Ancient Monuments Laboratory
Report 42/2000

TREE-RING ANALYSIS OF TIMBERS FROM WORCESTER CATHEDRAL, WORCESTER

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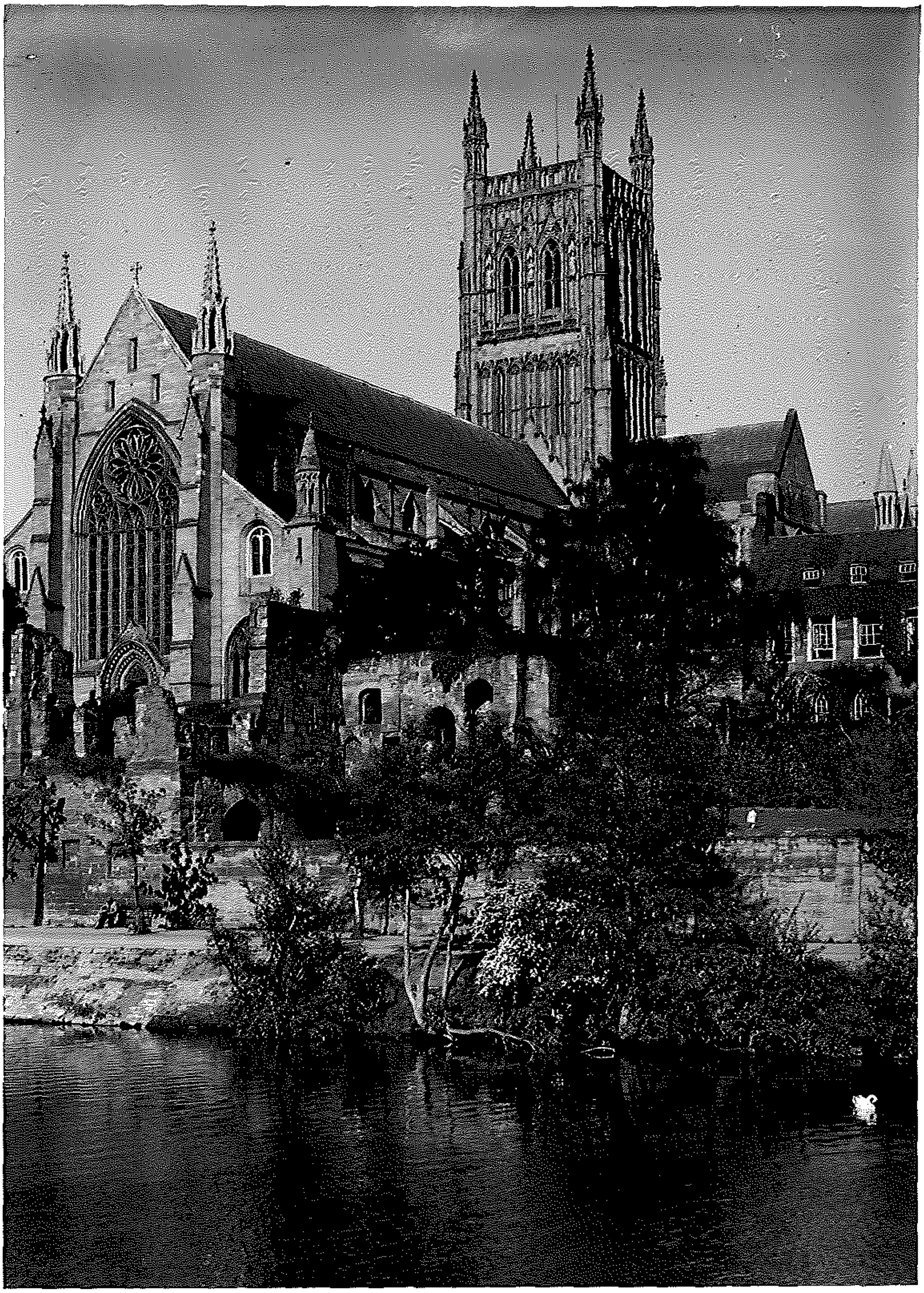

Frontispiece: Worcester Cathedral from the south-west, across the river Avon (©RCHME)

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Summary

A total of ninety-eight samples from the eastern roofs of Worcester Cathedral were analysed by tree-ring dating. This analysis produced six site chronologies. The first site chronology, WORCSQ01, consisting of forty-five samples, has 287 rings and spans the period AD 1443 - AD 1729. Interpretation of the sapwood on these samples indicates felling dates between AD 1724 and AD 1729. This shows that a substantial rebuilding or repair programme was undertaken in the choir, the north-east and south-east transepts, and in the crossing between the transepts at this time. This site chronology includes several timbers felled in AD 1650 - 3 and shows that some earlier material was incorporated in the eighteenth-century rebuilding programme. The second site chronology, WORCSQ02, consists of eighteen samples from timbers showing evidence of reuse. This site chronology has 191 rings spanning the period AD 1057 - AD 1247. The third site chronology, WORCSQ03, consisting of eleven samples from timbers which again show evidence of reuse, has 116 rings spanning the period AD 1096 - AD 1211. Interpretation of the sapwood on these two site chronologies combined indicates a range of felling dates in the early- to mid-thirteenth century, between about AD 1225 and AD 1260. Other later thirteenth-century material is represented by site chronology WORCSQ06. This is made up of two samples and has 77 rings spanning the period AD 1174 - AD 1250. The timbers represented have an estimated felling date in the range AD 1264 - AD 1299. The fourth site chronology, WORCSQ04, consists of four samples with 85 rings. This site chronology failed to date. The fifth site chronology, WORCSQ05, is made up of two samples with 97 rings. This site chronology also failed to date.

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Introduction

Worcester Cathedral (frontispiece), standing in a prominent position on the east bank of the river Severn (SO 850545; Fig 1) has a long history. The bishopric was founded in the seventh century and the first Cathedral was dedicated to St Peter. Oswald, who was made bishop in AD 961, built a new cathedral, dedicated to St Mary. The presbytery of St Peter's was rebuilt following a Danish raid in AD 1041. Both early Cathedrals appear to have been demolished around the time St Wulfstan started the present Cathedral in AD 1084 (although the current hypothesis is that the Chapter House is a remodelling of a late Anglo-Saxon rotunda).

Surviving work of St Wulfstan's period includes the crypt, western transepts, cloisters, and Chapter House. In AD 1175 the crossing tower fell down and was rebuilt (Guy 1994). It was rebuilt again the AD 1370s. In AD 1224 the construction of a new east end was started under bishop William of Blois. Much of the existing decorated architecture at the east end belongs to this phase, with additional work in the perpendicular style dating from the late-fourteenth or early-fifteenth century. There was also a considerable amount of rebuilding activity in the nineteenth century

A modest amount of sampling for tree-ring analysis has been undertaken from timbers of the nave roof. This was commissioned by the Dean and Chapter of Worcester Cathedral in 1993, the work being funded by English Heritage (Howard *et al* 1995). The 1993 analysis indicated that, although a significant number of samples could not be dated, a certain amount of timber was felled in the early-seventeenth century, for repair work undertaken at that time. That programme of sampling showed that some earlier timbers were reused.

The programme of sampling and analysis by tree-ring dating reported on here was commissioned by English Heritage. In this phase of the work the sampling and dating exercise was restricted to the eastern roof of the cathedral, that is the choir, the north-east and south-east transepts, and the crossing between them. A plan of these roofs is given in Figure 2.

The choir roof is known from documentary sources to have been rebuilt in the early-eighteenth century, with written records pointing to a construction date of AD 1728. It contains nine trusses comprising tall, slender king-posts standing on tiebeams, with upper and lower diagonal struts to principal rafters. The trusses of the transepts and the crossing are almost identical in form, though those of the transepts have spine or bridging beams running between each truss at tiebeam and collar level. It is known from documentary sources that the roofs of the transepts were rebuilt in AD 1730.

Most of the trusses, as well as other portions of the roof, contain timbers which show no evidence of reuse and are thus believed to belong to the early-eighteenth century work. However, the roof contains timbers which, on the evidence of redundant mortices, tenons, lap-joints, and peg holes, were reused in the eighteenth-century rebuilding. The purpose of this programe of sampling and dating was twofold. Its first purpose was to determine the age and likely origin of the reused timbers. It was also hoped that it might be possible to show that timbers reused in each part of the roof, the choir, the transepts, etc, originally came from these sections so allowing an attempt at reconstructing the form of these earlier roofs.

The second purpose of sampling and analysis was to confirm, if possible, the date of the early eighteenth-century work. An important element of sampling this material was to provide extensive data for a well-replicated tree-ring chronology for the eighteenth century for Worcestershire and the south-west Midlands.

The Laboratory would like to take this opportunity to thank all those who assisted with the sampling of the timbers. In particular thanks are due to the Dean and Chapter of Worcester Cathedral, the Clerk of Works,

and to the Vergers' Office, whose staffs assisted with access to the roof. The Laboratory would also like to thank Mr Christopher Guy, the Cathedral Archaeologist, who made a detailed study of the roof, produced the drawings used in this report, and who assisted with the descriptive introduction to the site given above.

Sampling

The Laboratory was asked to sample four different areas of the eastern roofs: the choir, the north-east transept, the south-east transept, and the crossing. Within each of these, it was believed, were timbers of two phases, one of the early-eighteenth century rebuild material, the second of medieval reused timbers. In effect this gave eight different sets of timbers. Within each area an attempt was made to sample the two sets of timbers separately. While this was relatively easy to do in most places, it was more difficult in the area of the choir near the crossing and in the crossing itself. In the former, work, possibly in connection with nineteenth- and twentieth-century piping and electrical work, made for confusion between eighteenth-century and reused material. In the latter, within the crossing itself, there appeared to be relatively little reused material except for the timbers beneath the walkway.

Thus, a total of ninety-eight samples was obtained. Each sample was given the code WOR-C (for Worcester Cathedral) and numbered 01 – 98. Twelve samples, WOR-C01 – 12, were obtained from the eighteenth-century timbers of the crossing. Ten samples, WOR-C13 – 22, were obtained from the eighteenth-century timbers of the north-east transept, with eight samples, WOR-C23 – 30, being obtained from the south-east transept. Seventeen samples, WOR-C31 – 47, were obtained from what were believed to be eighteenth-century timbers of the choir.

Samples from reused timbers included fourteen, WOR-C48 – 61, from the north-east transept, and twelve, WOR-C62 – 73, from the south-east transept. Fifteen samples, WOR-C74 – 88, were obtained from what were believed to be reused timbers from the choir. Ten samples, WOR-C89 – 98, were obtained from reused timbers in the crossing, mainly below the walkway in that area and from timbers reused as wall-plates.

The positions of the samples were recorded at the time of sampling on plans produced by Christopher Guy and provided by English Heritage. These are reproduced here as Figures 3a – 7. Details of the samples are given in Table 1. Trusses, bays, and frames have been numbered from north to south, or from east to west following those given on the plans and drawings provided.

Analysis

Each sample was prepared by sanding and polishing. At this stage it was seen that two samples, WOR-C87 and WOR-C95, had too few rings for satisfactory analysis, and they were not measured. The growth-ring widths of the remaining ninety-six samples were measured (data at the end of the report) and compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum t-value of 4.5 six groups of samples formed, with brief details as sumarised below.

Site chronology	Sample area	Number of samples	Number of rings	Date span
WORCSQ01	Eighteenth-century rebuilding timbers	45	287	AD 1443 - 1729
WORCSQ02	Reused thirteenth-century timbers	18	191	AD 1057 - 1247
WORCSQ03	Reused thirteenth-century timbers	11	116	AD 1096 - 1211
WORCSQ04		4	85	undated
WORCSQ05		2	97	undated
WORCSQ06	Reused thirteenth-century timbers	2	77	AD 1174 - 1250

Bar diagrams of the samples in each site chronology are given in Figures 8 – 13, with evidence for the dating of those which cross-match with the reference chronologies being given in the t-values of Tables 2 – 5.

The six site chronologies created were compared with each other and with the fifteen remaining measured but ungrouped samples. In no case was there any further satisfactory cross-matching. Each of the fifteen ungrouped samples was compared with a full range of reference chronologies but, again, there was no further satisfactory cross-matching and these samples remain undated.

Interpretation

Site chronology WORCSQ01: eighteenth-century rebuilding timbers, bar diagram Figure 8

It is apparent that the documentary evidence for the rebuilding of the roofs of the eastern end of the Cathedral in the early-eighteenth century is correct. Site chronology WORCSQ01 is made up of samples from timbers of this phase of the work, two samples of which have last measured complete sapwood ring dates of AD 1729. However, observation of the bar diagram of this site chronology in Figure 8 shows that in each section of the roof there may be a slight time difference in the felling date of the timbers cut specifically for this eighteenth-century rebuilding.

One sample from the south-east transept, WOR-C30, has a last measured complete sapwood ring date of AD 1724. Two samples from timbers of the choir, WOR-C42 and WOR-C44, have last measured complete sapwood ring dates of AD 1726 and AD 1725 respectively. A further sample from the choir, WOR-C45, has a last sapwood ring date of AD 1724, from which one or possibly two rings were lost in coring. This would give this timber a felling date of AD 1725 or AD 1726. Two samples from the crossing, WOR-C02 and WOR-C04, both have a last measured complete sapwood ring date of AD 1727 and three samples from the north-east transept, WOR-C14, WOR-C16, and WOR-C20, have last measured complete sapwood ring dates of AD 1729, AD 1728, and AD 1729 respectively.

Given that the number of samples from each section with complete sapwood is small, it is not certain whether or not these felling dates are truly indicative of their construction dates. However, it does appear possible that the felling dates of these timbers, from AD 1724 to AD 1729, may reflect the progress of the work in the roofs. Perhaps documentary or structural evidence may agree with the felling dates to show that work began in the south-east transept, moved to the choir, and then to the crossing, and finally the north-east transept.

Interpretation of the sapwood on seven or eight samples in the bar diagram of site chronology WORCSQ01 would suggest that there is another and earlier phase of felling represented by some timbers in the north-east and south-east transepts. Among these samples WOR-C17, C23, C24, and C28 all have complete sapwood, with last ring dates of AD 1653, AD 1652, AD 1650, and AD 1653 respectively. All these samples are from raking shores and the spine, or bridging, beams which run between the trusses of the transepts. This combination of factors suggests that these timbers are a definite sub-group, distinct from the other timbers in site chronology WORCSQ01.

Given that the raking shores and the spine beams are integral to the construction of the trusses of the transepts, they must be reused timbers. It is possible that when originally felled in the mid-seventeenth century they were used somewhere in the Cathedral roof. There is some documentary evidence for such work on the cathedral roofs in the mid-seventeenth century (Simpson 1993). Simpson (1994;19,21) suggests a rebuilding of the Nave roof in the first half of the seventeenth-century but it may have been later and associated with the post-Restoration repairs to the fabric. It is quite possible that the trees of this sub-group were felled in the AD 1650s but not immediately used.

Reused timbers

Site chronology WORCSQ02: thirteenth-century timbers, bar diagram Figure 9

It is more difficult to be so precise about the felling dates of the reused timbers represented by site chronology WORCSQ02 because the upper and lower limits of the relative positions of the heartwood/sapwood boundaries is wider. The earliest heartwood/sapwood transition is AD 1187, on sample

WOR-C71, and the latest heartwood/sapwood transition is AD 1247, on sample WOR-C32, a range of 60 years. This range is wider than would be expected on a group of timbers all felled at the same time.

Because of this range it is believed possible that the eighteen samples of site chronology WORCSQ02 are representative of three phases of felling. The earliest is thought to be represented by sample WOR-C71. Its heartwood/sapwood transition date of AD 1187 would give this timber an estimated felling date in the range AD 1214 – 37. This felling date range is based on a 95% confidence limit for the amount of sapwood on mature oaks of 15-50 rings, and allowing that the last measured ring on the sample is dated to AD 1213.

The next phase may be represented by thirteen samples, WOR-C49, C57, C58, C62, C64, C65, C67, C69, C70, C72, C83, C85, and C96. The average last heartwood ring date on these samples is AD 1212. Using the same confidence limit for the number of sapwood rings as given above gives an estimated felling date in the range AD 1235 – 62 for the timbers represented by these samples, allowing that sample WOR-C69 has a last measured ring date of AD 1234.

The final possible phase of felling is represented by samples WOR-C32, C74, C84, and C89. The average last heartwood ring date on these samples is AD 1241. Using the same sapwood estimate as above gives the timbers represented by these samples a felling date in the range AD 1256 – 91. If the assumption that these four timbers were felled at the same time is correct, then it is likely that the felling was after AD 1260. This is because sample WOR-C32 has a heartwood/sapwood boundary date at AD 1247, and the timber it represents is unlikely to have been felled before AD 1262, based on a minimum number of 15 sapwood rings.

Site chronology WORCSQ03: reused mid-thirteenth century timbers, bar diagram Figure 10

The relative positions of the heartwood/sapwood boundaries on the six samples in site chronology WORCSQ03 where this survives are closer together, varying only by seven years, as shown in the bar diagram Figure 10. This suggests that these timbers were felled in a single phase. The average last heartwood ring date of this group is AD 1207. Using a 95% confidence limit for the amount of sapwood on mature oaks of 15 – 50 rings gives these timbers an estimated felling date in the range AD 1222 – 57. The five remaining samples have no heartwood/sapwood boundary. It is possible that this has simply been trimmed off, but the dates of the last rings suggest that they too could have been felled sometime in this period, though some are possibly a little later than the six timbers which do have the heartwood/sapwood boundaries.

Site Chronology WORCSQ06: mid to late thirteenth-century timbers, bar diagram Figure 13

The two samples of this site chronology appear to represent a single felling phase. Having an average last heartwood ring date of AD 1249 gives the timbers represented an estimated felling date in the range AD 1264 – 99.

The dating information thus obtained can be summarised as follows:

Site chronology	Number of samples	Estimated felling date range
WORCSQ01 (felling phase 1)	8	AD 1650 – 1653
WORCSQ01 (felling phase 2)	37	AD 1724 – 1729
WORCSQ02 (felling phase 1)	1	AD 1214 – 1237
WORCSQ02 (felling phase 2)	13	AD 1235 – 1262
WORCSQ02 (felling phase 3)	4	AD 1256 – 1291
WORCSQ03	11	AD 1222 – 1257
WORCSQ06	2	AD 1264 – 1299

It is possible that the timbers represented by the samples in site chronology WORCSQ02, felling phase 2, and site chronology WORCSQ03 are in fact all part of the same programme of felling. If the dates of the heartwood/sapwood transitions, on those samples where it exists, are combined we get an average heartwood/sapwood transition date of AD 1210. Using a 95% confidence limit for the amount of sapwood on mature oaks of 15-50 rings would give the timbers represented an estimated felling date in the range AD 1225 – 60.

It is also possible that the timbers represented by the samples in site chronologies WORCSQ02, felling phase 3, and WORCSQ06 are of the same programme of felling. If the dates of the last heartwood ring on each of the relevant samples are combined we get an average last heartwood ring date of AD 1245. Using the same sapwood estimate as above would give the timbers represented an estimated felling date in the range AD 1260 – 95.

In both these cases it appears possible that although the timbers used were felled at or about the same time, it is possible that they may have come from different sources. This is known to have occurred in the post medieval period (Simpson and Fearn 1997), and it would account for the failure of the samples or site chronologies to cross-match with each other.

Timber analysis

It seems possible that a number of timbers come from the same tree, while other timbers came from trees which were growing quite close to each other. This is particularly so with the timber felled in the eighteenth century, but less so with the earlier material. It is likely, for example, that samples WOR-C17, C23, and C24 are from the same tree, cross-matching as they do with values of about t=11.0. Samples WOR-C27 and C28 are also possibly from the same tree, cross-matching with a t-value of 9.8. However, not all samples which cross-match with each other with significant t-values are from the same tree. Samples WOR-C33, C34, C35, C37, C44, and C46, for example, cross-match well with each other but each is from a timber comprising a whole tree. In this case the trees are likely to have been growing quite close to each other.

Again, particularly with the eighteenth-century material, there appears to a greater degree of high t-value cross-matching between samples within each area of the roof than between samples from different areas of the roof. That is, samples from the choir appear to cross-match best with other samples from the choir, and less well with samples from the transepts, for example, though this is not exclusively the case. It is thus possible that individual woodland compartments were largely used for each phase of work, although, as might be expected, there was some spread of timbers into different phases.

The earlier, thirteenth-century, reused material appears to be less homogeneous. Two site chronologies composed of reused material were created, WORCSQ02 and WORCSQ03, both having roughly the same time span, AD 1057 – 1247 and AD 1096 – 1211, respectively. These two site chronologies cross-match with each other with a low, though maximum, value of t=3.9 at the suggested relative offset, plus 39 years. This low t-value cross-matching would suggest that the timbers represented came from different and widely separated sources.

It is also to be seen that the timbers for these two site chronologies are distributed amongst each part of the roof. Timbers from the choir, the crossing, and the north-east and south-east transepts, are found in both sequences.

Conclusion

This analysis has shown that the roof of the east end of the Cathedral was substantially rebuilt using timber felled between AD 1724 and AD 1729. This is almost certainly the work referred to in the documentary evidence. This work included the reuse of timber felled in the mid-seventeenth century, either purposely for the Cathedral, or possibly for elsewhere. The timber representing this earlier work shows no sign of reuse and it existence here was previously unsuspected.

The eighteenth-century timber all appears to have come from a reasonably homogeneous source. There is a possibility that individual blocks of woodland or stands of trees went into particular sections of the roof, though there was, of course, some intermixing as work progressed. It is probable that some trees were used to make more than one timber.

It will be seen from Table 1, where the number of rings that each sample contains is listed, that the trees used for the seventeenth-century work were much longer lived than the trees used for the eighteenth-century work. Allowing for some missing rings to the centres of the trees it is estimated that a number of trees felled in the AD 1650s were over 200 years old when felled; those felled in the AD 1720s were hardly ever more than 100 years old.

The eighteenth-century work also reused timbers that were felled earlier. It is possible that a small amount of this was felled in the early-thirteenth century, but most of it appears to have been felled in the early- to mid-thirteenth century. This is possibly the timber which was obtained purposely for the roof of the new east end, construction of which was begun under bishop William of Blois in AD 1224. A second group of timbers is represented which was felled in the mid- to late-thirteenth century.

The felling dates for the thirteenth-century timbers would seem to agree with the phasing of the work east of the Tower. The timbers represented by the samples in site chronology WORCSQ02, felling phase 2, and WORCSQ03 may relate to the roofing of the Lady Chapel, construction of which was started in AD 1224. The timbers represented by the samples in site chronology WORCSQ02, felling phase 3, and WORCSQ06 could have belonged to the roof of the Choir, which was rebuilt to match the style of the Lady Chapel after that had been completed.

Much of the reused thirteenth-century material is of similar scantling and it contains similar joints and other details of carpentry. Furthermore, the reuse of a lot of broadly contemporaneous material supports the probability that it does all come from the cathedral. One possible way of proving this may be to record the reused timbers and attempt a reconstruction of the medieval roofs.

It appears more likely that the thirteenth-century timber may have come from different sources, and may have been felled over a longer period. There is no way of knowing for certain that timber once used in the choir was used there again during the eighteenth-century rebuilding. This seems unlikely given the evidence for the mixing of timbers.

Nineteen samples remain undated. Most of these have a satisfactory number of rings for dating, and indeed some are quite long. Although a few of the samples are a little complacent, none of the very long undated samples show obviously complacent or stressed growth rings that would make dating difficult.

Of the ninety-six samples measured and analysed some 35 are from timbers with felling dates in the early-eighteenth century while 31 samples are from timbers that have, or probably have, felling dates in the thirteenth century. There are eight timbers which were felled in the mid-seventeenth century and three for which felling dates cannot be estimated due to the lack of the heartwood/sapwood boundary. Nineteen measured samples remain undated.

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Table 1: Details of samples from Worcester Cathedral, Worcester

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	The crossing					
WOR-C01	South principal rafter, truss 2 (East truss)	60	4	AD 1656	1711	1715
WOR-C02	North principal rafter, truss 2	69	16C	AD 1659	1711	1727
WOR-C03	King post, truss 1 (West truss)	89	5	AD 1621	1704	1709
WOR-C04	South principal rafter, truss 1	74	28C	AD 1654	1699	1727
WOR-C05	North strut, truss 1	81	11	AD 1620	1689	1700
WOR-C06	South strut, truss 1	80	8	AD 1620	1691	1699
WOR-C07	Tiebeam, truss 1	75	11	AD 1636	1699	1710
WOR-C08	North strut, truss 2	69	14	AD 1633	1687	1701
WOR-C09	South rafter 4	70	2	------	------	------
WOR-C10	South rafter 3	58	no h/s	------	------	------
WOR-C11	North rafter 1	61	no h/s	AD 1631	------	1691
WOR-C12	North rafter 4	55	no h/s	AD 1630	------	1684
WOR-C82	North principal rafter, truss 1	59	20C	AD 1667	1705	1725
	North-east transept					
WOR-C13	Spine/bridging beam, truss 2-3	240	17C	------	------	------
WOR-C14	King post, truss 1	67	28C	AD 1663	1701	1729
WOR-C15	East brace, truss 3	65	no h/s	------	------	------
WOR-C16	King post, truss 2	100	27C	AD 1629	1701	1728
WOR-C17	Raking shore, truss 3-4	195	26C	AD 1459	1627	1653
WOR-C18	Spine/bridging beam, truss 3-4	190	h/s	AD 1447	1636	1636
WOR-C19	King post, truss 4	57	19	------	------	------
WOR-C20	King post, truss 3	60	18C	AD 1670	1711	1729
WOR-C21	Tiebeam, truss 3	110	h/s	------	------	------
WOR-C22	Tiebeam, truss 2	87	no h/s	AD 1531	------	1617

Table 1: Continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	South-east transept					
WOR-C23	Spine/bridging beam truss 1-2	210	19C	AD 1443	1633	1652
WOR-C24	Raking shore, truss 2-3	193	26C	AD 1458	1624	1650
WOR-C25	Spine/bridging beam, truss 4-5	308	12	------	------	------
WOR-C26	Tiebeam, truss 2	70	10	------	------	------
WOR-C27	Spine/bridging beam, truss 3-4	178	no h/s	AD 1476	----	1653
WOR-C28	Upper spine/bridging beam, truss 3-4	141	14C	AD 15[illegible]	1639	1653
WOR-C29	Tiebeam, truss 4	57	14	------	------	------
WOR-C30	King post, truss 1	64	17C	AD 1661	1707	1724
	The choir					
WOR-C31	Tiebeam, truss 1	79	h/s	AD 1530	1608	1608
WOR-C32	Tiebeam, truss 2	85	h/s	AD 1163	1247	1247
WOR-C33	Tiebeam, truss 3	131	9	AD 1579	1700	1709
WOR-C34	Tiebeam, truss 5	92	h/s	AD 1606	1697	1697
WOR-C35	Tiebeam, truss 6	122	h/s	AD 1568	1689	1689
WOR-C36	Tiebeam, truss 7	150	10	AD 1562	1701	1711
WOR-C37	Tiebeam, truss 8	130	5	AD 1566	1690	1695
WOR-C38	King post, truss 1	63	12	------	------	------
WOR-C39	King post, truss 3	70	14	AD 1649	1704	1718
WOR-C40	King post, truss 4	54	h/s	AD 1655	1708	1708
WOR-C41	King post, truss 6	76	14	------	------	------
WOR-C42	King post, truss 8	95	28C	AD 1632	1698	1726
WOR-C43	North principal rafter, truss 7	72	10	AD 1649	1710	1720
WOR-C44	North common rafter 3, bay 3	72	24C	AD 1654	1701	1725
WOR-C45	North common rafter 4, bay 3	77	21c	AD 1648	1703	1724
WOR-C46	North common rafter 3, bay 4	100	no h/s	AD 1575	------	1674
WOR-C47	King post, truss 7	59	h/s	AD 1635	1693	1693

Table 1: Continued

Sample no	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	North-east Transept					
WOR-C48	West common rafter 3, bay 2	69	h/s	AD 1640	1708	1708
WOR-C49	West strut, truss 2	104	12c	AD 1121	1212	1224
WOR-C50	North purlin, east-west crossing trusses	77	no h/s	AD 1128	1204	1204
WOR-C51	East common rafter 2, bay 1	98	no h/s	AD 1491	------	1588
WOR-C52	East common rafter 1, bay 1	61	no h/s	------	------	------
WOR-C53	East common rafter 1, bay 2	66	4	AD 1530	1591	1595
WOR-C54	East purlin, truss 3-4	83	no h/s	------	------	------
WOR-C55	East wall plate, truss 3-5	100	no h/s	AD 1096	------	1195
WOR-C56	West purlin, truss 2-3	82	no h/s	AD 1129	------	1210
WOR-C57	West common rafter 4, truss 1 – crossing	93	no h/s	AD 1119	------	1211
WOR-C58	West strut, truss 1	70	h/s	AD 1149	1218	1218
WOR-C59	East strut, truss 5	79	h/s	------	------	------
WOR-C60	West strut, truss 3	70	no h/s	AD 1141	------	1210
WOR-C61	East strut, truss 2	75	no h/s	AD 1137	------	1211
	South-east transept					
WOR-C62	South purlin, east-west truss of crossing	95	h/s	AD 1120	1214	1214
WOR-C63	East strut, truss 5	71	h/s	------	------	------
WOR-C64	East strut, truss 4	79	h/s	AD 1138	1216	1216
WOR-C65	East strut, truss 2	81	h/s	AD 1120	1200	1200
WOR-C66	East strut, truss 3	54	h/s	AD 1152	1205	1205
WOR-C67	East purlin, truss 3-4	92	h/s	AD 1126	1217	1217
WOR-C68	West strut, truss 3	56	h/s	AD 1153	1208	1208
WOR-C69	West strut, truss 4	61	18	AD 1174	1216	1234
WOR-C70	West purlin, truss 3-4	95	no h/s	AD 1092	------	1186
WOR-C71	West purlin, truss 2-3	157	26	AD 1057	1187	1213
WOR-C72	East purlin, truss 5 – crossing	85	no h/s	AD 1097	------	1181
WOR-C73	West strut, truss 2	104	h/s	------	------	------

Table 1: Continued

Sample no	Sample location	Total Rings	*Sapwood rings	First measured ring date	Last heartwood Ring date	Last measured ring date
	Choir					
WOR-C74	North purlin, truss 4-5	66	h/s	AD 1169	1234	1234
WOR-C75	South purlin, truss 4-5	97	h/s	------	------	------
WOR-C76	South principal rafter, truss 6	67	15	AD 1657	1708	1723
WOR-C77	South common rafter 2, bay 6	66	3	AD 1626	1688	1691
WOR-C78	South common rafter 3, bay 7	77	no h/s	AD 1605	------	1681
WOR-C79	South common rafter 2, bay 7	60	h/s	AD 1632	1691	1691
WOR-C80	South common rafter 5, bay 7	90	21C	AD 1635	1703	1724
WOR-C81	South common rafter 4, bay 7	65	h/s	AD 1643	1707	1707
WOR-C83	North common rafter 2, bay 3	64	h/s	AD 1145	1208	1208
WOR-C84	North principal rafter, truss 1	103	no h/s	AD 1125	------	1227
WOR-C85	North purlin truss 1-west crossing truss	124	no h/s	AD 1066	------	1189
WOR-C86	South principal rafter, truss 3	64	no h/s	------	------	------
WOR-C87	North common rafter 3, bay 6	nm	---	------	------	------
WOR-C88	North common rafter 4, bay 6	54	hs	------	------	------
	Timbers beneath walkway					
WOR-C89	Reused beam	80	h/s	AD 1162	1241	1241
WOR-C90	Reused beam	66	2	------	------	------
WOR-C91	Reused beam	76	h/s	AD 1126	1201	1201
WOR-C92	Reused beam	61	h/s	AD 1148	1208	1208
WOR-C93	Reused beam	79	h/s	AD 1129	1207	1207
WOR-C94	Reused beam	79	h/s	AD 1129	1207	1207
WOR-C95	Reused beam	nm	---	------	------	------
WOR-C96	Wall plate	62	h/s	AD 1142	1203	1203
WOR-C97	Wall plate	74	h/s	AD 1177	1250	1250
WOR-C98	Wall plate	74	h/s	AD 1174	1247	1247

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

Table 2: Results of the cross-matching of site chronology WORCSQ01 and relevant reference chronologies when first ring date is AD 1443 and last ring date is AD 1729

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	4.9	(Laxton and Litton 1988)
St Hugh's Choir, Lincoln Cathedral	AD 401 – 1981	9.2	(Laxton and Litton 1988)
Bradgate Park, Leics	AD 1595 – 1975	7.6	(Laxton and Litton 1988)
Rufford Mill, Notts	AD 1571 – 1744	5.8	(Laxton and Litton 1988)
Westhorpe Frm, Killamarsh, Derbys	AD 1528 – 1629	7.0	(Howard *et al* 1994b)
Mansfield Woodhouse, Notts	AD 1431 – 1660	6.2	(Howard *et al* 1997)
Sutton Scarsdale Hall, Derbys	AD 1526 – 1658	6.2	(Howard *et al* 1996a)
Worcester Cathedral, Nave roof	AD 1597 – 1730	8.7	(Howard *et al* 1995)
Quenby Hall, Leics	AD 1648 – 1765	7.9	(Howard *et al* 1993 unpubl)
Ragnall barn, Ragnall, Notts	AD 1607 – 1717	6.6	(Howard *et al* 1997)
Southwell Minster, Notts	AD 1573 – 1716	7.2	(Howard *et al* 1996b)

Table 3: Results of the cross-matching of site chronology WORCSQ02 and relevant reference chronologies when first ring date is AD 1057 and last ring date is AD 1247

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	6.2	(Laxton and Litton 1988)
England	AD 401 – 1981	6.3	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	5.1	(Bridge 1988)
Angel Choir, Lincoln Cathedral	AD 912 – 1248	6.8	(Laxton and Litton 1988)
Brecon Cathedral, Powys	AD 996 – 1227	6.5	(Howard *et al* 1994a)
Salisbury Cathedral, Wilts	AD 1119 – 1201	6.1	(Howard *et al* 1992)
Horninglow St, Burton-on-Trent, Staffs	AD 1101 – 1345	5.9	(Howard *et al* 1995)

Table 4: Results of the cross-matching of site chronology WORCSQ03 and relevant reference chronologies when first ring date is AD 1096 and last ring date is AD 1211

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	5.1	(Laxton and Litton 1988)
England	AD 401 – 1981	3.5	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	4.9	(Bridge 1988)
Quaintree House, Braunston, Leics	AD 1165 – 1305	4.6	(Alcock *et al* 1991)
Angel Choir, Lincoln Cathedral	AD 912 – 1248	5.4	(Laxton and Litton 1988)
Reading A	AD 1160 – 1407	5.4	(Groves *et al* 1997)
Severns, Nottm	AD 1030 – 1325	4.7	(Howard *et al* 1996b)
Cross-Keys Inn, Leicester	AD 1104 – 1309	4.8	(Howard *et al* 1988)

Table 5: Results of the cross-matching of site chronology WORCSQ06 and relevant reference chronologies when first ring date is AD 1174 and last ring date is AD 1250

Reference chronology	Span of chronology	t-value	
East Midlands	AD 882 – 1981	4.4	(Laxton and Litton 1988)
England	AD 401 – 1981	3.4	(Baillie and Pilcher 1982 unpubl)
Southern England	AD 1083 – 1589	3.9	(Bridge 1988)
Angel Choir, Lincoln Cathedral	AD 912 – 1248	4.9	(Laxton and Litton 1988)
Quaintree House, Braunston, Leics	AD 1165 – 1305	3.6	(Alcock *et al* 1991)
Severns, Nottm	AD 1030 – 1325	5.3	(Howard *et al* 1996b)
Worcester Cathedral, Nave roof	AD 1181 – 1291	4.6	(Howard *et al* 1995)
Brecon Cathedral, Powys	AD 996 – 1227	3.6	(Howard *et al* 1994a)
Horninglow St, Burton-on-Trent, Staffs	AD 1101 – 1345	4.5	(Howard *et al* 1995)

Figure 1: Map to show general location of Worcester Cathedral

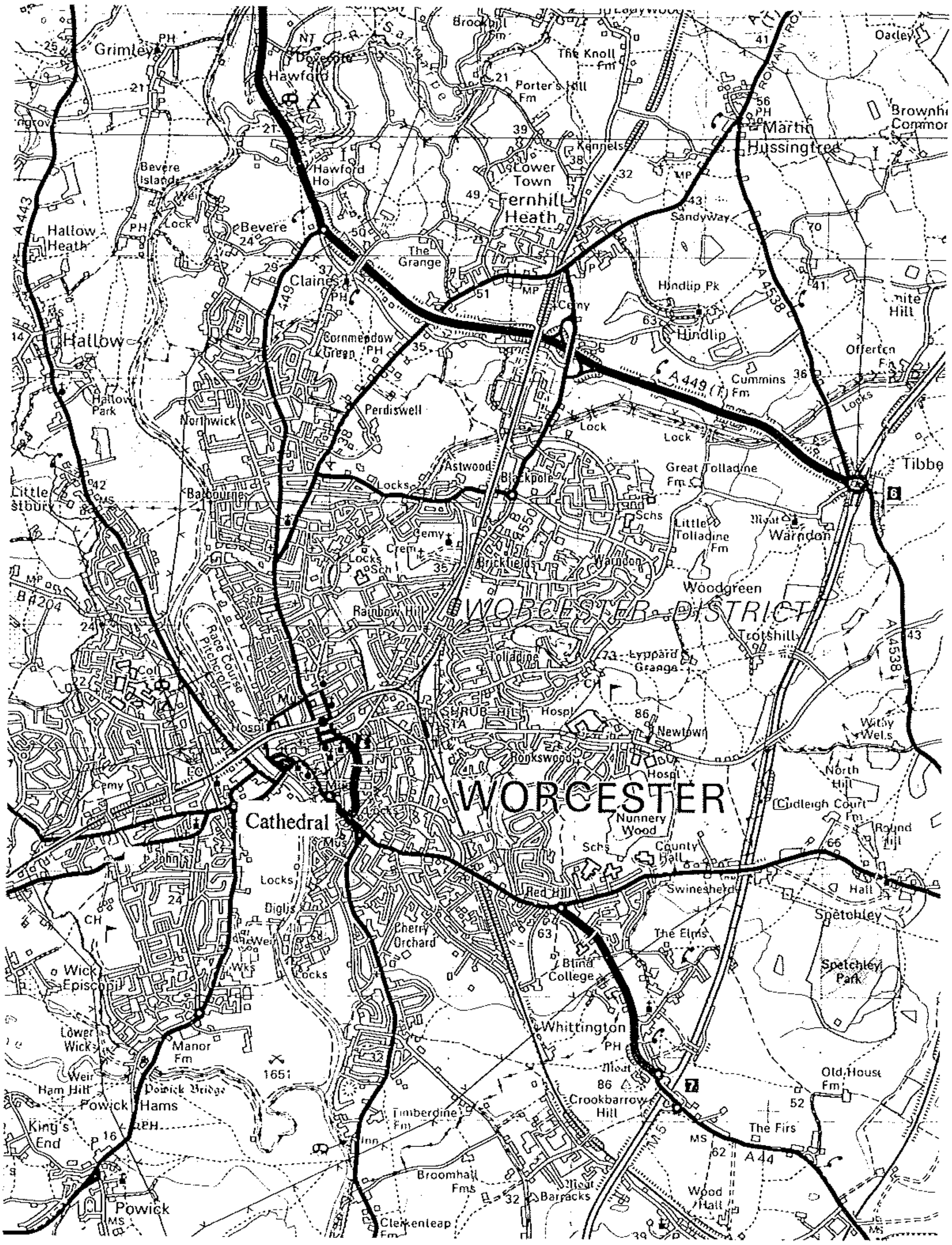


Figure 2: Plan showing the positions of the trusses in the choir, the crossing, and the north-east and south-east transepts

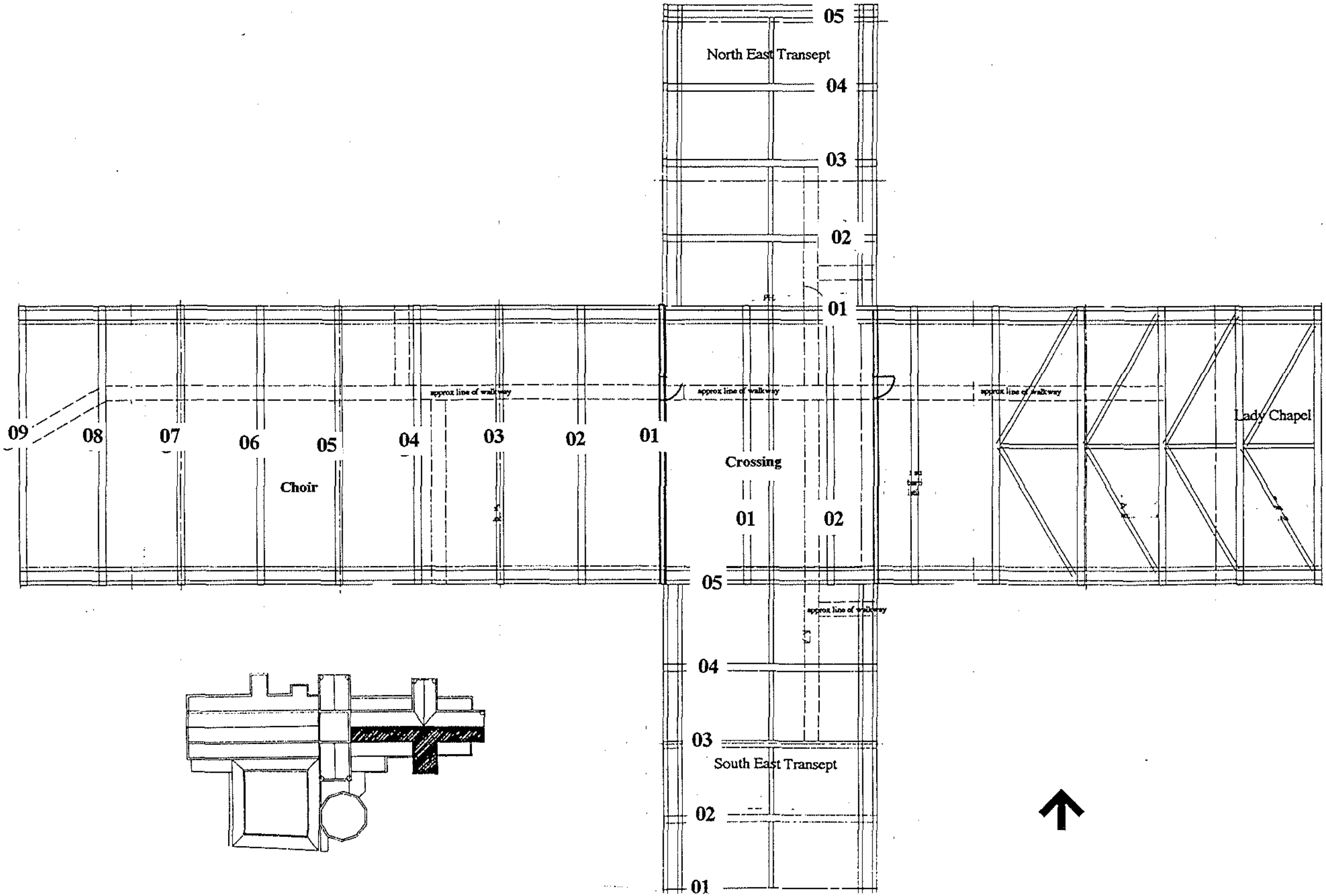


Figure 3a: Choir roof truss 1 showing position of samples

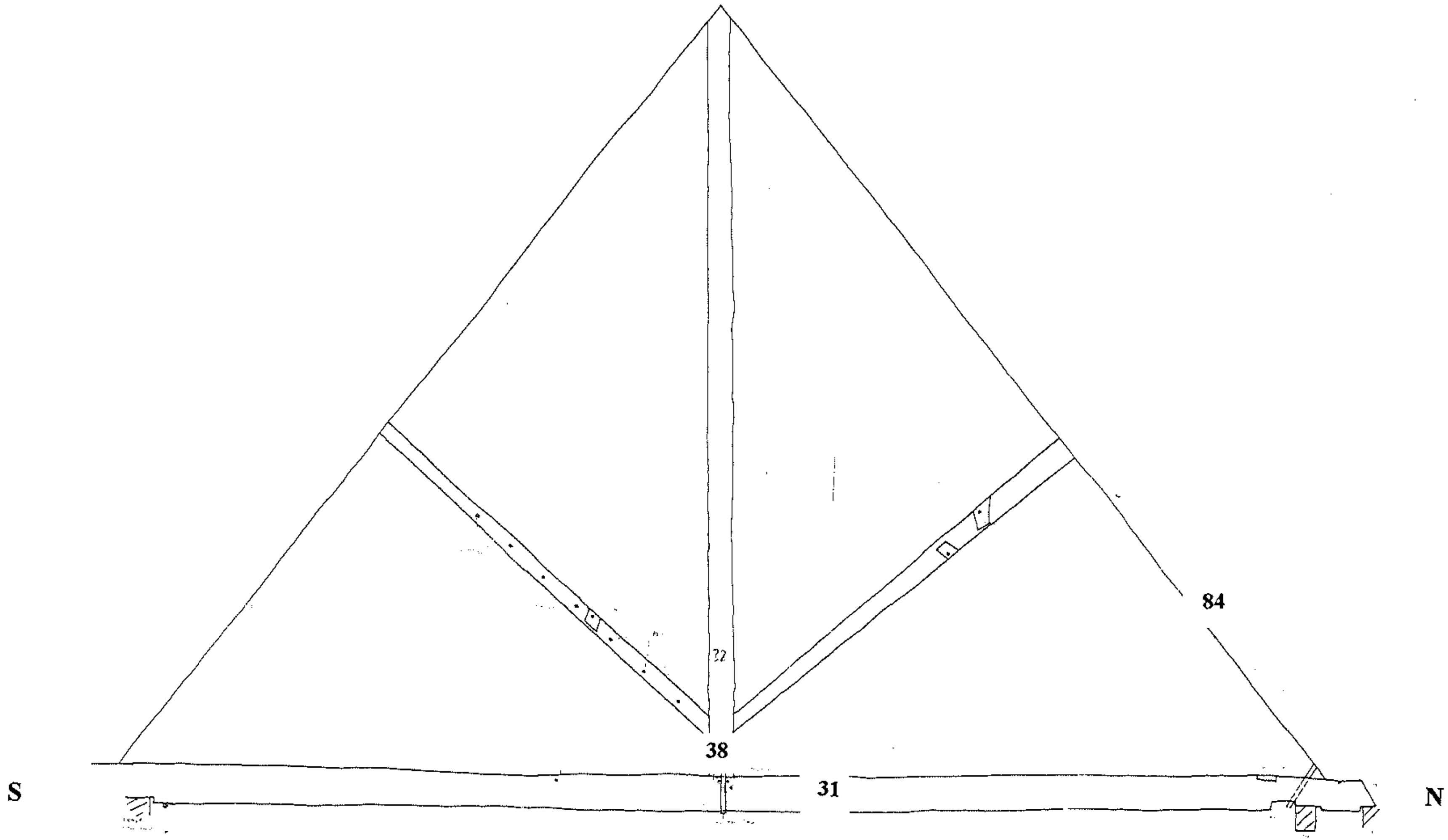


Figure 3b: Choir roof truss 2 showing position of samples

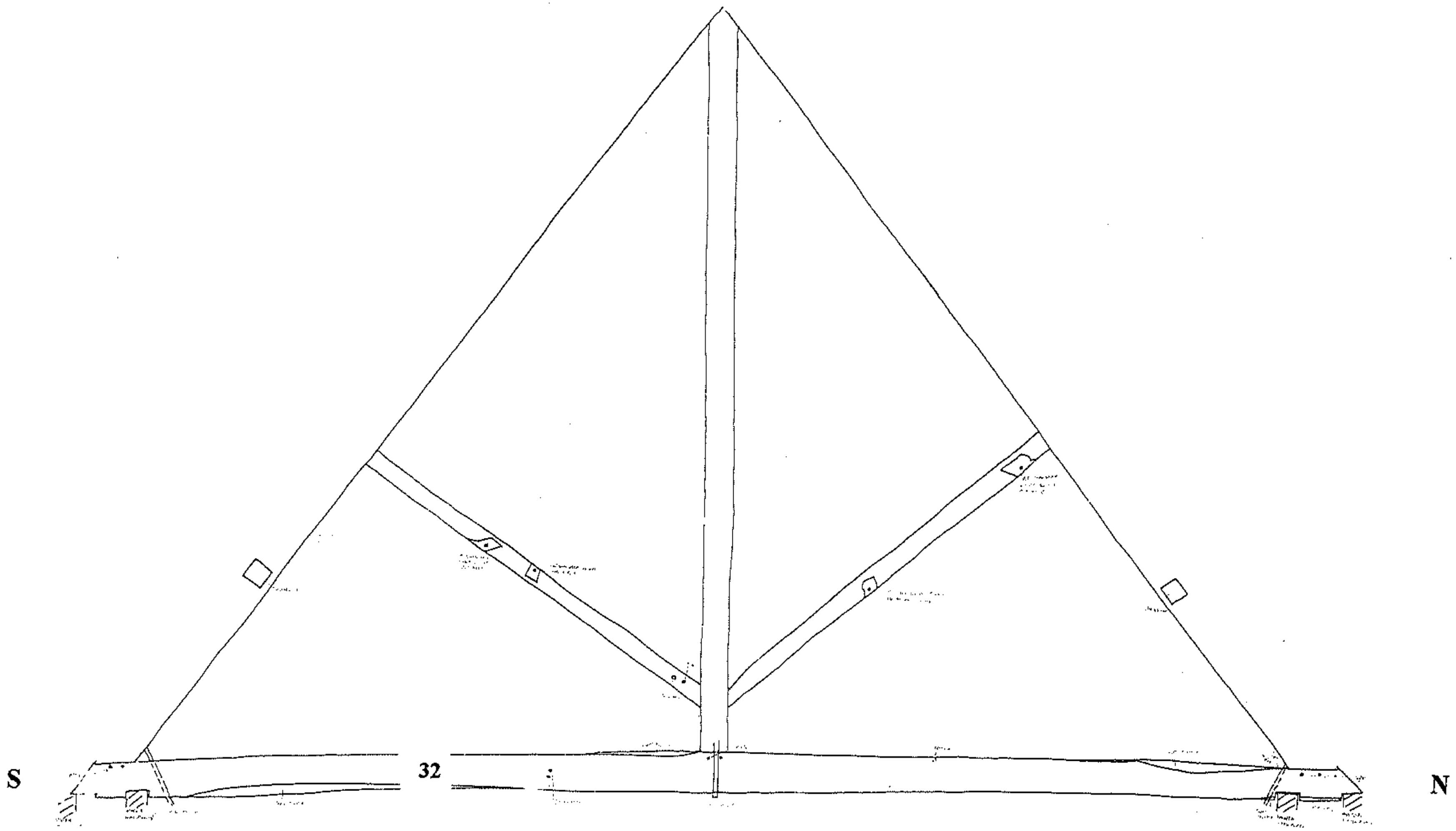


Figure 3c: Choir roof truss 3 showing position of samples

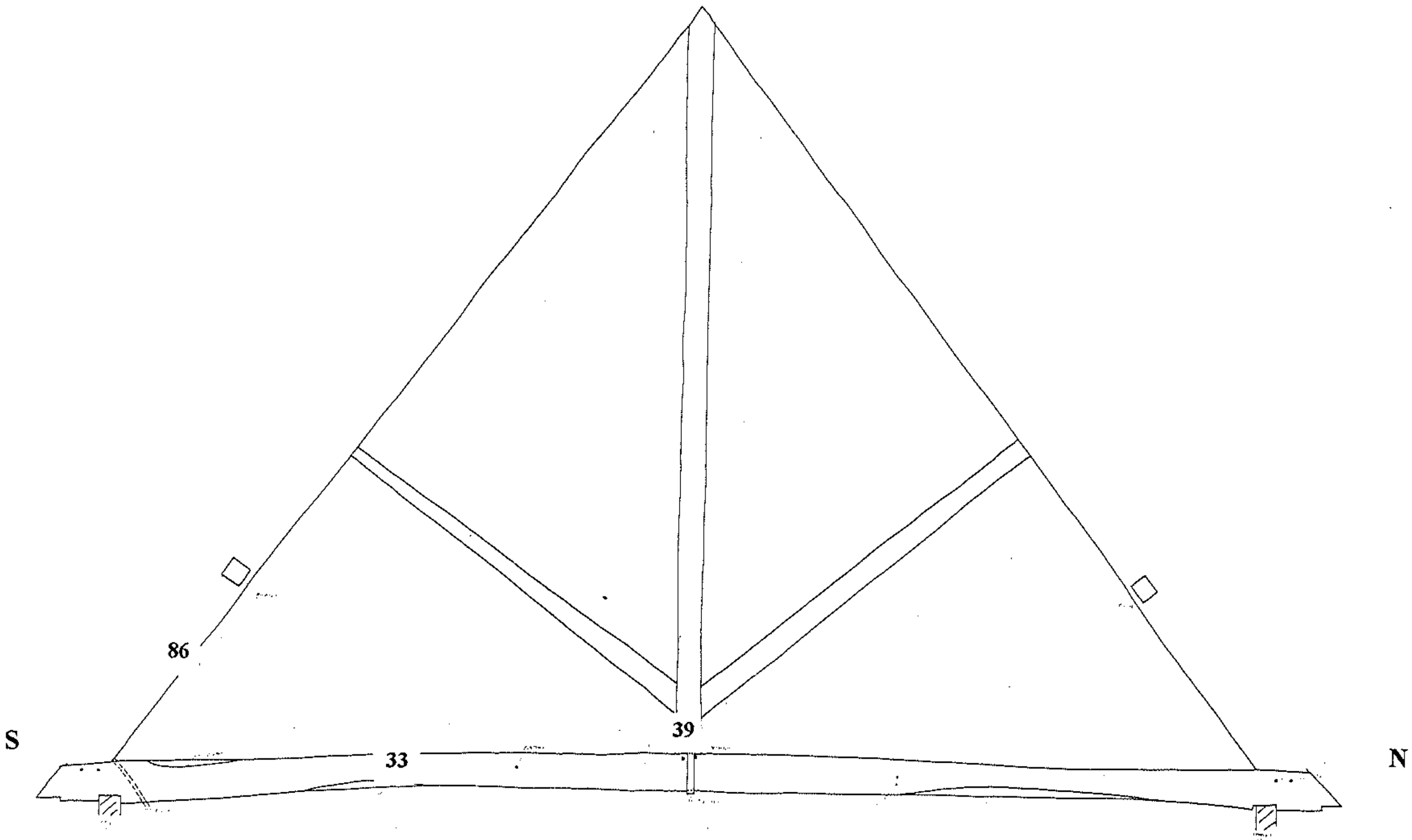


Figure 3d: Choir roof truss 4 showing position of samples

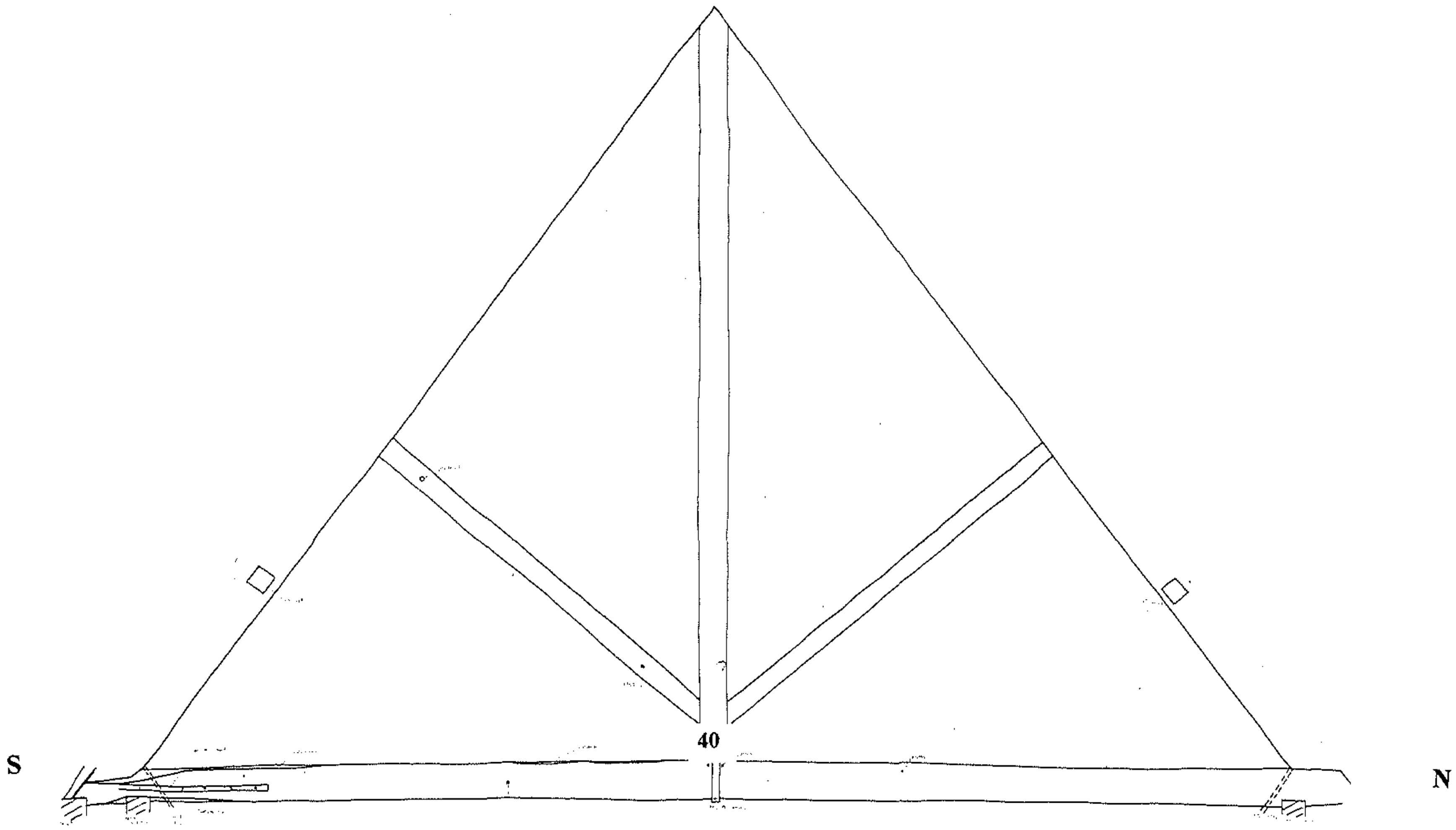


Figure 3e: Choir roof truss 5 showing position of samples

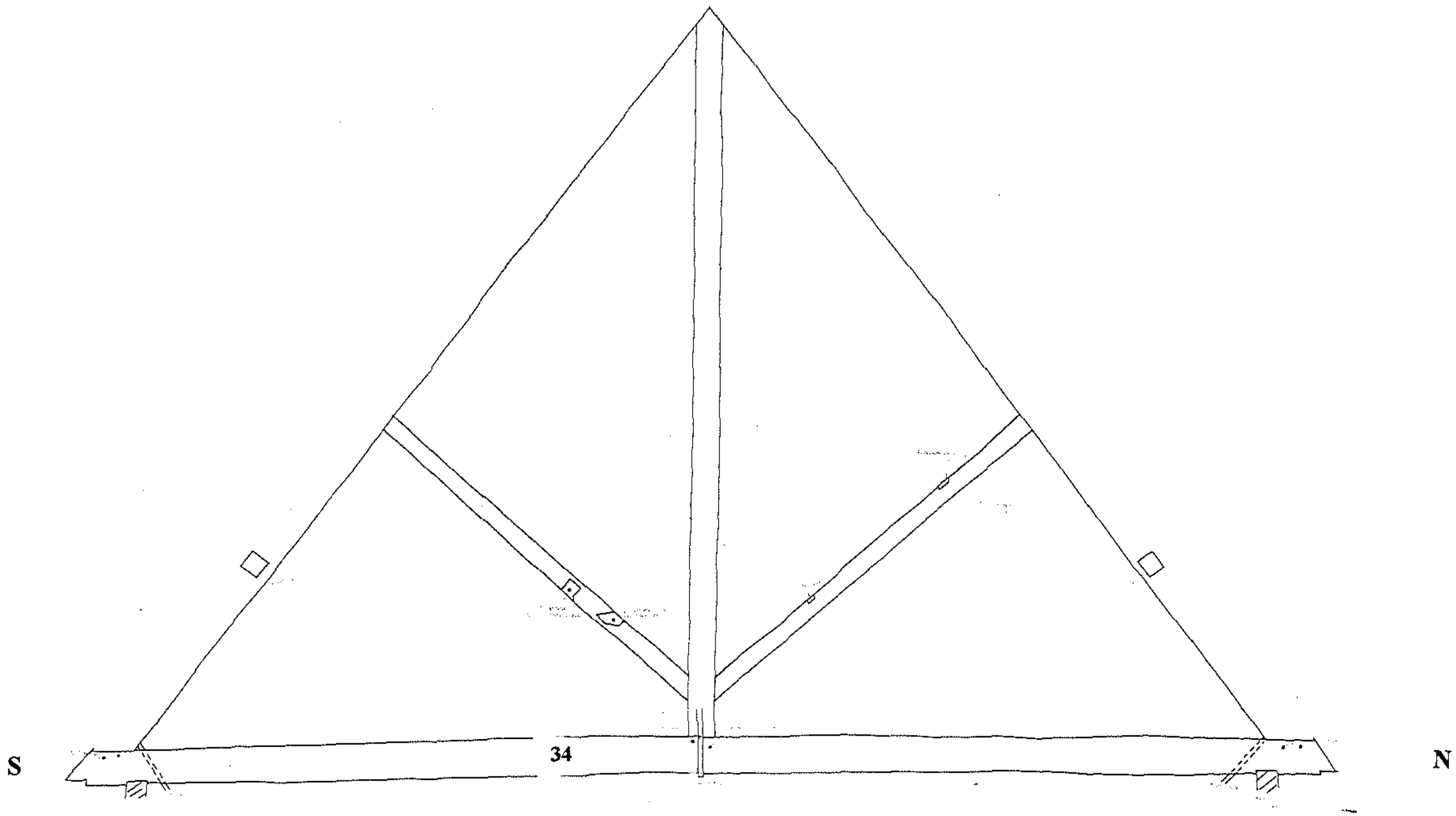


Figure 3f: Choir roof truss 6 showing position of samples

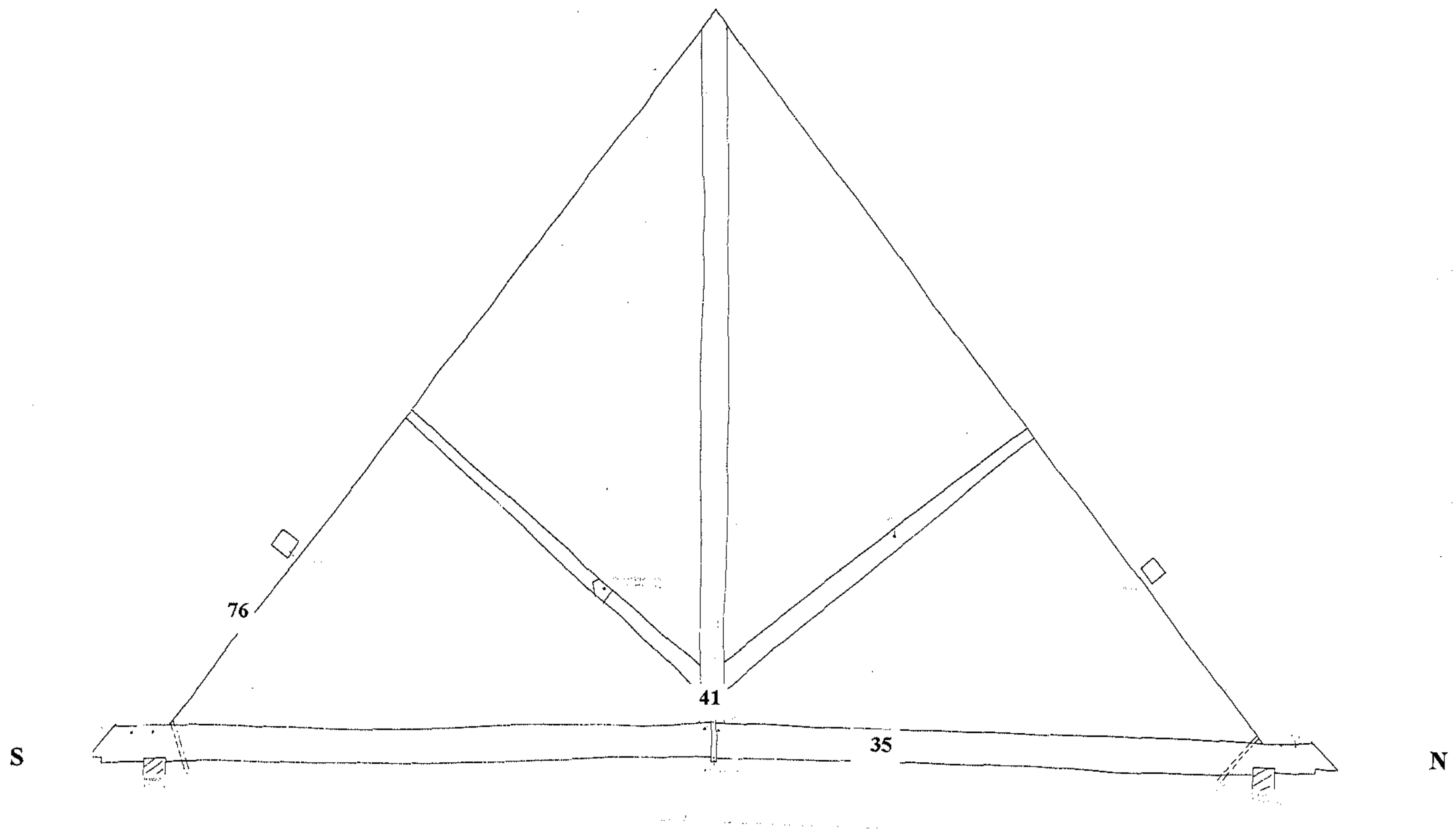


Figure 3g: Choir roof truss 7 showing position of samples

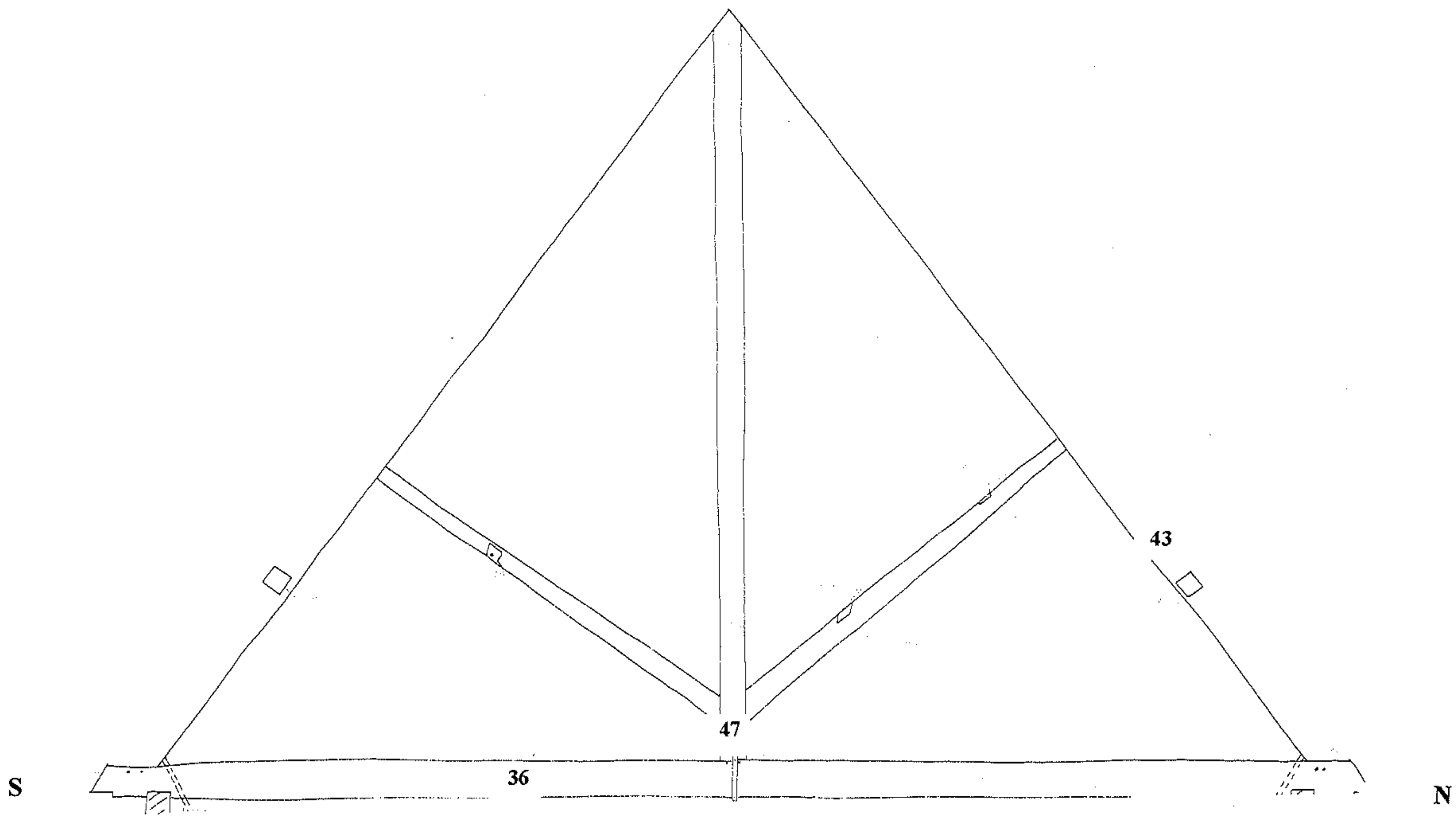


Figure 3h: Choir roof truss 8 showing position of samples

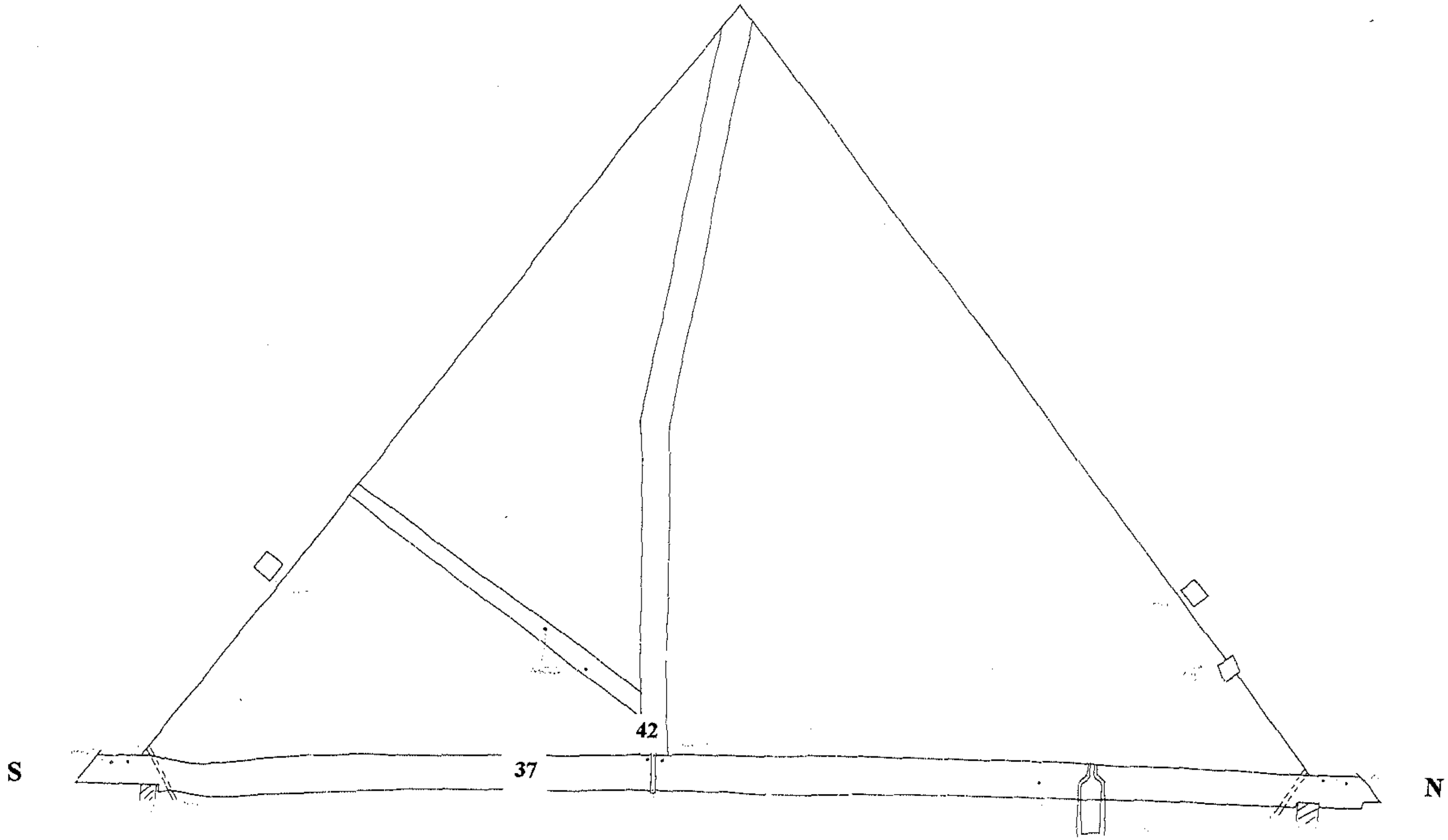


Figure 3i(1): North elevation of choir roof (western half) to show sample locations

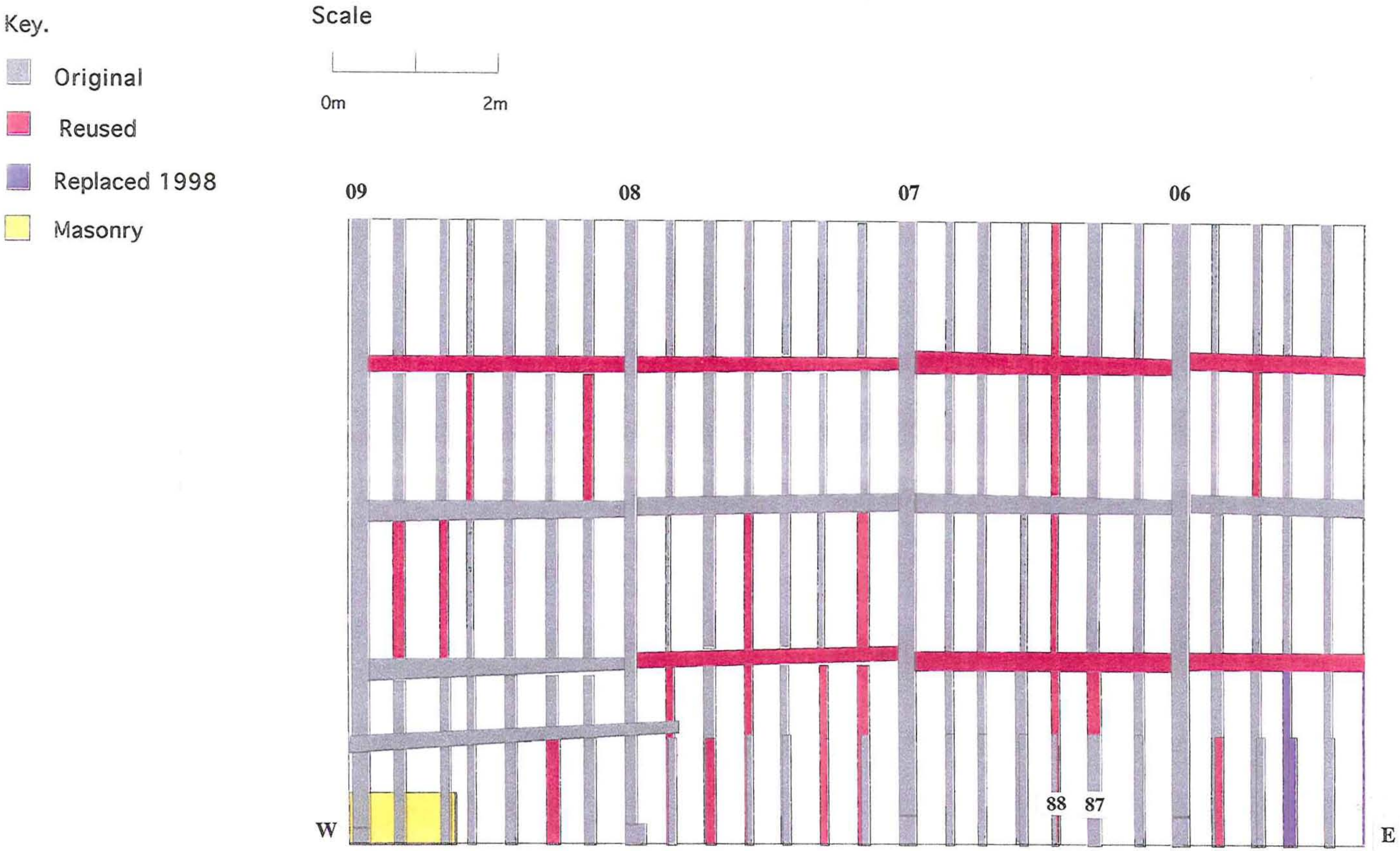


Figure 3i(2): North elevation of choir roof (eastern half) to show sample locations

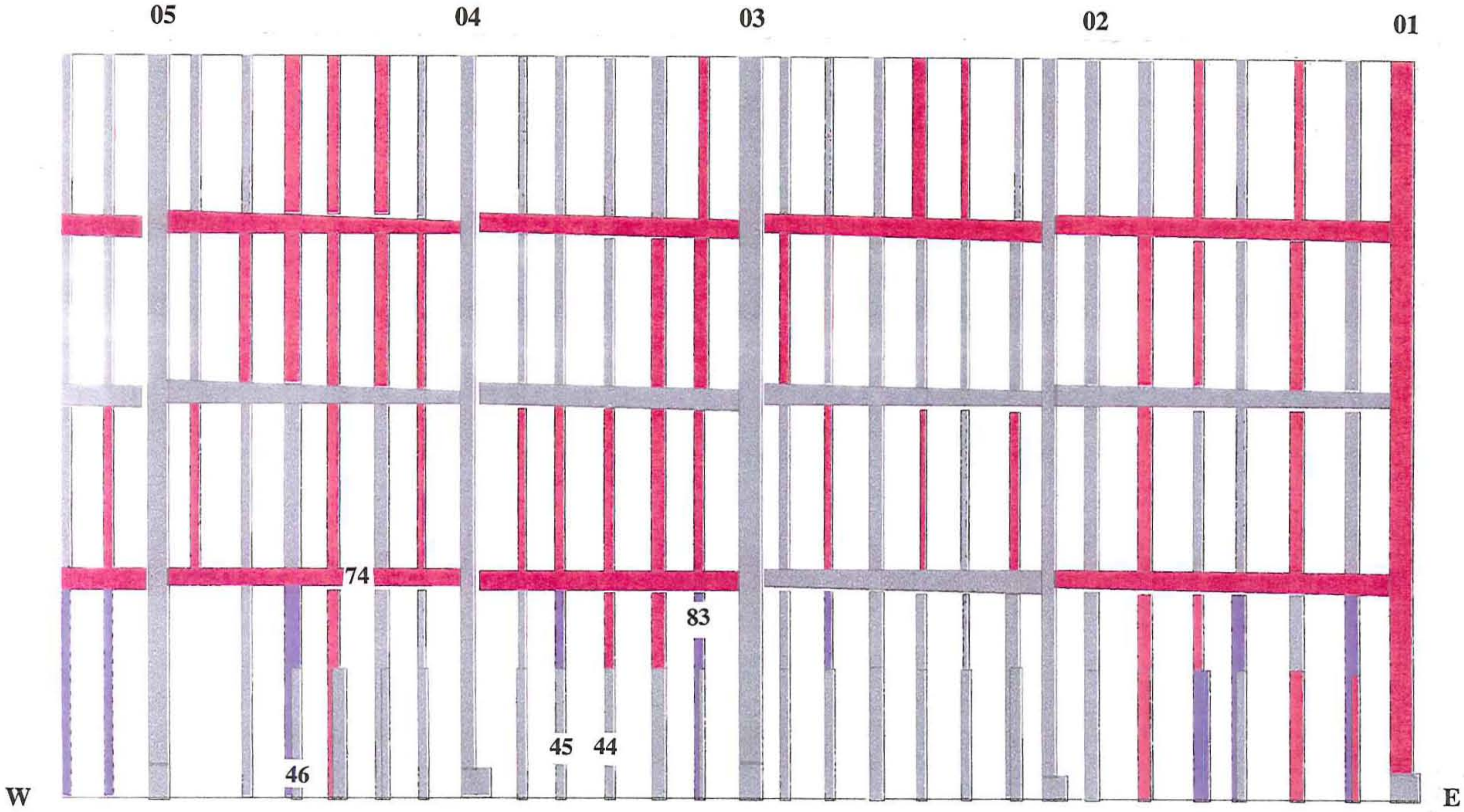


Figure 3j(1): South elevation of choir roof (eastern half) to show sample locations

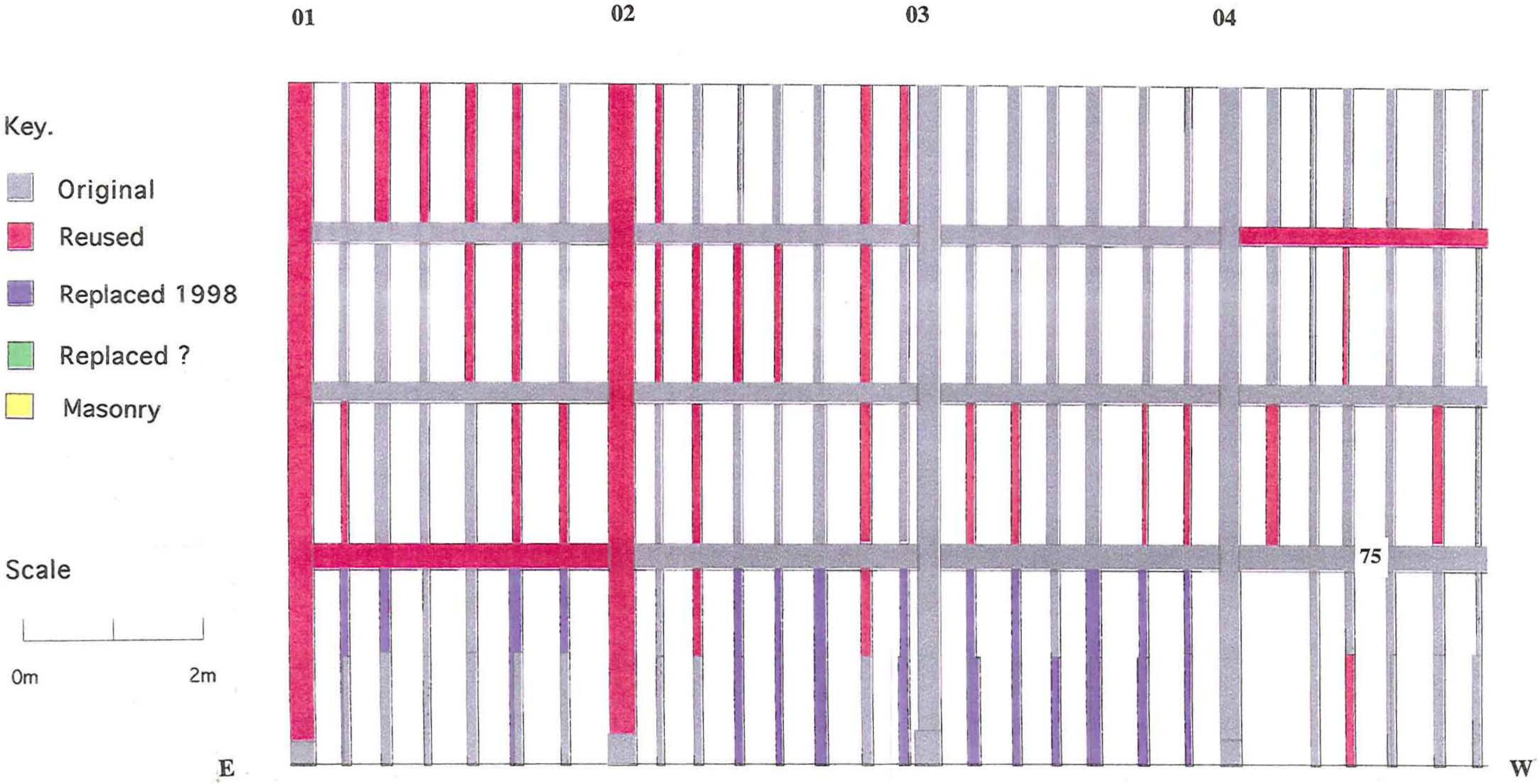


Figure 3j(2): South elevation of choir roof (western half) to show sample locations

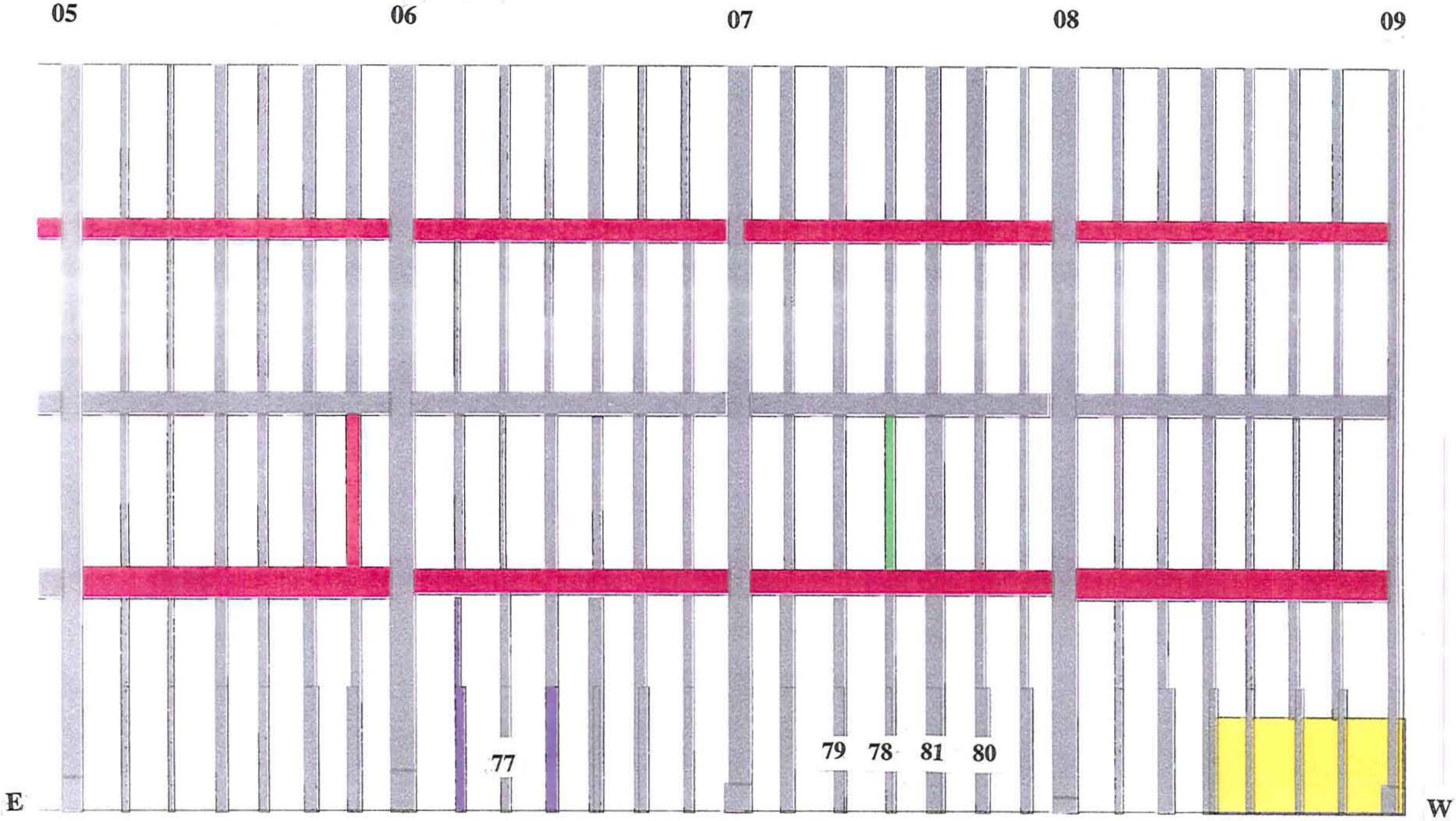


Figure 4a: Crossing roof truss 1 showing position of samples

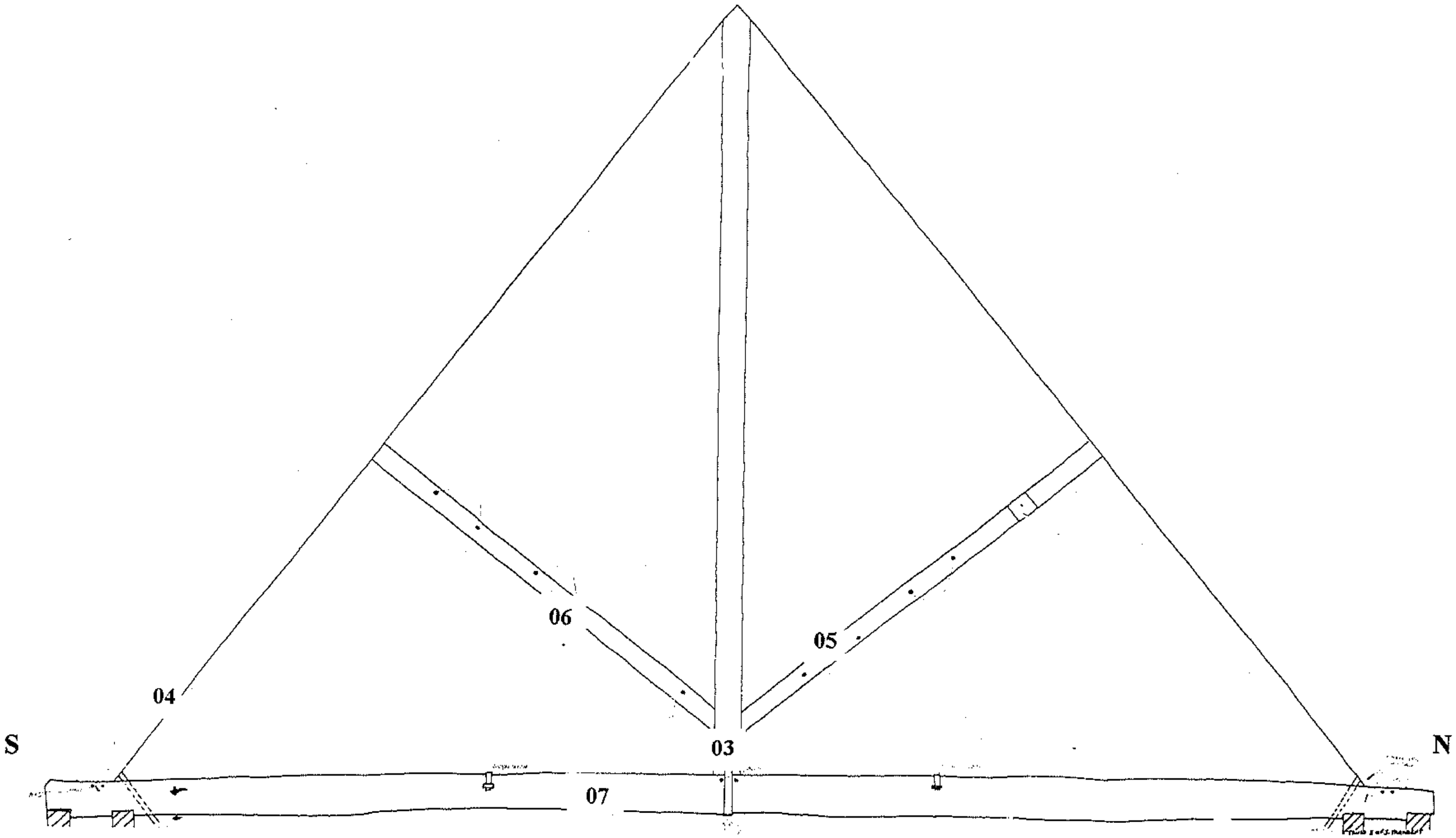


Figure 4b: Crossing roof truss 2 showing position of samples

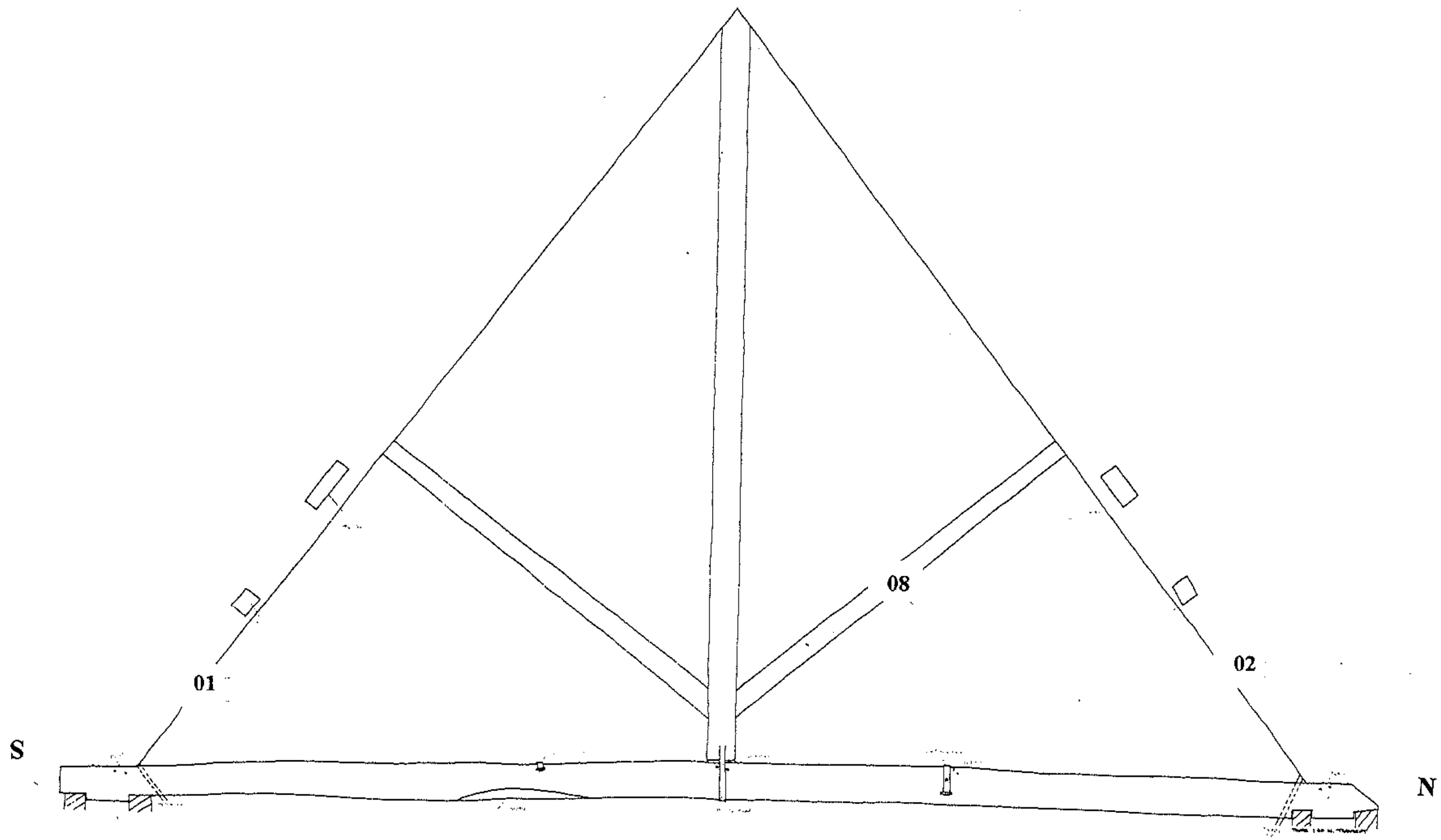


Figure 4c: Crossing roof north elevation to show sample locations

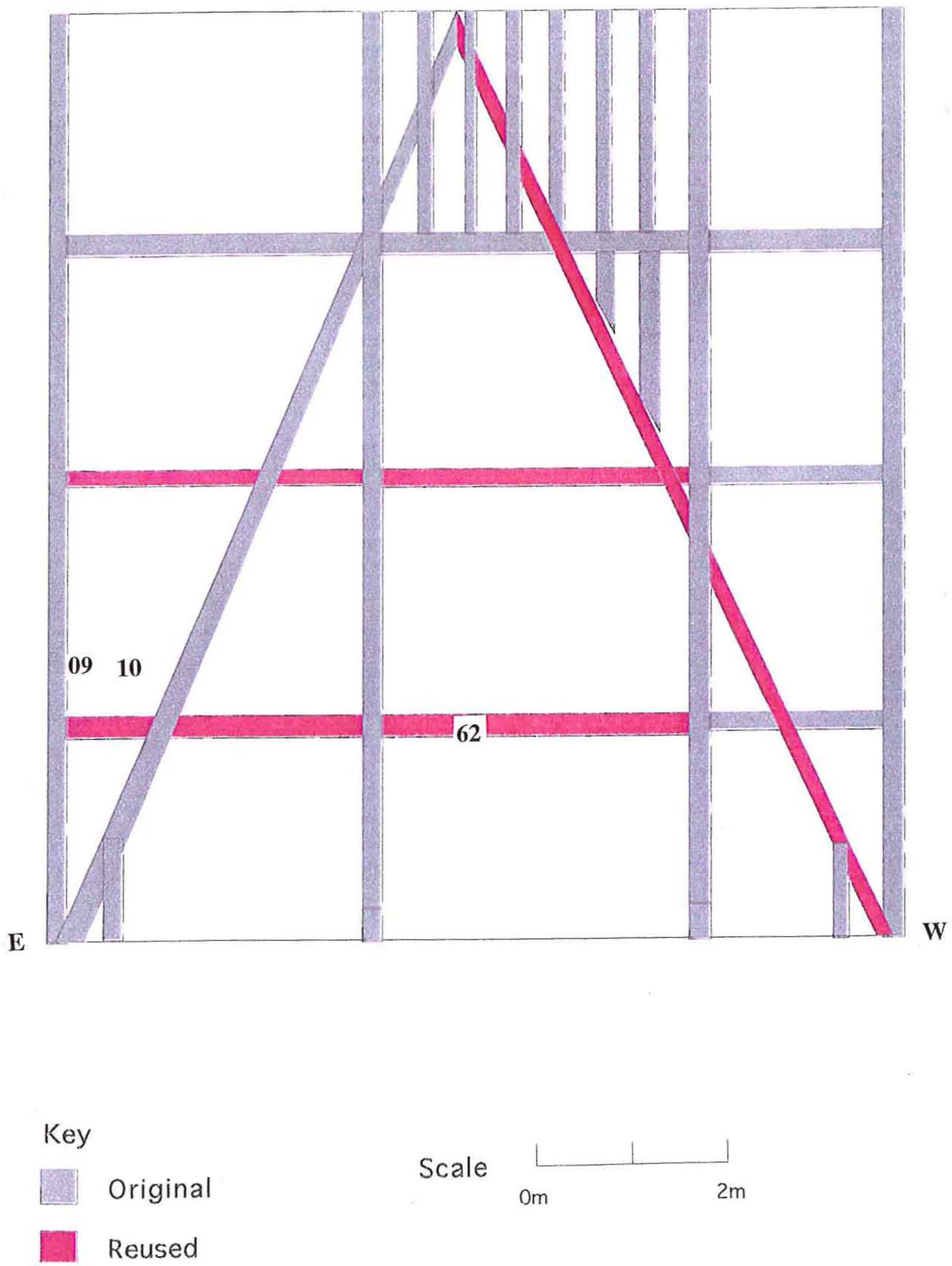


Figure 4d: Crossing roof south elevation to show sample locations

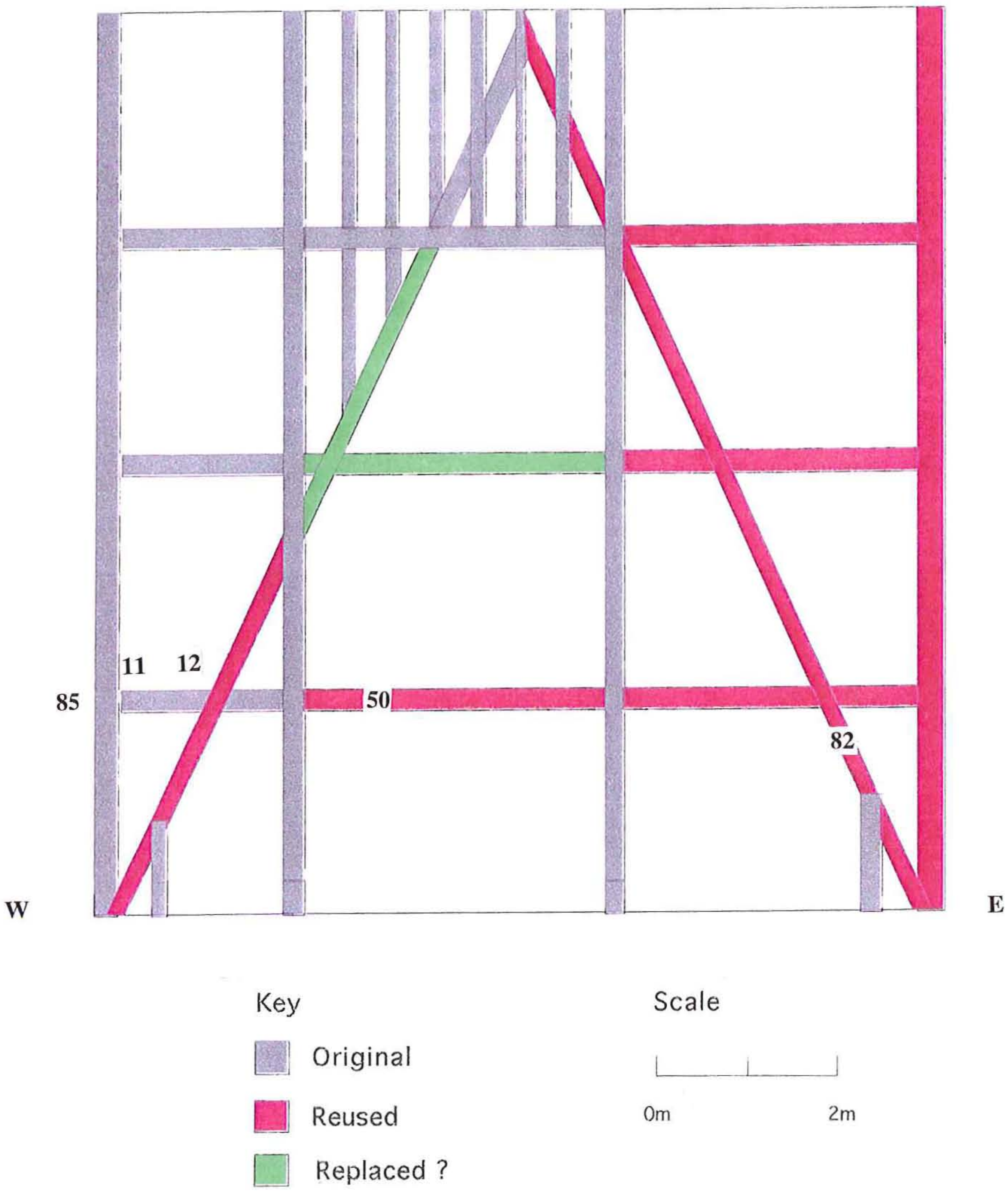


Figure 5a: North-east transept roof truss 1 showing position of samples

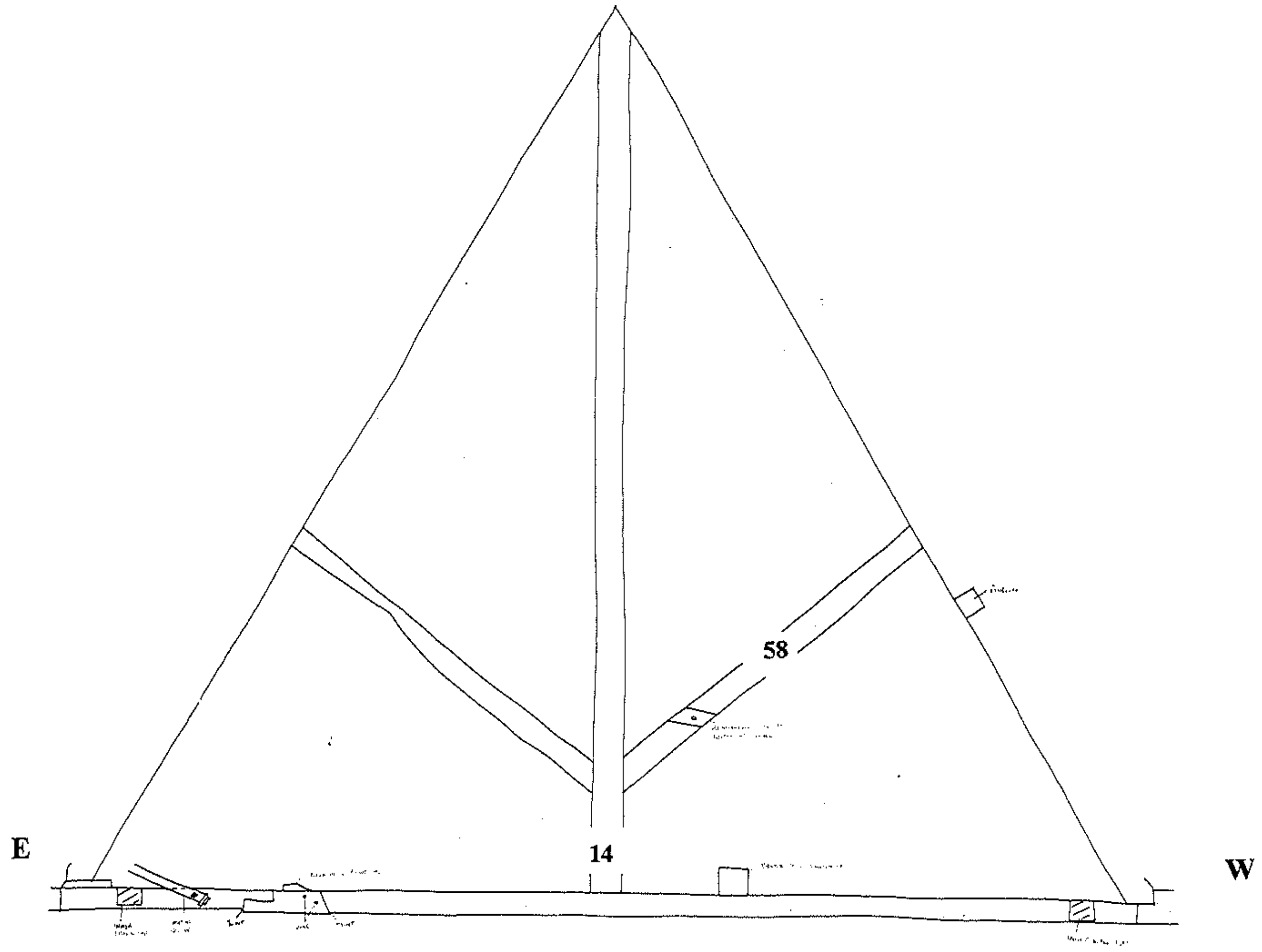


Figure 5b: North-east transept roof truss 2 showing position of samples

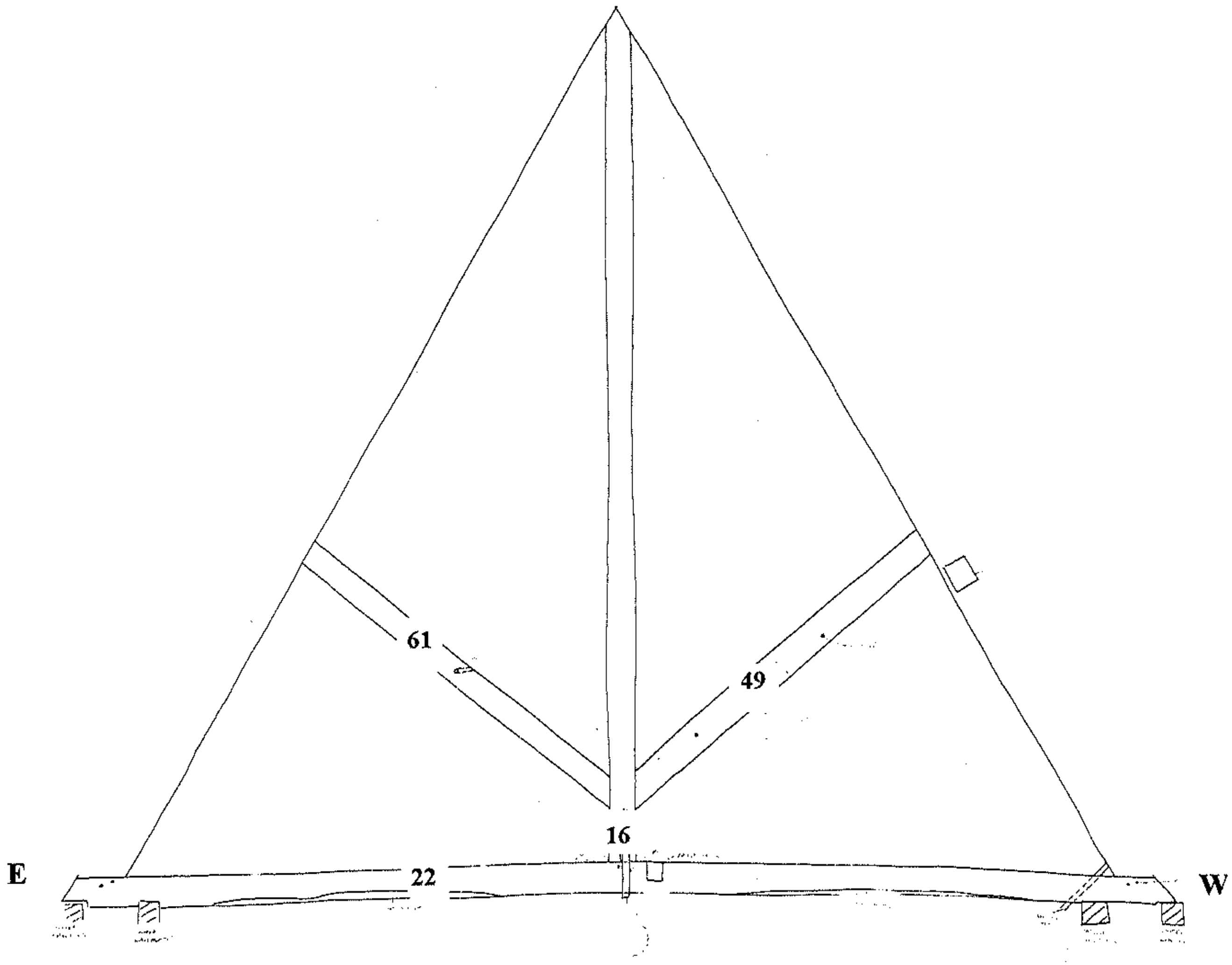


Figure 5c: North-east transept roof truss 3 showing position of samples

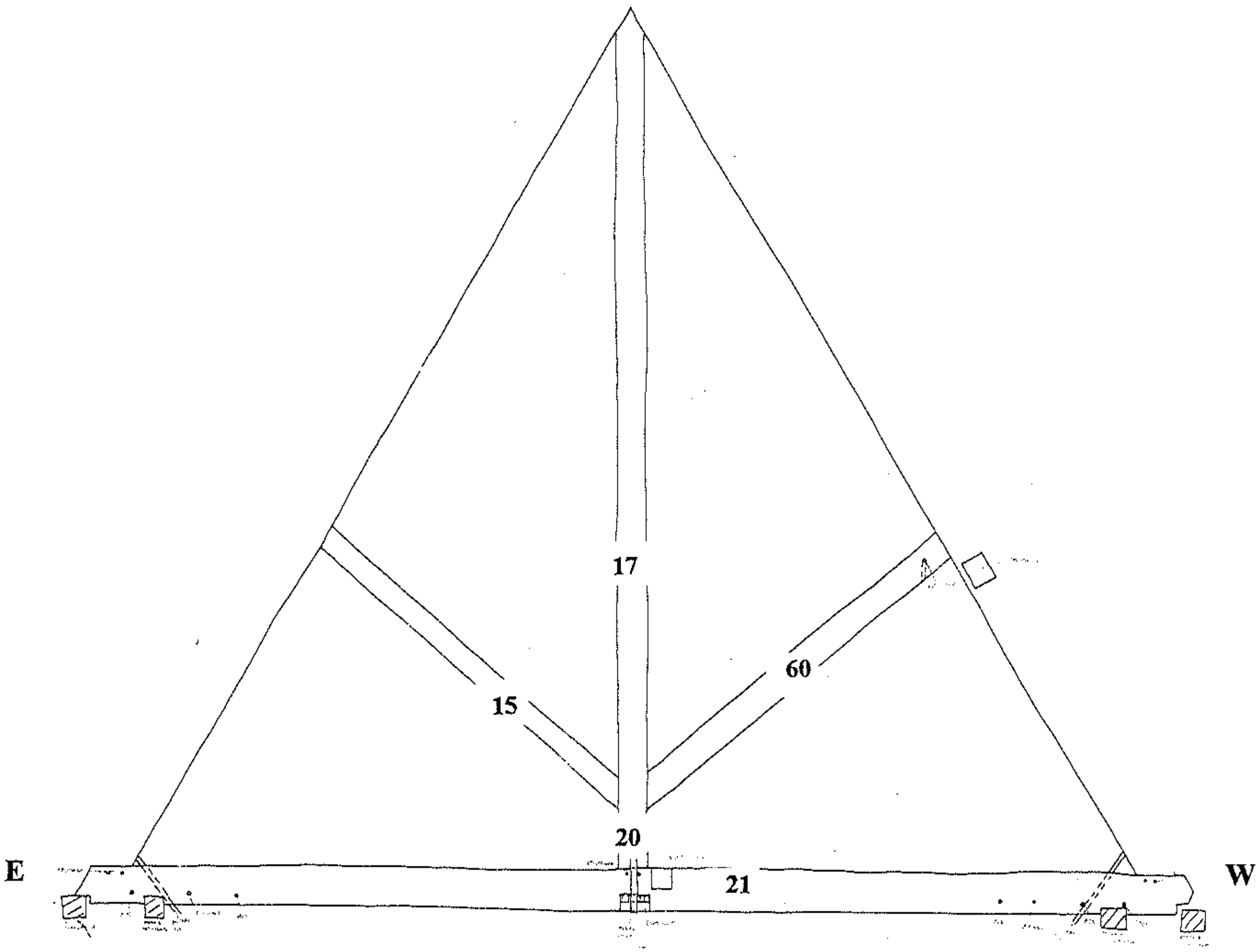


Figure 5d: North-east transept roof truss 4 showing position of samples

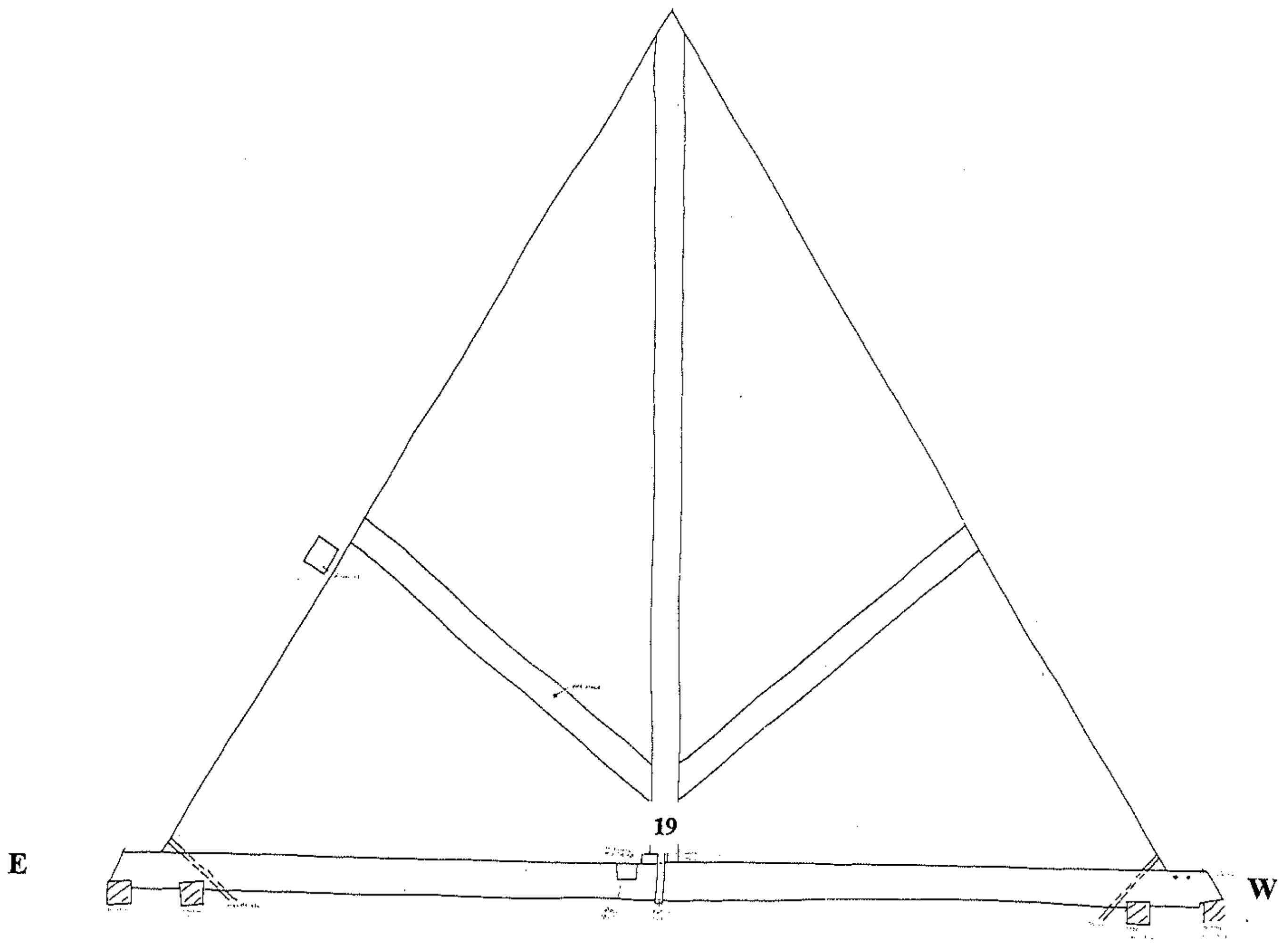


Figure 5e: North-east transept roof truss 5 showing position of samples

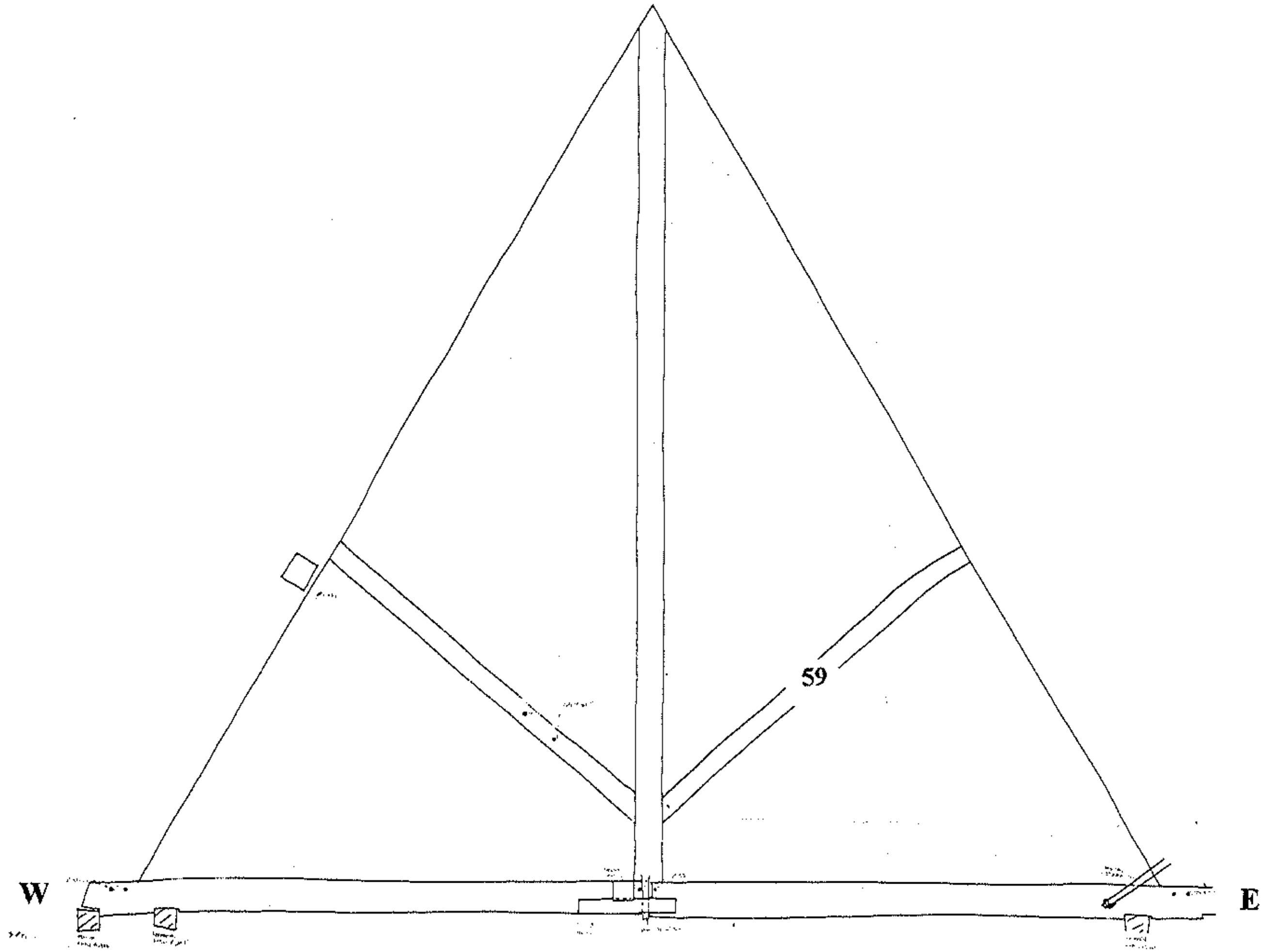


Figure 5f: North-east transept roof east elevation showing position of samples

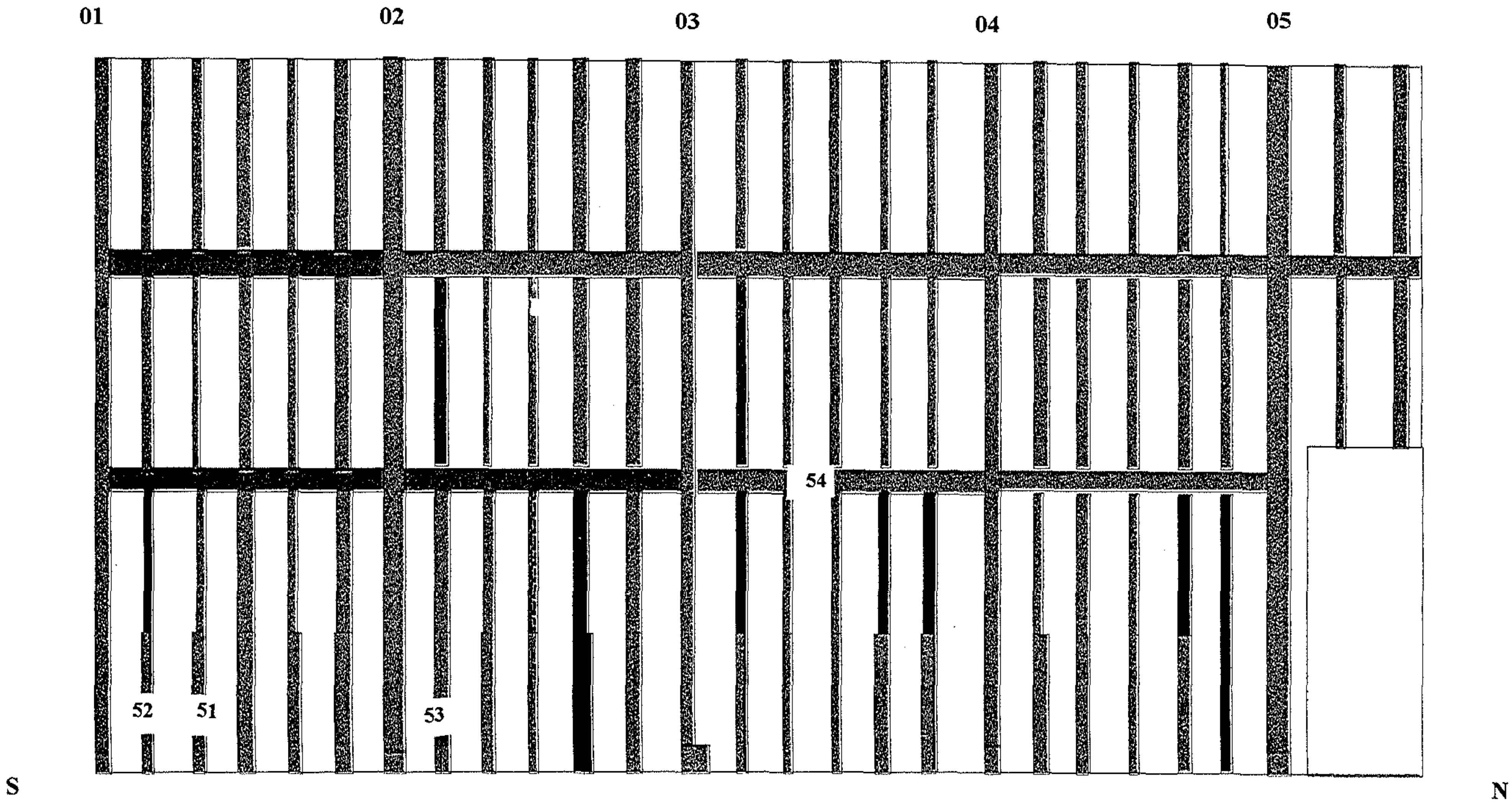


Figure 5g: North-east transept roof west elevation showing position of samples

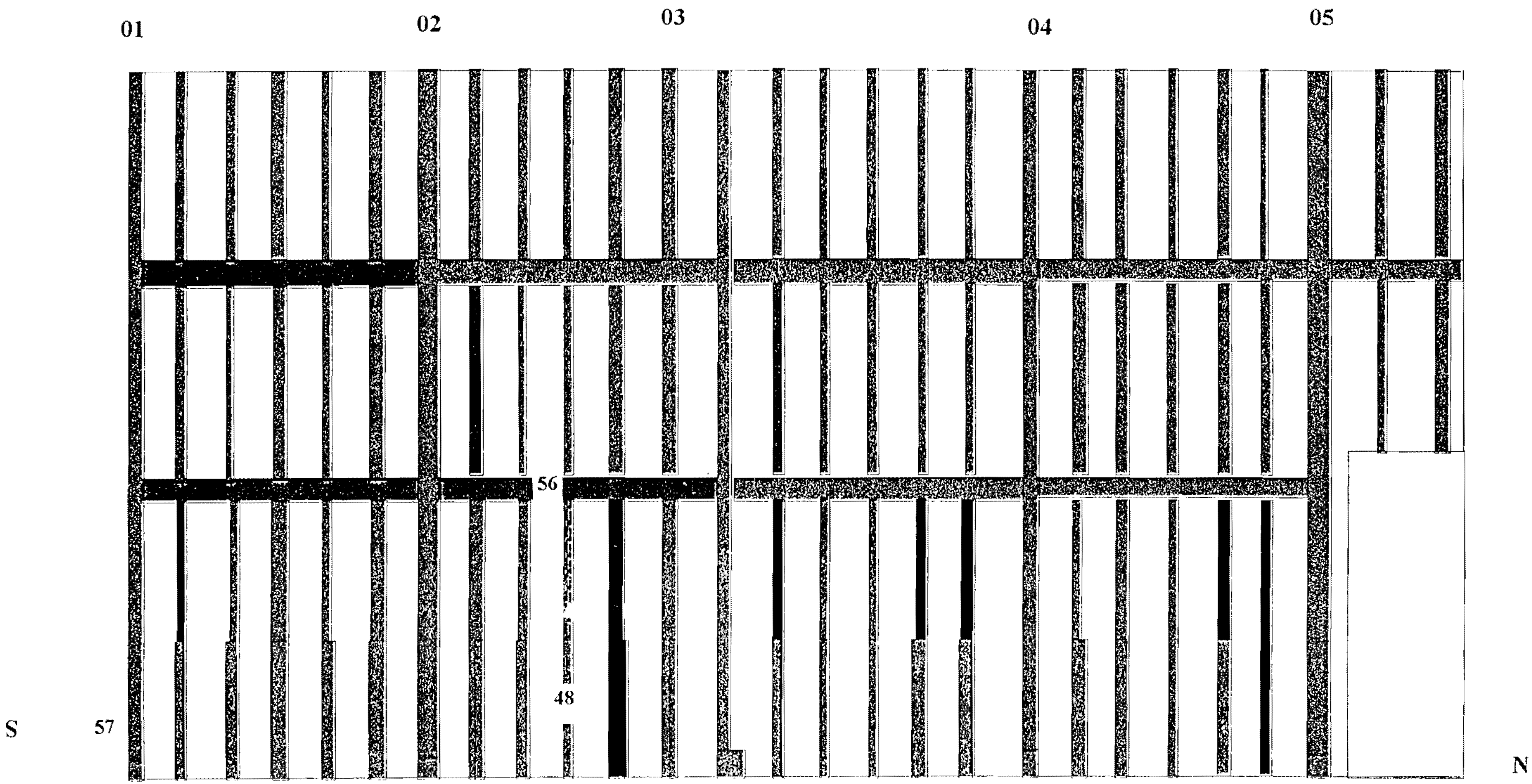


Figure 5h: Plan of north-east transept to show sample locations

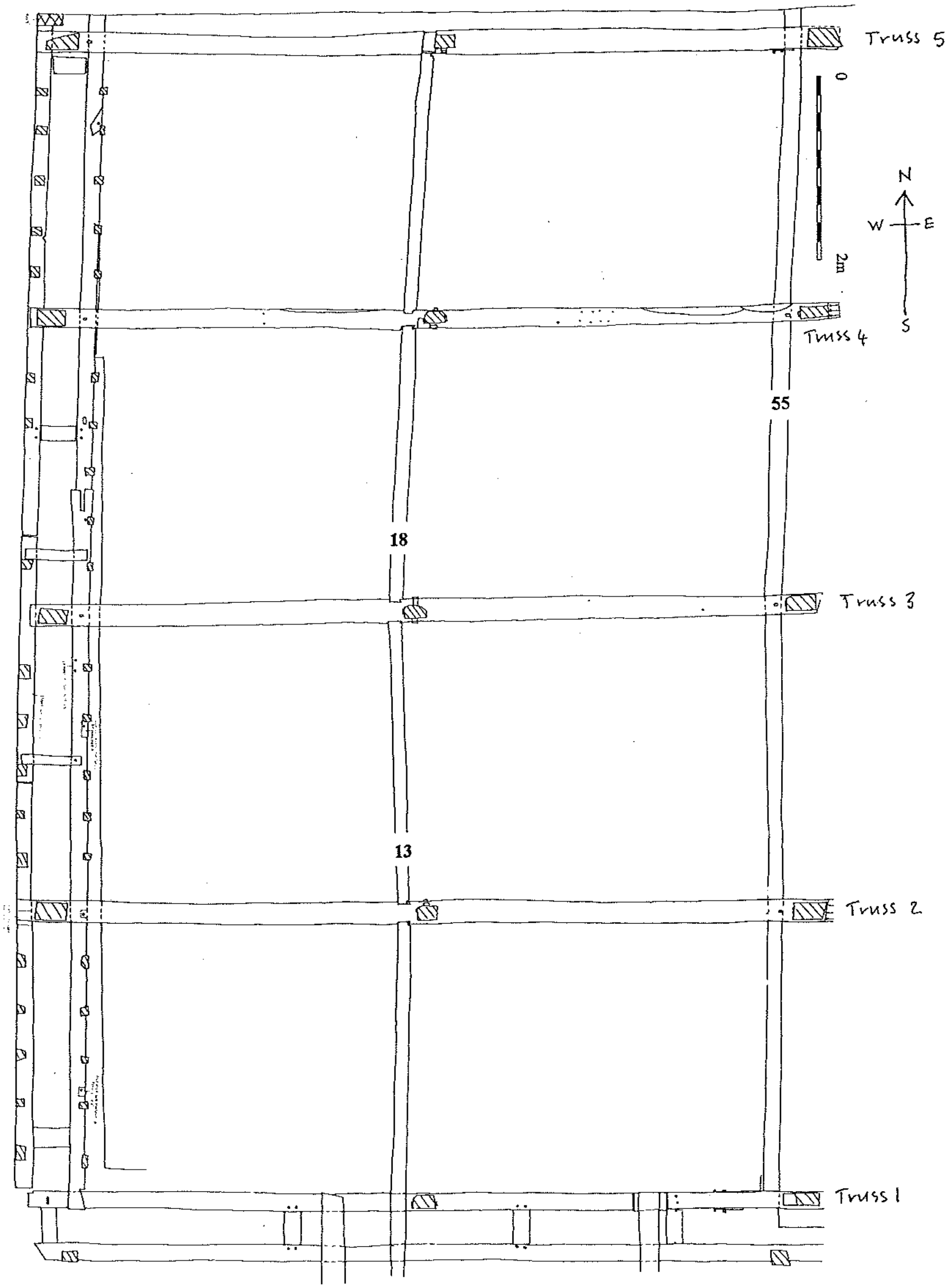


Figure 6a: South-east transept roof truss 1 showing position of samples

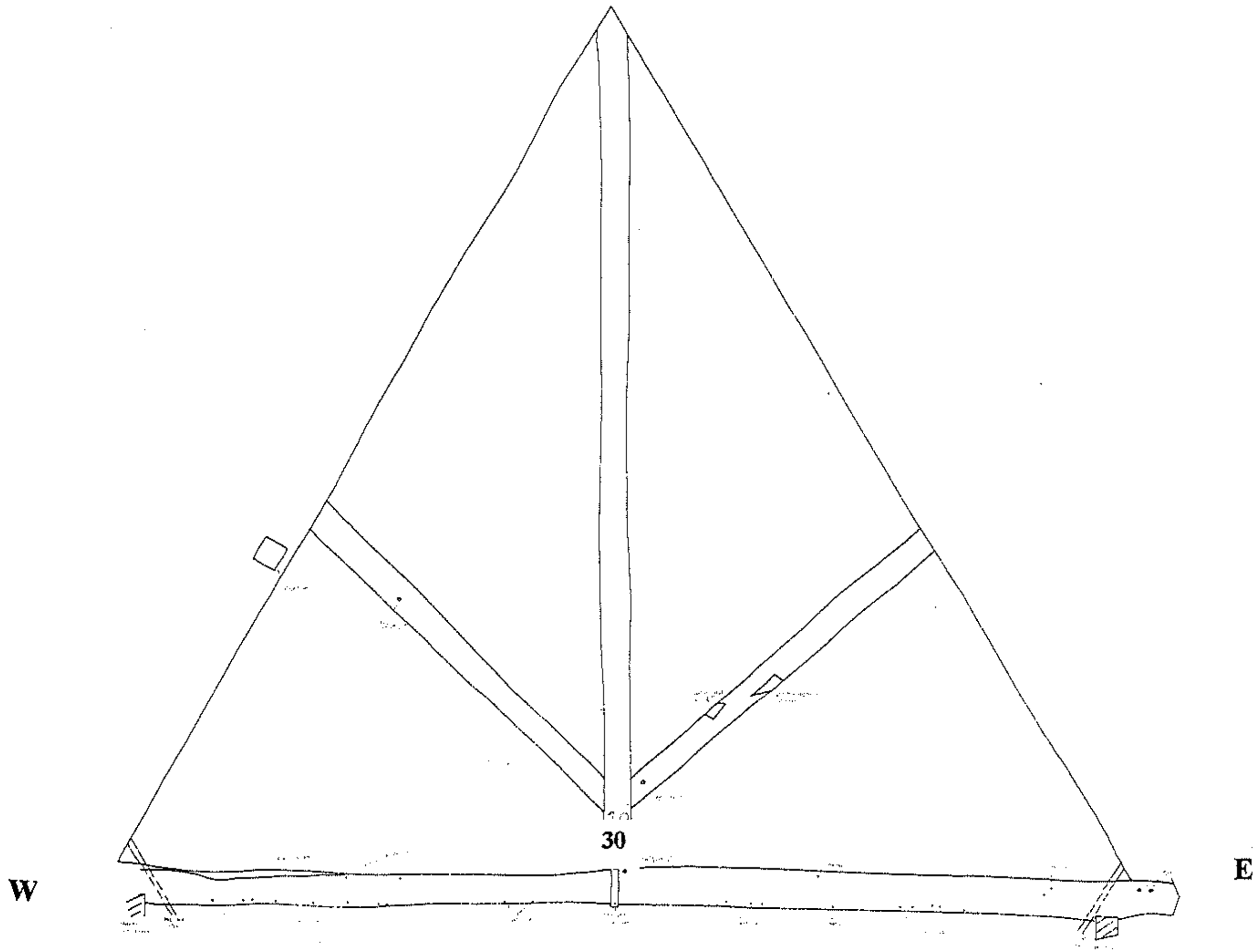


Figure 6b: South-east transept roof truss 2 showing position of samples

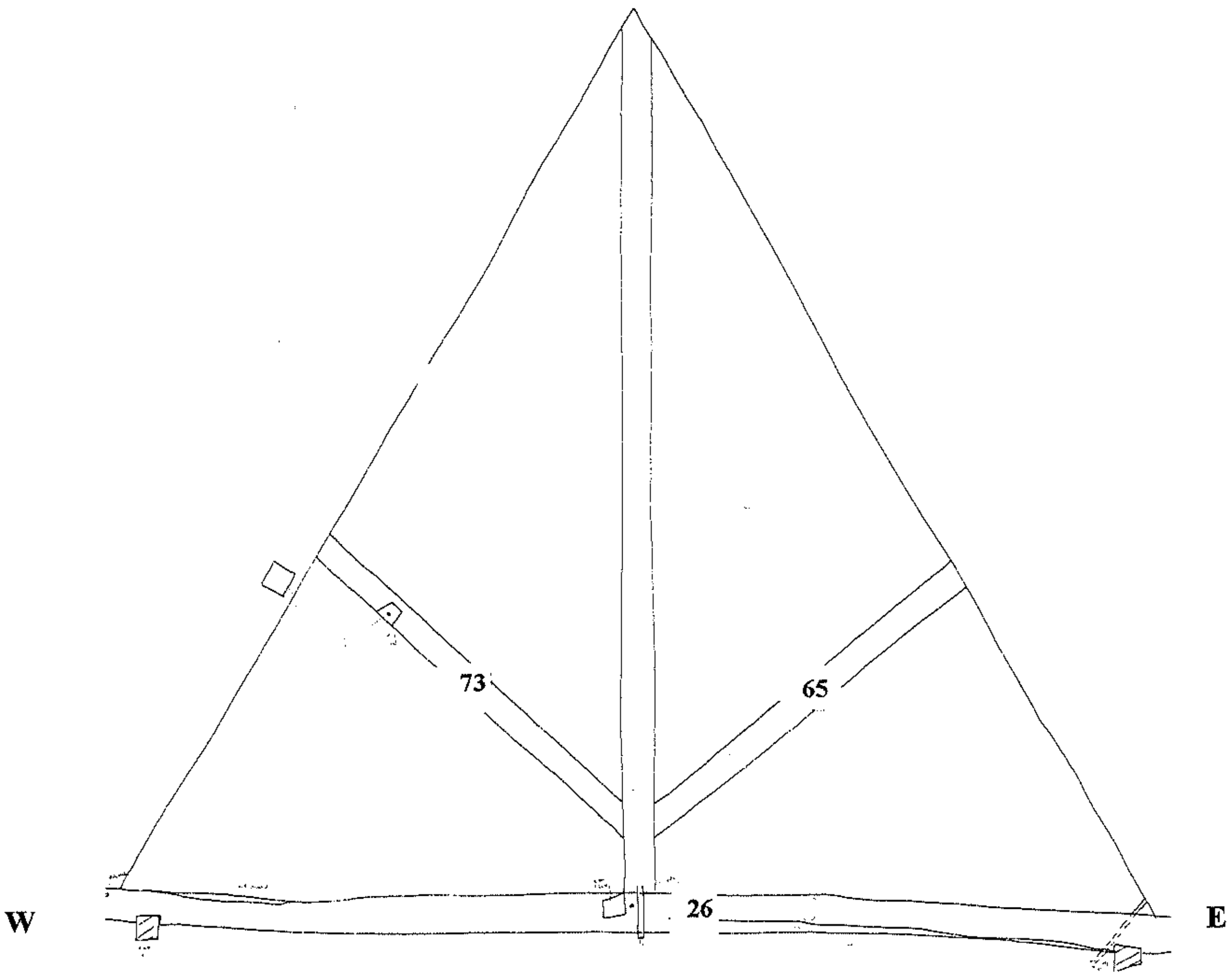


Figure 6c: South-east transept roof truss 3 showing position of samples

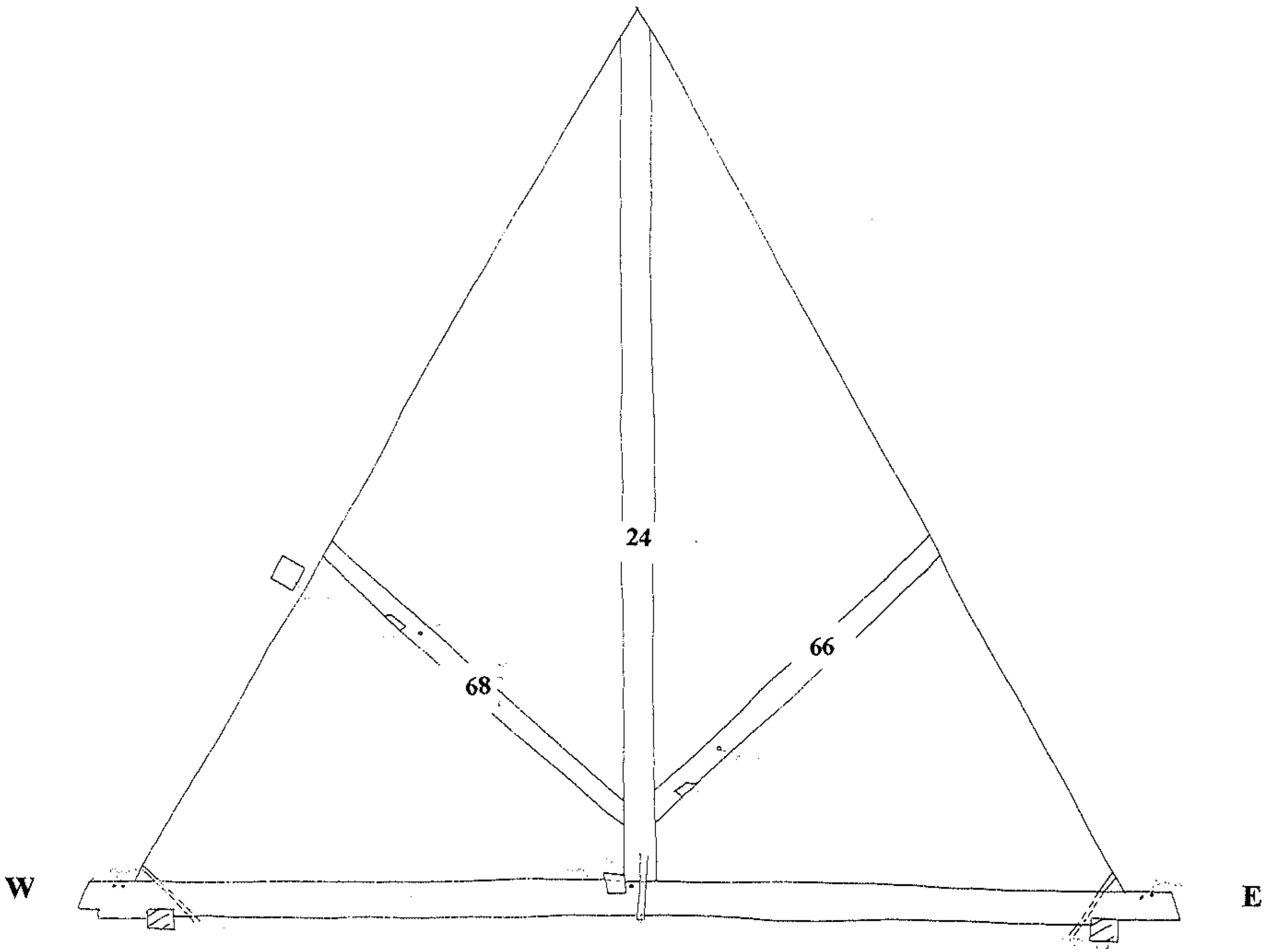


Figure 6d: South-east transept roof truss 4 showing position of samples

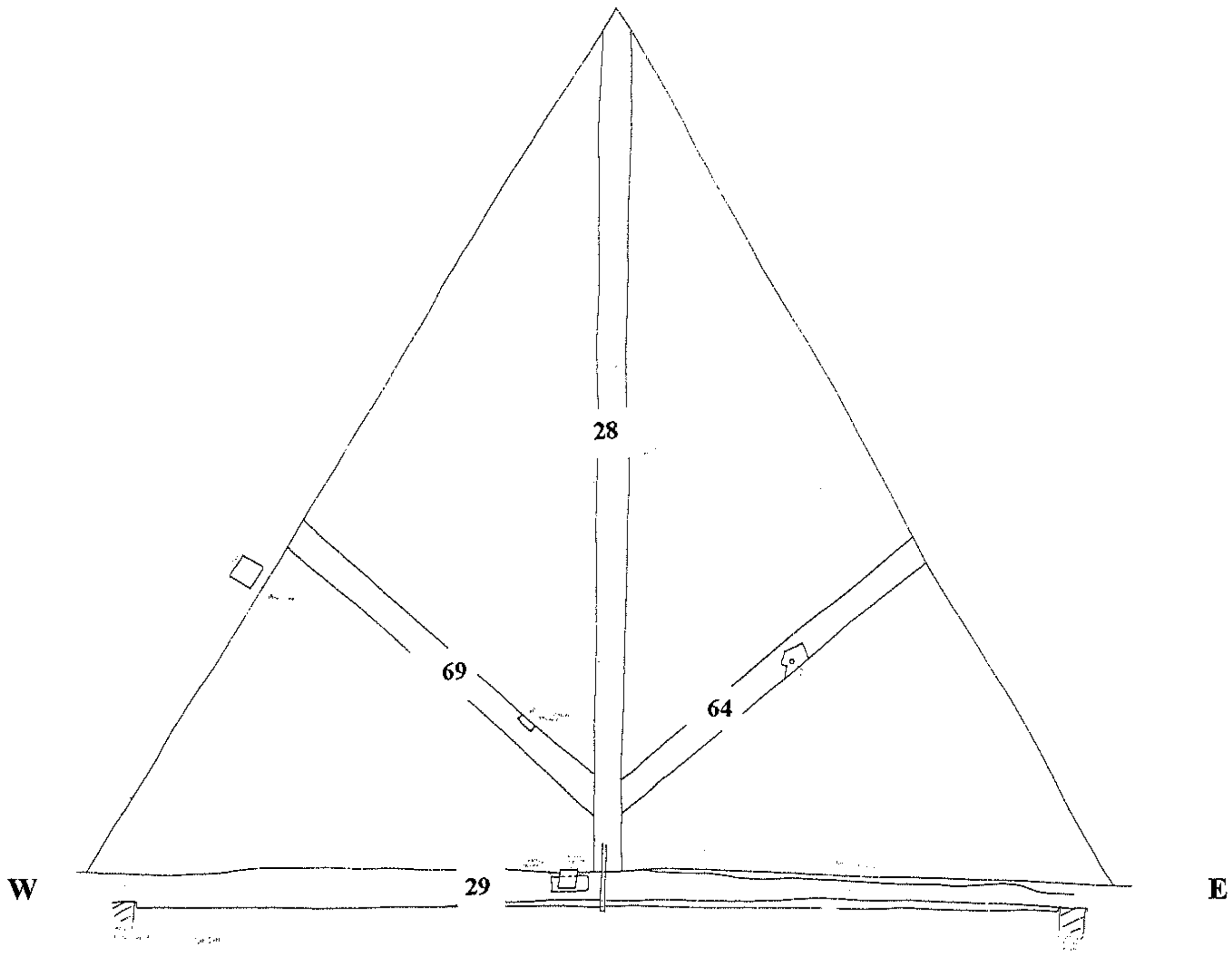


Figure 6e: South-east transept roof truss 5 showing position of samples

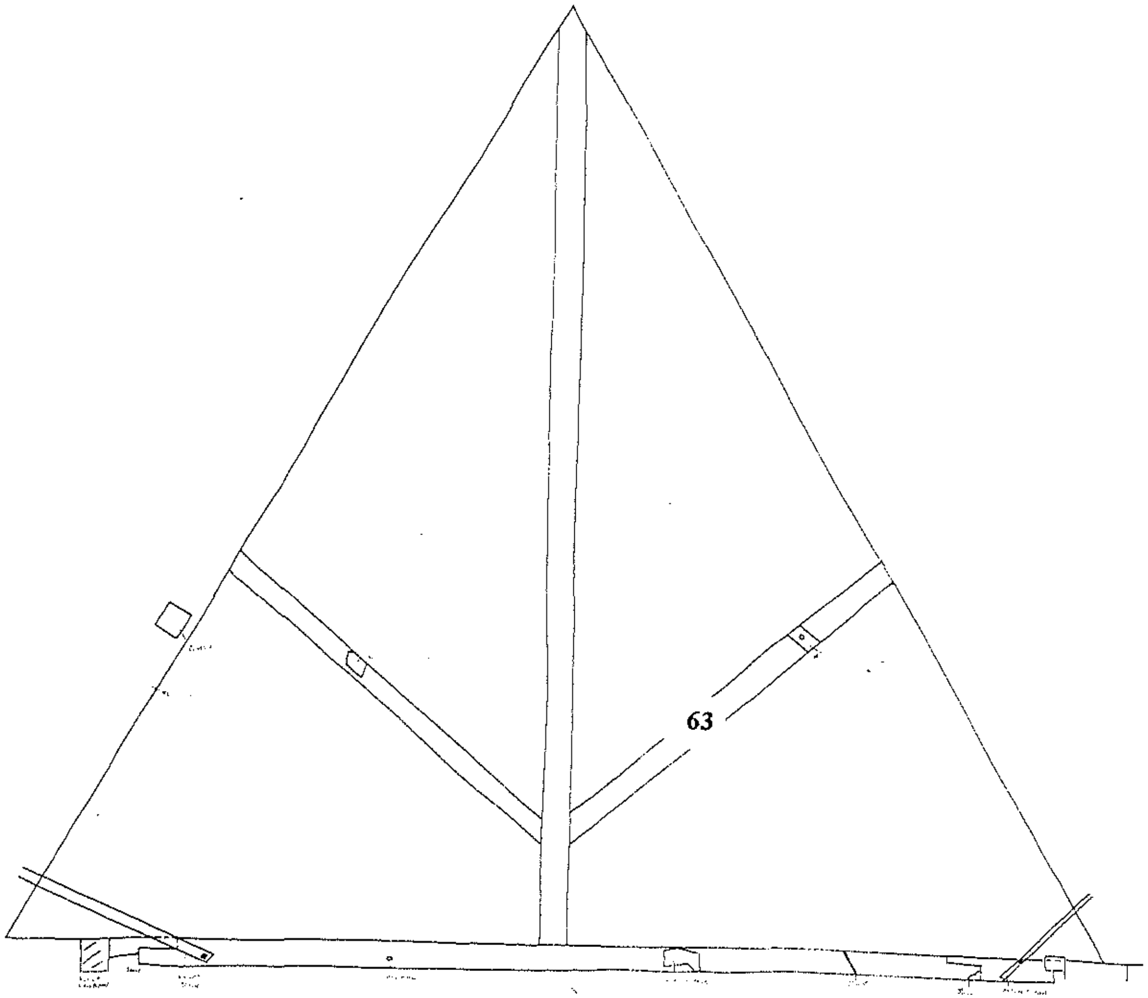


Figure 6f: South-east transept roof east elevation showing position of samples

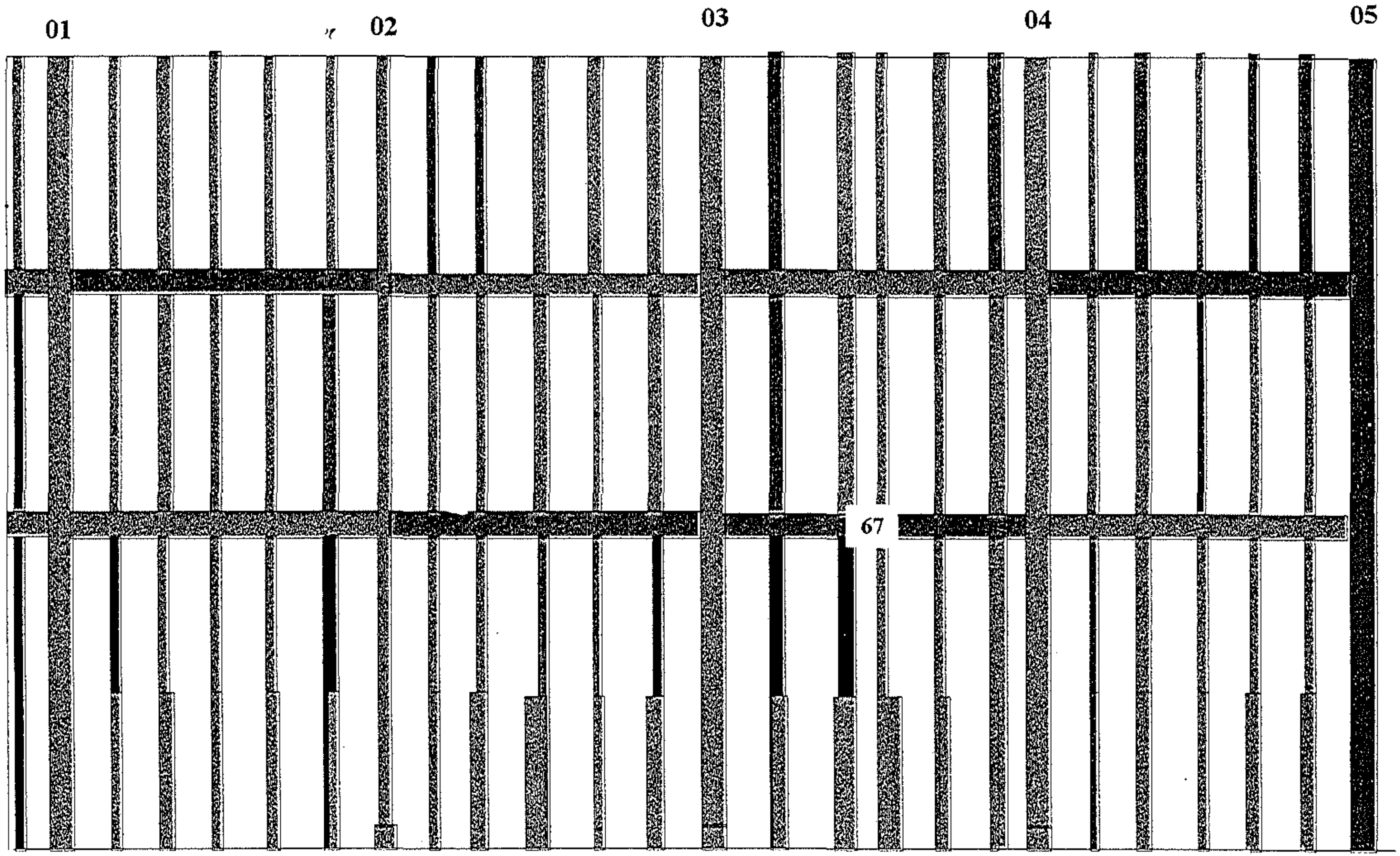


Figure 6g: South-east transept roof west elevation showing position of samples

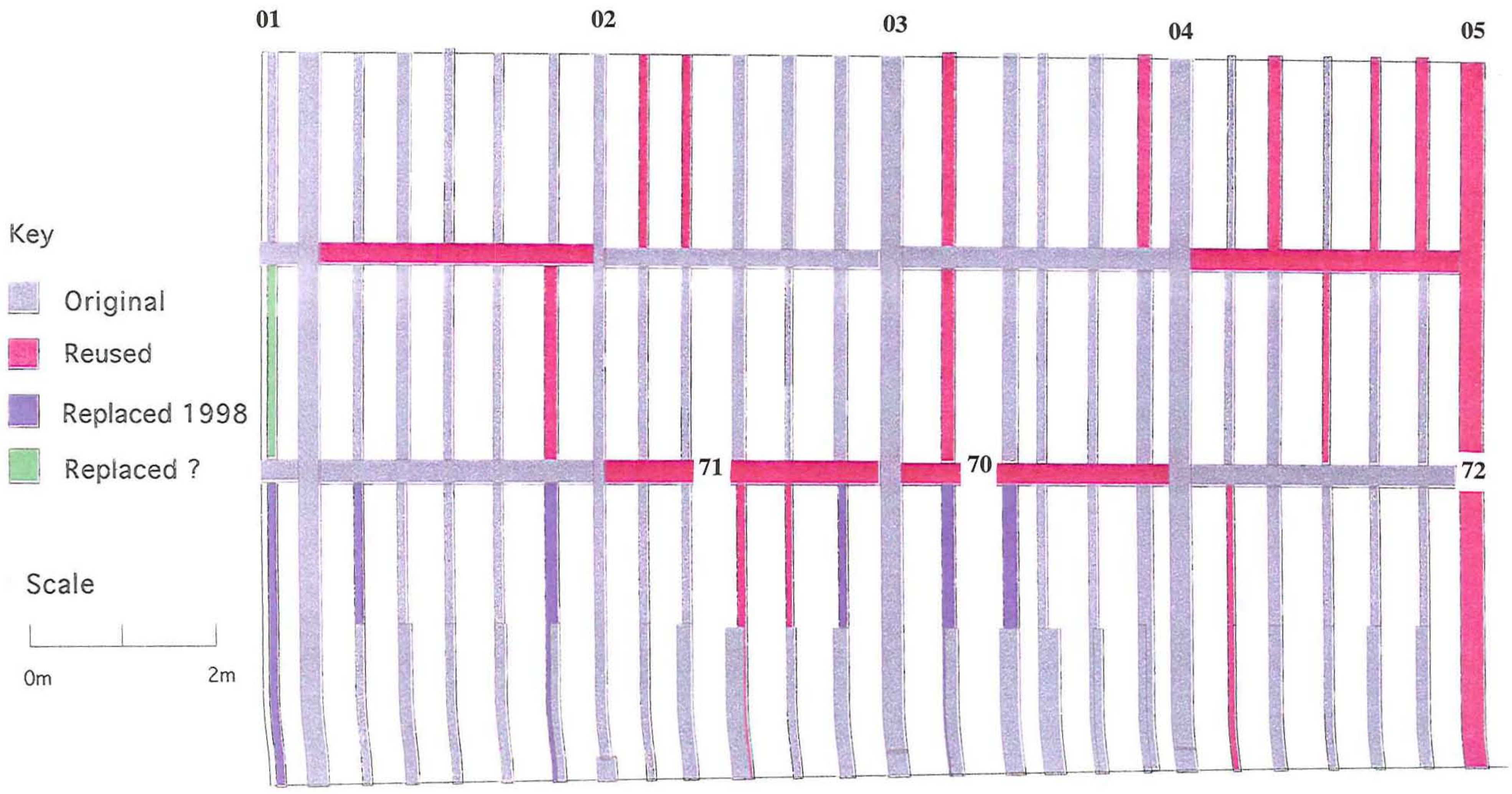


Figure 6h: Plan of south-east transept to show sample locations

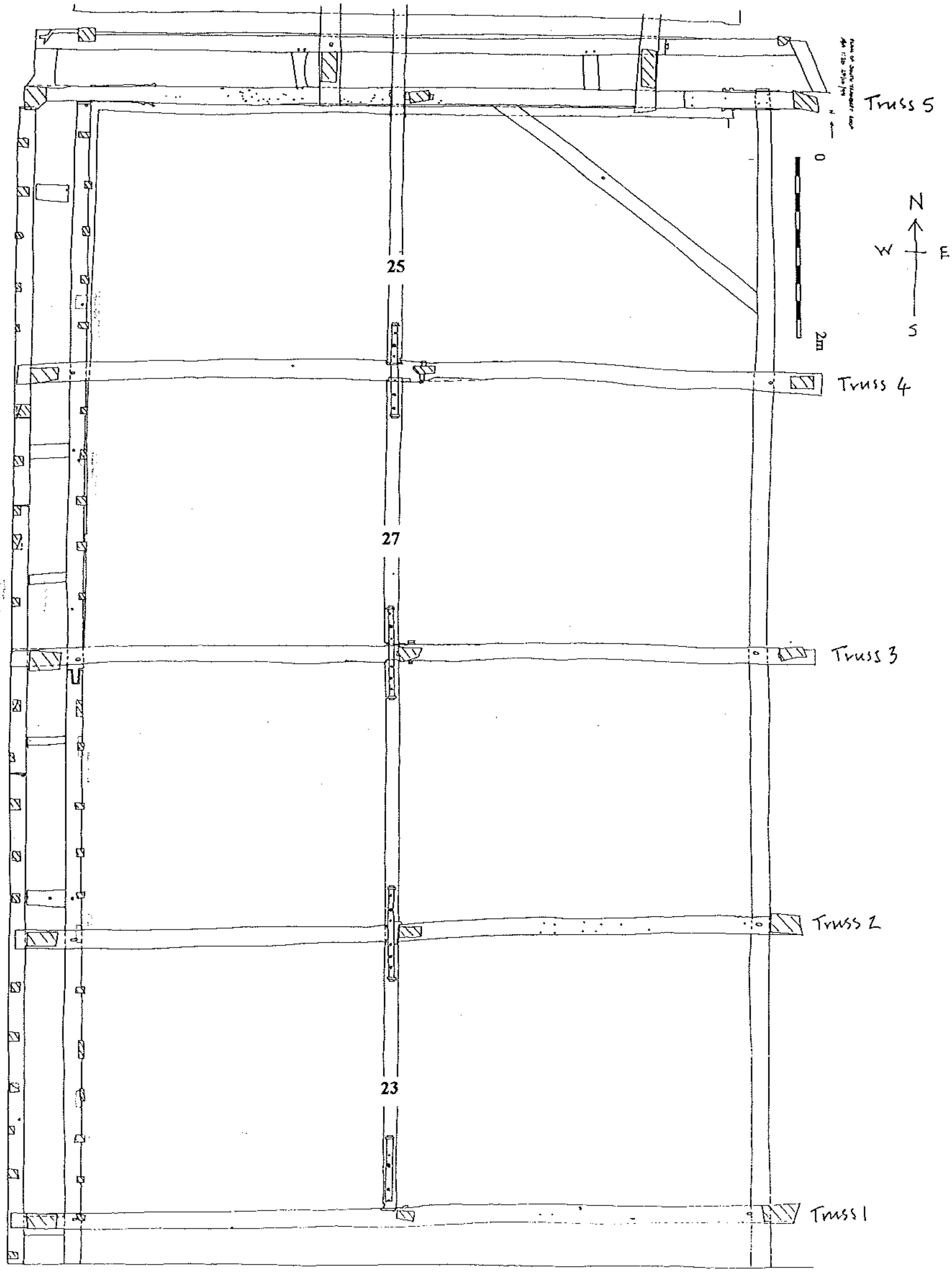


Figure 7: Plan to show position of samples 89-95 from the reused timbers beneath the walk-way of the crossing

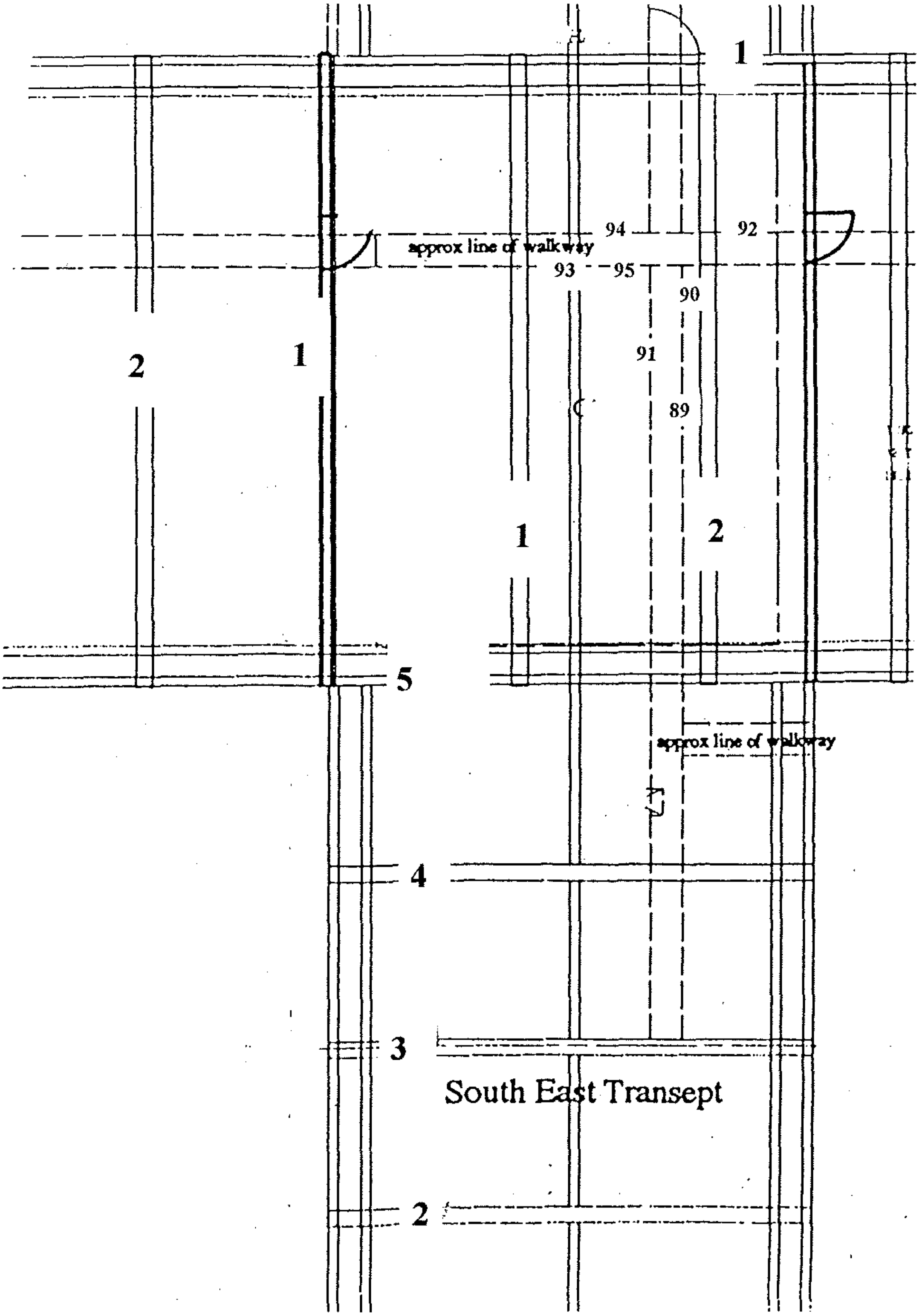
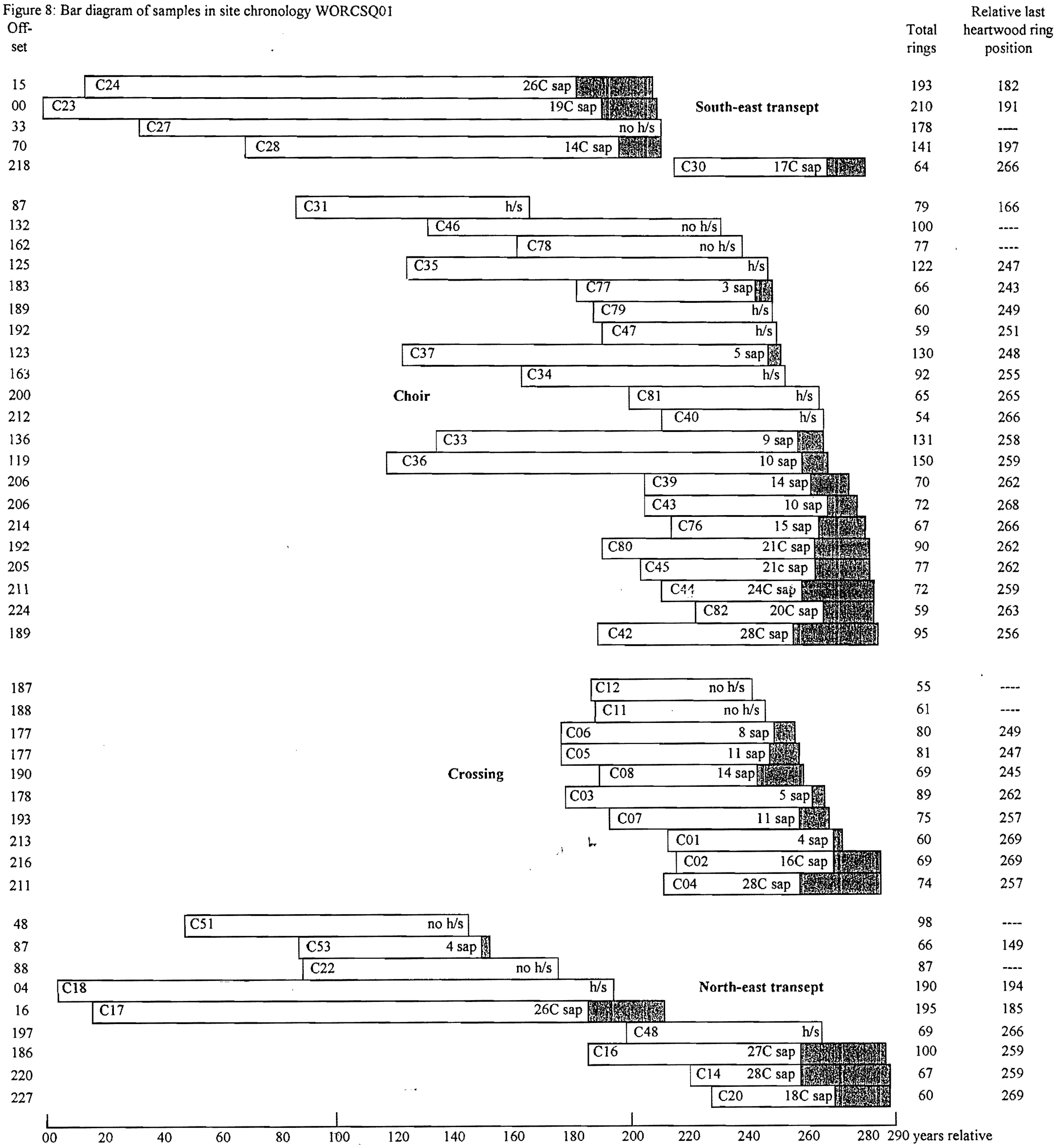
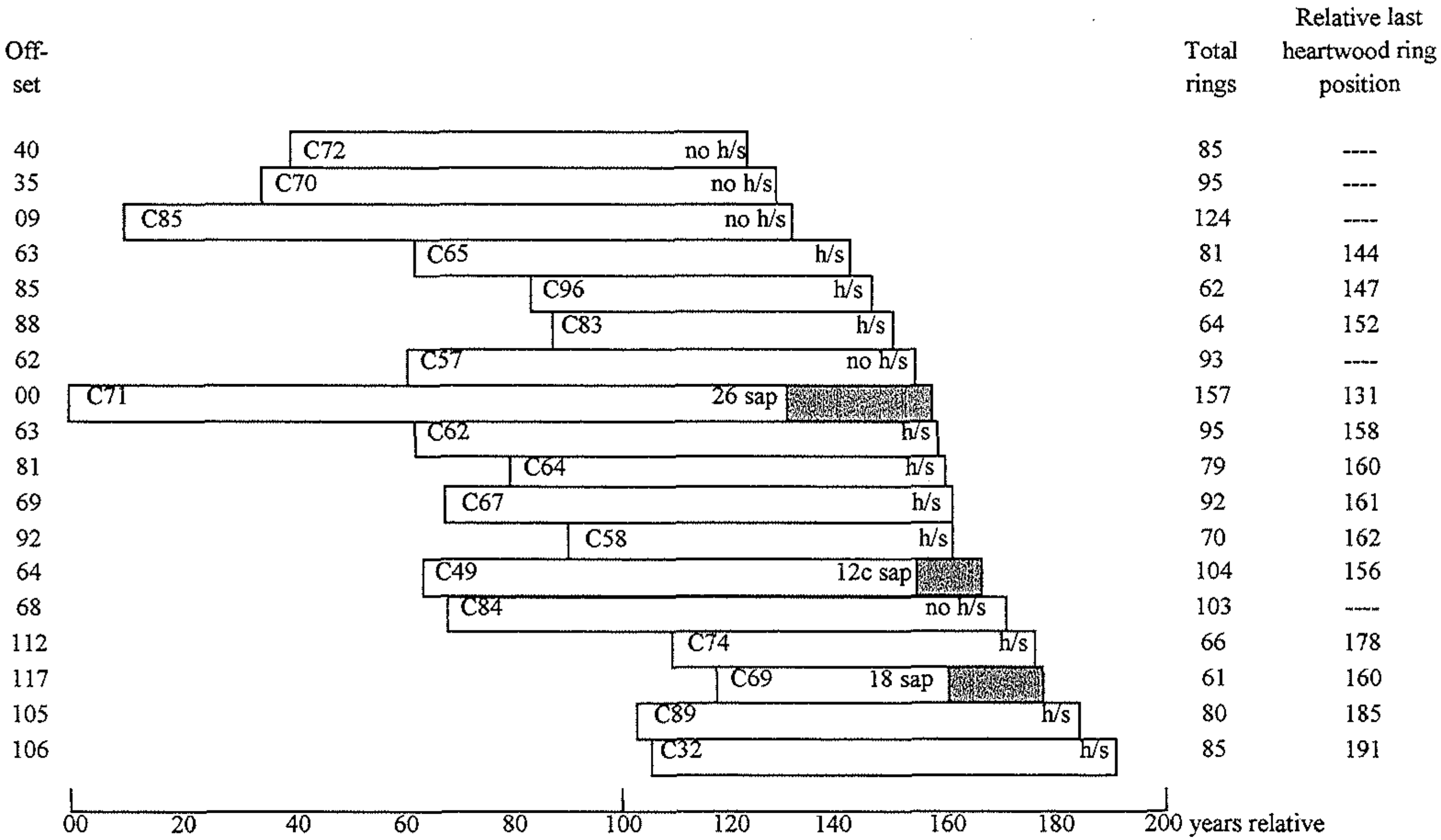


Figure 8: Bar diagram of samples in site chronology WORCSQ01



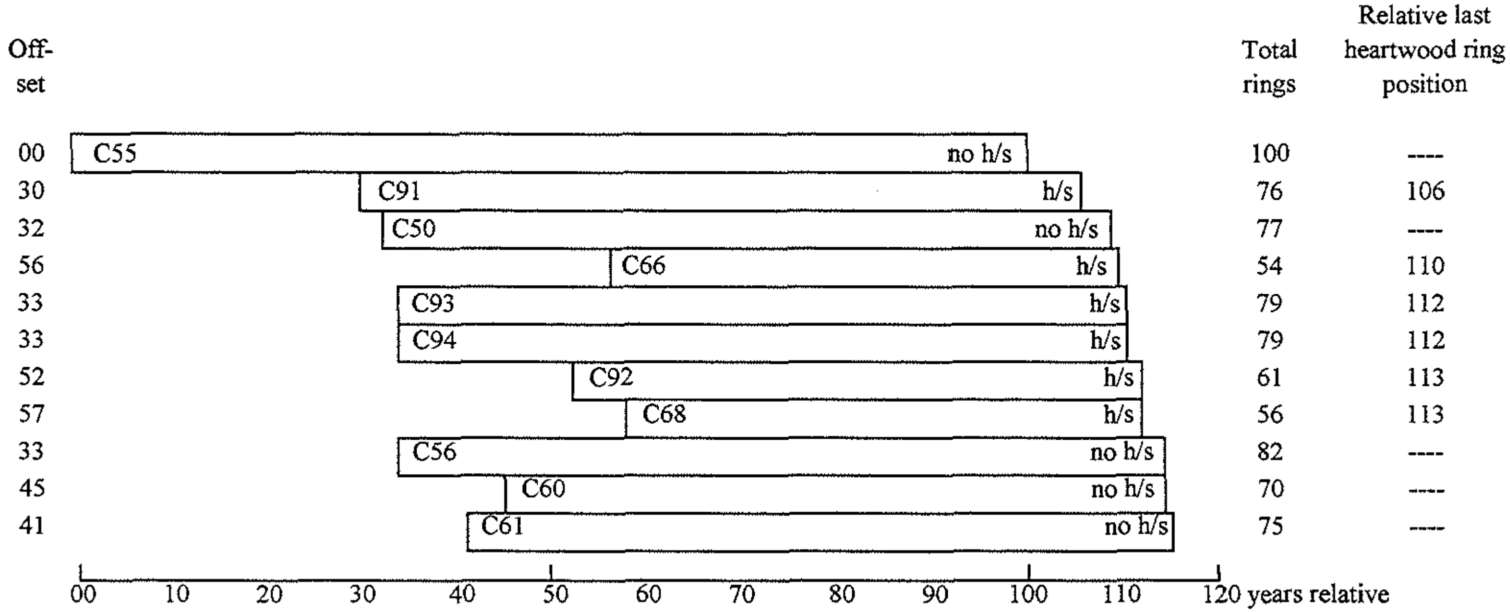
White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample
c = complete sapwood on timber, all or part lost in coring

Figure 9: Bar diagram of samples in site chronology WORCSQ02



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

Figure 10: Bar diagram of samples in site chronology WORCSQ03



White bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Figure 11 Bar diagram of samples in site chronology WORCSQ04

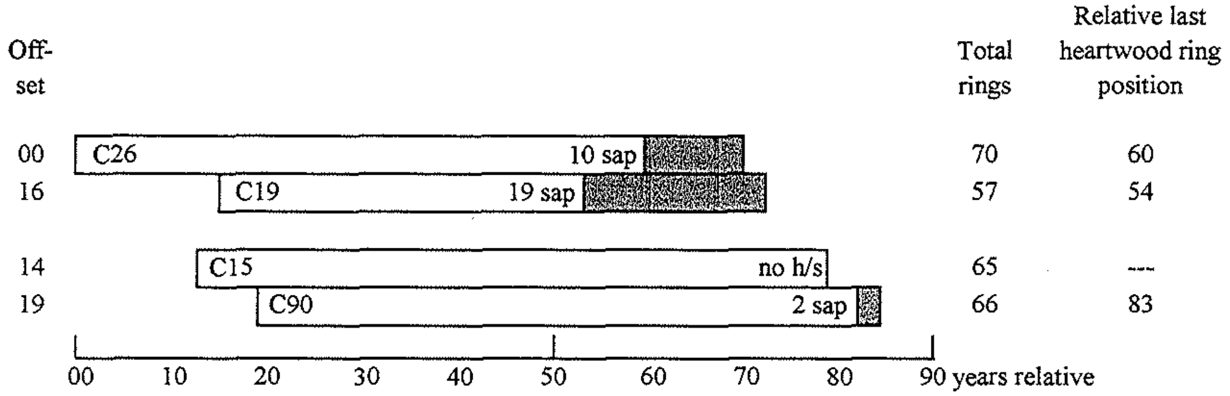
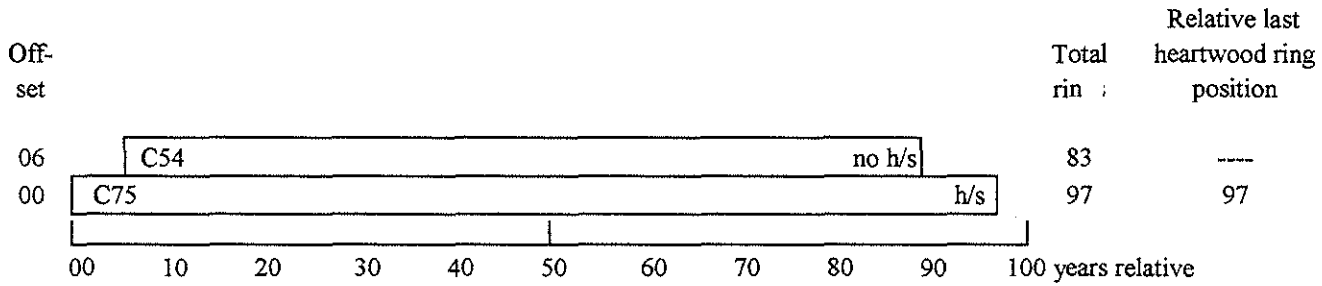
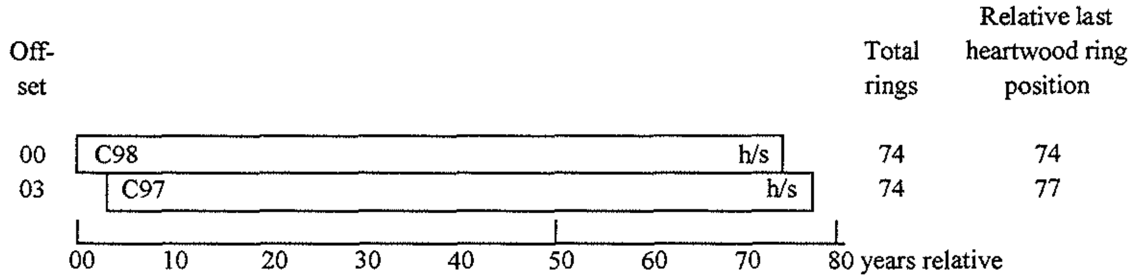


Figure 12: Bar diagram of samples in site chronology WORCSQ05



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

Figure 13: Bar diagram of samples in site chronology WORCSQ06



White bars = heartwood rings
h/s = heartwood/sapwood boundary is last ring on sample

Data of measured samples – measurements in 0.001 mm units

WOR-C01A 60
839 735 566 436 434 282 310 347 353 379 330 322 444 341 354 429 377 360 392 425
422 368 402 398 342 428 322 272 242 225 308 325 364 323 301 431 317 463 374 292
346 296 335 238 258 234 253 266 268 157 288 314 406 437 418 248 308 317 188 376
WOR-C01B 60
847 732 551 456 430 291 295 358 353 386 361 332 456 328 349 402 370 351 422 420
420 380 397 401 352 432 299 273 232 228 309 342 345 336 281 461 316 463 369 289
374 301 343 231 258 242 254 266 255 159 279 299 418 444 421 274 315 302 179 364
WOR-C02A 69
395 410 312 331 361 368 355 278 272 355 344 364 389 365 340 428 578 424 484 413
410 324 355 278 286 241 230 349 338 275 283 300 315 268 336 329 297 309 275 336
266 292 304 311 278 321 177 232 279 319 285 222 264 306 310 232 257 266 256 308
276 307 310 276 217 304 248 260 347
WOR-C02B 69
417 419 313 331 362 376 353 283 267 354 368 356 417 369 329 433 541 439 472 409
406 323 325 290 321 236 239 355 337 283 278 299 322 282 349 337 296 305 299 337
258 297 292 295 283 311 177 241 255 346 294 223 266 302 322 219 259 249 279 289
269 307 327 263 214 270 278 264 330
WOR-C03A 89
301 249 214 137 189 197 248 166 232 184 235 250 206 141 199 157 167 314 173 242
250 188 228 230 173 234 143 233 181 168 261 200 121 149 208 162 207 262 229 300
271 279 322 366 335 274 260 308 306 262 469 362 399 225 223 193 235 323 239 247
206 192 232 138 103 128 160 144 130 162 276 301 217 107 108 161 180 205 144 155
135 147 135 188 123 159 225 155 216
WOR-C03B 89
272 262 219 145 205 199 254 161 243 178 288 241 211 136 210 128 198 306 171 237
253 185 247 212 183 234 187 250 180 170 256 208 106 140 210 163 206 261 215 316
265 283 335 368 348 215 228 322 246 246 431 364 396 247 200 201 210 286 224 247
235 186 217 140 90 128 176 125 138 145 303 288 231 117 103 154 183 206 132 166
138 143 143 176 128 164 211 161 252
WOR-C04A 74
420 462 592 579 574 469 561 408 440 450 461 452 374 420 425 373 468 400 388 449
381 425 410 417 384 300 311 292 285 238 169 214 241 190 199 174 182 222 260 372
325 276 251 214 231 168 211 199 159 164 179 179 163 163 154 170 201 223 254 269
234 218 220 227 213 178 170 195 144 147 179 175 123 133
WOR-C04B 74
413 465 581 578 571 467 557 404 426 456 463 450 370 428 427 376 469 402 390 443
386 423 403 426 379 305 309 280 279 222 170 198 243 188 208 172 180 232 255 384
329 268 251 220 225 170 213 196 156 172 203 145 172 171 158 169 211 220 256 276
214 208 189 228 223 173 176 198 142 141 177 178 133 137
WOR-C05A 81
104 123 135 161 81 177 228 254 239 255 259 253 394 423 222 359 329 303 515 427
521 410 414 465 439 398 402 269 374 346 358 273 259 230 155 355 132 439 281 136
151 147 161 288 337 265 195 256 402 83 51 43 66 122 98 132 118 211 133 128
244 201 309 160 146 100 295 191 183 173 194 236 250 197 160 208 215 210 284 196
236

WOR-C05B 81
86 126 145 143 92 182 229 243 247 258 260 255 390 388 227 357 322 294 534 444
527 407 448 467 443 387 393 276 361 337 357 265 237 234 140 335 139 477 344 153
139 159 166 286 328 263 192 247 400 82 46 52 78 127 103 143 119 188 139 118
230 209 300 169 144 105 307 204 170 186 188 226 240 203 146 191 220 238 260 174
257
WOR-C06A 80
136 116 177 161 113 160 251 280 231 248 260 261 440 376 186 272 227 247 497 413
477 353 394 380 421 332 400 253 392 331 324 284 288 265 149 537 141 113 121 74
121 144 173 283 306 197 139 202 261 105 114 118 126 186 79 98 80 123 126 145
329 380 422 190 157 129 354 182 145 193 271 303 255 227 203 216 277 296 332 237
WOR-C06B 80
81 116 180 154 119 198 238 279 225 251 252 266 460 383 181 274 231 244 485 430
495 355 388 372 412 321 414 250 386 327 323 283 300 269 159 531 141 123 118 81
120 143 165 289 312 189 143 194 265 107 123 113 129 181 84 106 79 112 126 145
326 385 416 194 152 140 341 186 147 194 273 303 249 240 193 232 271 296 319 236
WOR-C07A 75
380 378 290 349 292 319 309 270 380 243 345 229 289 238 227 253 156 79 58 58
87 118 125 111 140 124 178 206 155 151 155 129 190 197 176 191 179 256 182 141
133 164 238 209 261 202 199 197 156 152 121 122 165 174 177 223 242 245 135 109
153 189 234 179 142 176 152 190 160 121 158 169 173 150 173
WOR-C07B 75
371 376 298 348 307 309 307 264 377 245 319 234 287 239 225 257 163 70 62 63
78 127 126 115 140 133 175 208 158 155 148 142 190 200 178 192 192 260 168 146
132 161 239 205 264 207 199 198 158 145 126 116 172 176 166 228 230 237 138 108
149 189 233 182 149 175 153 201 159 123 159 183 139 199 152
WOR-C08A 69
376 180 234 238 261 484 344 405 276 317 272 295 336 365 262 397 279 242 215 198
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149 92 181 155 174 210 166 191 214
WOR-C08B 69
329 167 242 234 268 476 339 395 275 304 269 299 341 357 276 398 278 233 210 206
169 123 399 125 66 63 83 113 110 134 186 244 197 152 187 209 82 70 62 84
95 86 100 55 111 90 84 115 106 128 101 96 106 228 115 99 116 89 136 195
162 93 160 149 187 208 169 167 198
WOR-C09A 70
223 233 207 247 291 330 337 334 261 209 179 165 144 287 187 200 212 231 151 216
253 207 220 210 280 325 224 324 307 260 245 222 140 145 157 299 333 286 330 276
364 271 272 271 294 316 233 266 240 181 220 288 237 215 186 135 176 164 169 153
160 156 157 193 150 106 108 143 162 175
WOR-C09B 70
243 229 207 255 286 324 334 333 300 185 183 165 132 272 192 208 192 235 154 209
248 210 221 216 272 325 225 328 315 257 225 222 148 146 162 310 337 293 324 278
352 270 267 272 293 325 247 262 239 203 203 302 235 206 179 147 169 170 163 166
152 157 156 193 139 105 103 143 146 171
WOR-C10A 58
157 215 242 256 216 172 205 211 217 160 216 206 202 250 229 198 215 177 162 191
283 265 227 204 209 187 170 193 148 241 141 147 129 125 120 129 144 101 131 142
202 238 179 295 268 267 219 183 159 132 165 265 245 229 253 239 322 330
WOR-C10B 58
168 209 234 259 218 196 211 201 227 143 211 192 208 268 240 179 218 178 164 174
290 245 225 218 217 212 154 189 147 232 136 152 122 126 115 125 142 99 132 146
178 220 186 306 268 272 217 200 147 117 144 230 219 225 252 235 325 343

WOR-C11A 61
292 220 223 247 197 147 190 377 359 316 352 284 296 316 285 358 272 375 292 251
276 193 85 64 67 85 106 108 98 148 151 153 218 191 179 177 146 224 208 219
273 222 257 173 109 122 178 261 176 286 252 212 210 150 151 125 172 161 202 187
292
WOR-C11B 61
327 207 204 237 189 171 174 380 383 328 353 277 316 357 284 339 266 368 286 233
284 181 102 57 78 86 109 125 113 135 142 157 225 186 161 180 169 228 199 221
286 219 267 160 114 122 175 254 187 282 256 206 217 150 152 147 169 180 204 205
314
WOR-C12A 55
197 315 238 250 267 205 160 170 355 381 339 383 289 306 348 253 336 262 351 269
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209 279 220 268 187 122 104 178 263 182 185 103 117 114 172
WOR-C12B 54
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212 276 232 261 186 117 102 176 264 188 163 152 119 163
WOR-C13A 240
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114 98 82 82 65 66 62 63 66 81 57 61 41 54 58 53 56 34 57 60
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91 129 116 90 93 92 73 88 102 94 87 78 90 83 83 100 86 78 92 85
74 89 87 83 56 77 63 60 56 62 51 59 45 54 41 45 58 42 55 60
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43 41 30 27 35 33 39 43 49 44 52 50 55 61 59 48 56 49 52 61
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89 140 112 90 90 91 69 87 102 93 80 85 89 79 88 81 84 81 95 96
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WOR-C14A 67
145 125 143 159 107 135 147 156 191 118 195 144 214 144 196 129 107 103 114 134
137 102 109 144 121 116 129 109 127 124 163 126 154 153 131 133 94 105 97 95
108 101 69 80 75 94 99 110 120 103 113 83 71 100 98 115 98 91 80 102
88 102 108 125 123 131 114
WOR-C14B 67
138 134 145 154 109 139 161 143 186 132 198 150 199 151 191 115 104 110 110 133
150 103 98 140 118 110 123 107 131 129 167 132 147 155 121 139 103 116 98 85
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98 88 114 137 126 118 106

WOR-C15A 65
483 410 349 265 185 164 104 95 96 71 120 165 132 205 209 116 163 152 166 150
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238 209 191 169 142 129 119 145 206 162 152 164 109 107 121 151 138 125 154 130
139 138 155 162 235
WOR-C15B 65
437 428 395 230 188 174 113 113 81 60 120 180 148 208 182 121 161 163 158 150
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215 207 171 175 156 126 121 150 212 166 158 152 123 115 116 133 154 120 154 126
137 143 143 171 239
WOR-C16A 100
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104 90 118 69 122 104 182 113 157 121 68 86 89 125 118 71 75 107 81 93
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WOR-C16B 100
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107 91 124 86 115 99 167 122 165 103 75 101 78 113 112 82 73 119 76 76
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124 83 123 180 114 70 79 108 116 111 120 123 114 137 102 128 124 159 128 118
WOR-C17A 195
99 82 101 68 62 87 111 58 94 91 99 69 84 107 139 75 51 38 56 61
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WOR-C17B 195
113 84 100 58 75 87 105 60 100 65 85 48 96 100 126 71 47 42 53 75
80 87 87 96 86 81 68 95 88 109 160 171 127 121 108 124 146 119 145 165
177 182 92 110 98 140 104 66 88 98 118 91 107 135 105 112 130 89 95 101
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WOR-C18A 190
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101 62 100 99 79 72 83 69 86 92 58 101 59 54 84 88 97 93 89 76
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78 72 61 63 64 83 65 82 88 91 83 68 79 73 80 105 66 58 90 65

80 64 71 67 93 69 77 88 98 84 89 89 75 70 92 81 77 59 63 67
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77 69 57 69 42 62 48 57 67 79
WOR-C18B 190
219 185 186 161 70 139 169 291 168 210 302 308 186 199 202 154 119 179 170 125
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96 138 136 148 120 77 130 95 115 97 86 93 100 93 57 69 87 101 70 76
57 74 74 82 78 68 67 94 69 58 80 72 73 56 106 99 98 63 122 91
106 66 93 102 80 69 77 75 90 82 62 94 61 57 86 85 90 93 99 83
97 80 90 84 99 86 98 110 92 72 78 74 106 79 81 73 75 82 53 80
76 64 56 57 67 89 70 82 82 88 84 65 89 77 72 109 74 62 80 65
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76 77 59 57 51 65 46 54 65 68
WOR-C19A 57
440 322 341 261 343 209 368 187 180 344 340 314 265 188 210 178 220 243 255 190
224 176 277 280 273 268 251 283 195 187 183 183 206 192 180 232 252 306 311 291
280 362 351 174 160 183 169 162 209 173 162 219 216 314 266 341 289
WOR-C19B 57
384 323 348 265 345 218 358 191 172 336 353 322 265 192 208 182 215 234 257 197
191 181 286 285 342 250 269 268 198 154 191 182 202 197 174 233 239 314 328 265
303 369 329 189 136 199 162 173 202 182 175 204 207 303 286 325 312
WOR-C20A 60
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233 273 233 336 322 365 210 188 219 180 216 219 181 241 217 171 246 239 270 257
212 277 348 310 143 135 153 187 187 235 207 220 249 218 308 342 359 286 209 261
WOR-C20B 60
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208 263 345 311 145 146 163 194 193 239 212 199 258 224 304 340 325 325 227 233
WOR-C21A 110
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287 161 214 178 153 140 153 165 185 150 172 136 137 146 165 125 114 67 58 50
99 319 260 314 171 147 127 141 158 141 145 157 186 159 109 57 56 126 217 343
205 153 176 161 190 196 206 272 154 164 211 162 169 181 194 179 183 175 144 157
190 177 181 215 142 220 233 200 232 202
WOR-C21B 110
135 106 150 136 258 234 188 174 164 173 172 131 153 149 139 117 79 104 116 81
102 131 92 104 166 465 336 313 247 155 187 135 172 140 183 182 209 206 219 256
296 177 182 178 160 144 160 160 194 152 169 128 145 129 162 146 94 58 65 64
89 339 255 301 159 139 131 138 161 141 147 165 179 156 115 61 69 123 227 342
202 167 175 165 169 197 209 273 156 181 195 170 167 164 213 175 174 192 146 152
151 171 191 211 170 218 201 215 237 210
WOR-C22A 87
243 193 178 161 255 208 214 187 178 258 259 167 225 322 328 264 285 262 276 276
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229 188 257 262 200 104 56 74 111 150 121 117 142 162 143 147 158 119 142 118
184 122 140 180 198 146 162 182 179 106 168 155 145 148 96 144 159 156 131 129
118 115 145 154 123 131 165
WOR-C22B 87
284 202 187 133 227 234 215 201 167 231 269 171 203 372 291 272 298 253 253 233
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188 125 134 186 183 153 165 177 169 132 155 149 149 143 118 138 140 169 133 126
106 110 137 133 136 129 150
WOR-C23A 210
218 122 183 168 184 182 106 151 126 136 163 160 137 150 189 175 127 130 214 146
112 140 127 84 105 108 158 78 117 116 133 56 58 94 82 78 102 93 90 77
89 88 76 83 79 90 113 130 93 72 72 119 127 104 125 124 130 104 75 88
150 164 111 63 101 125 110 102 115 110 100 113 85 70 65 76 55 42 48 45
71 62 67 73 60 54 74 72 99 72 88 67 73 66 77 63 44 42 55 67
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81 76 80 77 70 48 82 61 58 66 70 83 89 87 82 66 73 87 74 88
51 53 66 69 61 65 98 72 79 58 70 73 79 61 47 74 55 59 69 49
73 47 44 47 47 42 54 38 63 81 57 70 58 50 52 52 39 45 38 61
80 51 65 41 51 48 38 46 58 58 65 60 46 55 55 46 65 68 66 60
66 53 59 77 67 80 61 89 53 70
WOR-C23B 210
182 125 193 171 185 196 110 141 126 119 169 167 129 154 184 168 126 121 222 142
116 138 126 84 110 118 167 69 114 116 139 46 60 89 81 79 93 94 93 82
86 89 81 75 76 95 115 130 92 81 82 110 125 113 123 126 133 100 73 96
134 154 116 70 97 136 109 90 112 118 108 101 82 68 69 87 59 42 51 43
66 64 69 72 59 48 79 75 105 65 87 61 71 65 79 59 47 54 51 59
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88 71 71 83 72 42 81 71 46 69 71 89 92 75 87 82 69 92 60 87
53 41 67 76 63 62 89 74 75 69 73 69 86 63 49 73 49 61 55 48
72 57 40 55 43 47 47 32 69 79 58 74 56 54 55 46 45 42 42 55
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61 53 65 72 77 69 62 91 52 58
WOR-C24A 193
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64 82 57 95 95 85 71 65 67 73 78 89 108 81 101 73 89 101 107 113
122 115 99 64 81 92 127 87 67 98 107 104 77 76 94 86 91 97 93 79
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WOR-C24B 193
196 134 99 136 100 79 112 134 78 101 131 118 75 83 83 100 77 43 48 88
70 76 64 96 92 82 70 53 75 70 77 82 107 78 85 92 79 108 93 101
123 121 96 67 84 88 118 90 68 98 104 99 79 77 92 81 85 104 82 85
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WOR-C25A 308
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80 85 63 23 85 59 61 83 41 74 49 53 62 39 57 47 77 41 63 54
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WOR-C25B 275
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WOR-B26A 70
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324 215 221 169 212 474 402 528 501 348 378 367 347 251 269 256 293 242 294 372
296 202 373 414 277 302 299 280 278 289 186 256 291 332 259 215 189 280 245 179
261 182 240 245 315 266 239 220 198 226
WOR-B26B 70
130 251 149 141 92 84 145 119 100 273 324 246 200 210 228 248 334 272 362 320
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299 217 383 434 312 294 300 268 291 290 174 265 288 317 259 208 192 266 258 174
256 176 264 246 308 290 196 226 201 258
WOR-B27A 178
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134 141 115 86 120 79 62 103 134 97 64 88 116 128 173 190 136 146 144 165
159 122 166 183 126 180 151 101 136 136 132 121 93 74 100 109 93 95 76 90
85 86 94 88 96 116 126 110 80 98 127 122 79 99 96 105 98 106 125 122
109 80 74 87 100 92 104 114 103 97 109 117 93 107 131 115 136 101 142 93
112 99 94 101 111 107 124 110 102 115 94 107 82 98 79 84 85 103 78 100
96 109 106 108 128 120 113 82 70 48 52 50 63 65 71 79 99 51 53 51
64 79 73 79 62 78 71 86 76 70 64 80 68 74 65 59 76 63 63 74
65 76 74 85 66 76 98 79 84 80 76 83 75 90 62 77 95 81
WOR-B27B 178
129 158 98 126 96 96 128 130 104 127 189 153 198 149 143 134 124 150 111 101
129 146 115 85 120 74 65 98 132 86 59 86 119 128 167 178 154 140 157 146
169 111 166 177 131 178 152 103 132 133 138 131 86 76 95 110 94 82 81 108
89 93 92 86 97 114 123 104 83 102 120 127 80 91 107 95 108 105 125 102
119 79 78 83 104 92 110 110 105 99 104 109 93 110 132 101 141 112 136 102
104 105 88 103 107 100 135 102 107 113 113 103 65 105 71 96 75 98 90 101
95 109 101 100 128 124 105 97 60 60 44 59 56 60 78 82 100 57 55 48

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133 172 119 138 134 115 137 150 149 147 126 121 129 130 138 98 147 99 106 117
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105 115 105 84 116 117 103 117 141 210 155 121 148 122 102 107 87 100 108 118
138
WOR-B28B 141
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117 116 119 120 110 127 122 108 143 164 144 127 122 143 146 113 104 149 129 132
131 160 142 111 104 81 93 109 108 120 125 160 136 123 136 125 139 171 134 173
113 175 128 141 139 122 132 154 140 156 121 121 122 127 141 100 133 92 124 119
122 134 145 140 138 112 136 183 149 160 139 82 60 60 54 82 98 94 97 124
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110 117 110 89 112 118 114 123 126 186 155 133 143 118 96 111 98 100 97 110
168
WOR-B29A 57
198 159 214 207 284 365 307 342 270 370 268 271 206 332 102 307 392 278 243 246
212 227 221 223 205 268 106 239 284 388 147 255 301 197 245 291 169 289 322 204
306 260 212 259 192 228 300 304 115 168 146 138 146 112 91 156 171
WOR-B29B 57
212 159 217 200 293 368 300 330 293 369 258 279 197 336 128 278 381 270 264 235
224 223 218 226 191 261 108 244 298 375 138 247 296 219 250 291 179 282 310 216
305 272 211 257 192 212 289 295 129 166 157 130 151 110 91 142 186
WOR-B30A 64
493 298 358 364 228 180 175 230 298 226 293 322 492 318 301 165 162 159 171 217
205 328 151 105 102 208 113 132 155 122 132 132 145 135 138 115 138 161 132 133
118 148 189 182 125 151 117 169 173 128 171 189 181 86 86 122 155 159 170 199
134 119 122 144
WOR-B30B 64
465 316 384 351 254 194 195 246 288 234 300 313 496 327 296 170 170 153 172 206
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124 147 186 175 128 150 132 169 169 138 188 202 178 106 86 131 149 143 185 206
180 113 129 148
WOR-B31A 79
263 337 345 299 245 185 204 181 202 198 251 295 209 232 263 247 212 204 217 266
269 323 312 344 404 464 341 227 176 294 326 355 350 330 330 267 208 228 182 217
243 319 249 267 243 201 138 115 117 146 217 176 180 197 206 206 235 213 192 203
151 167 160 134 239 228 184 194 202 186 137 162 176 168 173 133 143 162 191
WOR-B31B 79
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WOR-D71B 157
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157 145 113 164 93 104 126 113 140 120 130 120 117 86 94 89 80 81 78 76
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107 128 129 99 152
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128 159 169 168 139 168 177 131 145 177 196 187 172 203 168 161 161 142 125 111
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71 78 90 104
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202 262 179 272 264 187 237 228 257 214 212 222 139 171 211 217 192 258 250 136
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77 104 108 186 157 136 94 116 81 93 73 114 133 116 119 186 139 129 136 167
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298 227 200 260 279 255 272 264 200 220 196 307 210 245 236 253 209 228 144 206
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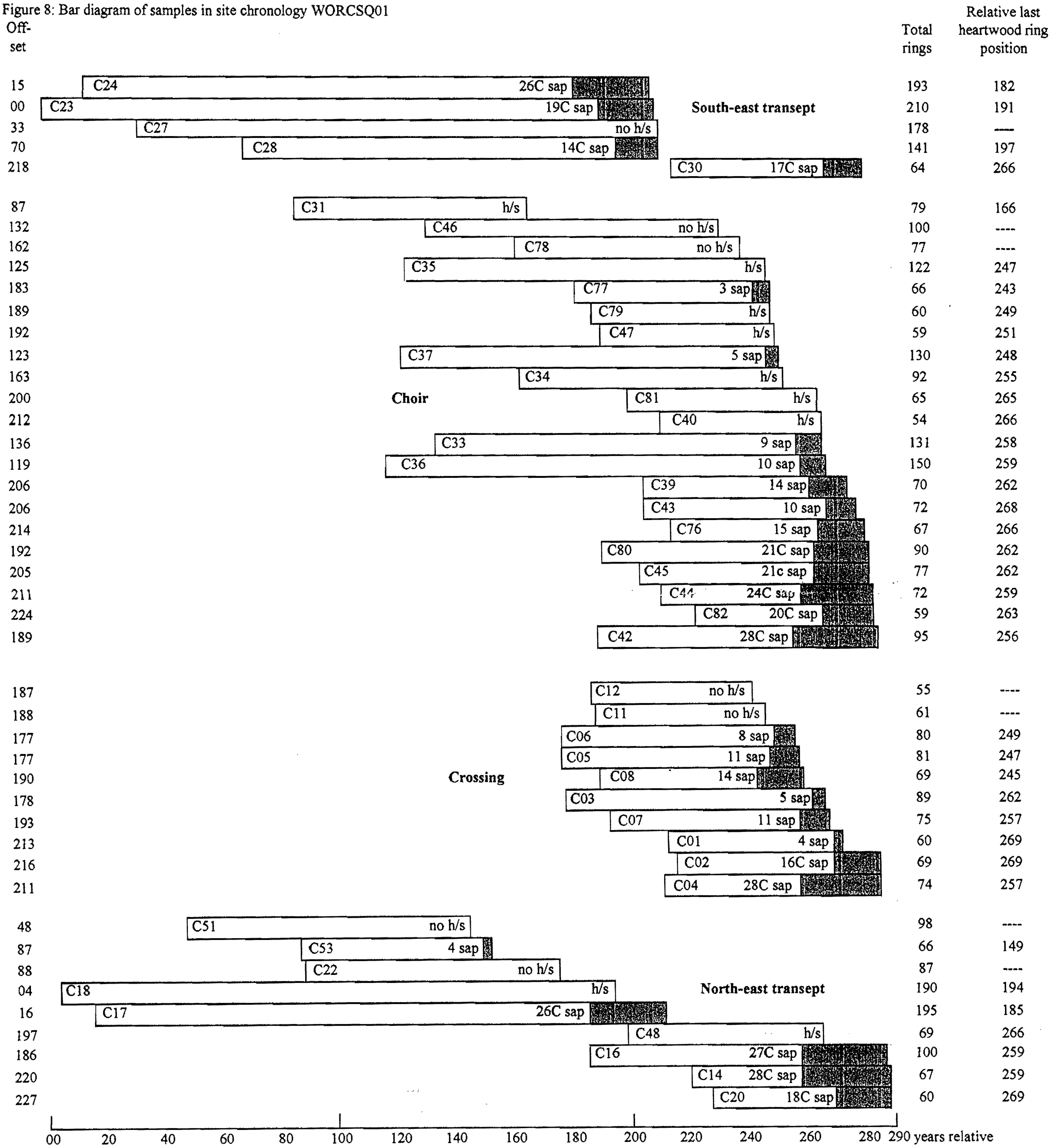
Figure 8: Bar diagram of samples in site chronology WORCSQ01



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

APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The *width* of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring..

If the bark is still on the sample, as in Figure 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

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

1. ***Inspecting the Building and Sampling the Timbers***. Together with a building historian we inspect the timbers in a building to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure 2 has about 120 rings; about 20 of which are sapwood rings. Similarly the core has just over 100 rings.

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

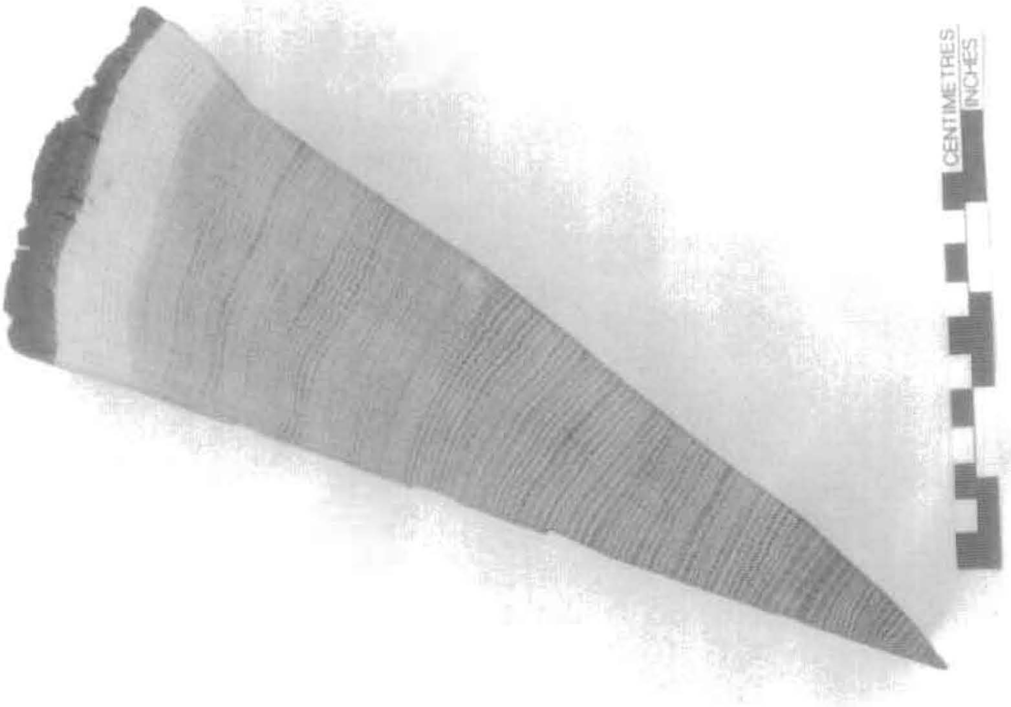


Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

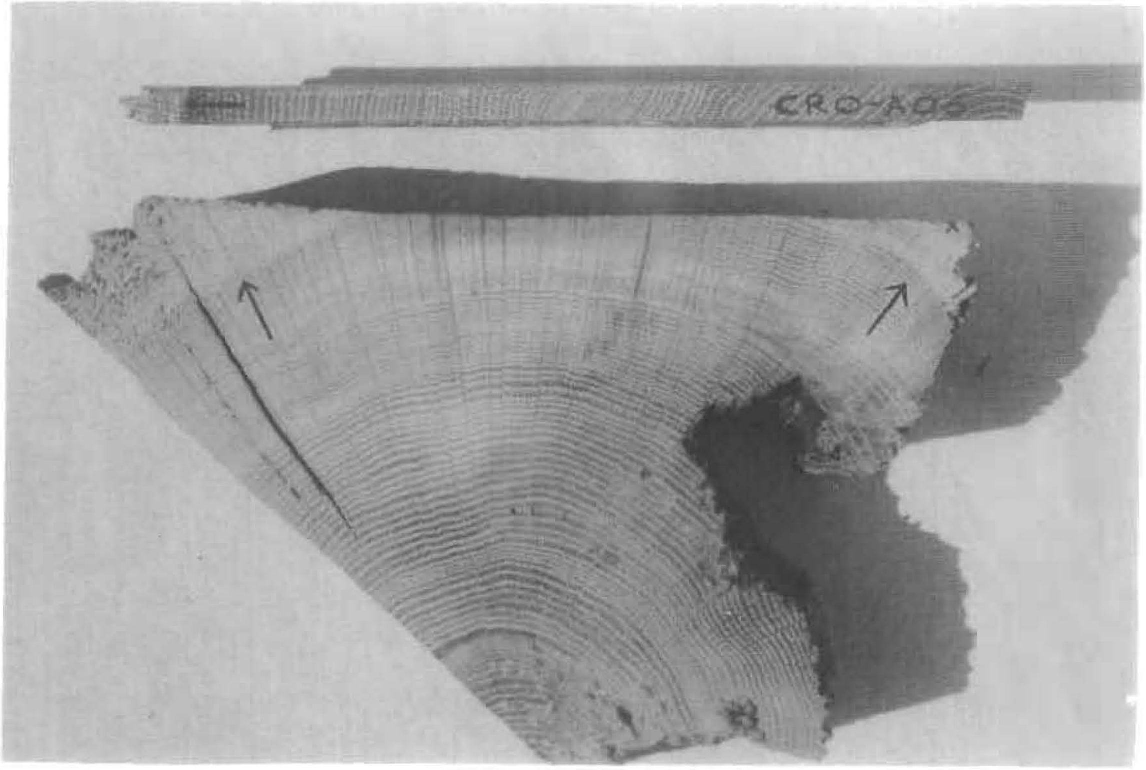


Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig 3. Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis.

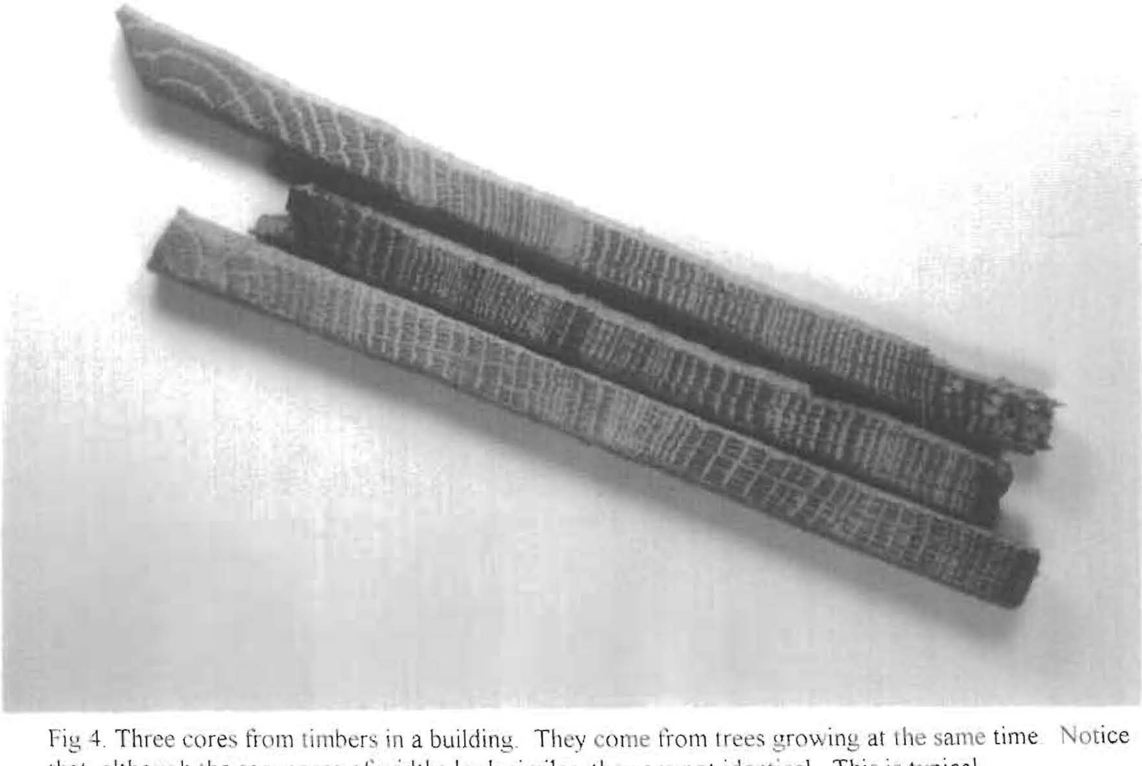


Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost This can be difficult as these outer rings are often very soft (see below on sapwood) Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

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

All sampling by the Laboratory is undertaken according to current Health and Safety Standards.
The Laboratory is insured with the CBA.

2. ***Measuring Ring Widths.*** Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples.*** Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum t-value among the t-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a t-value of at least 4.5, and preferably 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

   This is illustrated in Fig 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN- C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the t-value between C45 and C08 is 5.6 and is the maximum between these two whatever the position of one sequence relative to the other.

   It is standard practice in our Laboratory first to cross-match as many as possible of the sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely for these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

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

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

More precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 40 years later we would have estimated without this observation.

T-value/Offset Matrix

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

Bar Diagram

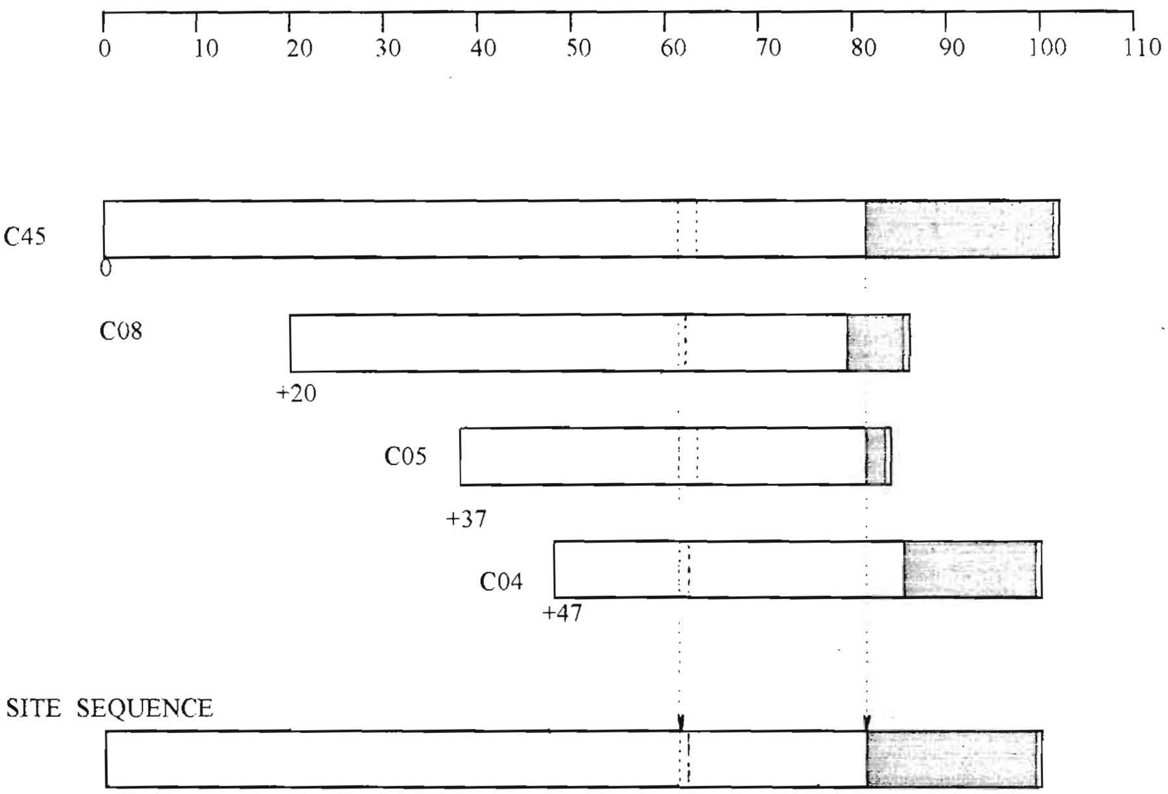


Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t-values*.
The *t-value offset* matrix contains the maximum t-values below the diagonal and the offsets above it.
Thus, the maximum t-value between C08 and C45 occurs at the offset of +20 rings and the t-value is then 5.6.
The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

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

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

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ,* and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed for this.

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

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

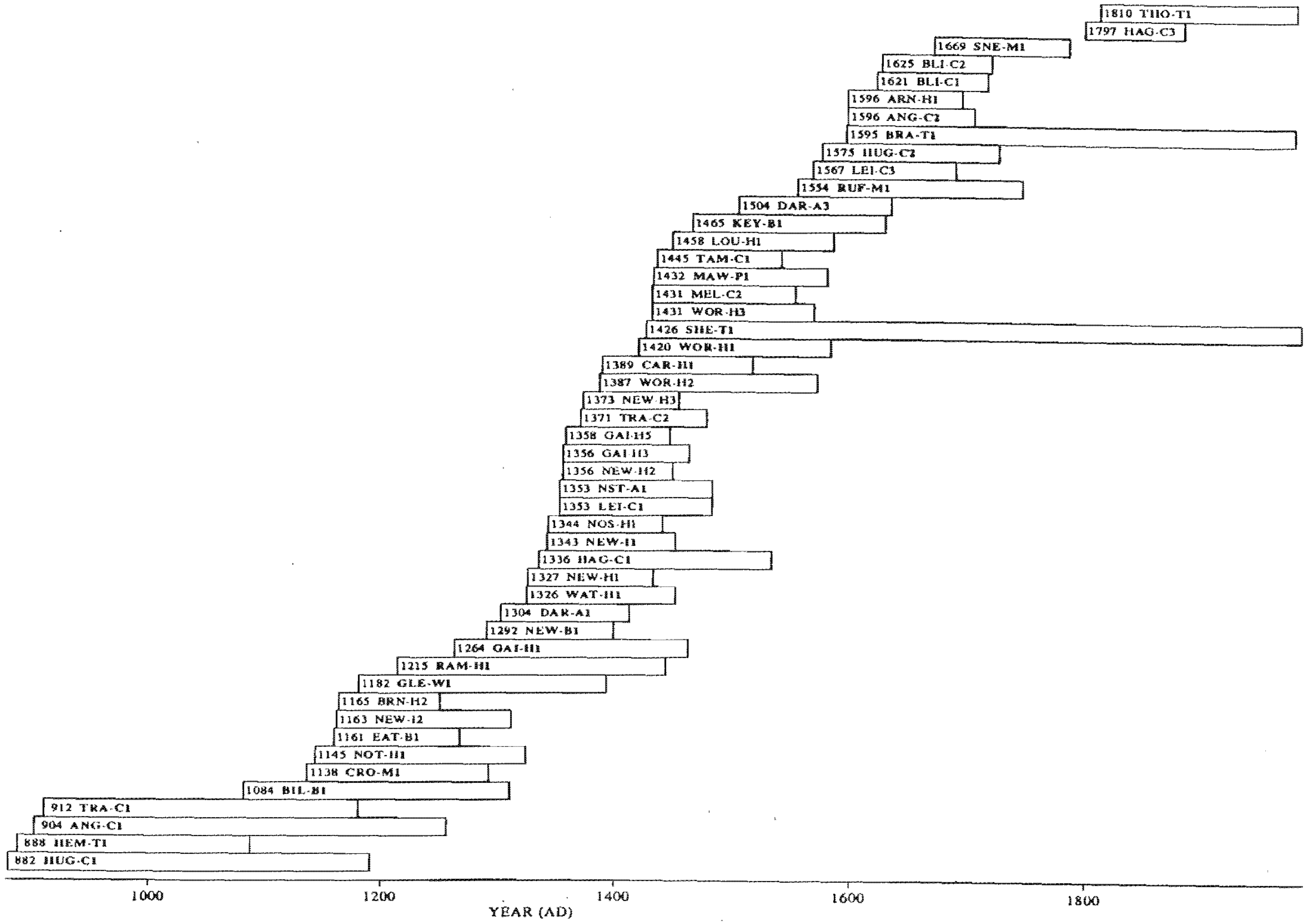


Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

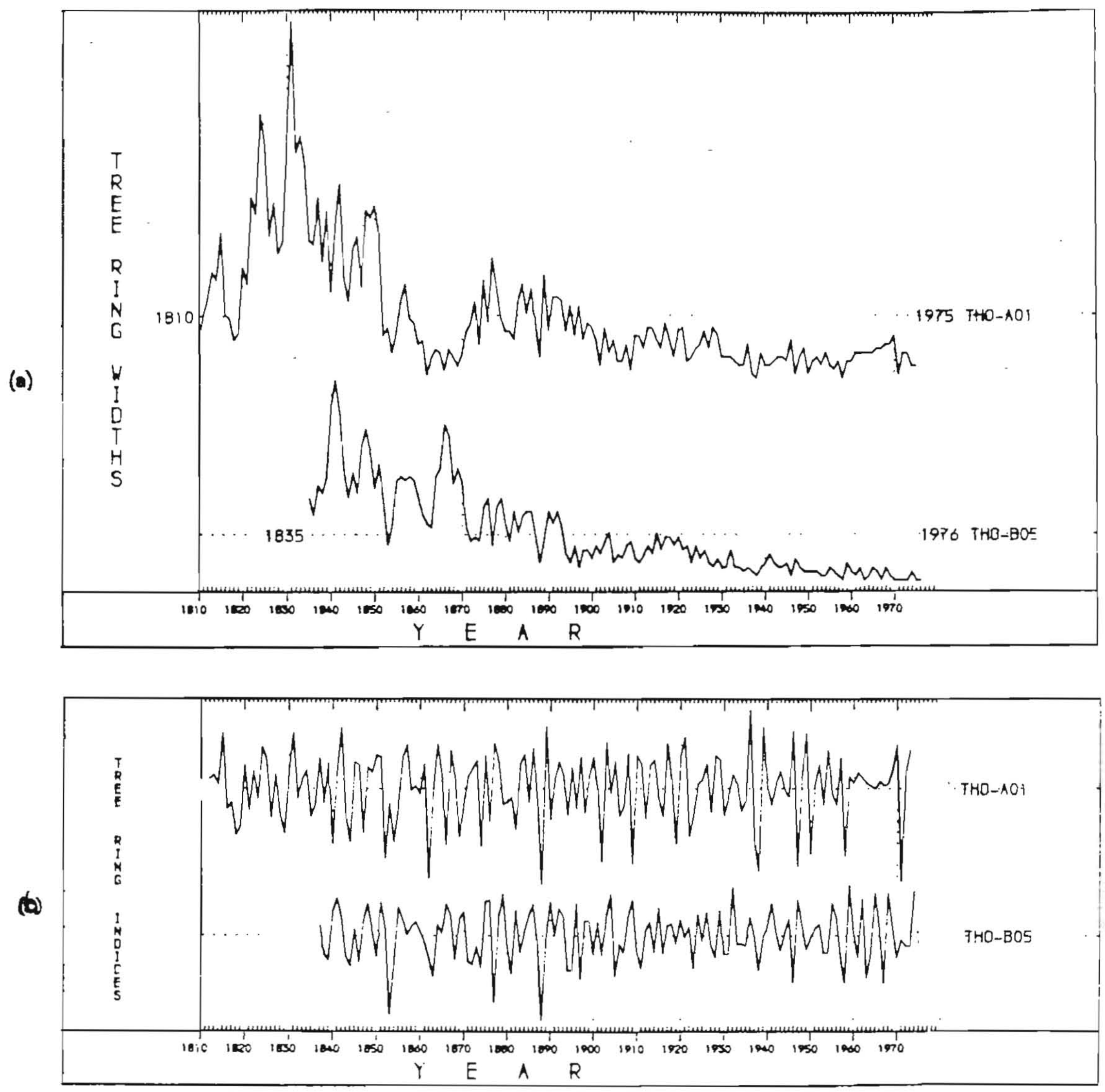


Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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