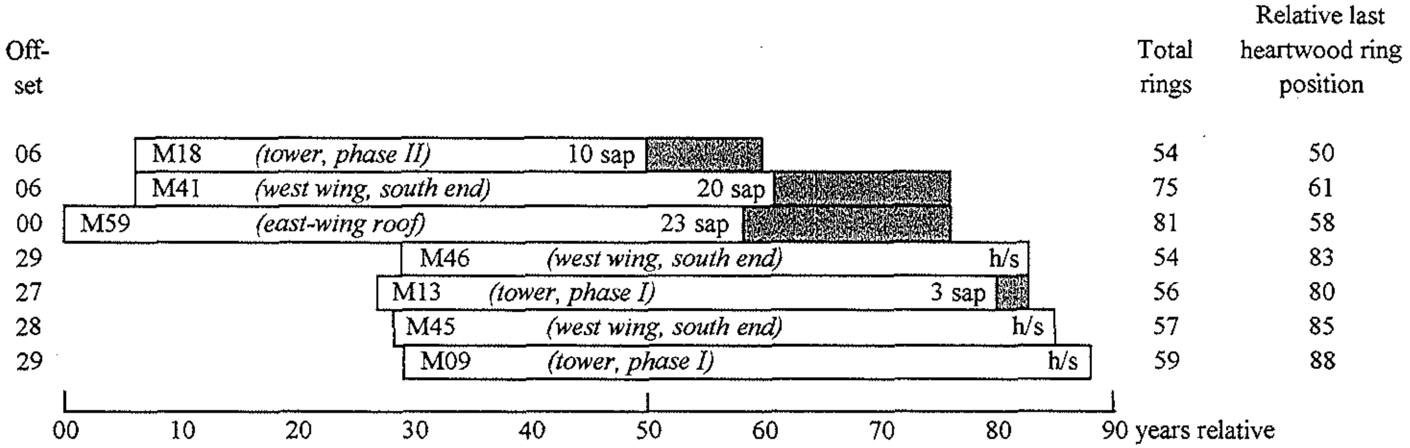


Figure 7: Bar diagram of samples in site chronology HEDMSQ03

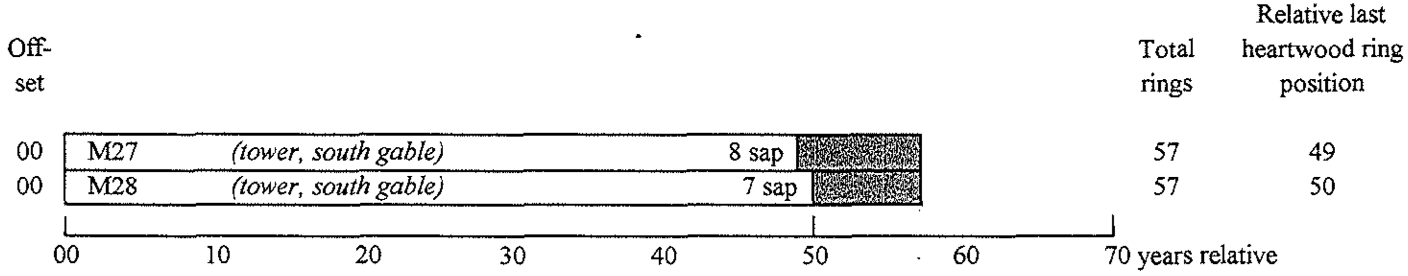


Figure 8: Bar diagram of samples in site chronology HEDMSQ04

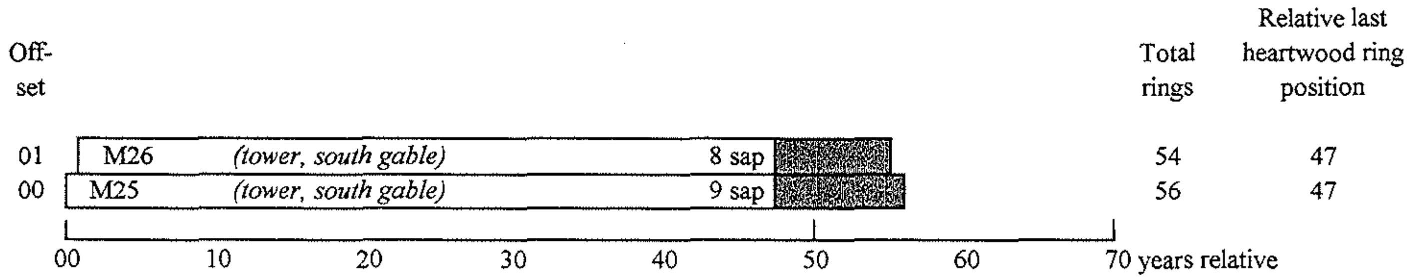


Figure 9: Bar diagram of samples in site chronology HEDMSQ05

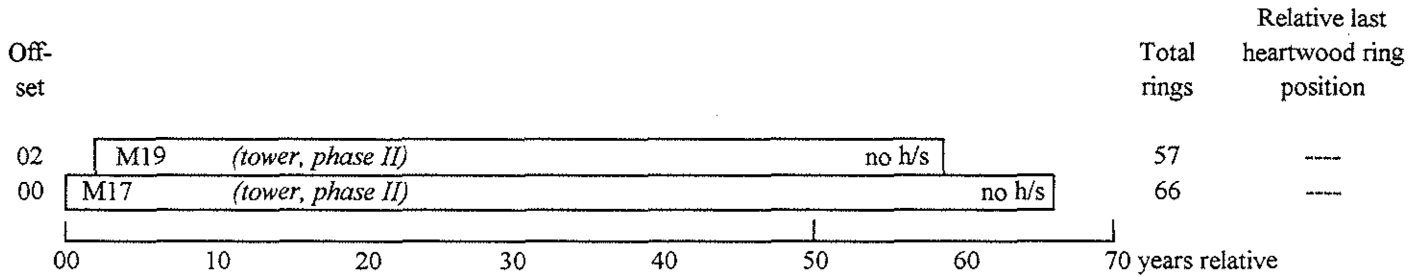


Figure 10: Bar diagram of samples in site chronology HEDMSQ06

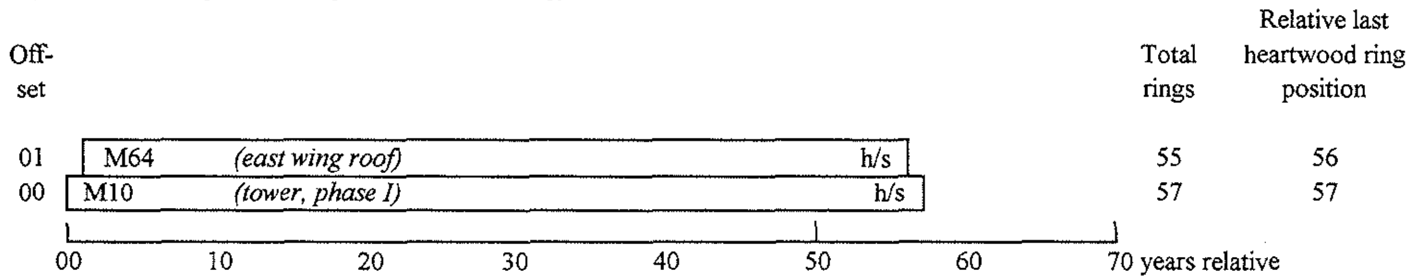
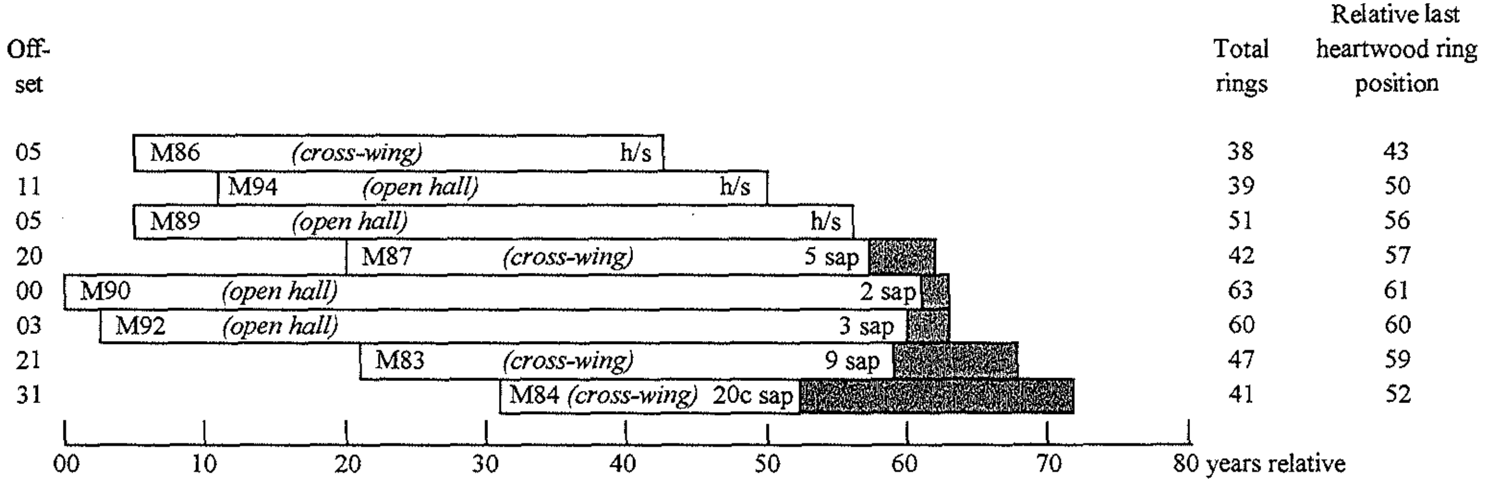


Figure 11: Bar diagram of samples in site chronology HEDMSQ07



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
c = complete sapwood on timber, all or part lost in sampling

Data of measured samples - measurements in 0.01 mm units

HED-M01A 55
91 96 145 171 184 297 229 194 192 148 134 202 192 246 251 206 175 109 125 120
150 165 195 256 194 197 202 171 202 282 178 213 199 170 165 212 211 280 262 322
269 176 177 130 184 192 254 177 137 182 195 295 216 203 198
HED-M01B 55
85 103 146 178 200 293 227 194 193 137 137 204 192 253 255 218 171 103 122 124
156 168 198 258 177 189 206 172 200 272 193 219 205 159 166 197 212 285 281 323
250 186 168 149 165 177 281 255 151 178 187 286 227 192 193
HED-M02A 54
101 139 183 274 241 263 291 185 197 102 133 108 136 111 121 182 159 139 141 145
141 178 118 148 183 153 161 178 187 252 267 277 285 192 285 192 216 266 110 150
108 142 120 145 176 164 135 141 156 143 164 140 129 207
HED-M02B 54
108 149 173 288 256 247 301 193 212 128 111 109 128 99 156 158 152 133 148 142
130 168 120 155 195 148 160 182 162 252 263 265 304 181 267 202 213 218 97 136
118 120 126 130 170 159 138 155 149 137 181 135 137 195
HED-M03A 62
144 180 291 350 225 266 239 167 308 202 226 263 309 231 220 217 166 205 205 188
238 318 134 58 75 50 27 34 33 38 45 48 48 70 49 56 68 50 78 94
48 79 41 23 35 28 37 25 31 41 42 46 42 48 39 48 42 58 43 39
43 43
HED-M03B 59
123 194 314 344 240 310 211 182 297 169 222 315 309 219 223 204 186 198 200 202
249 312 120 64 76 50 34 32 27 35 40 37 61 50 61 53 70 55 73 83
61 74 40 27 36 24 39 39 45 42 44 46 44 46 45 57 38 43 48
HED-M04A 71
41 33 42 37 46 42 45 42 52 59 77 49 59 78 71 57 97 64 44 60
61 80 91 71 62 73 57 91 113 104 134 126 55 97 128 100 124 188 101 121
175 80 103 140 100 82 69 108 98 64 73 30 81 67 55 76 81 75 49 68
65 60 32 66 82 98 48 79 108 82 61
HED-M04B 71
38 34 36 48 44 33 52 43 50 59 66 54 68 69 70 64 83 67 47 63
60 71 93 68 69 68 67 88 109 107 146 131 63 92 126 104 131 193 115 121
175 93 118 127 105 81 73 94 87 66 82 36 82 63 54 73 84 72 45 63
68 50 44 63 77 89 55 84 114 77 57
HED-M05A 67
156 314 388 320 267 350 335 206 198 341 375 238 298 206 328 278 368 168 205 287
200 333 270 338 230 271 232 192 233 211 272 305 308 333 360 284 447 251 363 230
411 446 278 293 243 193 295 254 165 279 246 196 232 213 228 284 247 277 271 211
148 187 178 169 228 198 208
HED-M05B 67
169 310 390 337 318 305 339 205 198 335 374 260 321 201 295 275 337 184 193 276
187 350 258 360 210 248 234 200 231 210 269 317 287 351 332 292 463 258 363 218
409 421 279 275 231 193 262 239 162 265 233 199 243 194 210 309 239 263 281 229
176 166 177 181 224 191 209

HED-M06A 54
435 290 351 299 469 444 489 372 418 337 495 774 529 494 218 254 254 194 141 218
217 183 237 192 255 197 291 259 295 177 304 495 389 389 282 280 316 380 278 235
340 208 119 100 147 144 191 187 122 200 117 92 109 187
HED-M06B 54
444 277 374 292 481 427 497 382 400 340 491 756 537 488 226 259 242 204 151 202
199 198 238 183 243 196 278 278 265 191 306 470 387 378 298 264 307 374 295 234
350 204 125 109 143 184 172 168 153 234 105 92 129 158
HED-M07A 52
268 345 302 473 421 493 384 415 325 522 771 535 498 216 268 231 194 153 188 199
188 237 183 248 194 274 282 282 204 322 466 405 364 307 281 331 383 281 238 344
213 124 87 130 176 184 121 201 207 117 101 103
HED-M07B 52
271 339 311 466 422 499 358 409 337 499 800 524 492 216 277 253 213 185 180 201
181 250 195 238 201 281 253 252 198 298 475 401 378 305 269 351 377 296 233 343
205 110 107 107 166 188 176 206 215 114 107 122
HED-M08A 63
57 65 67 43 50 68 75 90 45 85 106 79 53 26 25 29 31 30 38 62
72 56 71 99 71 52 79 58 99 80 61 99 112 54 62 46 90 71 89 72
79 44 35 42 33 45 41 54 78 74 79 126 73 142 112 77 107 96 82 80
71 83 111
HED-M08B 63
54 67 66 51 44 67 82 91 47 80 108 74 55 30 25 24 27 39 43 50
63 51 73 101 76 39 89 64 96 73 62 98 114 48 71 49 87 63 89 67
66 47 33 41 40 43 39 56 77 68 84 125 73 141 105 81 103 94 109 65
64 71 137
HED-M09A 59
338 342 408 78 61 28 45 41 36 58 67 71 80 73 74 104 101 135 163 130
183 207 210 199 194 233 124 44 68 54 53 33 56 76 93 149 131 190 162 136
90 108 121 203 179 164 150 216 206 239 50 58 58 59 56 61 77 97 113
HED-M09B 59
402 362 425 87 56 28 45 35 40 59 64 72 78 65 81 104 105 151 135 121
194 190 225 206 192 204 136 57 51 49 51 49 48 76 99 146 152 193 140 146
94 117 128 196 197 157 159 200 211 245 37 51 60 58 65 59 80 92 120
HED-M10A 57
209 381 444 317 387 377 319 239 249 286 307 149 63 65 65 82 77 93 101 155
135 127 151 126 153 159 151 142 205 193 192 161 234 210 180 158 177 195 184 251
187 201 385 326 188 232 302 295 182 94 136 67 84 67 105 93 153
HED-M10B 57
221 373 463 299 327 377 345 202 244 286 272 136 81 61 74 81 78 94 97 157
138 129 141 139 134 176 139 146 176 200 195 158 244 217 179 155 315 201 234 231
150 233 359 328 177 255 270 294 87 96 105 71 85 77 87 99 151
HED-M11A 40
232 384 441 247 370 385 322 166 255 276 264 76 125 73 77 90 77 98 96 151
139 132 142 130 144 173 140 145 186 198 191 161 224 217 152 157 317 212 229 251
HED-M11B 40
235 394 446 329 401 367 322 233 233 282 281 144 74 71 65 82 76 108 94 150
143 137 144 133 138 177 146 122 193 202 193 168 228 216 173 166 316 199 254 263
HED-M12A 37
402 320 155 262 280 295 146 60 76 63 78 83 100 91 165 143 133 137 131 136
191 138 141 186 195 195 157 236 214 172 172 298 179 232 238 146 179

HED-M12B 37
369 318 252 231 275 288 170 66 84 71 78 74 105 93 153 146 124 152 121 157
175 135 145 155 189 195 162 234 220 173 159 325 188 233 225 163 186
HED-M13A 56
300 247 208 291 272 162 143 192 321 275 334 396 311 325 398 293 306 246 298 338
375 317 323 301 252 198 289 256 163 150 192 196 171 254 220 154 156 128 116 151
128 154 127 177 142 184 140 135 127 146 132 123 90 78 124 161
HED-M13B 56
295 244 202 280 259 168 138 166 286 308 301 392 279 333 371 330 293 263 300 328
374 337 313 297 256 182 290 260 161 144 170 203 177 258 229 159 158 136 103 146
125 160 134 185 136 164 153 128 125 128 127 109 103 82 125 155
HED-M14A 53
184 135 99 89 102 106 117 186 208 192 195 139 109 75 114 95 135 231 229 310
297 118 190 234 202 165 155 103 77 103 103 173 252 250 187 120 176 196 257 136
146 162 232 147 208 185 120 204 233 178 159 108 154
HED-M14B 53
180 131 105 84 104 101 95 183 217 183 196 139 98 79 111 94 132 248 225 311
291 115 196 220 182 158 157 103 65 103 116 187 251 242 168 141 179 196 236 148
145 168 223 157 185 171 123 206 259 173 169 135 170
HED-M15A 57
149 88 356 421 340 359 331 320 418 370 327 421 363 303 240 265 201 187 141 179
219 179 185 279 196 205 227 243 372 313 406 355 375 324 241 348 273 261 302 256
252 180 213 135 157 110 151 153 196 208 242 186 187 255 262 242 179
HED-M15B 57
162 82 275 473 288 349 336 308 453 352 332 415 366 300 232 256 207 173 133 183
208 202 167 288 187 219 218 244 322 317 440 357 358 304 260 348 275 258 309 243
245 174 213 151 145 112 149 156 194 197 252 183 182 248 271 229 175
HED-M16A 58
284 355 333 357 472 338 342 414 385 319 239 246 204 177 128 172 203 208 173 268
179 247 210 252 340 316 435 343 387 313 265 338 274 272 292 250 245 165 226 140
162 118 151 157 194 189 253 210 172 259 276 239 176 161 193 189 285 316
HED-M16B 58
286 367 318 311 423 361 332 410 359 310 239 254 199 181 135 187 211 199 169 269
186 218 236 234 340 313 421 357 365 311 247 350 276 261 307 246 235 176 225 114
157 128 130 160 196 211 240 192 176 244 266 246 184 154 195 198 260 333
HED-M17A 66
122 154 159 97 86 75 111 88 150 116 142 111 133 160 148 190 184 194 189 169
119 127 164 126 133 151 124 118 149 134 109 159 154 225 244 275 186 127 138 146
206 180 210 162 150 166 193 187 186 215 154 121 126 133 143 142 159 136 142 135
121 125 131 143 123 147
HED-M17B 66
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113 134 169 125 136 147 123 107 160 126 122 166 165 234 227 309 188 149 144 137
210 168 214 153 154 176 187 188 195 214 156 120 108 139 141 145 167 130 149 140
117 134 127 125 129 175
HED-M18A 54
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148 155 158 117 142 206 142 55 46 46 62 77 62 54 40 27 72 84 92 82
122 99 122 106 138 142 171 200 191 180 213 210 199 231

HED-M18B 54
379 376 463 491 450 365 391 355 68 88 64 68 94 119 103 140 114 138 127 138
162 155 152 124 134 218 165 58 46 42 69 81 56 53 43 29 68 85 90 78
125 96 121 106 137 135 207 179 187 188 205 228 198 249
HED-M19A 56
100 83 73 113 83 145 117 141 133 125 139 140 177 190 195 194 170 129 123 164
133 137 145 128 110 164 114 131 164 152 221 224 277 188 148 137 139 200 161 241
170 161 172 182 182 189 217 161 122 113 149 145 159 165 130 143
HED-M19B 55
100 97 79 114 80 157 114 135 147 131 126 137 189 190 195 193 168 120 128 170
128 154 129 121 122 145 132 135 168 150 234 239 268 187 135 120 164 188 182 205
164 152 167 185 194 198 192 166 137 109 135 147 154 160 130
HED-M20A 48
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159 176 175 202 191 183 148 145 199 172 70 45 86 81 103 81 90 48 64 77
131 136 123 134 133 160 130 158
HED-M20B 48
209 165 59 48 84 96 99 71 92 61 56 79 130 123 141 126 128 155 121 156
171 175 176 187 193 181 154 140 201 169 72 48 79 106 106 96 93 39 62 88
137 124 132 130 129 148 134 154
HED-M21A 59
190 178 238 268 122 58 56 60 50 56 51 93 100 88 87 313 363 418 233 270
154 217 255 230 338 168 208 226 140 164 154 206 224 272 132 62 54 58 48 60
46 82 100 84 60 118 104 130 82 72 135 130 96 179 148 190 264 277 203
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167 215 262 234 334 170 210 224 136 173 170 198 235 267 139 59 58 50 51 64
45 89 98 84 66 103 105 133 81 72 134 133 102 180 141 180 264 253 207
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197 316 178 152 284 268 266 200 311 168 152 297 295 243 240 231 414 359 433 237
203 162 161 258 226 340 165 201 216 134 140 177 141 184 170 110 36 41 44 36
39 87 59 88 68 93 107 116 120 90 159 153 118 239 167 227
HED-M22B 56
195 322 183 151 279 308 245 218 308 188 150 263 324 254 258 238 411 358 420 234
215 145 156 247 254 325 178 207 207 126 130 179 135 210 151 108 55 45 28 43
82 79 73 86 64 94 113 113 129 79 164 159 109 240 156 227
HED-M23A 64
289 141 113 147 130 185 116 135 139 98 86 144 162 182 182 112 38 31 49 51
45 53 75 99 85 82 116 121 170 147 103 147 154 93 179 164 220 317 199 85
31 26 26 42 59 60 69 86 85 145 72 90 67 67 76 74 73 69 61 85
75 83 83 88
HED-M23B 64
216 131 121 153 127 198 114 138 148 97 87 134 169 188 187 105 41 34 47 45
50 47 81 98 82 80 118 122 175 144 97 158 154 112 170 173 225 307 209 96
31 17 22 52 57 61 75 81 87 142 78 82 70 76 70 69 80 61 64 83
78 79 87 91
HED-M24A 69
353 198 156 106 110 85 87 64 52 68 65 92 101 163 127 110 163 136 101 122
98 150 180 148 152 118 92 95 109 126 144 151 161 172 129 172 110 132 130 142
184 163 178 228 217 291 315 209 167 153 174 218 263 189 277 223 185 232 206 279
295 256 183 156 169 214 157 176 217

HED-M24B 69
321 219 155 114 107 96 94 56 53 64 62 101 106 164 111 134 168 137 107 110
97 148 185 152 141 107 100 93 105 132 135 165 166 157 153 165 109 137 120 148
185 165 198 220 214 308 318 197 160 160 174 230 252 206 247 249 156 232 214 272
279 251 181 154 175 179 166 166 242
HED-M25A 56
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348 299 342 372 261 232 157 184 174 201 190 206 199 247 263 282
HED-M25B 56
402 191 260 200 277 321 513 596 436 397 335 345 265 339 420 350 365 289 267 196
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333 317 326 378 271 228 165 178 186 182 215 221 188 258 254 279
HED-M26A 54
177 254 187 273 311 546 727 506 384 332 310 231 359 417 332 344 278 268 195 205
178 232 238 187 183 177 185 248 229 264 225 317 295 370 442 524 490 473 375 341
308 336 373 249 247 147 171 184 193 209 206 186 265 267
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177 227 225 222 151 175 181 253 211 254 217 320 293 372 444 494 520 474 396 332
321 335 360 272 231 161 183 195 186 191 228 183 262 277
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636 504 593 569 520 441 431 398 426 315 344 418 416 502 525 558 532 589 483 482
560 489 499 563 574 361 378 311 334 413 319 384 329 304 125 171 156
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251 190 172 118 265 304 371 255 411 338 326 376 345 598 478 572 487 564 477 471
630 552 555 546 468 430 428 388 412 336 356 398 420 493 503 583 534 605 457 488
556 484 523 527 586 362 385 306 328 413 297 333 342 322 116 167 169
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268 174 187 114 261 312 377 272 388 328 344 381 340 591 481 590 499 611 505 472
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553 472 547 553 561 361 395 294 325 416 316 349 294 324 134 165 150
HED-M28B 57
284 184 186 112 265 295 375 291 386 343 304 384 342 595 479 596 463 596 515 474
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541 482 529 556 567 364 376 298 337 411 317 371 333 289 126 165 172
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587 497 606 484 480 572 476 512 536 572 364 389 300 343 409 306 378 312 309 130
59 157 163 286 400 366 311 340 295 318 132 169 257 288
HED-M29B 54
316 357 406 417 478 513 580 535 609 466 425 481 523 568 573 604 462 477 561 474
567 504 612 467 481 582 484 518 549 580 358 387 294 342 396 307 356 289 333 132
65 167 278 272 409 307 358 287 336 320 150 155 267 234
HED-M30A 55
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130 115 129 156 142 195 141 118 90 113 112 96 83 90 121 230 176 171 101 153
223 200 138 95 106 90 122 98 149 129 276 182 141 307 288

HED-M30B 55
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126 118 136 155 147 173 165 113 98 98 130 75 86 86 120 236 178 180 110 156
190 222 119 90 80 110 93 114 163 97 303 218 135 284 293
HED-M31A 54
218 131 151 198 126 143 169 216 213 214 179 193 310 270 221 218 154 133 192 167
121 137 108 155 124 112 115 186 201 233 180 187 210 182 177 179 166 201 277 211
207 166 193 187 246 218 266 258 351 410 391 395 362 367
HED-M31B 54
206 129 145 180 152 128 179 205 215 197 177 200 341 277 217 234 124 130 188 167
121 122 117 156 111 113 118 183 215 221 172 187 213 186 182 187 157 201 291 197
192 163 202 185 267 214 265 260 343 396 390 414 372 345
HED-M32A 55
70 42 79 73 62 66 64 64 86 83 61 65 60 72 78 121 123 137 152 96
84 89 82 95 66 97 77 68 66 59 73 95 88 66 91 95 80 117 125 143
127 83 106 86 65 85 97 86 112 138 135 134 120 137 152
HED-M32B 55
87 80 65 68 64 70 68 86 71 128 103 138 171 94 81 62 61 65 77 79
122 123 134 152 105 78 81 93 92 73 92 82 63 64 56 88 79 100 76 95
84 93 96 137 130 134 84 96 96 74 94 87 83 122 132
HED-M33A 71
206 154 114 137 100 216 175 108 182 152 261 214 184 140 92 101 177 132 182 123
115 72 82 78 82 98 140 89 69 72 68 47 53 70 54 79 82 82 67 68
82 98 115 79 63 53 40 48 65 90 69 79 90 69 94 93 66 57 44 48
40 48 51 43 41 52 49 56 61 77 45
HED-M33B 71
218 153 118 135 113 208 160 117 176 139 272 222 178 142 88 109 163 137 183 121
106 81 85 73 86 114 126 89 81 59 71 53 47 76 54 69 102 79 66 70
87 92 108 77 67 43 47 49 78 81 73 76 85 79 87 85 80 48 49 36
47 41 39 47 46 58 47 49 64 64 68
HED-M34A 58
41 38 40 40 54 45 66 76 49 68 68 63 107 115 76 110 82 94 65 93
81 62 69 66 59 78 82 45 69 76 72 109 79 62 68 90 106 116 102 188
133 110 107 141 137 95 158 93 82 114 91 114 143 122 101 113 122 158
HED-M34B 58
38 35 37 46 48 52 64 81 53 57 63 70 101 110 77 114 86 94 58 89
88 61 72 63 62 87 76 45 63 82 64 105 82 71 60 89 109 116 104 187
146 100 114 139 146 90 145 92 89 110 91 90 150 117 112 119 144 154
HED-M35A 52
226 274 252 299 368 347 339 343 326 177 166 212 248 185 166 242 177 219 173 259
195 194 246 187 163 136 162 172 127 178 238 175 198 176 233 182 181 177 159 309
177 213 230 350 297 185 245 171 209 218 221 262
HED-M35B 52
221 306 217 297 389 324 335 446 252 193 202 200 238 200 182 250 170 229 161 250
208 205 245 177 162 120 178 150 145 179 246 198 206 172 215 173 192 150 196 283
145 216 230 326 382 198 240 180 211 216 221 217
HED-M36A 68
86 110 184 196 272 124 139 138 62 109 235 176 167 126 145 183 182 133 132 150
178 110 144 172 119 96 127 121 116 199 113 106 98 88 63 94 145 147 191 155
135 167 183 174 96 98 126 98 106 99 130 108 136 141 132 178 221 138 76 108
100 71 69 86 74 76 146 160

HED-M36B 68
99 118 179 159 323 94 143 143 67 91 194 187 171 134 127 196 173 180 143 173
149 107 155 169 124 93 141 101 115 182 116 99 96 82 70 104 112 162 181 165
143 201 199 135 122 106 142 100 89 91 158 121 122 146 125 176 247 162 93 114
94 77 73 76 75 74 164 150
HED-M37A 56
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HED-M37B 56
43 72 68 50 69 79 78 71 61 62 53 63 70 77 143 112 104 154 137 147
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109 82 78 72 83 77 65 86 69
HED-M39B 69
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HED-M40A 77
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HED-M40B 77
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HED-M41A 75
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HED-M41B 75
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HED-M42A 54
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HED-M43A 81
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HED-M44B 54
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HED-M45A 57
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HED-M45B 57
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HED-M46A 54
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HED-M46B 54
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395 364 346 411 401 365 453 321 244 285 330 311 282 253 162 117 83 75 58 101
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HED-M48A 56
274 294 404 193 119 293 290 387 151 153 235 318 378 104 108 62 68 48 85 224
139 310 397 245 266 232 273 256 233 364 347 224 245 314 246 179 177 204 212 171
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HED-M48B 56
226 299 417 141 104 275 293 395 122 95 227 334 391 108 102 70 68 43 78 234
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175 143 239 211 274 249 213 192 245 159
HED-M50A 57
386 675 669 596 577 552 390 421 254 270 201 194 267 342 251 254 343 555 502 360
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HED-M50B 57
408 655 618 586 607 588 345 422 244 265 198 227 291 320 264 269 346 505 503 369
265 183 193 280 260 259 204 265 262 214 120 108 185 171 192 186 139 144 141 110
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HED-M51A 55
149 252 296 104 159 190 170 122 120 188 209 170 121 192 171 150 141 133 118 195
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HED-M52A 57
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263 203 126 105 140 171 207 182 228 195 167 139 143 145 120 155 163
HED-M52B 57
99 126 113 132 68 103 88 117 90 58 66 79 70 71 66 73 60 72 71 63
69 67 58 50 57 74 58 67 83 116 79 100 99 89 68 117 173 170 345 343
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HED-M53A 54
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134 186 166 116 157 154 117 138 129 160 161 206 216 200
HED-M53B 54
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HED-M54A 56
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HED-M54B 56
444 506 402 381 579 410 221 240 157 253 272 528 343 189 224 281 282 308 272 239
280 207 195 193 219 125 194 269 265 336 328 287 472 363 291 324 290 206 200 174
177 262 222 313 244 245 211 200 207 373 522 430 451 550 441 335
HED-M55A 57
213 116 125 105 149 163 157 122 138 137 153 206 139 177 268 458 359 182 239 221
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148 117 163 162 125 114 126 191 150 127 106 110 139 101 131 138 151
HED-M55B 57
229 129 114 78 164 159 153 114 140 147 127 224 137 190 312 448 328 187 219 243
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137 119 170 177 103 100 135 217 142 130 114 128 125 99 106 138 173
HED-M56A 56
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HED-M56B 56
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HED-M57A 95
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185 170 117 143 152 123 200 129 150 106 103 132 159 131 116 123 129 120 169 97
134 135 121 116 127 112 112 85 126 89 90 93 88 84 106 93 80 131 135 91
173 181 108 128 98 130 110 104 105 145 207 120 121 83 167
HED-M57B 95
157 150 118 105 118 72 98 119 131 88 157 140 183 162 132 177 153 166 150 137
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168 166 128 123 103 132 106 110 103 127 209 115 111 91 169
HED-M58A 66
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188 222 165 185 202 269

HED-M58B 66
171 194 176 167 245 234 191 248 179 215 155 94 141 132 113 122 199 117 115 178
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225 208 154 170 219 278
HED-M59A 81
401 283 343 283 193 160 119 186 137 176 172 153 206 236 158 165 138 112 125 132
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382 279 350 280 195 161 111 187 152 175 180 162 209 239 151 175 134 103 125 134
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128
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212 192 227 107 173 187 128 184 187 171 196 174 137 151 220 195 295 222 148 190
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HED-M60B 79
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HED-M61A 55
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HED-M61B 55
418 368 345 310 226 252 292 310 210 285 407 343 382 375 289 383 233 185 246 179
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HED-M62A 54
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229 226 104 116 106 173 176 187 182 304 290 182 299 294
HED-M62B 54
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HED-M63A 55
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HED-M63B 55
227 179 258 252 268 321 223 187 183 209 289 243 306 185 176 256 442 347 258 260
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HED-M64B 55
224 198 229 151 247 164 159 227 208 341 156 174 210 255 255 202 201 156 192 146
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HED-M65A 56
221 195 143 244 201 338 148 186 218 256 260 190 211 147 185 131 225 287 216 262
213 303 146 133 280 194 222 213 276 254 256 225 174 110 196 231 137 172 124 158
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HED-M65B 56
243 159 169 227 211 332 149 179 221 258 256 185 219 133 188 163 216 287 180 300
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178 192 116 159 236 168 232 140 250 161 172 137 109 142 124 165
HED-M66A 54
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205 120 146 168 132 131 157 203 292 262 220 186 249 177
HED-M66B 54
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HED-M67A 55
174 213 273 217 246 269 203 173 163 188 201 126 197 193 175 75 135 146 128 191
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175 125 164 185 244 208 227 227 242 297 219 241 276 187 150
HED-M67B 55
174 208 240 264 259 244 204 166 200 202 199 115 187 188 170 82 126 160 115 187
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170 136 156 197 244 199 222 224 241 273 234 285 260 193 192
HED-M68A 54
257 135 195 207 269 122 125 105 127 234 139 146 121 255 152 191 235 344 197 233
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164 174 130 156 161 148 197 110 112 83 96 106 106 111
HED-M68B 54
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168 177 148 156 176 136 205 98 106 92 90 100 104 109
HED-M69A 50
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HED-M69B 50
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155 165 136 177 142 151 133 102 138 181

HED-M70A 48
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HED-M70B 48
193 223 192 242 297 285 198 209 233 306 293 192 240 200 196 175 187 141 117 127
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191 193 234 226 140 147 193 138
HED-M71A 52
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HED-M71B 52
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HED-M72A 47
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HED-M72B 47
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115 169 154 163 153 110 69
HED-M73A 57
90 104 118 95 93 74 81 92 160 141 151 128 124 131 241 223 150 145 136 130
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HED-M73B 57
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HED-M74A 58
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HED-M74B 58
389 534 277 227 186 271 205 231 241 366 343 244 339 346 290 308 330 153 145 103
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24 26 38 43 66 77 104 69 74 93 70 35 36 46 59 60 52 48
HED-M75A 56
402 223 333 284 542 579 716 644 695 648 606 384 425 507 445 486 189 178 182 142
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HED-M75B 56
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HED-M76A 56
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HED-M76B 56
321 316 325 241 274 281 335 343 333 284 298 211 270 198 202 240 239 158 207 186
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HED-M78B 54
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HED-M79A 53
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HED-M79B 53
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HED-M80A 58
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HED-M81A 59
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HED-M81B 54
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177 184 116 105 102 173 158 114 113 145 109 125 109 92

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HED-M82B 80
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HED-M83A 47
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221 212 222 102 171 158 159
HED-M83B 47
261 240 266 197 224 202 163 262 157 195 158 205 184 247 400 340 274 222 212 308
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213 223 233 100 153 176 183
HED-M84A 36
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HED-M84B 33
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HED-M85A 55
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HED-M85B 48
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HED-M86A 38
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HED-M86B 38
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127 81 72 87 54 94 80 84 56 70 78 65 94 93 65 71 42 69
HED-M87A 42
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135 181 145 194 197 248 276 266 301 321 277 405 426 263 214 297 275 298 375 343
322 278
HED-M87B 42
132 227 268 329 168 317 303 255 247 166 188 215 203 248 200 237 240 174 173 157
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319 280
HED-M88A 18
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HED-M88B 18
563 611 718 484 492 352 239 242 295 330 300 174 135 141 188 201 164 157

HED-M89A 51
211 202 156 240 254 160 187 180 212 200 350 414 266 321 249 311 469 503 416 160
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HED-M89BB 51
159 198 164 234 245 158 183 163 203 212 353 418 263 316 251 314 485 512 402 148
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209 214 145 167 193 134 253 238 159 130 249
HED-M90A 63
399 424 269 430 391 438 533 301 436 711 383 428 463 553 343 441 374 299 345 299
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255 183 222
HED-M90B 63
394 415 269 502 399 450 513 326 446 716 385 421 470 534 321 439 383 292 332 286
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183 166 130 189 175 209 258 202 260 240 145 223 208 146 93 145 190 221 274 257
261 177 230
HED-M91A 29
194 270 316 397 417 413 558 421 542 533 485 333 398 397 465 481 425 371 292 411
369 440 303 435 429 425 538 488 382
HED-M91B 29
179 265 313 386 462 455 578 402 536 543 485 330 385 402 454 474 405 371 276 400
403 419 322 421 434 444 518 493 382
HED-M92A 52
285 244 298 203 282 257 236 241 177 192 221 221 259 162 219 175 197 180 140 195
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HED-M93A 33
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213 139 260 206 193 245 196 250 235 227 189 260 290
HED-M93B 33
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212 151 269 204 188 233 187 250 216 228 192 240 336
HED-M94A 39
426 449 488 372 495 467 329 366 403 337 642 506 210 172 328 396 394 425 318 382
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HED-M94B 39
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HED-M96A 39
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HED-M97A 35
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HED-M97B 35
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HED-M98A 35
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HED-M98B 35
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HED-M99A 66
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60 65 128 142 159 132 146 224 204 182 171 248 221 332 278 201 181 250 225 191
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HED-M99B 66
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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.

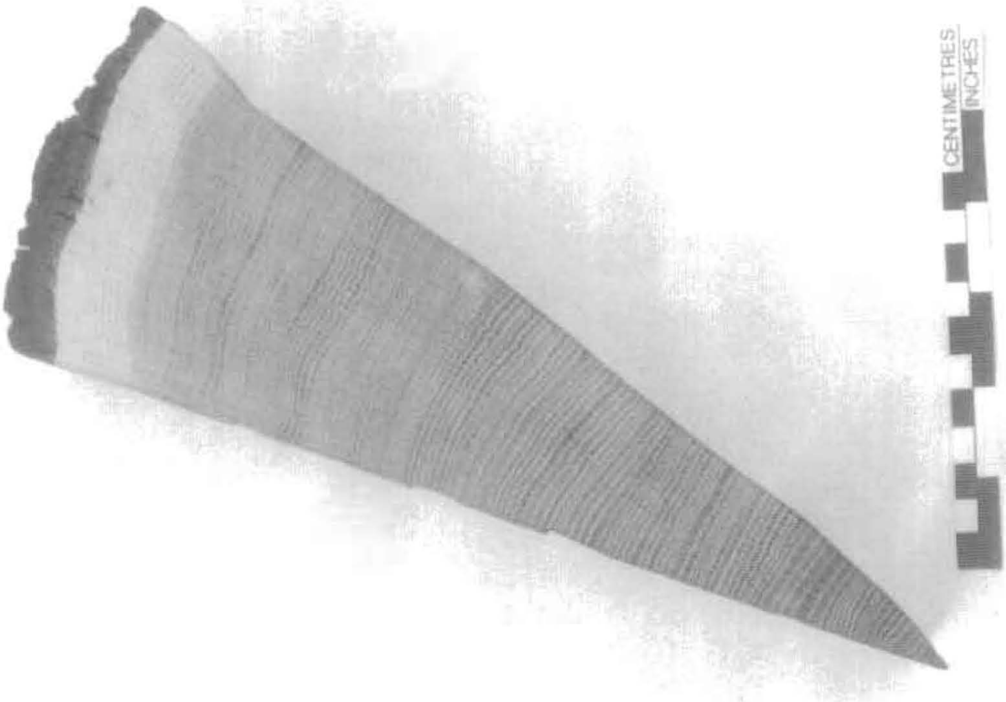

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

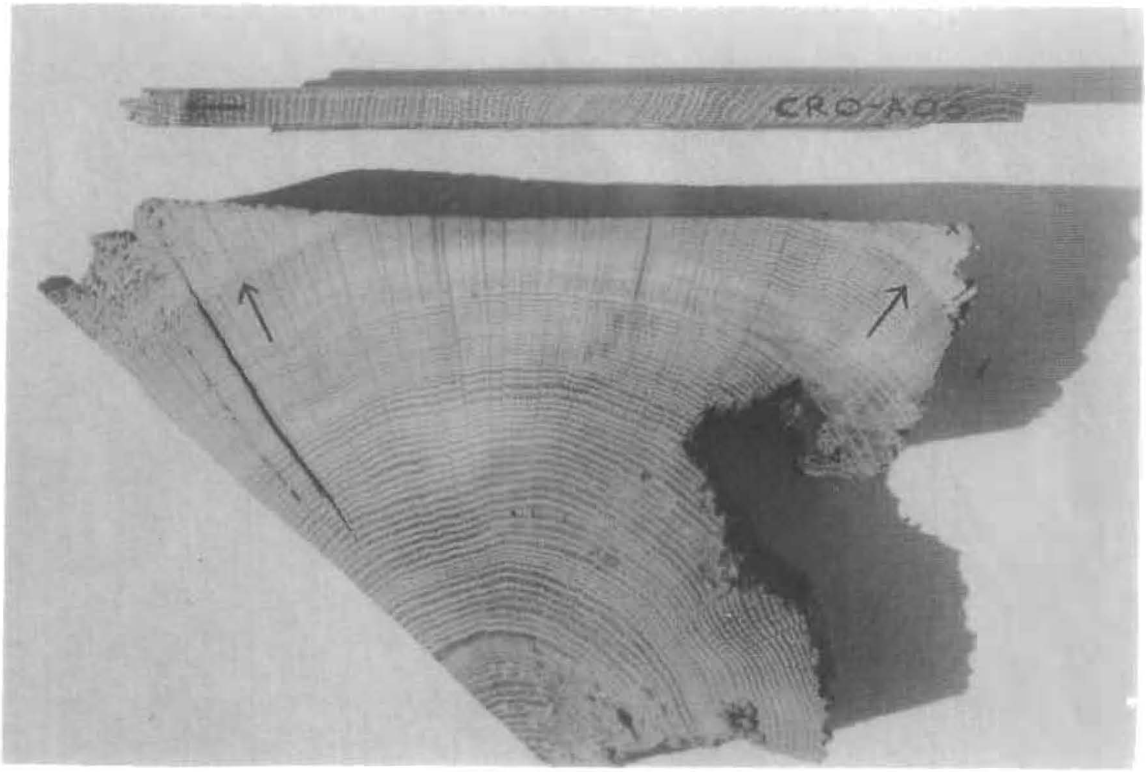

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

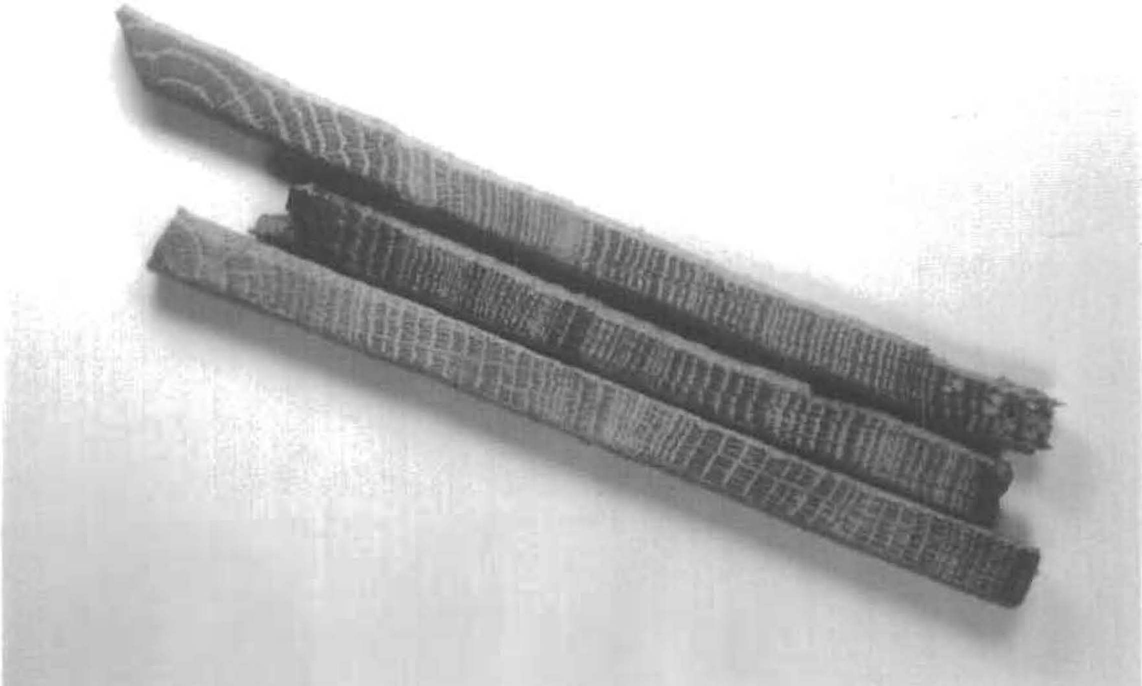

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

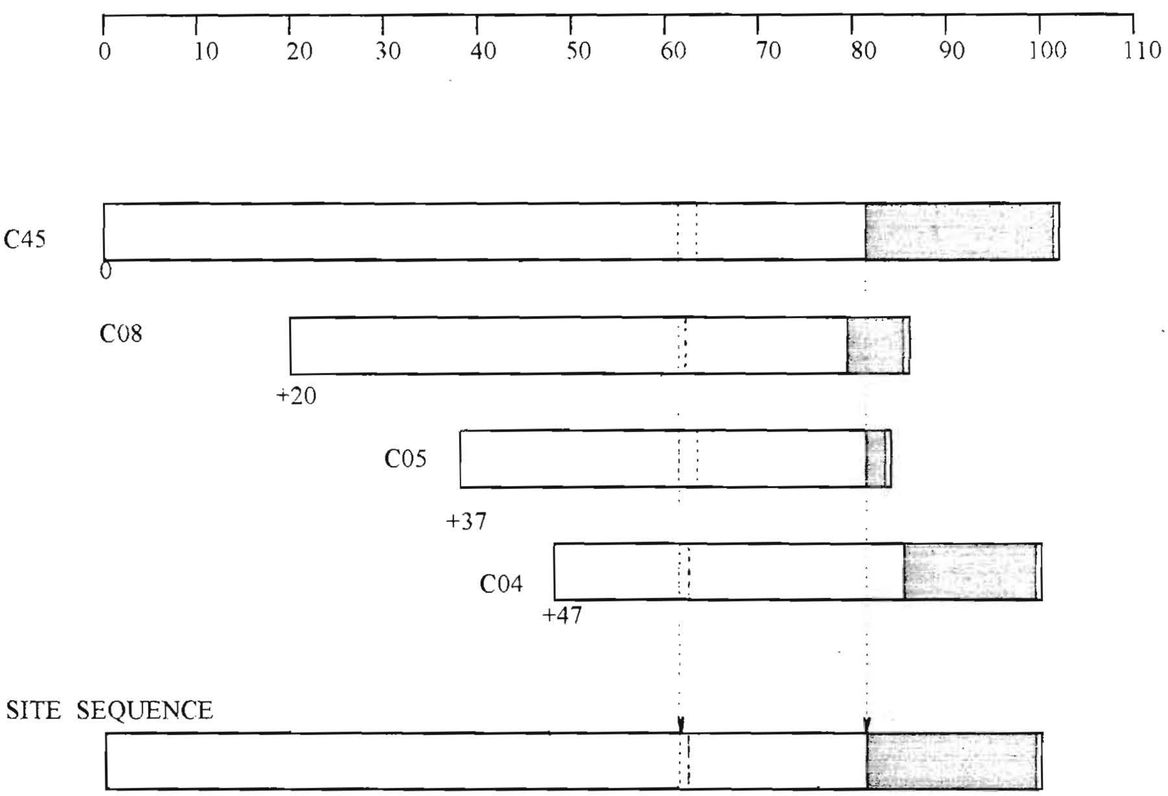

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

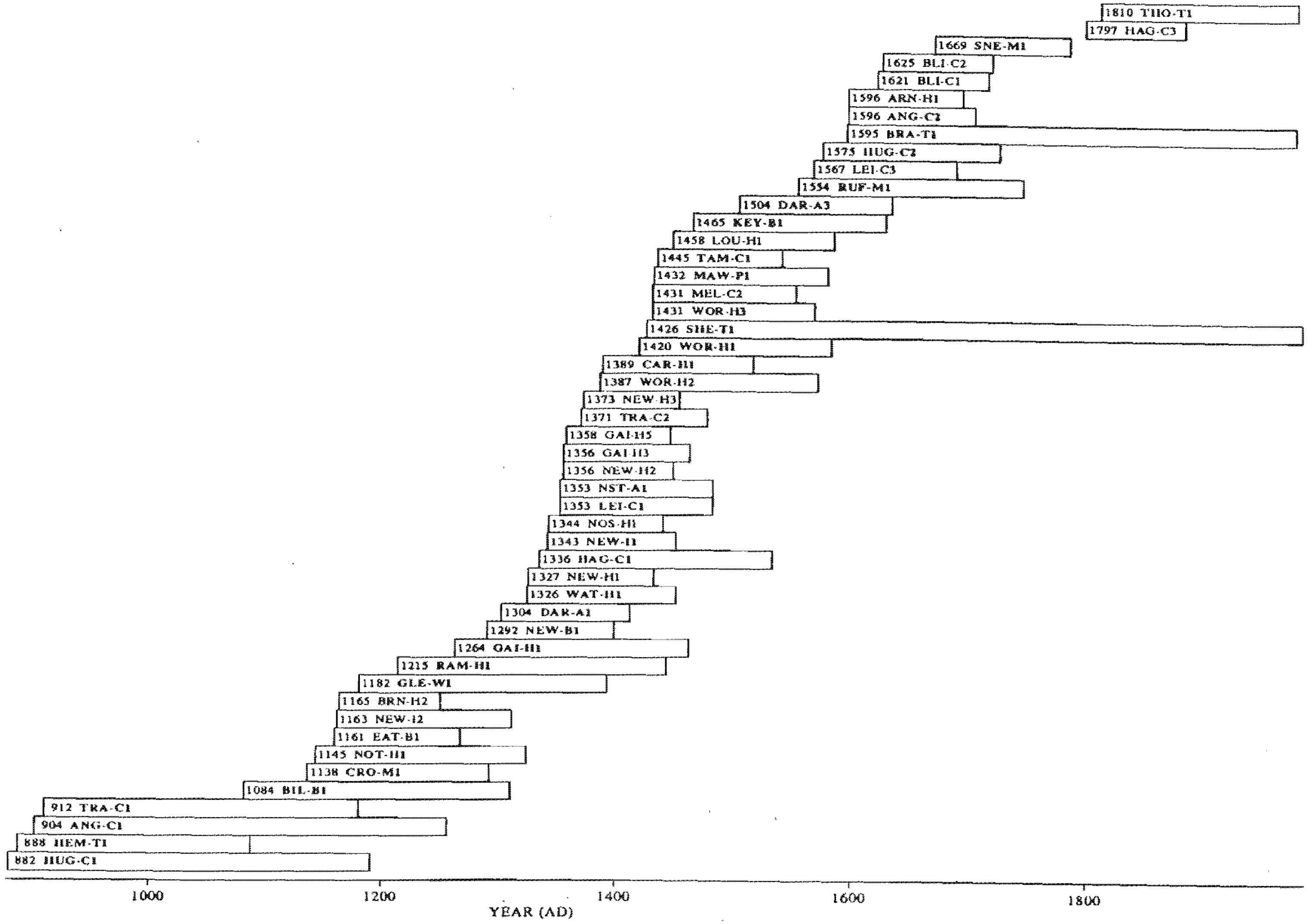

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

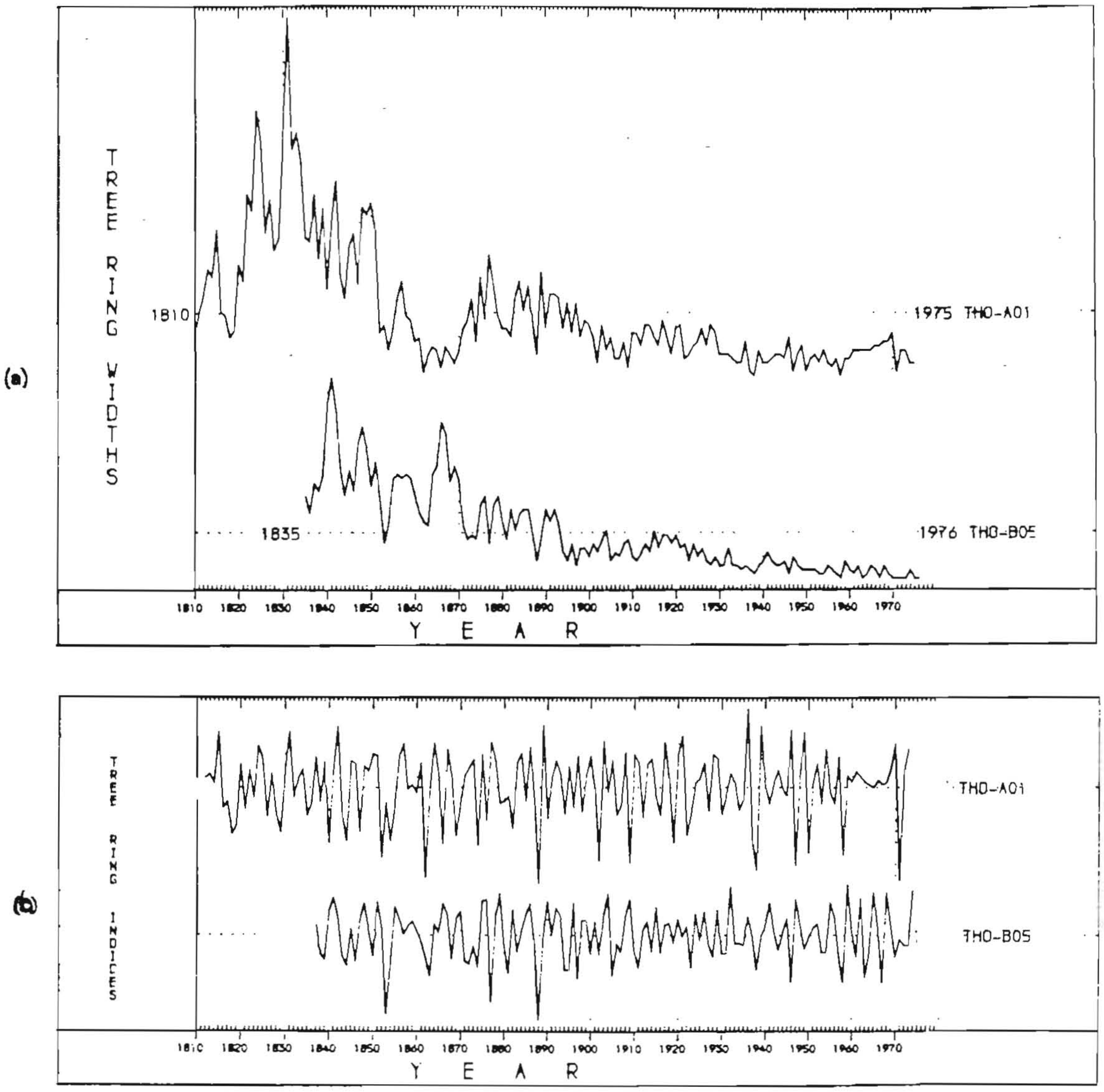

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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