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HALES HALL, LITCHMERE LANE, LODDON, NORFOLK
TREE-RING ANALYSIS OF TIMBERS FROM THE HALL RANGE, BARN, AND BOTHY

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY

Dendrochronological analysis was undertaken on 86 of the 91 core samples obtained from the hall range, barn, and bothy at Hales Hall, Loddon, Norfolk. Interpretation of the sapwood on the 74 dated samples would suggest the likelihood that construction of the original hall range and barn took place in the AD 1490s, although a few possibly slightly earlier timbers were incorporated. The extant roofs to the east and middle sections of the hall range, the east-end ground- and first-floor ceilings of the hall range, and the original part of the bothy date to the mid-AD 1590s, although again incorporating a few possibly slightly earlier timbers. The ground-floor ceiling in the bothy extension uses reused timbers originally felled in AD 1410–35 and AD 1468–93.

CONTRIBUTORS

Alison Arnold and Robert Howard

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Union House
Gressenhall
Dereham NR20 4DR

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

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INTRODUCTION

Hales Hall, set on the edge of Hales Green close to Lodden in Norfolk (Fig 1), comprises a complex of extant buildings of varying dates and listing designation. To the west are the moats (Fig 2) which enclosed a hall constructed in the AD 1480s by Sir James Hobart (*c* AD 1440–1517), Attorney General to Henry VII from AD 1485 until his retirement in AD 1507, of which only the foundations of the principal building survive and which is a Scheduled Ancient Monument. The present Grade I listed hall range (Fig 3), and the barn form respectively the north and south sides of an enclosure east of the moat. The following background information is from the listing descriptions *(http://list.english-heritage.org.uk)* and Heywood (pers comm).

Hall range

The hall range, originally constructed as a jettied timber frame over a brick ground floor, may have fifteenth-century origins. The framing has been replaced with brickwork, although the odd stud still survives. The eastern half of this range (Fig 4) is believed to have been severely damaged by a fire in AD 1599, and it is thought that the present roof represents the rebuilding after this fire. It is a high-quality roof of butt purlin and collar construction and is accompanied by a very impressive floor with flat joists apparent in the rooms below for which an early seventeenth century date has been suggested. It is unclear how much of the ground-floor ceiling was damaged in the fire.

Parts of the hall range may have undergone alteration in the seventeenth century, and the roof of the middle section (Fig 4) was replaced in the eighteenth century, this being typical of the period in having lap-jointed collars and butt purlins with tapered tenons sharing single mortises producing diagonal pegging.

The earliest, and apparently only, surviving section of original roof is at the west-end of the hall range above the gatehouse and westward beyond it (Fig 4). The gatehouse has the remains of a crown-post roof, whilst the room to the west has a queen-post roof. The timber of the gatehouse walls is largely a reconstruction of the early 1970s but the original work is easily discernable. The floor and stud partitions of the rest of the building have several modern replacements yet retain a lot of the original timbers. The first floor consists of heavy transverse beams with the common joists jointed to them.

Barn

The Grade 1 listed barn to the south side of the enclosure (Fig 5) is believed to be the largest and possibly the oldest medieval brick-built barn in England. It is about 170 feet (*c* 52 metres) long and has a continuous 10-bay roof of queen-post trusses. The trusses of a further four bays at the easternmost end of the barn also have crown-posts mounted on the collars, there being a mezzanine in these four bays as well. The east gable-end bay has

a hearth and living accommodation. The barn is also believed to be of late fifteenth-century date, having also been built by Sir James Hobart, but there is some debate about this, and it is unclear if it is all of a single phase of construction. There are additional, probably agricultural, outbuildings adjacent to the barn, these probably dating to the nineteenth century at the earliest.

Bothy

To the immediate south-east of the hall range is a small Grade II* listed building, described as a 'small barn' and known as the 'bothy' (Fig 6), which is currently used as domestic accommodation. The bothy is a red and blue brick construction with a steep pantile roof with coped gable ends. This building appears to be of two parts. The west (front) part is believed to be the earlier original structure and is roofed by five clasped-purlin trusses. The east (rear) part is believed to be a later addition and referred to as the 'bothy extension'. It is roofed by common rafter frames. There are also moulded timbers to the ground-floor ceilings of this part, these likely to be reused in their present positions.

SAMPLING

Dendrochronological analysis of various buildings of the Hales Hall complex was requested by David Eve, English Heritage Inspector of Historic Buildings and Areas. This programme of analysis was commissioned to better understand the significance of the site and its development, the results being used to inform an on-going schedule of works at the site and its future protection and management.

Prior to sampling, a detailed assessment was made of the timbers throughout the Hales Hall complex as to their suitability for tree-ring analysis. This assessment, combined with the potential phasing as identified by Stephen Heywood, ensured that a suitable sampling strategy was employed in order to address the potential complexities with respect to the development of this group of buildings.

Thus from the suitable timbers of each area a total of 91 samples was obtained by coring. Each sample was given the code HHB-A (for Hales Hall site 'A') and numbered 01–91 (Table 1). The locations of these samples were recorded at the time of sampling on sketch drawings and photographs before being transferred to a set of architects drawings provided by English Heritage, these being shown as Figures 7–9. In Table 1, the trusses, frames, beams, and bays have been numbered from east to west, with individual timbers then being further identified on a north–south basis as appropriate.

It should be noted that some potential areas of historic significance, as outlined in the introduction paragraphs, have not been sampled. These include the only surviving section of original roofing of the hall range above the gatehouse and the rooms to the west, the middle sections of the hall-range roof, and the roof of the bothy extension. These, and other timbers, were deemed to be unsuitable for analysis. This was generally as a result of

the timbers being derived from fast-grown trees and thus having insufficient rings for dating (<40), though some timbers were simply too small and again contained too few rings. It was also noted during the assessment that there were some timbers that were not oak; these included a small number of pine timbers which are therefore likely to be later replacements or insertions.

ANALYSIS AND RESULTS

Each of the 91 samples obtained from the timbers of the various buildings and elements of the Hales Hall complex was prepared by sanding and polishing. It was seen at this time that five samples had fewer than the minimum of 40 rings deemed necessary for reliable dating, and these were rejected as being unsuitable. The annual growth-ring widths of the remaining 86 samples were, however, measured, the data of these measurements being given at the end of this report.

The data of the 86 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process producing two separate groups of cross-matching samples. The first group comprises 36 samples, which were combined at their indicated offset positions to form site chronology HHBASQ01, this having an overall length of 259 rings. The second group comprises 38 samples which were combined at their indicated offset positions to form site chronology HHBASQ02, this having an overall length of 137 rings. The two site chronologies thus account for 74 samples between them. The constituent samples of the two site chronologies are shown in Figure 10.

The two site chronologies were then compared to an extensive corpus of reference material for oak, this process resulting in the successful dating of both of them; both site chronologies matching repeatedly and consistently with a series of reference chronologies. Site chronology HHBASQ01 is dated as spanning the years AD 1236–1494, while site chronology HHBASQ02 is dated as spanning the years AD 1458–1594 (Tables 2 and 3).

The two site chronologies were then compared with the 12 remaining measured but ungrouped single samples. There was, however, no further satisfactory matching. The 12 remaining ungrouped samples were than compared individually with the full range of reference chronologies for the oak, but again there was no conclusive cross-matching, and all these samples must remain undated.

This analysis may be summarised as below:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
HHBASQ01	36	259	1236–1494
HHBASQ02	38	137	1458–1594
Ungrouped	12	---	undated
Unmeasured	5	---	---

INTERPRETATION

Analysis by dendrochronology of timbers from the different buildings of Hales Hall and their various elements has produced two site chronologies, these providing dates for all areas sampled in the hall range, the barn, and the bothy. The sapwood estimate used for the estimate of felling date ranges or *terminus post quem* felling dates is 15-40 (95% confidence interval).

Hall range

West end ground-floor ceiling

The ground-floor ceiling to the west end of the hall range is represented by four dated samples (Fig 10). None of them retains complete sapwood (the last ring produced by the tree before it was cut), and it is thus not possible to indicate a precise felling date for any of the timbers. One sample, however, HHB-A38, retains the heartwood/sapwood boundary, this being dated to AD 1402 which produces an estimated felling date in the range of AD 1417–42.

The felling date of the other three timbers cannot be reliably determined because they do not have the heartwood/sapwood boundary and are thus missing not only their sapwood rings, but an unknown number of heartwood rings as well. However, with the latest heartwood ring on any sample, HHB-A42, dated to AD 1367, and allowing for a minimum of 15 sapwood rings, it is unlikely that they were felled before AD 1382.

It is thus possible that all the timbers represented by all these samples were felled at the same time, although this cannot be proven.

Gatehouse passage ceiling

The ceiling to the gatehouse passage is represented by eight dated samples (Fig 10). Likewise, none of them retains complete sapwood, and it is again not possible to indicate a precise felling date for any of the timbers. Seven of the samples, do though, retain some sapwood or at least the heartwood/sapwood boundary. This boundary varies by 17 years from AD 1465 on sample HHB-A45, to AD 1482 on sample HHB-A48, such a variation suggesting that these timbers were cut as part of a single episode of felling. The average date of this boundary is AD 1474, which gives the timbers an estimated felling date in the range AD 1489–1514. The remaining sample has an outermost measured heartwood ring dating to AD 1455 which, combined with the high level of overall cross-matching, makes it likely that this timber was also felled during AD 1489–1514.

Ground-floor middle ceiling

The ground-floor ceiling to the middle section of the hall range is represented by five dated samples. None of these five samples retain complete sapwood, but all do retain at least the heartwood/sapwood boundary. On four of these samples the boundary varies by only six years suggesting that the timbers were again cut as part of a single episode of felling. The average date of the boundary on these four is AD 1477, which gives the timbers an estimated felling date in the range AD 1492–1517.

The fifth sample of this group, HHB-A36, has slightly earlier heartwood/sapwood boundary, this being dated to AD 1455 and hence an estimated felling date in the range AD 1470–95. Thus, while it appears to have been felled slightly earlier than the other ceiling beams to this area, there is a possibility that it was felled at the same time if it had more than the usual number of sapwood rings.

Ground-floor east ceiling

The ground-floor ceiling to the east section of the hall range is also represented by five dated samples. In this case, one sample, HHB-A26, does retain complete sapwood, this last sapwood ring, and thus the felling of the tree represented, being dated to AD 1594.

The heartwood/sapwood boundary on two other samples, HHB-A27 and A28, is at a generally similar position to that on HHB-A26. The average date of the heartwood/sapwood boundary is AD 1568 which produces a felling date range of AD 1583–1608. This encompasses the precise felling date of AD 1594 and suggests that they too were cut at a similar, if not identical, time.

The two remaining samples, HHB-A30 and A31, are without the heartwood/sapwood boundary. With last heartwood ring dates of AD 1560 and AD 1540, and allowing for a minimum of 15 sapwood rings, they were unlikely to have been before AD 1575 and AD 1555, respectively and thus it is possible that they were also felled at a similar time.

Middle roof

The roof to the middle section of the hall range is represented by four dated samples. On three of these samples the heartwood/sapwood boundary is at very similar positions, suggesting a single episode of felling. Given that the average date of the boundary on these three is dated AD 1569, they have an estimated felling date in the range AD1584–1609. However one of these samples, HHB-A13, has an estimated 20 sapwood rings which are too indistinct to measure. Given that the heartwood/sapwood boundary on this sample is dated to AD 1568, this would suggest that it, and therefore probably the other two samples, were felled in AD 1588 at the earliest.

The fourth sample of this sub-group, HHB-A16, has an earlier heartwood/sapwood boundary, this being dated to AD 1543 and hence producing an estimated felling date in the range of AD 1558–83. It thus appears to have been felled slightly earlier than the other roof timbers to this area, although there is a possibility that it was felled at the same time as the others, if it had more than the usual maximum number of sapwood rings.

First-floor ceiling east end

The first-floor ceiling to the east end of the hall is represented by eight dated samples, all retaining some sapwood or at least the heartwood/sapwood boundary. This boundary varies by only seven years from AD 1570 on four samples to AD 1577 on two samples, which suggests that all of the timbers were cut as part of a single episode of felling. The average boundary date is AD 1573 which indicates that felling occurred at some time in the range of AD 1588–1613.

East end roof

The roof to the east end of the hall range is represented by 12 dated samples. Three of these samples retain complete sapwood, the date of the last ring thus indicating the felling of the tree represented. Sample HHB-A11 was felled in AD 1593, whilst HHB-A03 and HHB-A12 provide felling dates of AD 1594.

The heartwood/sapwood boundary of the other nine samples varies by 16 years, from AD 1566 (HHB-A08) to AD 1582 (HHB-A08), this variation suggesting that while all the timbers may not have been cut at exactly the same time, they are all likely to be coeval and represent a single felling period. The average date of the heartwood/sapwood boundary of the nine samples is dated AD 1574 giving these timbers a felling at some time in the range AD 1589–1614, a range which brackets the known felling dates of the three other timbers from this roof. This, combined with the overall level of cross-matching within this group of timbers, suggests that they are all likely to be felled at a similar time in the AD 1590s.

Hall range - summary interpretation

Forty-six timbers have been dated from this range suggesting two main phases of felling, as well as a less well represented additional earlier felling (Fig 10; Table 1).

Four timbers from the ground-floor ceiling in the west end of this range appear to be the earliest of those dated with a felling date range of AD 1417-42.

The 13 dated timbers from the gatehouse passage ceiling and the ground-floor ceiling to the middle section of this range, with one possible exception (HHB-A36), appear to be coeval, with heartwood/sapwood boundary dates varying from AD 1465 (HHB-A45) to

AD 1482 (HHB-A48). This suggests that the timbers from these two areas were part of a single programme of felling, possibly spanning more than one year. This is further supported by the very high level of cross-matching between some samples within, and between, the two areas suggesting that the timbers they represent were derived from the same-tree (eg HHB-A43 and HHB-A44, two joists from the gatehouse passage ceiling that cross-match with a *t*-value of 15.4; HHB-A32, a main beam from the ground-floor ceiling in the middle section of the range, that matches HHB-A48, a joist from the gatehouse passage ceiling, with a *t*-value of 12.0). Thus, with an average heartwood/sapwood boundary date of AD 1475, a felling date range of AD 1490–1515 is obtained for the timbers from the gatehouse passageway ceiling and the ground-floor ceiling to the middle section of this range. It should however be noted that HHB-A36, a main beam from the ground floor ceiling in the middle section of the range, appears to have been felled slightly earlier in AD 1470–95, although it remains a possibility that it is coeval with the rest of these timbers.

The twenty-nine dated timbers representing the east end ground-floor ceiling, first-floor ceiling and roof, as well as the roof to the middle section of this range appear to be coeval, although again there is a single exception (HHB-A16). The heartwood/sapwood boundary dates for the bulk of the samples vary from AD 1566 (HHB-A08) to AD 1582 (HHB-A04) and three of these samples, all from the east end roof, have felling dates of AD 1593, AD 1594, and AD 1594. In addition a sample from the east end ground-floor ceiling was also felled in AD 1594, although it does have an earlier heartwood/sapwood boundary at AD 1554. Hence it seems likely that the timbers from these four elements of the hall range were a single felling programme in, or around, AD 1593 and AD 1594. It should however be noted that HHB-A16, with a heartwood/sapwood boundary date of AD 1543, appears to be felled slightly earlier in AD 1558–83, although again it remains a possibility that it is coeval with the rest of these timbers.

Barn

East end roof

The east end roof of the barn is represented by three dated samples, all of which retain the heartwood/sapwood boundary at a very similar position. Given that the average boundary is dated at AD 1469, it is likely that the timbers were cut as part of a single episode of felling at some time in the range of AD 1484–1509.

West end roof

The west end roof of the barn is represented by 11 dated samples, all of which again retain the heartwood/sapwood boundary, here varying by 20 years. Given that the average heartwood/sapwood boundary is dated AD 1469, it is likely that the timbers

were cut as part of a single episode of felling at some time in the range AD 1484–1509, although not necessarily all at exactly the same time.

Mezzanine floor

The mezzanine floor of the barn is represented by two dated samples. One of these samples, HHB-A59, retains complete sapwood, the last ring, and thus the felling of the tree, being dated to AD 1494. The heartwood/sapwood boundary on the second sample is at a very similar position, indicating a felling date range of AD 1488–1513, suggesting that, while it may not have been felled at exactly the same time, it is coeval with the first timber.

Barn - summary interpretation

The 16 dated timbers from the mezzanine floor and both the east and west ends of the roof appear to represent a single programme of felling (Fig 10; Table 1) with heartwood/sapwood boundary dates ranging from AD 1459 (HHB-A77) to AD 1479 (HHB-A69). One of these timbers, from the mezzanine floor, was felled in AD 1494 and it thus seems likely that the dated timbers from throughout the barn were all felled in, or around, AD 1494.

Bothy

East section (extension) – ground-floor ceiling

The ground-floor ceiling to the bothy extension has provided three dated samples. One of these, represented by HHB-A91, has a heartwood/sapwood boundary date of AD 1395 giving this timber an estimated felling date in the range AD 1410–35. A second timber has a heartwood/sapwood boundary date of AD 1453, giving this timber a felling date in the range AD 1468–93.

The third timber, represented by sample HHB-A89, is without a heartwood/sapwood boundary. However, with a last heartwood ring date of AD 1432, and allowing for a minimum of 15 sapwood rings, it is unlikely to have been felled before AD 1447. However it cross-matches HHB-A90 with a *t*-value of 10.7 which suggests that it may have been derived from the same tree, and thus it seems likely that this third timber was also felled in the range AD 1468–93.

West section (original) - roof

The original section of the bothy has provided nine dated samples. Two of these samples, HHB-A79 and A87, retain complete sapwood, the last rings of both, and the felling of the trees represented, being dated to AD 1594.

The heartwood/sapwood boundary on the other seven dated samples are all at a broadly similar position, suggesting that they are basically coeval but, as they vary in date from AD 1550 to AD 1573, they may not have been felled at precisely the same time. It is possible that the two timbers (HHB-A80 and HHB-A86) with a heartwood/sapwood boundary date of AD 1550 were felled slightly earlier, in the range AD 1565-90. However, one of the timbers felled in AD 1594 has a heartwood/sapwood boundary date of AD 1554 and thus it is possible that HHB-A80 and HHB-A86 simply had slightly more sapwood than usual and hence are coeval with the rest of the timbers. The average heartwood/sapwood boundary on all of these seven other samples is dated AD 1564 giving them a felling date in the range AD 1579–1604. It will be seen that this date range brackets the known felling date of two other timbers from the area and hence all nine dated timbers may well represent a single felling period.

Bothy - summary interpretation

A total of twelve timbers have been dated from the bothy of which the majority probably represent a single programme of felling, although there are two somewhat earlier fellings (Fig 10; Table 1).

Three timbers from the ground-floor ceiling in the east section (extension) are fifteenth-century in date, one having a felling date range of AD 1410–35, whilst the other two were both probably felled during the period AD 1468–93.

There are nine dated timbers from the west section (original) roof of which two, with heartwood/sapwood boundary dates of AD 1554 and AD 1564, were felled in AD 1594. The heartwood/sapwood dates on two of the remaining samples vary from AD 1550 to AD 1573 which, whilst it is possible that two timbers were felled slightly earlier, suggests that these timbers may well represent a single programme of felling that perhaps spanned a small number of years in the AD 1590s

DISCUSSION AND CONCLUSION

Analysis by dendrochronology has thus produced two dated site chronologies which between them account for 74 of the 86 measured samples, with samples from all elements of the hall range, barn, and bothy being dated.

Interpretation of the sapwood on the dated samples indicates that the gatehouse passage ceiling and the ground-floor ceiling of the middle section of the hall range, as well as the barn are largely constructed of timbers felled in the last decade of the fifteenth century or the early years of the sixteenth century, with a single precise felling date of AD 1494 obtained. It is however possible that one of the timbers from the middle section ground-floor ceiling was felled slightly earlier. Given this dating evidence, it would appear most likely that the original hall range, along with the barn, was indeed constructed during the time of Sir James Hobart, who is known to have died AD 1517. However, rather than dating to the AD 1480s as initially believed, it would appear more likely that construction took place in the AD 1490s, and is thus very slightly later than expected.

Two of the timbers from the ground-floor ceiling in the east section (extension) of the bothy that appear likely to be reused in their current positions may have been originally used in the primary construction phase in the AD 1490s, although they also may have been felled slightly earlier. However the remaining dated timber from this ceiling and the dated timbers from the ground-floor ceiling in the west-end of the hall range are clearly earlier, being felled in the first half of the fifteenth century, and are thus also likely to have been reused in their current positions from some earlier building.

The second main phase of felling is associated with the east and middle sections of the hall-range roof and the ground- and first-floor ceilings, also in the east section of the hall range, as well as the roof of the west section (original) of the bothy. These are largely constructed of timbers felled in, or around, AD 1594, although again it is possible that a very small number of timbers were felled slightly earlier. It would appear, therefore, that these elements of the complex are not replacements after a fire of AD 1599, dating instead to the middle years of that decade. This discrepancy can perhaps only be accounted for by the fire having occurred slightly earlier than is generally supposed or alternatively not being as disastrous as previously thought

As may be seen from Tables 2 and 3, although compared with reference data for all parts of England, and indeed matching well with chronologies from many areas, there is a clear tendency for the dated material from the Hales Hall complex to have the highest levels of similarity with chronologies constructed of data from other sites in eastern and south-east England. This suggests that the oak timbers used here are from relatively local regional woodland sources.

Twelve of the 86 measured samples remain ungrouped and undated. The majority of these have sufficient rings for reliable dating and none shows any problems with its annual growth rings, such as distortion or compression, which would make cross-matching and dating difficult. A few samples, do though, have ring numbers towards the lower limit of reliability, and this may influence their cross-matching. It is, however, a common feature of tree-ring analysis for some samples not to combine with the main group or to date individually. In this respect the analysis undertaken here has been particularly successful in dating 86% of the samples measured, a figure which would be perfectly acceptable in any

region of the country, but especially so in Norfolk, a county which frequently produces large numbers of undateable samples.

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TABLES

Table 1: Details of tree-ring samples from the Hales Hall complex, Loddon, Norfolk

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Hall, east end roof					
HHB-A01	North principal rafter, truss 1	55	h/s	1519	1573	1573
HHB-A02	North principal rafter, truss 2	69	h/s	1509	1577	1577
HHB-A03	South principal rafter, truss 2	99	25C	1496	1569	1594
HHB-A04	South principal rafter, truss 3	96	h/s	1487	1582	1582
HHB-A05	South principal rafter, truss 4	98	h/s	1476	1573	1573
HHB-A06	North principal rafter, truss 6	80	h/s	1492	1571	1571
HHB-A07	South principal rafter, truss 6	88	h/s	1486	1573	1573
HHB-A08	South principal rafter, truss 8	79	h/s	1488	1566	1566
HHB-A09	North principal rafter, truss 11	74	3	1504	1574	1577
HHB-A10	South principal rafter, truss 11	62	h/s	1515	1576	1576
HHB-A11	South principal rafter, truss 12	79	23C	1515	1570	1593
HHB-A12	Collar, truss 13	56	21C	1539	1573	1594
	Hall, middle roof					
HHB-A13	North principal rafter, truss 1	74+20nm	h/s+20nm	1495	1568	1568
HHB-A14	South principal rafter, truss 1	79	h/s	1493	1571	1571
HHB-A15	Collar, truss 1	59	h/s	1510	1568	1568
HHB-A16	Crown post, truss 1	54	6	1496	1543	1549
	Hall, first-floor ceiling, east end					
HHB-A17	Main ceiling beam 4	69	h/s	1502	1570	1570
HHB-A18	Common joist 8, beam 2–3	58	h/s	1513	1570	1570
HHB-A19	Common joist 8, beam 3–4	82	h/s	1494	1575	1575
HHB-A20	Common joist 2, beam 4–5	46	h/s	1525	1570	1570

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Hall, first-floor ceiling, east end					
HHB-A21	Main ceiling beam 6	73	h/s	1502	1574	1574
HHB-A22	Main ceiling beam 7	58	h/s	1513	1570	1570
HHB-A23	Main ceiling beam 11	102	17	1493	1577	1594
HHB-A24	Main ceiling beam 13	85	9	1502	1577	1586
	Hall, ground-floor ceiling, east end					
HHB-A25	North common joist 8, bay 7	nm	---	------	------	------
HHB-A26	North common joist 9, bay 7	75	40C	1520	1554	1594
HHB-A27	Main ceiling beam 10	92	19	1495	1567	1586
HHB-A28	Main ceiling beam 11	97	h/s	1472	1568	1568
HHB-A29	Common joist 4, bay 10	64	h/s	------	------	------
HHB-A30	Common joist 3, bay 11	102	no h/s	1458	------	1560
HHB-A31	Common joist 4, bay 11	81	no h/s	1460	------	1540
	Hall, ground-floor ceiling, middle section					
HHB-A32	Main ceiling beam 13	80	h/s	1401	1480	1480
HHB-A33	Common joist 8, bay 13	109	h/s	1371	1479	1479
HHB-A34	Common joist 9, bay 13	114	h/s	1361	1474	1474
HHB-A35	Common joist 11, bay 13	100	h/s	1376	1475	1475
HHB-A36	Main ceiling beam 16	75	5	1386	1455	1460
	Hall, ground-floor ceiling, west end					
HHB-A37	Central main ceiling beam	77	h/s	------	------	------
HHB-A38	Common joist 4, bay 1	95	h/s	1308	1402	1402
HHB-A39	Common joist 11, bay 1	62	h/s	------	------	------
HHB-A40	Common joist 5, bay 2	60	no h/s	1288	------	1347
HHB-A41	Common joist 6, bay 2	98	no h/s	1254	------	1351
HB-A42	Common joist 13 bay 2	103	no h/s	1267	------	1367

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Hall, gatehouse passage ceiling					
HHB-A43	North common joist 7	111	h/s	1359	1469	1469
HHB-A44	North common joist 8	124	h/s	1357	1480	1480
HHB-A45	North common joist 11	114	2	1354	1465	1467
HHB-A46	South common joist 6	92	2	1389	1478	1480
HHB-A47	South common joist 8	110	no h/s	1346	------	1455
HHB-A48	South common joist 9	77	h/s	1406	1482	1482
HHB-A49	South common joist 10	61	h/s	1410	1470	1470
HHB-A50	South common joist 11	74	h/s	1404	1477	1477
	Barn, east end roof					
HHB-A51	North queen post, truss 1	nm	---	------	------	------
HHB-A52	South brace, wall post–tiebeam, truss 1	130	h/s	1341	1470	1470
HHB-A53	Tiebeam, truss 2	104	2	------	------	------
HHB-A54	North queen post, truss 2	71	h/s	------	------	------
HHB-A55	South brace, wall post-tiebeam, truss 2	71	h/s	1403	1473	1473
HHB-A56	Tiebeam, truss 3	56	2	------	------	------
HHB-A57	South queen post, truss 3	59	h/s	1406	1464	1464
HHB-A58	Tiebeam, truss 4	nm	---	------	------	------
	Barn, mezzanine floor beams					
HHB-A59	Main ceiling beam 1	90	16C	1405	1478	1494
HHB-A60	Main ceiling beam 2	95	5	1384	1473	1478
HHB-A61	Common joist 2, bay 2	51	h/s	------	------	------
HHB-A62	Common joist 3, bay 2	43	12	------	------	------
HHB-A63	Common joist 4, bay 3	nm	---	------	------	------
HHB-A64	Common joist 1, bay 4	40	h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Barn, west end roof					
HHB-A65	North wall post, truss 1	98	h/s	1363	1460	1460
HHB-A66	South wall post, truss 1	87	h/s	1380	1466	1466
HHB-A67	South brace, post-tiebeam, truss 1	59	2	1410	1466	1468
HHB-A68	Tiebeam, truss 2	103	h/s	1366	1468	1468
HHB-A69	Tiebeam, truss 3	70	h/s	1410	1479	1479
HHB-A70	South lower queen post, truss 3	65	h/s	------	------	------
HHB-A71	Tiebeam, truss 6	105	h/s	1372	1476	1476
HHB-A72	Tiebeam, truss 7	102	10	1387	1478	1488
HHB-A73	North lower queen post, truss 7	82	h/s	1387	1468	1468
HHB-A74	North principal rafter, truss 8	66	h/s	1406	1471	1471
HHB-A75	South lower queen post, truss 8	89	h/s	1379	1467	1467
HHB-A76	Tiebeam, truss 9	56	h/s	------	------	------
HHB-A77	South lower queen post, truss 9	89	h/s	1371	1459	1459
	Bothy, original timbers					
HHB-A78	Tiebeam, truss 1	74	h/s	1496	1569	1569
HHB-A79	Collar, truss 1	63	34C	1532	1564	1594
HHB-A80	North purlin, truss 1–2	51	h/s	1500	1550	1550
HHB-A81	South purlin, truss 1–2	nm	---	------	------	------
HHB-A82	Collar, truss 2	45	h/s	1524	1568	1568
HHB-A83	Collar, truss 3	67	h/s	1499	1565	1565
HHB-A84	Collar, truss 4	51	h/s	1522	1572	1572
HHB-A85	North principal rafter, truss 5	92	h/s	1482	1573	1573
HHB-A86	Tiebeam, truss 5	81	h/s	1470	1550	1550
HHB-A87	Collar, truss 5	77	40C	1518	1554	1594

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Bothy extension, ground-floor ceiling					
HHB-A88	Common joist 4	56	no h/s	------	------	------
HHB-A89	Common joist 10	131	no h/s	1302	------	1432
HHB-A90	Common joist 11	126	h/s	1328	1453	1453
HHB-A91	Common joist 12	160	h/s	1236	1395	1395

h/s = the heartwood/sapwood ring is the last ring on the sample nm = sample not measured
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented.

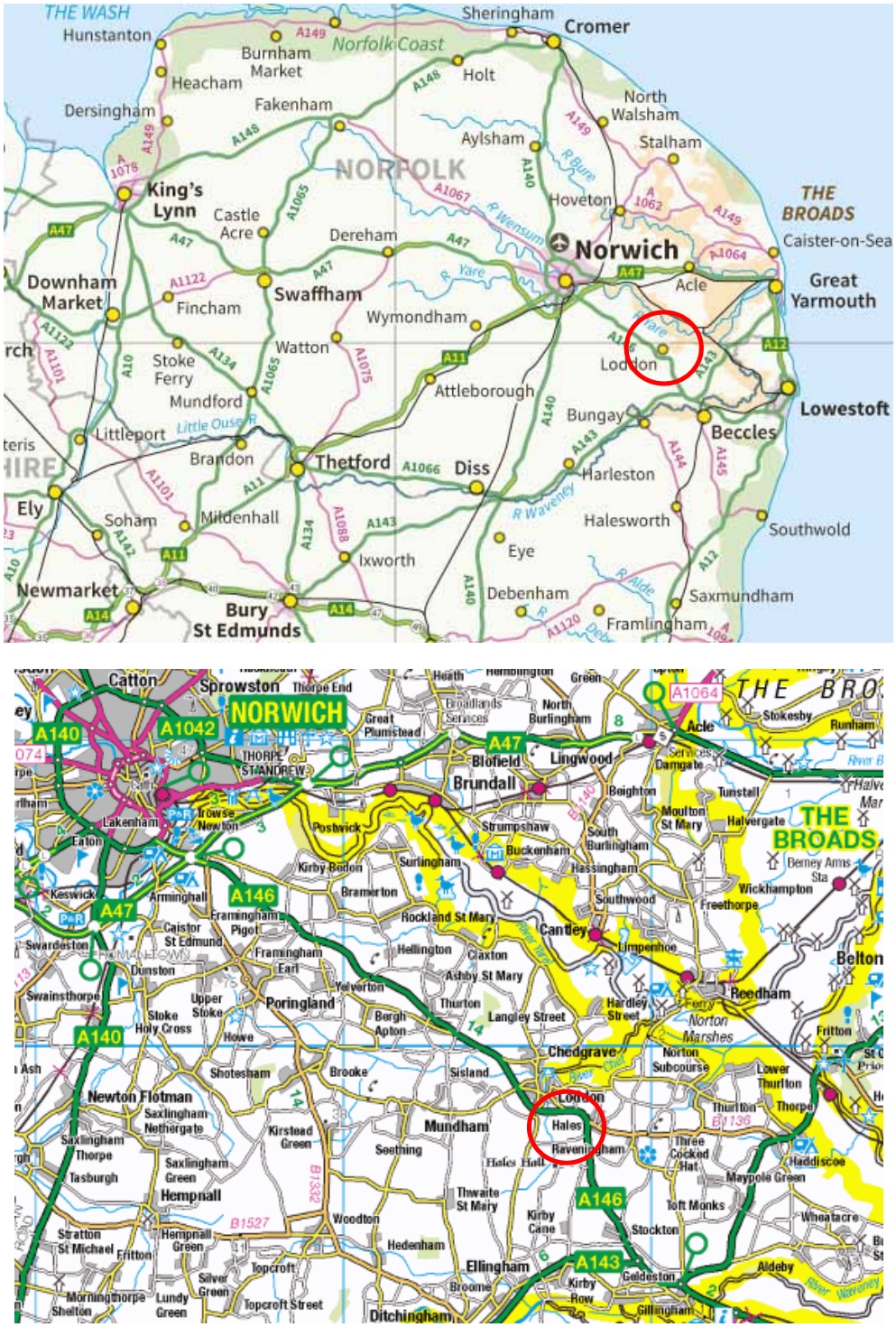
Table 2: Results of the cross-matching of site sequence HHBASQ01and relevant reference chronologies when the first-ring date is AD 1236 and the last-ring date is AD 1494

Reference chronology	Span of chronology	*t*-value	Reference
St Andrew's Church, Cotton, Suffolk	AD 1375–1461	9.3	(Arnold and Howard 2012)
Apethorpe Hall, Apethorpe, Northamptonshire	AD 1292–1740	8.3	(Arnold and Howard 2008)
Peterborough Cathedral Presbytery roof, Cambridgeshire	AD 1208–1500	8.9	(Tyers 2004a)
Castle Acre Priory, Norfolk	AD 1237–1356	8.8	(Tyers 2000)
Cann Hall, Clacton, Essex	AD 1301–1511	8.4	(Tyers 1998)
Dragon Hall, Norwich, Norfolk	AD 1289–1426	8.2	(Boswijk and Tyers 1998)
Oxburgh Hall, Norfolk	AD 1221–1427	8.1	(Tyers 2004b)
Chicksands Priory, Bedfordshire	AD 1200–1541	8.0	(Howard *et al* 1998)

Table 3: Results of the cross-matching of site sequence HHBASQ02 and relevant reference chronologies when the first-ring date is AD 1458 and the last-ring date is AD 1594

Reference chronology	Span of chronology	*t*-value	Reference
Apethorpe Hall, Apethorpe, Northamptonshire	AD 1292–1740	9.7	(Arnold and Howard 2008)
Queen's Hall, Ely Cathedral, Cambridgeshire	AD 1466–1593	8.4	(Arnold *et al* 2004)
Powcher's Hall, Ely Cathedral, Cambridgeshire	AD 1457–1609	7.9	(Arnold *et al* 2004)
Astley Castle, Warwickshire	AD 1495–1627	7.5	(Howard *et al* 1997)
Aldeby Hall (barn), Aldeby, Norfolk	AD 1422–1608	7.4	(Arnold and Howard 2013 unpubl)
Wakelyn Old Hall, Hilton, Derbyshire	AD 1415–1573	7.4	(Arnold *et al* 2008)
Manor House, Alford, Lincolnshire	AD 1500–1668	7.3	(Arnold *et al* 2003b)
Church of St Nicholas, Bringhurst, Leicestershire	AD 1502–1687	7.3	(Arnold *et al* 2005)

FIGURES



Figures: 1a-b: Map to show the location of Loddon (top) and Hales (bottom) © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900.

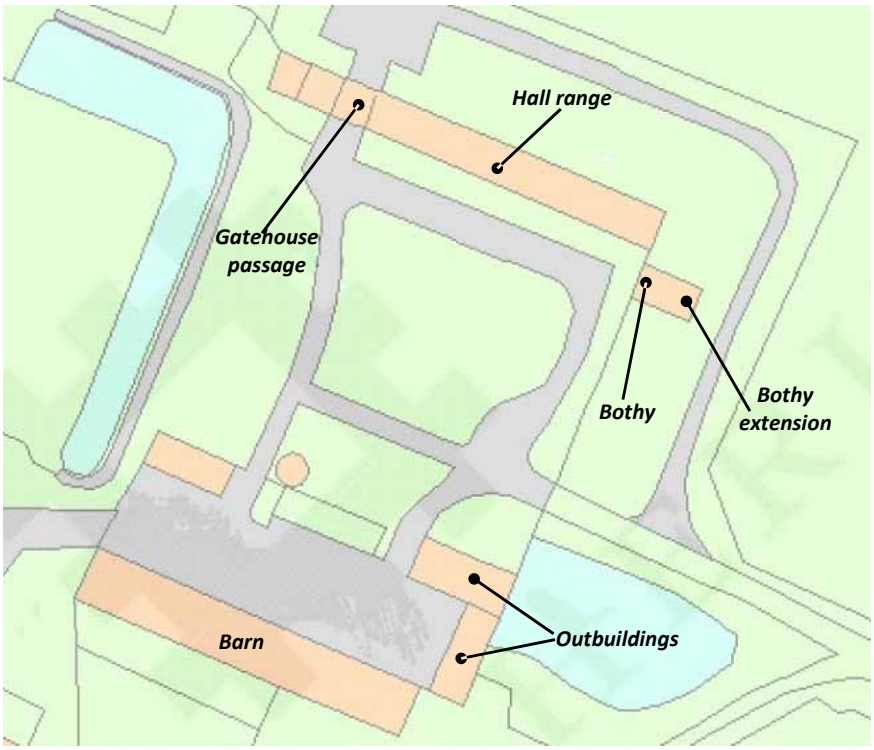


Figure 2: Plan of Hales Hall complex to show the layout and arrangement of the buildings © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3a-c: Views of the hall range with its gatehouse (top), its roof (middle) and east-end ground-floor ceiling beams (bottom) (photographs Robert Howard)

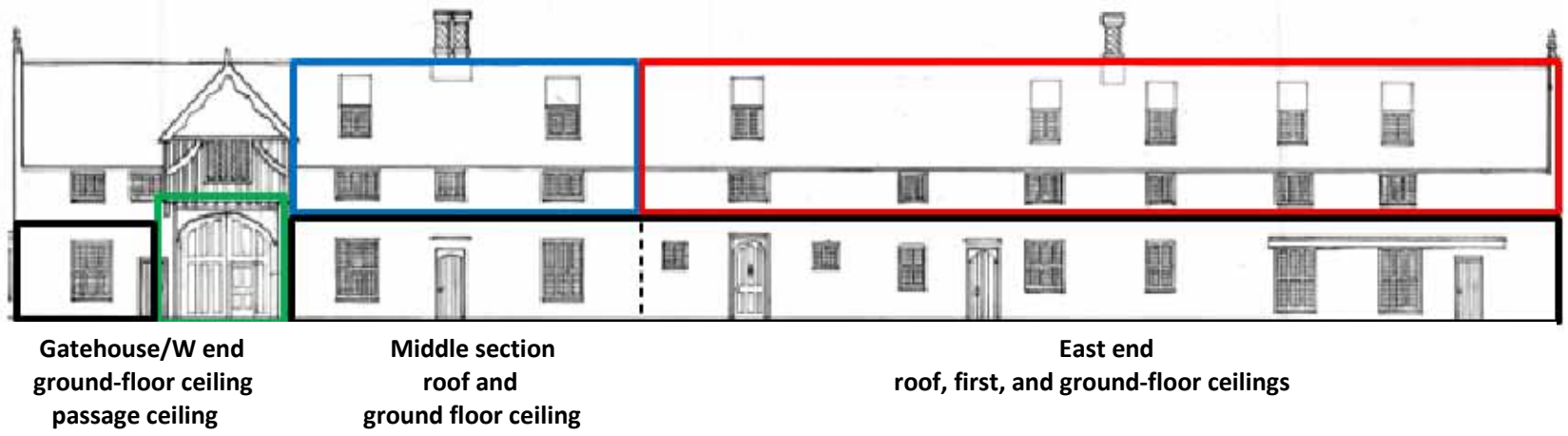


Figure 4: Illustration of the potential phases and/or areas of sampling from the hall range

Figure 5a-c: Exterior view of the barn (top), its west-end roof (middle) and quee- post with crown-post roof trusses to easternmost four bays (bottom) (photographs Robert Howard)

Figure 6a-c: Views of the clasped-purlin roof to the original part of the bothy (top), the roof to the extension (middle) and the ground-floor ceiling to the bothy extension (bottom) (photographs Robert Howard)

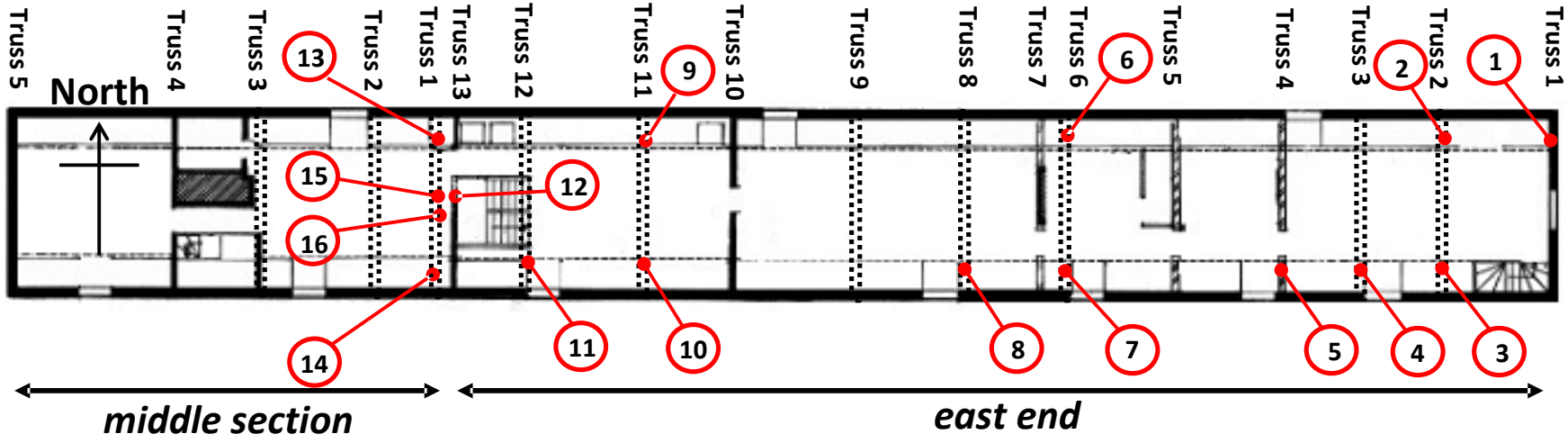


Figure 7a: Simple plan of the hall range at roof level to help locate sampled timbers

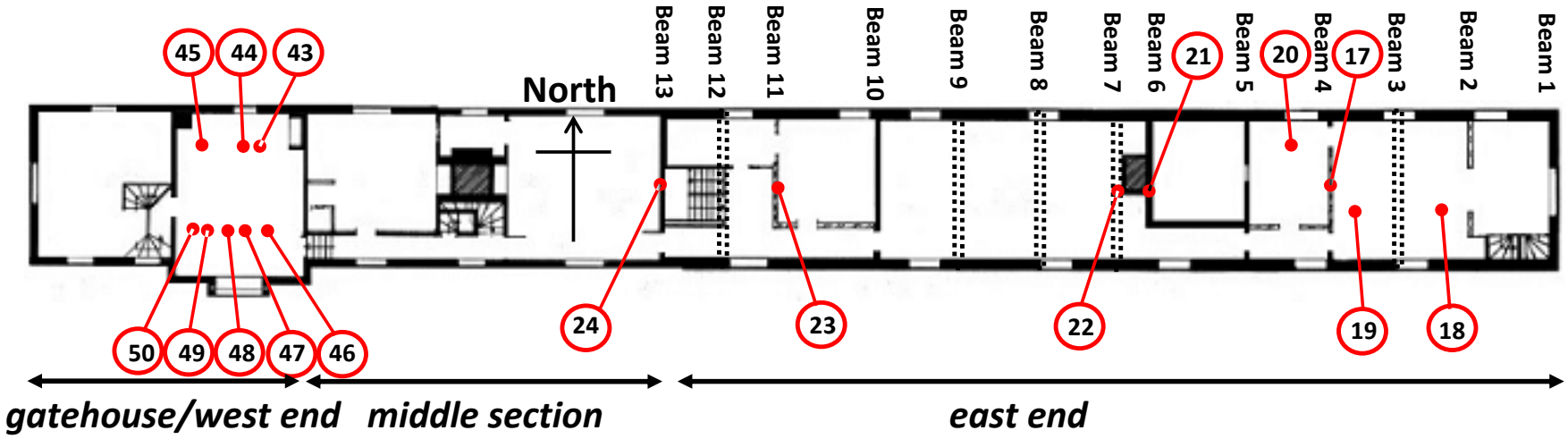


Figure 7b: Simple plan of the hall range at first-floor level to help locate sampled timbers

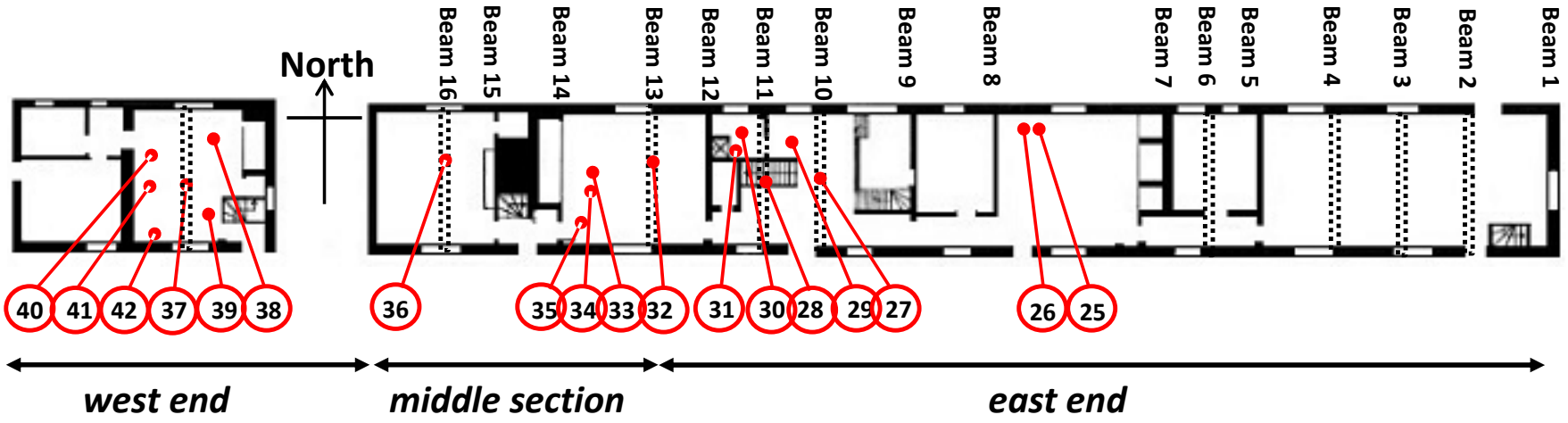


Figure 7c: Simple plan of the hall range at ground-floor level to help locate sampled timbers

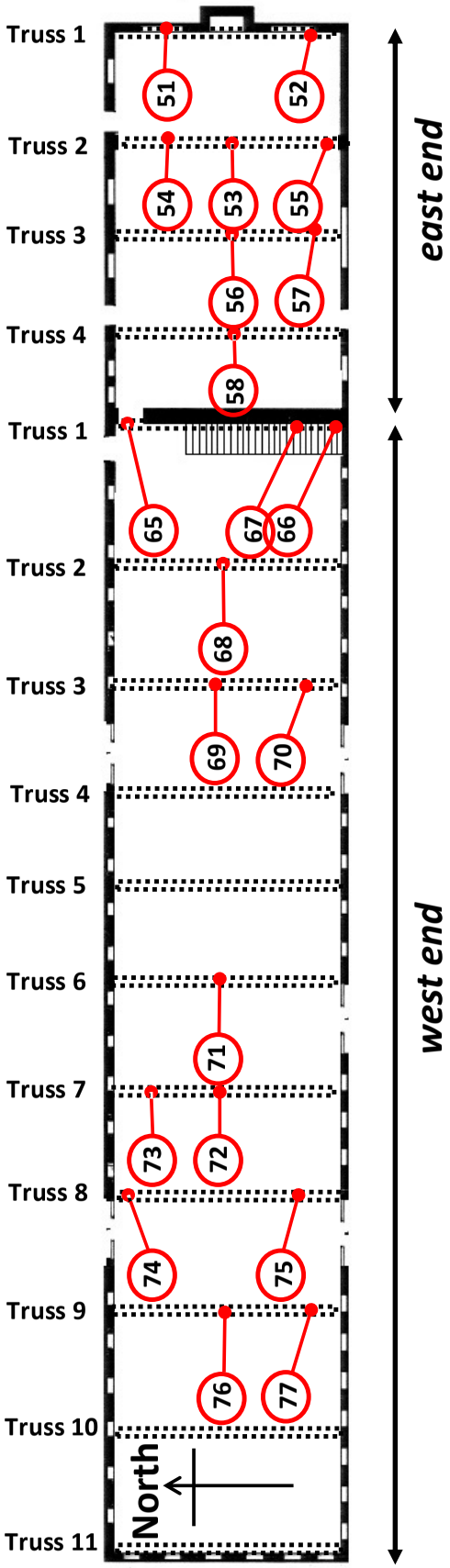


Figure 8a: Simple plan of the barn to help locate sampled timbers

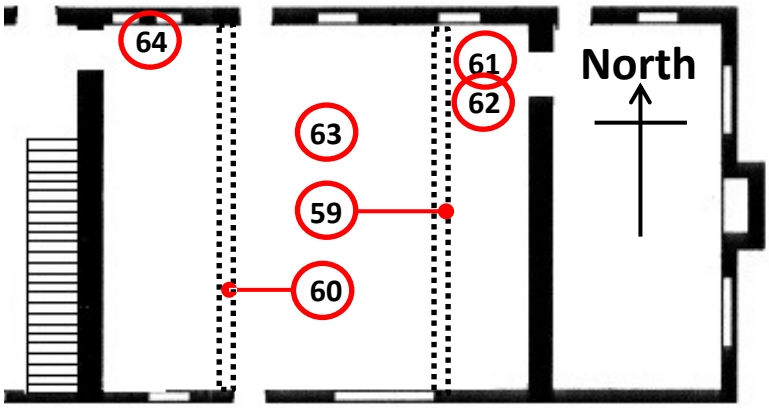


Figure 8b: Simple plan of the ground-floor rooms to the easternmost bays of the barn to help locate sampled timbers

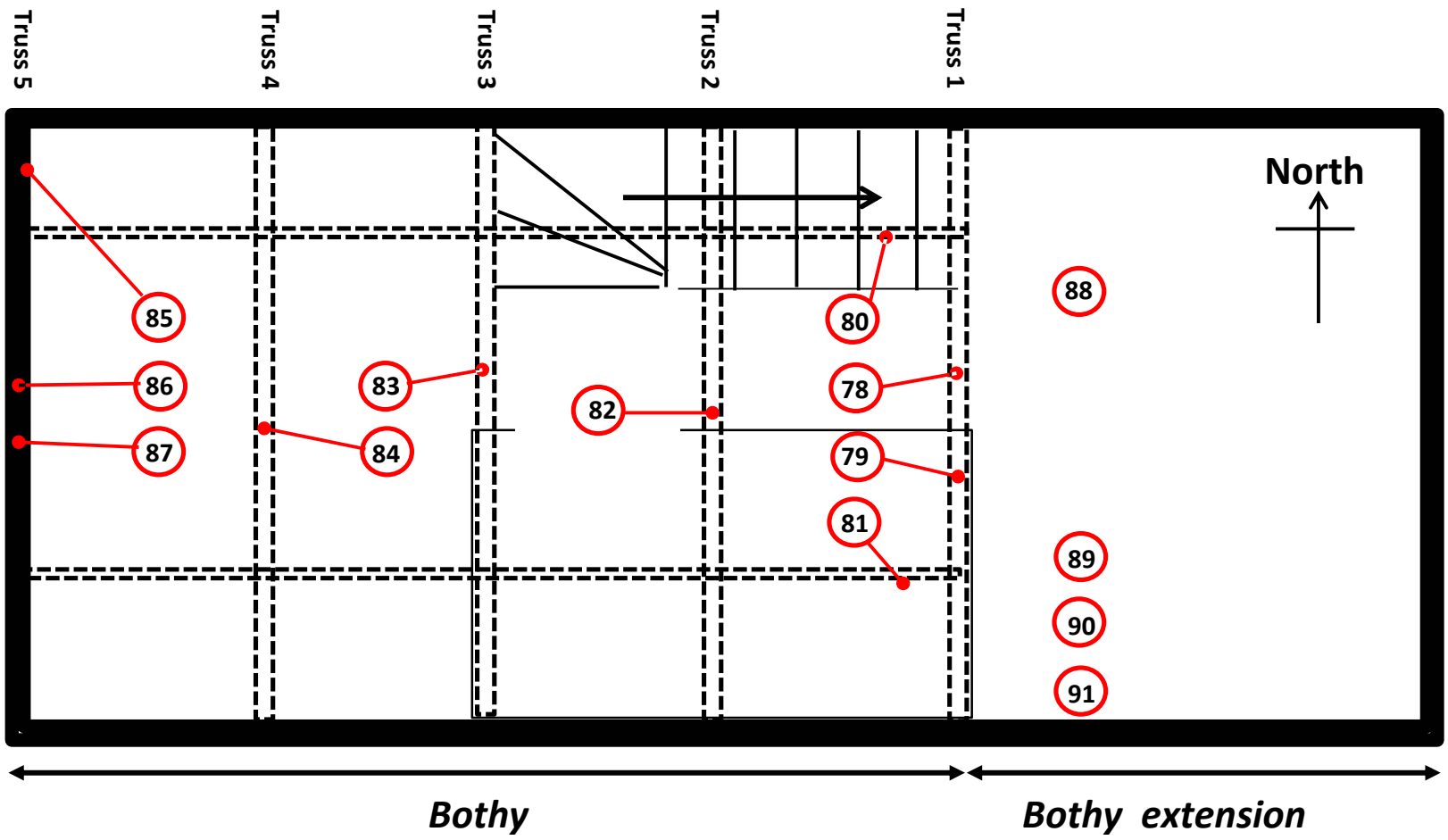
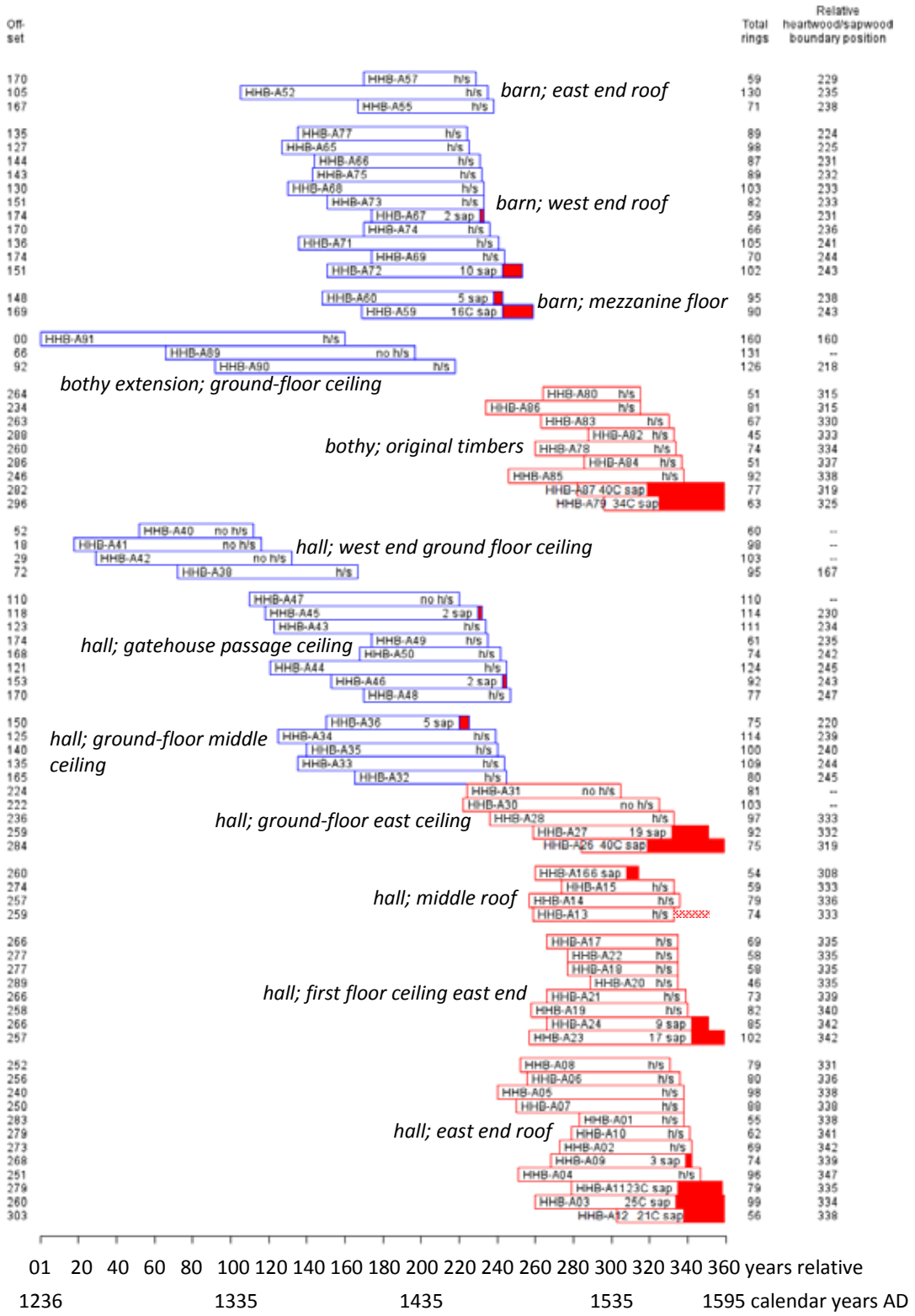


Figure 9: Simple plan of the bothy and bothy extension to help locate sampled timbers



white bars = heartwood rings, filled bars = sapwood rings; C = sapwood is complete
h/s = heartwood/sapwood boundary

Figure 10: Bar diagram of the samples in site chronologies HHBASQ01 (blue outline bars) and HHBASQ02 (red outline bars) at their relative offset positions

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HHB-A01A 55
329 225 186 178 173 155 150 229 244 277 284 360 305 254 235 251 407 289 219 322
305 381 293 205 250 221 249 176 129 203 243 217 192 196 189 157 202 155 128 115
142 143 145 184 137 105 106 107 106 106 115 123 103 66 80
HHB-A01B 55
341 212 188 192 167 164 152 175 245 297 282 346 303 241 217 274 396 277 221 318
311 386 298 203 252 221 226 185 140 190 242 200 198 184 190 170 206 143 114 112
139 160 143 192 142 104 92 107 104 101 119 120 104 45 92
HHB-A02A 69
282 198 125 154 179 244 255 241 263 351 289 275 223 208 169 221 226 229 217 257
224 161 225 223 192 179 217 225 253 204 257 298 276 182 175 232 240 262 216 219
293 310 240 209 226 268 230 307 220 173 206 271 309 240 185 146 231 168 171 178
185 200 118 127 112 152 123 115 145
HHB-A02B 69
261 190 125 153 191 234 244 255 237 369 300 266 221 218 181 199 230 212 223 241
224 169 219 223 178 193 205 231 241 215 260 290 259 196 170 250 227 253 196 239
271 307 243 217 217 265 226 315 229 160 210 275 295 251 166 165 216 168 193 191
195 187 134 108 118 138 125 116 136
HHB-A03A 99
416 295 216 217 258 342 366 310 282 208 295 252 299 290 264 165 221 248 210 196
226 227 215 178 128 137 170 116 141 164 145 162 203 198 154 231 239 192 217 282
232 318 206 215 332 321 217 231 297 293 164 179 215 228 200 218 181 164 168 154
196 198 144 165 199 182 228 197 138 145 114 87 112 150 193 139 110 71 77 102
93 80 72 84 85 83 82 91 118 172 161 106 87 93 106 153 132 145 169
HHB-A03B 99
426 299 216 230 268 342 380 298 271 207 296 245 303 285 279 162 164 208 215 200
229 244 201 168 146 132 159 107 129 162 150 168 184 204 162 243 245 209 220 268
254 319 210 214 314 325 196 225 310 311 175 179 217 235 201 214 180 157 178 144
200 199 136 165 192 192 234 193 138 133 115 82 118 190 190 146 99 76 71 107
87 73 75 80 78 85 90 78 143 159 175 115 80 103 103 146 140 134 166
HHB-A04A 96
144 148 165 171 152 102 67 123 133 187 127 117 71 69 93 156 141 114 120 125
139 174 179 143 80 60 67 77 75 92 86 121 130 83 64 70 60 67 65 78
89 131 256 227 354 248 293 235 292 204 185 154 275 257 223 85 129 131 190 132
101 104 164 93 106 79 76 65 92 118 75 51 51 87 75 129 90 70 57 68
65 107 96 110 67 70 65 75 89 82 81 65 76 98 96 107
HHB-A04B 96
204 156 157 175 150 100 71 120 125 187 125 108 76 75 96 151 144 116 120 144
150 172 185 137 82 67 72 74 82 93 85 119 155 96 62 69 66 64 57 82
90 123 258 251 331 269 292 249 287 201 182 164 260 267 224 87 126 136 182 139
89 107 148 90 96 78 71 64 91 122 65 56 50 83 81 125 95 64 58 64
64 112 95 119 58 72 70 76 85 96 89 68 84 98 89 106
HHB-A05A 98
183 245 259 246 253 198 183 198 169 175 133 177 157 144 155 116 85 50 69 105
141 98 58 41 56 77 114 139 127 148 190 153 139 135 106 85 71 58 85 80
92 63 123 124 96 82 69 67 63 68 103 105 151 151 158 194 171 203 206 235
170 162 142 189 223 195 108 138 135 168 129 100 129 159 121 132 103 150 125 208
148 107 114 88 125 131 153 104 65 81 78 93 171 175 124 118 106 115

HHB-A05B 98
189 241 245 255 233 217 183 217 154 173 141 169 156 147 146 119 87 51 71 103
135 93 68 41 60 69 113 140 128 152 175 145 142 138 107 79 64 64 85 85
89 54 130 128 96 74 76 64 70 78 91 121 139 153 150 196 165 213 205 234
173 167 146 187 210 206 104 135 146 153 139 107 103 156 117 126 110 146 126 217
134 116 108 93 134 133 154 93 68 77 80 101 173 152 139 125 91 146
HHB-A06A 80
243 273 283 334 298 193 134 96 99 137 174 396 414 371 371 326 326 269 265 125
136 192 232 181 273 117 256 171 167 137 173 117 106 100 126 145 181 185 157 239
255 143 164 164 147 138 235 218 209 197 104 118 126 195 182 127 128 267 181 175
159 178 120 196 143 100 81 80 115 153 146 103 42 85 67 69 106 117 124 73
HHB-A06B 80
267 259 284 326 325 193 135 103 103 132 183 391 407 376 375 321 332 310 264 124
135 199 221 192 271 114 260 165 161 140 168 128 98 98 135 148 192 170 164 276
256 143 177 161 171 157 225 208 222 205 106 115 115 184 192 118 121 228 189 160
164 175 115 187 150 103 71 80 122 155 137 104 48 75 72 73 118 114 126 56
HHB-A07A 88
463 422 373 362 366 357 344 298 362 364 360 246 158 122 157 166 317 342 364 338
302 311 331 240 242 145 193 300 284 220 274 92 241 176 209 153 142 89 82 153
125 170 225 243 212 228 221 158 183 209 192 182 206 205 237 162 100 149 167 265
165 132 139 244 190 177 156 180 128 172 159 93 80 91 126 164 139 116 48 81
90 98 111 121 125 76 77 78
HHB-A07B 88
465 429 354 345 391 358 346 316 360 366 375 233 168 121 171 170 336 391 357 317
299 292 325 240 264 132 179 298 262 212 260 94 260 179 207 159 140 98 81 137
132 164 225 243 215 221 238 153 180 208 203 174 198 211 235 155 118 143 165 265
175 126 150 242 194 168 161 181 138 171 165 95 81 95 130 156 135 114 51 68
100 103 95 137 132 74 67 98
HHB-A08A 79
177 204 170 153 112 92 167 170 204 134 109 157 187 217 232 146 189 271 173 182
152 225 147 92 189 178 219 329 288 250 378 344 203 239 310 239 331 204 214 271
272 218 194 193 184 207 201 370 205 247 271 328 270 303 275 228 231 306 176 147
153 317 190 172 124 145 164 300 136 158 178 151 350 193 332 195 204 236 162
HHB-A08B 79
169 198 184 159 105 98 184 178 186 143 114 144 184 223 235 144 189 254 166 197
129 242 159 107 174 203 212 346 282 230 381 348 190 228 326 242 334 194 207 285
276 212 186 194 196 204 196 365 224 242 275 326 273 287 292 228 235 302 175 150
153 319 183 206 106 134 168 303 134 140 186 149 350 196 325 194 207 237 178
HHB-A09A 74
179 196 176 172 162 144 146 89 106 285 203 335 328 193 287 231 169 113 129 202
239 179 221 257 227 293 236 250 220 215 232 299 237 257 223 258 275 201 148 181
171 207 140 125 110 210 178 154 139 140 133 179 209 106 137 148 160 176 178 148
92 120 109 153 207 182 172 170 153 185 146 138 114 150
HHB-A09B 74
202 186 185 167 161 142 150 89 112 284 207 335 290 180 285 209 169 115 125 213
225 175 217 249 250 305 263 242 232 211 219 301 226 261 229 237 295 210 151 179
170 206 150 118 118 204 179 163 142 140 154 167 198 119 127 156 162 163 176 154
98 115 115 152 203 228 177 172 159 174 162 141 115 128
HHB-A10A 62
229 345 221 300 275 257 203 225 161 214 203 223 256 371 525 364 460 326 391 365
380 273 290 326 498 501 328 159 202 284 365 217 200 229 280 232 203 155 170 185
209 198 118 126 142 172 171 196 195 153 220 206 202 195 206 198 119 165 141 231
239 212

HHB-A10B 62
225 338 218 300 279 259 204 231 169 221 200 228 257 380 524 363 462 318 403 366
374 283 295 321 445 510 323 157 206 276 371 202 217 229 270 235 183 154 170 178
212 196 123 121 148 157 182 190 183 150 216 194 201 203 178 210 119 141 142 221
238 183
HHB-A11A 79
537 505 412 407 331 280 182 288 187 198 243 227 257 219 276 204 246 238 207 231
266 324 376 238 291 391 306 185 310 297 255 172 246 282 280 222 191 182 222 202
187 290 204 176 195 267 264 278 236 217 221 187 204 262 181 190 115 109 112 125
128 118 81 89 87 98 98 93 103 146 161 198 153 109 152 128 156 175 173
HHB-A11B 79
545 518 401 421 318 282 184 285 201 191 257 215 257 216 268 208 233 247 207 264
262 322 382 236 288 396 298 176 319 309 264 164 254 275 276 228 198 190 218 203
179 287 214 183 187 264 276 280 235 205 228 187 196 259 185 193 115 117 109 112
138 110 90 81 79 96 102 87 109 152 165 203 143 118 159 115 154 168 178
HHB-A12A 56
400 388 439 277 361 435 380 284 217 303 439 250 307 191 200 165 234 258 173 151
146 206 157 208 153 132 152 183 152 159 128 123 92 89 93 78 111 89 78 76
81 134 103 64 45 43 84 84 59 64 66 64 65 76 101 125
HHB-A12B 56
399 380 413 274 351 446 396 282 212 301 430 259 325 195 198 163 246 221 201 142
151 204 164 220 181 103 135 179 167 156 120 109 92 87 100 81 114 90 78 62
88 136 90 69 43 45 85 73 65 66 63 68 75 81 90 112
HHB-A13A 74
353 357 159 103 100 92 97 130 166 172 130 142 142 167 232 207 178 155 203 186
243 228 159 212 185 139 155 120 105 128 115 132 163 192 160 157 202 103 132 134
175 131 145 203 196 278 177 93 98 109 140 101 92 95 143 112 126 79 76 85
95 95 54 73 73 95 79 103 73 53 54 51 32 53
HHB-A13B 74
369 356 160 108 117 97 102 130 169 200 142 139 146 176 219 197 169 146 213 198
255 216 163 227 203 132 151 130 96 128 109 120 158 189 172 164 189 101 124 135
195 139 150 202 189 260 156 93 100 126 141 92 92 96 143 109 126 87 79 66
102 84 51 75 64 101 79 96 78 62 39 48 47 64
HHB-A14A 79
257 301 356 364 236 170 132 178 189 183 194 216 159 166 130 207 269 215 196 194
207 200 192 216 153 219 215 139 150 139 96 160 122 165 207 240 312 301 343 206
214 221 228 209 229 228 217 318 221 128 99 159 212 140 140 193 196 167 128 140
100 77 107 107 73 76 90 117 104 148 107 65 81 86 68 84 96 96 125
HHB-A14B 79
236 301 330 365 231 184 121 197 197 188 194 207 156 160 137 200 262 221 189 192
226 202 203 235 137 230 214 131 158 124 78 158 138 165 203 244 315 293 347 192
200 204 239 201 220 222 209 323 212 137 106 185 215 126 145 179 207 165 162 117
100 89 95 114 60 70 95 124 112 146 85 67 81 89 68 87 88 112 115
HHB-A15A 59
227 158 132 216 260 280 319 185 269 223 135 153 128 92 117 89 157 194 142 142
111 132 74 100 103 111 103 145 182 157 193 153 106 100 113 147 112 132 110 172
117 121 99 110 153 107 98 54 82 100 98 73 118 71 48 57 82 93 130
HHB-A15B 59
215 162 131 222 255 274 318 194 248 216 139 146 122 91 119 98 167 184 135 156
128 132 65 108 108 104 102 154 170 157 203 149 102 112 103 157 110 122 114 175
110 118 107 110 134 111 99 48 87 100 102 64 121 71 51 62 76 76 143
HHB-A16A 54
252 163 97 95 159 171 150 197 115 101 151 130 173 162 134 106 105 143 149 182

183 110 141 174 115 96 123 84 67 85 85 128 110 122 110 110 143 144 114 143
159 121 129 109 116 103 52 90 92 103 84 75 70 114
HHB-A16B 54
247 166 99 98 163 159 160 216 105 101 158 132 164 189 121 102 103 151 151 184
178 88 158 171 117 96 120 83 74 86 78 120 114 136 84 118 135 145 123 147
163 128 124 115 117 99 53 92 61 119 96 75 69 98
HHB-A17A 69
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163 193 158 128 159 151 167 168 154 156 137 104 142 189 197 218 225 187 159 143
93 159 158 163 203 174 150 176 118 189
HHB-A59B 90
382 634 531 442 417 323 320 399 427 328 282 413 460 543 381 466 351 345 371 343
267 278 194 202 322 248 326 292 225 187 229 212 298 280 296 240 260 289 264 139
196 232 210 195 225 206 151 202 215 200 215 221 212 190 148 147 165 157 195 175
153 197 148 137 166 155 159 163 162 150 150 92 154 179 200 218 228 187 148 138
93 140 193 234 201 190 143 179 109 194
HHB-A60A 95
132 170 142 180 201 147 202 129 97 105 135 182 221 152 138 173 176 130 119 166
207 140 220 164 180 139 96 131 128 175 96 96 128 101 107 107 126 160 128 197
128 151 129 98 139 199 134 145 182 154 117 153 142 164 162 164 182 214 186 209
118 100 143 156 129 126 70 76 140 131 146 160 160 120 104 87 139 126 150 111
110 97 114 100 96 90 93 79 104 118 82 69 81 67 94
HHB-A60B 95
126 172 144 186 202 150 192 125 101 117 145 182 207 142 141 182 160 144 125 159
203 140 222 174 183 132 105 121 122 177 90 95 133 97 110 102 122 162 128 210
134 150 121 100 135 201 140 146 187 154 107 154 137 164 162 135 207 228 175 206
120 110 145 137 131 157 75 85 132 129 142 159 147 129 110 78 109 123 142 139
127 106 110 96 84 78 81 100 82 109 89 64 81 68 100
HHB-A61A 51
154 179 166 187 184 198 162 181 202 201 217 221 198 242 280 257 332 314 313 319

259 239 345 314 253 327 293 326 264 270 242 221 176 257 234 203 207 218 226 256
295 265 300 293 235 167 220 168 206 157 201
HHB-A61B 51
144 180 164 189 182 196 158 181 189 208 195 222 223 253 289 271 332 314 303 297
260 242 348 309 249 321 295 336 260 270 250 207 185 253 233 200 215 223 209 257
305 272 306 295 239 168 195 183 204 158 204
HHB-A62A 43
530 456 428 331 325 410 443 413 432 354 401 346 271 331 250 225 251 212 192 226
358 237 326 299 267 199 185 137 229 150 129 157 204 206 267 301 276 237 187 241
290 289 325
HHB-A62B 43
517 460 423 327 362 407 469 408 437 373 425 352 285 368 255 218 242 210 192 215
343 253 348 285 245 207 181 120 231 135 146 134 216 217 254 303 287 245 173 212
335 292 333
HHB-A64A 40
315 299 393 321 303 523 621 562 342 217 114 89 89 203 227 258 264 217 114 125
156 196 257 235 134 182 185 250 158 287 246 154 159 160 280 160 92 82 103 104
HHB-A64B 40
392 312 380 302 318 507 630 575 341 212 124 92 99 211 221 263 272 213 117 129
174 202 262 245 145 178 179 230 181 259 257 156 157 154 265 160 95 67 117 104
HHB-A65A 98
211 113 104 83 266 455 514 375 340 398 337 345 324 641 369 178 130 191 225 306
244 167 289 273 301 210 132 121 85 67 75 79 95 113 103 78 76 42 64 64
92 115 204 142 87 126 89 90 62 101 148 114 79 73 93 180 137 153 159 126
139 164 120 96 95 112 87 87 135 146 98 73 85 59 66 78 107 153 164 166
93 71 58 78 111 115 75 82 109 55 71 109 112 89 67 79 68 100
HHB-A65B 98
199 117 101 89 262 444 513 377 319 403 324 299 319 675 364 154 119 158 206 298
253 169 295 271 292 201 132 118 85 68 76 71 89 118 106 76 69 45 71 65
81 96 193 132 87 117 88 103 60 98 142 118 76 78 93 193 137 151 162 126
148 157 107 112 96 116 88 89 136 137 101 85 82 64 74 87 90 144 162 162
109 74 56 84 125 112 70 98 98 72 68 115 116 90 74 78 68 98
HHB-A66A 87
383 351 296 192 409 323 455 312 203 185 136 110 49 50 92 158 207 192 146 137
69 71 96 82 111 125 92 82 100 131 146 89 112 171 150 102 97 135 198 168
162 173 104 179 173 98 101 101 125 129 110 154 146 102 137 160 112 103 114 85
116 96 110 107 68 64 71 90 75 64 57 46 40 62 101 90 82 64 73 89
75 70 78 73 82 82 102
HHB-A66B 87
437 351 297 175 402 320 426 302 209 182 159 103 46 59 103 153 205 190 167 138
76 82 70 91 116 129 96 79 96 132 139 100 110 156 153 89 103 133 190 167
170 168 117 189 178 98 98 101 133 116 114 150 156 100 137 156 110 107 125 81
107 95 110 112 67 59 85 81 78 62 68 42 42 56 96 84 84 57 78 82
82 78 70 73 76 94 95
HHB-A67A 59
247 298 287 376 242 217 237 275 300 232 217 202 128 200 161 104 119 146 188 175
142 188 183 148 145 205 121 143 188 172 190 159 172 159 96 145 167 170 130 168
114 101 100 134 125 128 114 143 159 160 100 156 112 117 139 150 140 145 165
HHB-A67B 59
287 287 289 361 251 217 219 257 295 216 228 200 129 201 160 105 115 150 191 171
139 189 183 146 150 192 125 147 188 167 198 149 169 156 93 153 167 171 121 184
117 96 112 130 125 134 109 143 163 157 98 148 121 117 145 147 146 115 160
HHB-A68A 103

489 541 596 657 592 559 556 418 384 353 410 225 302 217 306 332 268 226 135 279
195 253 180 164 151 128 157 162 175 109 192 284 234 168 246 284 192 145 188 173
232 186 150 162 156 207 229 284 218 171 156 153 209 162 246 190 164 233 219 130
94 93 146 161 133 141 135 106 149 175 98 118 119 119 153 112 140 96 65 88
118 103 99 150 145 96 105 115 111 148 111 141 121 147 165 154 106 119 115 139
93 103 125

HHB-A68B 103

512 534 578 661 584 552 543 433 393 350 425 228 300 218 305 321 265 225 140 287
179 270 181 160 150 125 164 151 165 110 207 282 226 175 248 282 195 140 189 193
222 174 150 160 164 196 239 278 222 168 168 167 207 167 228 221 150 221 240 120
103 90 140 164 139 137 142 100 155 163 115 96 127 133 153 117 146 99 65 92
118 102 97 156 143 90 106 123 111 137 125 140 120 151 146 166 121 122 110 130
109 105 125

HHB-A69A 70

318 298 519 693 586 560 685 801 580 312 510 467 187 494 235 237 468 443 539 514
257 234 187 236 338 453 306 247 195 293 259 254 219 248 137 212 230 237 181 220
173 162 146 134 181 209 187 104 168 190 193 198 139 143 190 165 169 128 187 168
193 150 153 137 140 151 136 159 109 135

HHB-A69B 70

282 304 517 672 578 568 673 784 575 307 514 462 179 473 242 257 441 470 529 517
256 234 196 235 331 456 306 246 191 299 267 264 209 246 138 204 226 240 184 212
178 157 152 133 174 200 200 103 171 187 197 191 134 151 197 163 178 128 195 162
188 159 148 145 139 154 123 162 117 139

HHB-A70A 65

610 482 384 476 594 498 623 496 465 504 353 548 421 255 43 40 50 48 69 119
110 92 85 96 79 156 146 163 231 312 376 340 234 260 275 279 337 321 318 276
201 77 84 43 68 50 72 81 71 111 89 49 54 62 65 58 51 63 62 65
80 96 90 97 98

HHB-A70B 65

591 523 364 476 602 493 614 501 469 512 346 561 419 243 42 39 53 51 64 116
112 87 93 96 85 145 151 160 225 329 373 331 238 256 272 285 331 285 342 301
203 79 70 43 67 51 70 75 80 108 91 45 54 62 62 62 56 53 68 65
77 96 90 96 95

HHB-A71A 105

283 330 633 381 459 408 455 522 419 359 432 259 268 282 311 371 204 185 144 137
112 142 207 211 238 193 170 133 99 110 164 159 221 187 203 129 160 146 135 148
148 151 129 176 151 182 180 146 125 162 153 150 168 176 212 190 165 145 127 153
192 121 129 133 121 145 142 121 137 118 140 142 92 110 96 116 106 208 96 100
115 134 121 127 175 133 132 108 121 116 71 80 106 144 133 100 88 96 184 173
161 128 165 169 146

HHB-A71B 105

287 326 730 353 452 394 426 501 438 385 446 260 282 269 321 367 216 184 139 135
112 141 203 220 232 198 168 139 101 106 178 148 224 178 200 138 158 148 132 156
126 169 134 181 145 169 180 157 120 168 145 153 175 170 209 188 167 150 118 157
189 135 121 124 125 141 151 120 131 117 143 137 95 111 100 101 116 212 88 97
117 148 115 143 173 121 134 111 129 121 63 82 116 140 118 93 89 94 178 167
184 115 165 159 152

HHB-A72A 102

175 388 256 231 165 176 226 209 202 289 276 275 214 177 146 251 296 350 271 330
255 298 221 199 198 232 214 175 156 148 167 193 184 198 207 175 212 152 162 175
143 157 171 111 160 235 184 152 207 137 207 222 167 135 139 139 126 76 89 104
107 114 144 82 62 79 106 96 86 120 85 90 81 109 84 62 72 74 128 114
75 65 72 139 121 159 103 109 87 81 89 90 106 168 137 129 114 78 62 87

139 150
HHB-A72B 102
231 409 256 229 149 189 220 194 214 275 287 282 209 176 138 258 300 353 301 348
262 310 210 191 203 221 226 178 167 156 153 209 173 182 181 153 207 169 150 181
149 150 156 101 146 213 203 139 175 153 196 215 164 139 129 139 131 67 110 104
112 96 142 73 67 76 107 74 94 126 78 96 71 103 100 71 86 93 126 98
78 70 67 166 130 150 108 109 85 77 96 81 143 131 137 141 120 71 64 87
121 145
HHB-A73A 82
393 364 254 283 128 93 125 235 197 275 216 287 218 196 186 225 235 276 257 311
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181 190 312 270 198 203 154 121 242 179 170 181 157 178 151 175 126 85 95 125
132 106 129 90 84 114 133 189 221 189 205 155 203 187 234 127 131 140 115 181
99 170
HHB-A73B 82
409 347 268 287 134 79 146 240 205 266 227 282 217 205 200 235 228 271 262 326
110 98 114 110 139 223 200 128 128 121 127 133 122 160 164 189 254 260 234 238
189 178 326 260 197 210 159 123 237 176 170 183 152 188 156 171 119 86 98 125
139 98 126 95 85 110 132 192 225 184 200 153 202 200 227 140 112 150 92 203
124 173
HHB-A74A 66
252 222 314 347 353 307 377 424 359 275 340 306 434 264 396 407 361 421 311 370
353 339 423 405 289 242 362 309 279 443 445 315 359 293 243 206 171 303 171 307
236 278 200 237 146 183 153 215 176 286 188 166 144 168 181 206 114 121 121 153
135 139 178 131 165 172
HHB-A74B 66
241 205 316 350 363 301 397 416 359 283 328 307 439 258 385 407 358 435 300 373
343 342 418 415 276 250 378 291 298 464 443 298 350 290 247 205 177 299 175 271
242 281 200 242 150 178 154 217 178 279 184 171 146 162 190 204 109 129 124 168
135 121 181 131 145 168
HHB-A75A 89
465 711 500 563 433 162 449 372 471 414 238 240 130 53 87 159 186 310 271 296
201 207 217 226 192 245 168 253 117 96 106 79 85 139 155 104 110 76 123 167
98 153 151 141 187 201 122 131 118 185 295 270 289 276 172 118 232 148 176 185
154 145 106 164 92 84 93 100 125 87 137 84 97 77 172 131 274 149 92 104
129 131 124 106 106 95 127 112 125
HHB-A75B 89
459 688 509 566 429 153 458 366 474 407 236 231 132 48 83 162 184 314 264 292
196 228 206 232 204 253 159 265 106 93 90 81 78 146 162 112 110 84 114 177
92 140 137 137 192 189 135 120 106 180 310 286 303 274 167 117 234 150 179 187
137 131 115 142 83 105 88 89 131 94 138 87 96 99 157 164 237 146 90 103
99 137 128 93 84 101 125 112 127
HHB-A76A 56
584 554 401 355 569 418 514 368 291 348 460 399 342 342 285 252 194 336 227 394
293 193 123 173 226 268 323 260 304 251 159 147 142 215 223 159 157 187 164 272
323 300 363 236 212 370 151 200 268 272 244 328 231 171 261 280
HHB-A76B 56
602 553 352 345 469 416 528 355 282 360 450 404 345 343 296 250 194 329 220 403
289 196 124 171 229 264 317 262 309 243 165 140 151 207 228 160 160 185 162 268
326 303 354 237 212 374 153 193 267 267 262 330 234 180 228 267
HHB-A77A 89
581 353 404 447 403 469 358 321 355 483 422 418 378 130 266 257 350 370 271 287
134 67 101 139 164 244 309 275 185 123 118 145 173 314 212 281 96 98 138 127

151 171 202 159 168 165 145 167 129 126 118 145 230 229 212 225 163 227 337 284
272 252 190 139 203 218 182 159 202 192 185 196 131 96 106 143 131 93 196 97
65 109 146 182 281 208 209 155 190
HHB-A77B 89
484 363 399 451 396 473 366 312 392 518 417 421 382 137 277 261 360 384 278 287
137 65 101 137 181 248 305 278 184 138 117 153 168 301 207 285 96 99 130 127
159 176 181 166 175 173 134 171 117 123 104 146 234 228 208 227 157 212 323 275
274 253 193 145 217 211 166 193 192 210 156 214 118 103 103 145 127 112 159 103
77 105 155 184 275 209 210 156 180
HHB-A78A 74
274 152 89 184 157 125 93 71 37 55 81 106 106 129 98 61 61 86 105 151
163 126 210 191 171 114 152 150 134 128 150 185 268 236 210 284 296 215 185 231
172 208 173 262 309 365 185 192 234 251 202 156 184 217 225 215 151 225 146 203
214 227 153 176 206 162 179 115 71 89 103 100 167 154
HHB-A78B 74
300 146 87 191 152 125 92 76 37 36 92 99 109 131 98 78 60 82 98 157
162 120 207 194 171 113 148 156 128 121 160 186 267 239 206 286 300 216 180 233
176 206 173 264 306 342 206 195 228 235 208 162 187 218 240 201 168 217 146 195
218 235 153 176 206 164 187 90 64 92 106 103 170 143
HHB-A79A 63
172 224 221 337 229 200 226 290 286 251 262 176 209 266 128 118 131 235 118 149
91 89 102 210 134 150 146 135 253 153 203 128 128 171 133 143 132 181 156 148
107 146 137 138 117 83 84 98 114 84 60 76 79 100 82 94 89 100 85 100
89 68 109
HHB-A79B 63
188 210 227 343 223 199 230 298 282 255 264 174 205 270 132 120 125 239 125 146
81 100 103 207 139 153 156 137 250 139 208 125 133 166 139 145 129 181 159 151
112 143 137 142 117 85 78 104 114 75 62 84 87 92 81 85 93 99 85 86
82 83 104
HHB-A80A 51
340 344 273 192 198 320 247 140 107 120 131 114 121 178 162 191 221 160 223 129
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200 160 73 100 124 146 120 110 120 140 134
HHB-A80B 51
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118 74 57 96 104 75 88 122 128 131 97 135 105 110 119 174 142 142 105 162
210 164 65 96 125 151 116 108 113 142 123
HHB-A82A 45
202 117 125 129 98 109 98 186 115 138 103 194 123 114 101 159 137 121 116 94
90 117 105 75 125 187 125 153 83 110 67 142 118 127 153 139 189 100 125 139
117 199 135 122 167
HHB-A82B 45
212 117 123 126 94 106 104 184 122 140 111 187 120 92 110 189 134 125 96 82
82 119 78 87 112 180 114 155 78 96 79 132 135 128 157 146 187 103 139 125
114 192 135 117 181
HHB-A83A 67
162 236 221 259 168 268 275 176 200 142 201 157 98 187 166 139 196 182 132 264
316 190 192 264 214 278 201 201 261 242 270 221 239 220 176 162 273 190 214 203
268 239 207 208 162 181 192 120 92 137 214 145 129 97 100 126 214 145 140 153
104 198 110 259 215 157 216
HHB-A83B 67
159 227 232 257 169 269 250 166 191 143 192 164 95 175 169 139 207 177 153 268
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276 242 212 198 178 176 207 115 114 134 209 143 129 82 114 114 209 137 135 161
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HHB-A84A 51
208 142 259 153 170 119 111 135 108 184 98 154 111 251 173 147 153 228 136 151
106 110 91 139 157 100 143 226 160 155 103 122 89 166 147 170 186 196 246 149
150 133 179 278 159 124 161 259 226 203 254
HHB-A84B 51
196 160 263 172 156 108 99 125 107 211 108 130 131 241 167 147 139 219 141 144
101 109 95 145 154 104 138 228 142 170 98 121 80 135 162 165 178 197 263 142
160 138 170 290 156 135 156 251 183 253 246
HHB-A85A 92
270 209 196 184 125 148 150 143 156 117 76 63 83 148 185 139 105 83 77 121
142 141 151 217 234 176 257 265 201 117 130 295 236 230 260 156 253 201 157 131
102 69 92 90 133 175 206 215 167 265 220 130 155 290 221 242 210 251 269 129
92 105 123 160 120 113 150 250 161 145 102 109 100 123 115 56 54 70 106 106
176 106 66 62 81 70 123 153 84 46 63 128
HHB-A85B 92
284 221 193 167 140 137 153 125 171 131 82 55 84 130 180 148 96 83 79 106
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93 82 89 87 134 182 204 203 181 261 225 126 159 281 228 242 212 253 270 121
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156 95 63 64 84 71 112 142 86 64 59 121
HHB-A86A 81
159 176 369 333 383 423 418 447 316 384 357 282 328 211 203 256 204 269 269 269
221 228 194 174 200 265 270 195 142 114 114 154 127 198 278 262 249 184 242 281
208 112 93 146 195 196 201 151 243 201 128 92 90 92 53 73 78 100 176 205
134 153 121 121 68 127 153 168 160 224 228 123 66 81 101 108 105 72 108 136
151
HHB-A86B 81
156 175 382 343 379 424 434 466 319 365 347 265 321 225 200 260 197 273 272 268
233 199 213 187 198 250 262 207 143 127 107 150 150 201 268 273 264 189 237 276
193 112 82 165 209 187 204 139 252 207 134 112 92 78 66 69 84 102 175 215
140 154 128 131 71 125 128 156 137 211 229 127 68 90 93 103 96 78 109 140
154
HHB-A87A 77
271 280 162 150 209 210 241 140 157 167 207 184 161 210 166 141 128 202 184 175
189 280 224 217 205 172 199 236 128 105 123 209 131 148 77 81 85 164 114 129
121 98 160 101 185 137 96 106 125 132 109 111 140 79 79 95 84 94 48 48
54 53 53 52 42 34 54 51 41 48 43 48 50 53 42 52 72
HHB-A87B 77
245 278 157 168 216 195 238 138 151 158 203 187 164 214 167 132 128 210 173 182
172 264 221 225 196 183 200 245 128 107 117 209 139 144 75 85 85 165 112 125
126 99 164 95 190 136 93 112 108 150 101 109 146 95 75 105 84 95 54 40
56 54 60 46 45 35 57 51 40 49 40 53 50 53 42 54 84
HHB-A88A 56
409 316 173 126 127 81 92 120 178 171 230 223 305 268 334 307 196 197 211 164
156 178 154 146 163 319 297 222 171 200 134 87 112 70 73 100 126 178 129 115
103 103 126 190 196 189 169 140 170 208 227 207 195 198 159 200
HHB-A88B 56
413 318 179 121 137 83 84 122 164 176 226 246 307 301 342 311 189 195 202 176
153 176 157 140 165 325 288 225 170 201 122 95 112 75 67 102 131 179 123 120
95 110 128 177 205 193 153 150 178 206 187 207 201 176 154 184
HHB-A89A 131

142 96 106 123 105 147 170 182 126 140 160 190 196 201 162 142 107 92 115 175
146 119 104 84 75 108 144 160 128 92 104 72 109 150 113 118 92 96 135 142
142 107 103 100 157 128 161 84 144 144 126 109 105 143 117 101 82 90 92 60
100 99 95 118 100 65 109 153 114 57 75 51 71 56 71 73 90 59 50 70
51 67 54 59 68 85 73 60 59 37 32 38 53 51 73 67 51 56 49 42
54 53 92 87 78 57 71 67 58 54 65 87 62 54 59 76 78 75 78 73
59 101 87 73 60 48 76 79 44 50 84

HHB-A89B 131
138 93 114 125 108 150 179 195 132 136 170 183 195 200 166 135 107 86 127 171
146 121 105 78 75 110 150 160 127 92 101 75 109 146 114 118 96 97 125 142
146 104 100 98 163 130 160 67 149 153 126 115 107 129 122 104 75 81 95 62
92 92 90 114 102 67 109 146 118 57 75 51 70 60 67 79 96 53 45 67
58 68 53 60 64 81 84 46 56 40 32 33 55 58 73 62 62 51 53 43
47 52 95 85 75 59 65 66 58 51 73 76 64 61 52 75 82 78 79 64
56 97 91 71 60 57 62 68 54 43 77

HHB-A90A 126
167 279 136 106 104 78 113 173 153 113 153 132 169 170 191 171 114 135 205 167
211 82 203 166 184 126 119 112 148 139 84 110 121 78 123 110 102 98 105 79
128 146 104 52 94 65 102 78 89 99 98 60 50 76 79 84 47 70 57 89
112 73 78 52 39 60 65 62 64 90 98 114 82 64 81 67 128 97 118 71
90 56 57 66 57 72 62 79 84 70 103 104 123 100 70 115 106 121 95 68
78 73 65 71 124 97 65 77 56 75 94 96 103 99 145 122 62 59 70 100
70 84 81 62 84 90

HHB-A90B 126
172 282 137 105 106 81 107 177 165 113 151 130 164 169 205 169 116 133 214 168
191 100 176 174 182 133 110 115 157 131 89 105 136 72 124 105 100 97 112 85
121 144 107 56 88 64 103 82 97 93 95 57 49 70 81 79 41 74 59 89
104 79 67 53 49 51 65 65 64 67 113 111 87 67 81 68 128 103 114 73
93 55 59 65 59 75 57 79 87 73 100 106 126 93 73 116 103 124 89 68
81 78 65 77 107 115 67 75 54 79 91 94 105 100 143 117 61 66 75 78
70 89 85 59 77 86

HHB-A91A 160
153 168 105 48 53 58 89 175 134 155 154 121 63 91 92 125 94 162 150 50
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50 127 82 84 92 125 124 94 96 118 119 85 67 140 120 122 103 135 103 96
89 102 78 87 78 117 82 72 122 68 81 99 94 118 106 64 63 78 116 138
142 103 71 86 110 134 132 135 78 92 45 67 97 102 98 98 81 56 76 137
115 106 114 114 126 168 115 120 101 135 125 107 105 100 144 143 131 114 85 129
96 112 84 75 92 77 97 111 93 114 96 122 118 122 125 75 100 93 117 107
112 115 93 75 74 87 86 86 69 105 82 112 118 90 90 72 81 75 65 126

HHB-A91B 160
159 162 105 58 51 55 90 173 130 154 157 117 61 92 92 137 94 157 160 42
29 54 34 33 67 84 113 107 98 151 130 101 138 151 113 132 113 78 54 73
55 120 67 75 73 128 100 103 95 127 126 83 64 153 121 138 110 135 96 100
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115 83 128 118 115 148 132 109 104 131 134 118 101 104 148 148 117 123 82 114
106 113 83 75 98 68 100 112 86 122 97 117 125 131 121 76 101 93 110 108
112 114 97 68 81 90 81 83 78 101 90 114 107 96 71 85 78 68 85 118

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It

also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

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

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

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

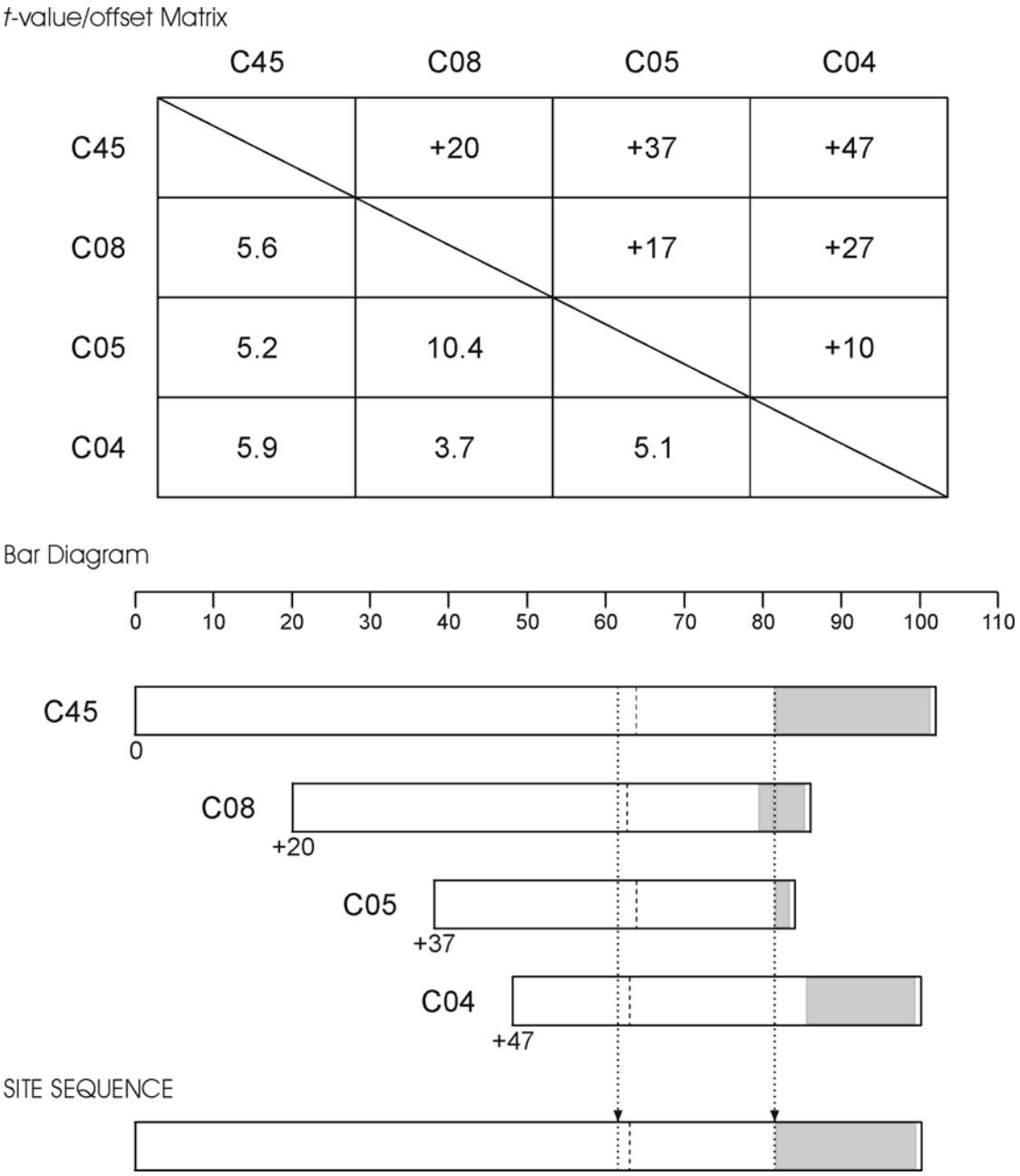


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

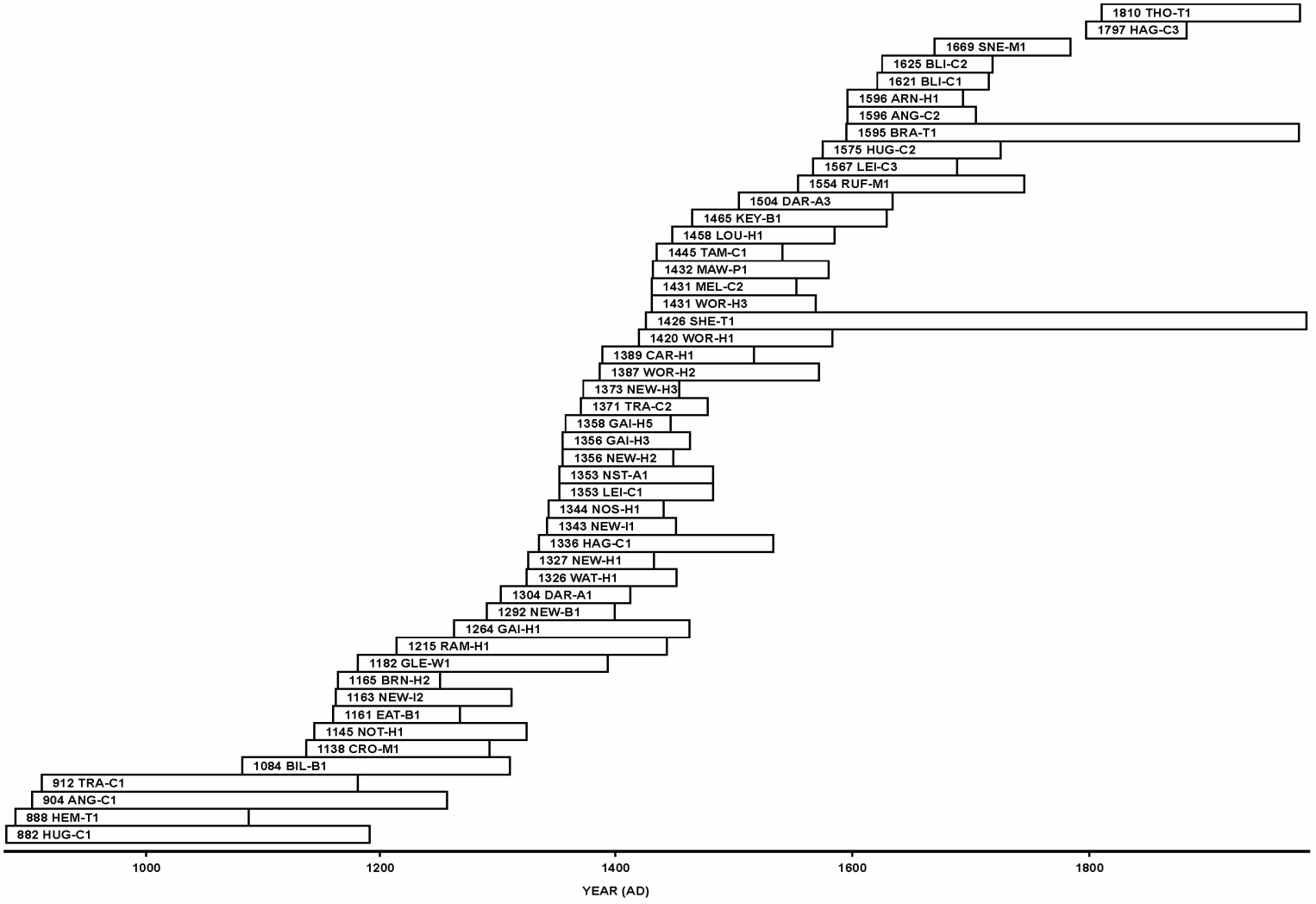
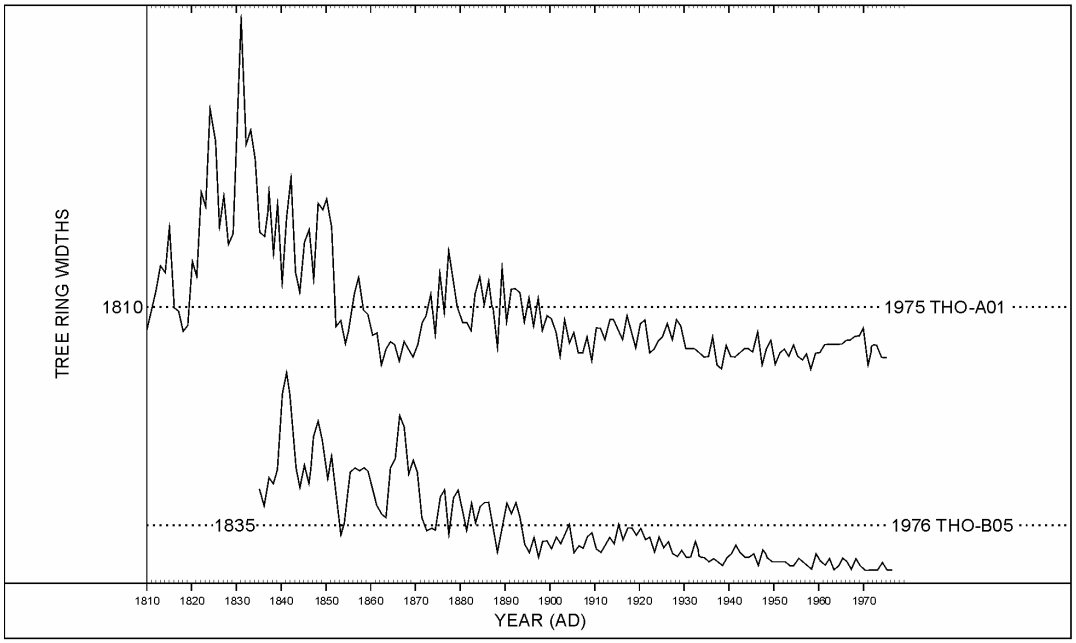


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

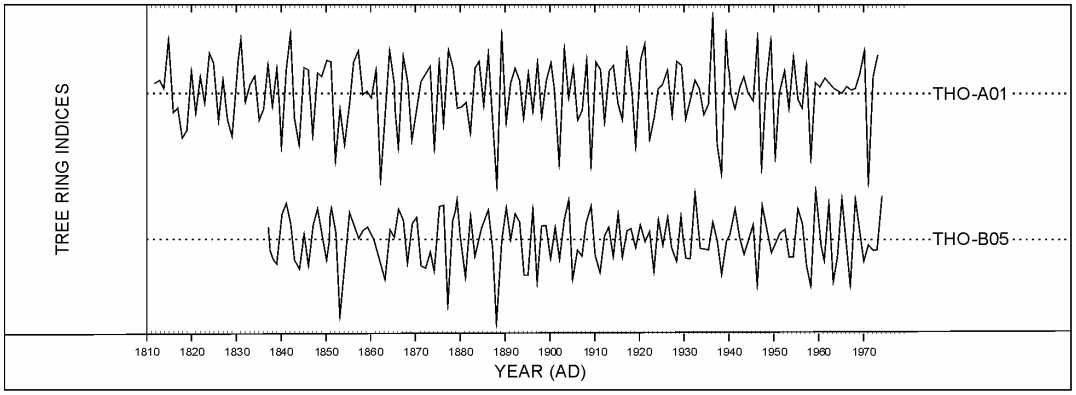


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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