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Tree-Ring Analysis of Timbers from Exeter Cathedral, Exeter, Devon, Part 1

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Summary

One hundred and four samples from the North Transept, the Choir, Crossing, and the Presbytery roofs of Exeter Cathedral were analysed by dendrochronology. This analysis produced eight site sequences. The largest, EXTCSQ01, contains 64 samples, having 184 rings spanning the period AD 1132 - AD 1315. Interpretation of the results suggests that timber used in these four roof areas was felled and used over a period between AD 1291 to AD 1315 during major alterations to the original Norman construction. A second site chronology EXTCSQ02 has thirteen samples and 109 rings spanning the period AD 1805 - AD 1911. These samples represent timbers used in repairs to the Presbytery and Choir in the AD 1920s. A third site chronology of 2 samples, EXTCSQ03, has 130 rings spanning the period AD 1555 - AD 1684. Interpretation of the sapwood would indicate that timber felled in AD 1683 and AD 1684 was used for repairs in the Crossing. A fourth and final dated site chronology, EXTCSQ05, has 72 ring spanning AD 1478 - AD 1549. Analysis of these timbers indicates that repairs were made to the North Transept roof using timber felled in AD 1549. This episode of repairs had not hitherto been distinguished. Four other site chronologies, one of three samples and two of two samples each, failed to date. This study shows that the presbytery roof contains some timbers which were certainly felled in the years AD 1291, AD 1293, AD 1294 and AD 1298. The choir roof contains some timbers certainly felled in AD 1294 and AD 1306. Some timbers for the high roof over the crossing were felled in AD 1292, AD 1310, AD 1314, and AD 1315. A single timber from the north transept was certainly felled in AD 1308. In relation to the documentary evidence available it is clear that some timbers were stockpiled for as much as 20 years before being used. This is perhaps not unusual for a construction on such a large scale.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM EXETER CATHEDRAL, EXETER, DEVON: PART I

Introduction

Although Exeter Cathedral (SX 921925; see Fig 1) has substantial Norman remains it is, as seen today, primarily a cathedral of the English Decorated period (Frontispiece). A collection of documents, mainly Fabric Rolls, allows for the general progress of the post-Norman building work to be followed in broad outline. Alterations to the Cathedral began between AD 1275 – 80, with the presbytery, at the east end, being vaulted, glazed, and painted by AD 1302.

Work on the choir followed in AD 1302 – 3, its vault bosses being carved in AD 1303 – 4 and its arcade corbels in AD 1303 – 4 and AD 1306 – 7. The removal of the old choir stalls from the Romanesque crossing to the new choir in AD 1310 may mark the completion of the structural works here, suggesting that the roof above the new choir dates to between AD 1303 – 10.

From the choir the work proceeded to the transepts and crossing. In the documentary sources for AD 1316 – 17 are payments for scaffolding, and references to the painting of the vault bosses. This suggests that the work took place in this part of the cathedral roofs during this time span. The relationship between these parts of the cathedral is shown in Figure 2.

While the documents give the outline of the work a number of questions still remain. Firstly, how reliable is the interpretation of the documents and how closely do they relate to the actual work on the roofs? Secondly, are the roofs of the presbytery and the choir each a single entity or was each constructed in stages, and how close together were these stages?

Thirdly, of what date are the timbers that have been inserted into the roof, particularly the diagonal props that relate to the problem of racking? The dating of these timbers might indicate whether the problem arose early on, or is a more recent phenomenon. Fourthly, what is the extent and date of post medieval repairs in the roof. Finally the English Heritage brief asked that the analysis provide information as to the possible reuse of timbers from the Romanesque church

In AD 1983 Sheffield University and the Royal Albert Memorial Museum, Exeter, jointly supervised an extensive programme of dendrochronology in the cathedral roof, sampling being undertaken by Robert Howard as part of a post-graduate training exercise. At that time the coring of timbers for dendrochronological purposes, particularly on a large scale, was relatively new. Due to lack of experience in sampling, difficulties with corers, and limited access to some timbers, some of the samples obtained in AD 1983 had fewer rings than were actually available from the timber and included relatively few samples that retained complete sapwood. Furthermore, work concentrated on the sole plates of the frames at the expense of other timbers. Also at that time more sampling was undertaken in the nave than in the presbytery, choir, or crossing; no work at all was undertaken in the transepts, aisles, or towers.

Thus, some 173 samples were obtained from the 150-odd frames of the entire roof, these being then analysed by Coralie Mills between AD 1984 and AD 1988 (Mills 1988). Of these 173 samples, 79, or approximately 46%, could be cross-matched to form three dated site chronologies. A further nineteen samples could be combined to form seven undated site chronologies. Seventy-five samples from the AD 1983 programme remain ungrouped and undated.

English Heritage commissioned a further session of sampling of timbers in the roofs of the presbytery, the choir, crossing, and the north transept in AD 1999, this being undertaken in conjunction with an archaeological and drawn survey (Brown 1999). This more recent work coincided with a major programme of grant-aided repairs to the high roofs which required the removal of the lead covering. Removal of the lead at this time presented an outstanding opportunity to gain better access to the outer face of timbers at higher levels, at positions where complete sapwood was more likely to be available.

It was hoped that sampling and analysis at this time would have a number of benefits. Better equipment and greater experience of the large-scale sampling of other cathedrals such as Lincoln and Ely, it was hoped, would produce better samples. These could not only help refine the earlier results but also the more recent analysis could be related to the archaeology observed during the survey. Such a combination might help answer the academic questions posed above.

Given that further repairs to the lead covering of the roof are to be undertaken and that additional timbers will become available for sampling it might be stressed that this document is an interim report. Additional reports will be produced for later sampling and re-assessment of samples taken to date. Further, any conclusions given here are provisional at this stage, and may be refined on the basis of further tree-ring sampling and analysis.

The Laboratory would like to take this opportunity to thank a number of people who assisted wholeheartedly with this project. Firstly the Dean and Chapter of Exeter Cathedral and the works staff, particularly the Chapter Clark Colonel Michael Woodcock. We would also like to thank John Allan of the Royal Albert Memorial Museum, Exeter, who, as Consultant Archaeologist to the Dean and Chapter, advised on the scope of the project, assisted with much of the administrative detail, and liased with the cathedral authorities.

The roofs

The general design of the frames is highly consistent throughout the length of the roof, though there are some minor variations. The principal frames are spaced from 1.9m – 2.4m apart with three regularly spaced intermediate common rafter frames between them. Side purlins run between the frames, and the principal frames also carry a collar purlin. The principal frames consist of rafters, upper and lower collars, crown-posts, struts, soulaces, and scissor braces. The intermediate frames do not have lower collars and therefore no soulaces, crown-posts, or collar purlins. Illustrations of typical frames of the choir and transept, taken from Hewett (1980), are shown in Figure 3a/b. For reference purposes a drawing by Martin Watts (Watts 1998) showing a typical principal frame with the elements named is shown in Figure 4.

The English Heritage brief requested sampling from five different parts of the eastern roof:

North Transept

The roof of the north transept is believed to date from AD 1313 – 19, though there is little reference in the Fabric Rolls to the work here. What little information there is records payments for sculpture and for the painting of the vault bosses in AD 1317.

Presbytery – original timbers

The presbytery roof covers bays 1 – 4 (counting from the east end). Archaeological survey of this roof showed that frames 1 – 37 were assembled as a single unit, with a continuous sequence of carpenter's marks (Brown 1999). The Fabric Rolls record that this part of the cathedral was completed by AD 1302, with references to the vaulting being in place, the painting of the bosses, and the insertion of glass into the windows. Only one sample from the earlier tree-ring analysis, from frame 7 (from the east end) has complete sapwood, with a last ring date of AD 1298.

Choir – original timbers

The choir roof covers bays 5 – 8 of the eastern roof. Archaeological survey of this part of the roof showed that frames 38 – 65 and possibly frame 66 were assembled as a single unit. It is believed that this roof was started after AD 1302 and was finished by AD 1310 when the choir stalls were inserted.

Presbytery and Choir - shore repair timbers

The presbytery and choir roofs contain a number of inserted diagonal props or "shores" which run from the tiebeams of one frame to the collar of the fourth adjacent frame. The purpose of these is to prevent or reduce "racking" or leaning of the frames away from the vertical. This is a problem with a number of long roofs where there is insufficient longitudinal stiffening. At Exeter Cathedral the apices of the frames are "racked" to the west some 2 – 3 feet out of the vertical. The date of these repairs at Exeter is uncertain. Prior to the dendrochronological analysis it was believed that they were possibly of late medieval to early post-medieval date, though it is probable that they are much more recent, possibly of eighteenth-century date. The degree of racking is illustrated in Figure 5, taken from Watts (1998).

Crossing

The bays immediately to the west of the choir incorporate frames of the crossing which belong to a later phase. It is believed that work in this area followed on after AD 1310. A small number of samples, eight in all, were obtained from these frames, 67 – 74.

Presbytery – east gable inserted timbers

Because of the racking or leaning of the frames westwards, a gap has been created between the east gable and frame 2 of the presbytery roof (frame 1 is close to the east gable and remains almost vertical). At some time in the past the gap has been filled with part of a secondary frame. The date, or possibly dates, of this insertion is unknown.

Sampling

After discussion with John Allan on the probable phasing of the roofs of the Cathedral, and with the brief provided by English Heritage, a total of 104 core samples was obtained from four of the five specified roof areas. Timbers were selected for sampling on the basis of their appearing to have sufficient rings for reliable dendrochronological analysis or having complete sapwood, or both. A number of timbers were rejected because they had insufficient rings. Each sample was given the code EXT-C (for Exeter Cathedral) and numbered 01 – 104. The sample numbers and their locations are summarised below.

Sampling location	Sample numbers
North transept	EXT-C01 – 15
Presbytery original timbers	EXT-C16 – 36
Presbytery shore repair timbers	EXT-C37 – 46
Choir original timbers	EXT-C47 – 80 EXT-C87 – 89
Choir shore repair timbers	EXT-C92 – 104
Crossing	EXT-C81 – 86 EXT-C90 – 91
Presbytery – east gable inserts	(rejected)

The inserted timbers available from the east gable of the presbytery roof proved to be a mixture of softwoods and oak. The oak timbers had too few rings for satisfactory analysis and this part of the roof was not sampled.

Details of the samples obtained are given in Table 1. The frames and bays of the presbytery and choir have been numbered from east to west, with those of the north transept being numbered from north to south. The individual timber members have been identified and named in accordance with the terminology given on the schematic elevation produced by Martin Watts for the Cathedral Architect. The position of the samples was recorded at the time of sampling on plans made by Stewart Brown. These are reproduced at the end of the report as Figures 14a-h, 15a-s, 16, and 17a-u.

Analysis

Each of the 104 samples was prepared by sanding and polishing. It was seen at this point that one sample, EXT-C87, had distorted rings and it was not measured. The growth-ring widths of the 103 measured samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix) and at a minimum *t*-value of 4.5 eight groups of samples formed. The relative off-set positions of the samples in each of these groups are shown in the bar diagrams of Figures 6 – 13. The data of the 103 measured samples is given at the end of the report.

The growth-ring widths of the samples in each of the eight groups were combined at the indicated relative off-set positions to form site chronologies EXTCSQ01 – EXTCSQ08. Each of the eight site chronologies was then compared with a series of relevant reference chronologies for oak. This indicated dates for four of them, the *t*-values for these being given in Tables 2 – 5. This analysis is summarised below.

Site chronology	Number of samples	Number of rings	Date span (where dated)	Sample locations
EXTCSQ01	64	184	AD 1132 – AD 1315	Presbytery North Transept Choir / Crossing
EXTCSQ02	13	107	AD 1805 – AD 1911	Presbytery (repairs)
EXTCSQ03	2	130	AD 1555 – AD 1684	Crossing
EXTCSQ04	3	170	Undated	Choir
EXTCSQ05	3	72	AD 1478 – AD 1549	North Transept
EXTCSQ06	2	118	Undated	Presbytery Choir
EXTCSQ07	2	173	Undated	North Transept Choir
EXTCSQ08	2	101	Undated	Presbytery repairs

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

Those site chronologies and samples which remain undated or ungrouped at the end of this present programme of work will be re-analysed in conjunction with further samples obtained in any future programme of work.

Interpretation

Site chronology EXTCSQ01

Site chronology EXTCSQ01 is made up of samples from three different parts of the roof, the presbytery

(original timbers), the choir, and the north transept. From each of these three areas samples with complete sapwood have been obtained, that is, the samples have the last ring which the tree produced before it was felled. This information is summarised below.

Sample location	Samples with complete sapwood	Respective last ring dates (all dates AD)	Respective frame number
Presbytery	C31, C34, C36, C24, C21	1291, 1291, 1293, 1294, 1298	1, 7, 29, 15, 11
Choir	C57, C50, C49	1294, 1306, 1306	53, 41, 41
Crossing	C86, C85, C91, C84	1292, 1310, 1314, 1315	71, 68, 74, 66
North Transept	C05	1308	1

It is known from documentary sources that the work on the roof of the presbytery and the choir proceeded from the east end towards the west. This documentary information is supported by the construction evidence which shows that any one frame had to be in place before the next one to the west could be erected. This, in conjunction with the dates and location of samples summarised above tends to suggest that timber was not being felled as and when needed, but rather that timbers were being felled and stored until required; that is, the felling date of a timber is not necessarily the date at which it is used.

If timber were being felled when needed as the work proceeded we would find that the felling date of the timber gets later as work progressed westwards; this is not clearly seen. We assume that work commences with frame 1 of the presbytery using timber felled in AD 1291 (on the basis of date for sample EXT-C31); timber with this felling date is also used in frame 7. The next frame westwards for which we have an exact date, frame 11, uses timber felled in AD 1298, while frame 15 uses timber felled in AD 1294, and frame 29 uses timber felled in AD 1293. The heartwood/sapwood boundary ring dates of all samples from the presbytery in site chronology EXTCSQ01 lie in the relatively short range of AD 1270 (sample C36) to AD 1281 (sample C26), with an average last heartwood ring date of AD 1275. Such consistency is indicative of all the dated timbers from the presbytery being felled in the range AD 1291 – 98, along with those with complete sapwood.

The same situation can be seen in the timbers of the choir and crossing also. The eastern-most frame for which we have an exact date is number 41 (sample EXT-C49), using timber felled in AD 1306. We see however, that frame 66 uses timber felled in AD 1315 (sample EXT-C84) while frame 71 uses timber felled in AD 1292 (sample EXT-C86). Because frame 66 had to be in place before frame 71, and because it could not have been so until AD 1315, such dating must mean that the timber used in frame 71, though felled in AD 1292, was not used until AD 1315 at the earliest; the timber must have been stored for at least 23 years. Most of the timbers that have been stored for some time appear to be rafters, though some timbers are used as crown posts or soulaces.

The earliest heartwood/sapwood boundary on timbers from the choir and crossing are AD 1259 (sample C80) and AD 1261 (samples C68 and C103), whose felling, it is estimated, are in the range AD 1275 – AD 1310. The latest heartwood/sapwood boundary dates are AD 1289 (sample C84), AD 1290 (sample C91), and AD 1291 (sample C83), the felling date of these being estimated as in the range AD 1305 – 40. This is consistent with the felling date of all the timbers in the choir and crossing as being in the range AD 1292 – AD 1315.

Site chronology EXTCSQ01 also contains material from the north transept. The one sample with complete sapwood from this area, EXT-C05, has a last measured ring date, and thus a felling date, of AD 1308. The heartwood/sapwood boundaries of the samples from this part of the roof range from AD 1262 (sample C03) to AD 1294 (sample C07), with an average date of AD 1274. This is very similar to the dates of the timbers from the choir and crossing. Thus the felling of timbers for work in this part of the roof appears to be generally coeval with those used in the choir and presbytery.

Site chronology EXTCSQ02

Site chronology EXTCSQ02 is made up of timbers forming the raking shore repairs to the choir roof, the site chronology produced from this material spanning the period AD 1805 – AD 1911. The average heartwood/sapwood boundary on these samples is AD 1894. Using a sapwood estimate of 15 – 50 rings, and allowing that the last measured ring date is AD 1911, would give the timbers represented by these samples an estimated felling date in the range AD 1912 – 1944. Recent documentary research by Stewart Brown Associates has shown that work was undertaken in the choir in AD 1923. These samples are almost certainly from timbers inserted at that time.

Site chronology EXTCSQ03

Site chronology EXTCSQ03 is made up of samples from two struts, both from frame 69, in the crossing roof. Both samples have complete sapwood, one with a last measured complete sapwood ring of AD 1683, and the other with a last measured complete sapwood ring date of AD 1684. It would appear that some hitherto unrecognised repairs might have taken place in this part of the roof in the late-seventeenth century.

Site chronology EXTCSQ05

Site chronology EXTCSQ05 is made up of three samples from the north transept, all from common rafters. One sample in this group, EXT-C13, has complete sapwood with a last measured ring date, and thus a felling date of AD 1549. The other two timbers represented are very likely to have been felled at the same time.

Conclusion

Analysis by dendrochronology has been able to provide a series of very precise dates for the felling of some of the timber used in north transept, presbytery, choir, and crossing of the Cathedral. This dating has in turn provided answers to most of the questions posed as part of the English Heritage brief and outlined in the introduction above.

The results confirm that work began at the east end of the roof as intimated by documentary sources and constructional details, using timber felled in AD 1291. The latest certain felling of timber for the presbytery roof is AD 1298, although the documents suggest it was not fully complete until AD 1302. Work then progressed westwards with the frames of the choir being built of timber with a latest certain felling date of AD 1306, which the documents suggest was completed between AD 1302 – 10. The frames of the crossing immediately to the west of the choir use timber with a latest certain felling date of AD 1315; the documents suggest work proceeded in this area after AD 1310. There appears to have been only a short time gap between the completion of the presbytery roof and the commencement of work on the roof of the choir.

Dendrochronology has thus been able to show that the documents are indeed reliable. However, tree-ring analysis has been able to refine the documentary details and provide some answer to the question posed in the introduction as to the relationship between the phases of work in the choir and presbytery. The relatively small variation in the felling dates of the timbers used in both parts provides some support for the presbytery and choir being single entities with only a very small time gap between the completion of one and the start of the other.

This analysis also shows that some timber at least was felled and stored over a period of time, and not used immediately as it was cut. This method of supply is more probably a feature of large scale, long-term building projects. Where it was known that substantial quantities would be required over a period of time the timber may have been acquired, either through purchases or by grants, and felled well in advance of use. This is a practice seen at other large sites, ie Lincoln Cathedral (Foot *et al* 1997; Laxton *et al* 2000), and is in contrast to smaller projects where documentary evidence suggests that the timber was felled and used almost at once (Howard *et al* forthcoming (a)).

Tree-ring analysis has also provided some information about the extent of later repairs. The analysis has shown that the raking shores of the presbytery and choir are representative of the early twentieth-century work undertaken at the Cathedral. There is no evidence for earlier attempts to prevent or stabilise the racking of the frames and it is possible that this was not a problem until the post medieval period, or at least no attempt to correct the racking was made until much later.

Analysis has also highlighted that a small amount of undocumented post medieval repairs were also made. The earliest of these are those made to the north transept roof using timber felled in the mid-sixteenth century. There is also a hint that repair work was undertaken in the crossing in the late-seventeenth century. So far these appear to be the only early post medieval repairs to be detected.

Finally, the analysis has so far not found any evidence for the reuse of timber from the Romanesque church, either in the post-Norman reconstruction nor in the small amount of later repairs.

The samples obtained in this more recent programme of analysis and dating by dendrochronology tend to have a greater number of growth-rings than those samples obtained in AD 1983 (Mills 1988). A greater number of the more recent samples also retain complete sapwood. This is no doubt due to the greater experience of coring obtained over the intervening years, and to the better access allowed by the removal of the lead covering.

This improvement in sample quality has led to a greater proportion of them being cross-matched and grouped with each other. A relatively high number of samples, 82 out of 103 measured, or almost 79%, have grouped and dated, while a further nine samples have been grouped but remain undated for the moment. A greater number of the samples now also have complete sapwood.

In relation to the dating of the site chronologies created from the recent Exeter Cathedral material, it is worth noting that in the years since the first programme of analysis a greater number of well replicated, relevant, reference chronologies have become available. It will be seen from Table 2 that a number of these cross-match with the Cathedral site chronologies with very high *t*-values. At the time of Coralie Mills' analysis these reference chronologies did not exist. This recent development has no doubt played a part in dating the site chronologies, allowing the greater number of samples with complete sapwood to provide precise felling dates for some timbers.

It is perhaps also worth noting that the nave, the lead covering of which will be replaced in the near future, contains a substantial number of timbers with complete sapwood. Furthermore, having built up a long and well replicated site chronology of material from the Cathedral roofs, it would be well be worth re-analysing the undated material obtained in AD 1983 – 88. Given further work it may be possible to make some assessment as to the source of the timbers, which at the moment is unknown.

Only twelve of the 103 measured samples remain ungrouped and undated. Some of these are of considerable length, the longest ungrouped and undated sample, EXT-C32, having 139 rings. Some of the samples do show signs of stressed growth which might make cross-matching and dating difficult; others however do not show any unusual characteristics. All such samples will be re-assessed when further sampling and analysis is undertaken.

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Table 1: Details of samples from Exeter Cathedral, Exeter, Devon

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	North transept					
EXT-C01	East common rafter, frame 2	68	h/s	------	------	------
EXT-C02	Collar purlin, north gable to frame 1	109	h/s	AD 1169	AD 1277	AD 1277
EXT-C03	North strut, crown post – collar purlin, frame 1	71	h/s	AD 1192	AD 1262	AD 1262
EXT-C04	Crown post, frame 1	84	h/s	AD 1191	AD 1274	AD 1274
EXT-C05	East principal rafter, frame 1	132	26C	AD 1181	AD 1282	AD 1312
EXT-C06	South strut, crown post – collar purlin, frame 1	69	h/s	AD 1198	AD 1266	AD 1266
EXT-C07	East scissor brace from rafter, frame 5	72	4	AD 1227	AD 1294	AD 1298
EXT-C08	Collar purlin, frame 1 – 2	110	h/s	------	------	------
EXT-C09	Crown post, frame 2	88	h/s	AD 1183	AD 1270	AD 1270
EXT-C10	South brace from crown post, frame 2	97	h/s	AD 1171	AD 1267	AD 1267
EXT-C11	East common rafter, frame 9	81	no h/s	AD 1181	------	AD 1261
EXT-C12	East common rafter, frame 10	75	no h/s	AD 1181	------	AD 1255
EXT-C13	West principal rafter, frame 1	72	19C	AD 1478	AD 1530	AD 1549
EXT-C14	West common rafter, frame 5	62	15c	AD 1485	AD 1531	AD 1546
EXT-C15	West common rafter, frame 6	56	13c	AD 1488	AD 1530	AD 1543
	Presbytery					
EXT-C16	North soulace, frame 5	86	h/s	AD 1193	AD 1278	AD 1278
EXT-C17	North rafter, frame 5	115	no h/s	AD 1144	------	AD 1258
EXT-C18	North rafter, frame 8	78	no h/s	AD 1186	------	AD 1263
EXT-C19	North soulace, frame 9	96	no h/s	AD 1162	------	AD 1257
EXT-C20	North rafter, frame 10	99	no h/s	AD 1169	------	AD 1267
EXT-C21	North rafter frame 11	127	18C	AD 1172	AD 1280	AD 1298
EXT-C22	North rafter, frame 13	77	h/s	AD 1200	AD 1276	AD 1276
EXT-C23	North rafter, frame 14	55	3	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Presbytery continued					
EXT-C24	North rafter, frame 15	90	21C	AD 1205	AD 1273	AD 1294
EXT-C25	North soulace. frame 15	70	h/s	AD 1205	AD 1274	AD 1274
EXT-C26	North soulace, frame 16	109	h/s	AD 1173	AD 1281	AD 1281
EXT-C27	North strut, frame 17	69	h/s	AD 1211	AD 1279	AD 1279
EXT-C28	South strut, frame 17	108	no h/s	AD 1157	------	AD 1264
EXT-C29	Crown post, frame 17	60	no h/s	------	------	------
EXT-C30	North rafter, frame 24	129	h/s	AD 1144	AD 1272	AD 1272
EXT-C31	Crown post, frame 1	96	18C	AD 1196	AD 1273	AD 1291
EXT-C32	North rafter, frame 27	139	37C	------	------	-----
EXT-C33	North rafter, frame 7	72	no h/s	------	------	------
EXT-C34	South rafter, frame 7	128	18C	AD 1164	AD 1273	AD 1291
EXT-C35	Lower collar, frame 1	59	13C	------	------	------
EXT-C36	North soulace, frame 29 check ABC in data	145	23C	AD 1149	AD 1270	AD 1293
	Presbytery repairs					
EXT-C37	North upper raking shore, frame 13 – 17	56	no h/s	------	------	------
EXT-C38	North upper raking shore, frame 17 – 21	67	h/s	AD 1819	AD 1885	AD 1885
EXT-C39	North upper raking shore, frame 21 – 25	50	h/s	AD 1834	AD 1883	AD 1883
EXT-C40	South upper raking shore frame 18 – 22	50	no h/s	AD 1826	------	AD 1875
EXT-C41	North upper raking shore, frame 22 – 26	100	h/s	------	------	------
EXT-C42	South upper raking shore, frame 22 – 26	101	no h/s	------	------	------
EXT-C43	North upper raking shore, frame 18 – 22	51	no h/s	AD 1826	------	AD 1876
EXT-C44	North upper raking shore frame 14 – 18	66	no h/s	AD 1807	------	AD 1872
EXT-C45	North upper raking shore, frame 10 – 14	58	h/s	------	------	------
EXT-C46	North upper raking shore frame 13 – 17	54	h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Choir and crossing					
EXT-C47	South soulace, frame 42	137	h/s	------	------	------
EXT-C48	North soulace, frame 42	149	no h/s	------	------	------
EXT-C49	North rafter, frame 41	127	41C	AD 1180	AD 1265	AD 1306
EXT-C50	South rafter, frame 41	115	43C	AD 1192	AD 1263	AD 1306
EXT-C51	South rafter, frame 49	82	h/s	AD 1805	------	AD 1886
EXT-C52	South rafter, frame 47	87	h/s	AD 1189	AD 1275	AD 1275
EXT-C53	North rafter, frame 47	87	3	AD 1194	AD 1277	AD 1280
EXT-C54	North rafter, frame 45	118	5	------	------	------
EXT-C55	North rafter, frame 56	68	3	AD 1217	AD 1281	AD 1284
EXT-C56	North rafter, frame 57	104	10	AD 1190	AD 1283	AD 1293
EXT-C57	North rafter, frame 53	124	20C	AD 1171	AD 1274	AD 1294
EXT-C58	Collar purlin, frame 45 – 49	110	h/s	AD 1168	AD 1277	AD 1277
EXT-C59	Crown post, frame 49	83	no h/s	AD 1173	------	AD 1255
EXT-C60	South soulace, frame 21	117	12	AD 1155	AD 1259	AD 1271
EXT-C61	South rafter, frame 21	115	h/s	AD 1154	AD 1268	AD 1268
EXT-C62	Crown post, frame 21	128	h/s	AD 1147	AD 1274	AD 1274
EXT-C63	Upper collar, frame 21	108	h/s	AD 1141	AD 1248	AD 1248
EXT-C64	South strut, frame 21	86	h/s	AD1192	AD 1277	AD 1277
EXT-C65	East strut, frame 21	94	no h/s	AD 1137	------	AD 1230
EXT-C66	North strut, frame 16	50	1	------	------	------
EXT-C67	North soulace, frame 17	92	1	AD 1183	AD 1273	AD 1274
EXT-C68	North soulace, frame 21	132	2	AD 1132	AD 1261	AD 1263
EXT-C69	North rafter, frame 21	110	h/s	AD 1164	AD 1273	AD 1273
EXT-C70	South strut, frame 9	117	h/s	AD 1152	AD 1268	AD 1268
EXT-C71	Crownpost, frame 41	89	h/s	AD 1191	AD 1279	AD 1279
EXT-C72	South strut, frame 37	95	h/s	AD 1180	AD 1274	AD 1274
EXT-C73	Upper collar, frame 36	73	h/s	AD 1195	AD 1267	AD 1267
EXT-C74	Upper collar, frame 37	80	h/s	AD 1194	AD 1273	AD 1273

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Choir and crossing continued					
EXT-C75	Crown post, frame 45	94	h/s	AD 1190	AD 1283	AD 1283
EXT-C76	South strut, frame 45	106	6	AD 1180	AD 1279	AD 1285
EXT-C77	North strut, frame 45	118	h/s	AD 1151	AD 1268	AD 1268
EXT-C78	South scissor brace, frame 49	65	1	AD 1225	AD 1288	AD 1289
EXT-C79	South scissor brace, frame 45	57	h/s	AD 1229	AD 1285	AD 1285
EXT-C80	South scissor brace, frame 44	77	h/s	AD 1183	AD 1259	AD 1259
EXT-C81	North strut, frame 69 (crossing)	130	23C	AD 1555	AD 1661	AD 1684
EXT-C82	South strut, frame 69 (crossing)	93	21C	AD 1591	AD 1662	AD 1683
EXT-C83	East strut, frame 69 (crossing)	90	h/s	AD 1202	AD 1291	AD 1291
EXT-C84	South rafter, frame 66 (crossing)	116	26C	AD 1200	AD 1289	AD 1315
EXT-C85	North rafter, frame 68 (crossing)	125	31C	AD 1186	AD 1279	AD 1310
EXT-C86	South rafter, frame 71 (crossing)	83	19C	AD 1210	AD 1273	AD 1292
EXT-C87	East brace, frame 65	nm	no h/s	------	------	------
EXT-C88	South scissor brace, frame 63	59	h/s	------	------	------
EXT-C89	South scissor brace, frame 64	151	30C	------	------	------
EXT-C90	South scissor brace, frame 72 (crossing)	86	22C	------	------	------
EXT-C91	South rafter, frame 74 (crossing)	120	24C	AD 1195	AD 1290	AD 1314
EXT-C92	North upper raking shore, frame 61 – 65	65	no h/s	------	------	------
EXT-C93	South upper raking shore, frame 61 – 65	60	no h/s	AD 1810	------	AD 1869
EXT-C94	North upper raking shore, frame 65 – 69	78	h/s	AD 1818	AD 1895	AD 1895
EXT-C95	South upper raking shore, frame 65 – 69	67	h/s	AD 1809	AD 1875	AD 1875
EXT-C96	South upper raking shore, frame 69 – 73	88	4	AD 1824	AD 1907	AD 1911
EXT-C97	South upper raking shore, frame 53 – 57	41	no h/s	AD 1830	------	AD 1870
EXT-C98	North upper raking shore, frame 53 – 57	52	9	AD 1853	AD 1895	AD 1904
EXT-C99	North upper raking shore, frame 49 – 53	77	5	AD 1824	AD 1895	AD 1900

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood Rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Choir and crossing continued					
EXT-C100	North upper raking shore, frame 41 – 45	67	h/s	AD 1212	AD 1278	AD 1278
EXT-C101	North stub tiebeam, frame 26	80	h/s	AD 1193	AD 1272	AD 1272
EXT-C102	North stub tiebeam, frame 23	56	no h/s	AD 1222	------	AD 1277
EXT-C103	North stub tiebeam, frame 22	90	h/s	AD 1180	AD 1261	AD 1269
EXT-C104	North stub tiebeam, frame 15	70	2	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood is retained on sample, last measured ring date is felling date of timber
nm = sample not measured.

Table 2: Results of the cross-matching of site chronology EXTCSQ01 with relevant reference chronologies when first ring date is AD 1132 and last ring date is AD 1315

Reference chronology	Span of chronology	*t*-value	
Chichester Cathedral, Sussex	AD 1173 – 1295	9.3	(Howard *et al* 1992a)
Southern England	AD 1083 – 1589	9.2	(Bridge 1988)
England London	AD 413 – 1728	8.5	(Tyers and Groves 1999 unpubl)
England	AD 401 – 1981	8.0	(Baillie and Pilcher 1982 unpubl)
Reading Waterfronts, Berks	AD 1160 – 1407	6.6	(Groves *et al* 1997)
East Midlands	AD 882 – 1981	6.5	(Laxton and Litton 1988)
Salisbury Cathedral, Wilts	AD 1155 – 1228	6.3	(Howard *et al* 1991)
Kent-88	AD 1158 – 1540	5.5	(Laxton and Litton 1989)

Table 3: Results of the cross-matching of site chronology EXTCSQ02 with relevant reference chronologies when first ring date is AD 1805 and last ring date is AD 1911

Reference chronology	Span of chronology	*t*-value	
East Midlands	AD 882 – 1981	4.9	(Laxton and Litton 1988)
England	AD 401 – 1981	4.6	(Baillie and Pilcher 1982 unpubl)

Table 4: Results of the cross-matching of site chronology EXTCSQ03 with relevant reference chronologies when first ring date is AD 1555 and last ring date is AD 1684

Reference chronology	Span of chronology	*t*-value	
Blidworth Church, Notts	AD 1625 – 1717	7.3	(Laxton and Litton 1988)
Ely Cathedral	AD 1592 – 1736	6.5	(Howard et al 1992b unpubl)
St Hughs Choir, Lincoln Cathedral	AD 1575 – 1724	6.2	(Laxton and Litton 1988)
Old Barn, Stratford om Avon, Warwicks	AD 1591 – 1735	5.6	(Howard *et al* 1996)
East Midlands	AD 882 – 1981	5.4	(Laxton and Litton 1988)
Stowmarket Church, Suffolk	AD 1542 – 1671	4.8	(Howard *et al* 1994)
England London	AD 413 – 1728	4.1	(Tyers and Groves 1999 unpubl)
England	AD 401 – 1981	4.0	(Baillie and Pilcher 1982 unpubl)
Wales and West Midlands	AD 1341 – 1636	3.9	(Siebenlist-Kerner 1978)

Table 5: Results of the cross-matching of site chronology EXTCSQ05 with relevant reference chronologies when first ring date is AD 1478 and last ring date is AD 1549

Reference chronology	Span of chronology	*t*-value	
26 Westgate Street, Gloucester	AD 1399 - 1622	4.8	(Howard *et al* forthcoming b)
Sinai, Staffs	AD 1227 – 1750	4.4	(Tyers 1997)
England London	AD 413 – 1728	3.7	(Tyers and Groves 1999 unpubl)
England	AD 401 – 1981	5.1	(Baillie and Pilcher 1982 unpubl)
East Midlands	AD 882 – 1981	5.6	(Laxton and Litton 1988)
New Mills, Derbys		4.2	(Esling *et al* 1990)

Figure 1: Map to show general location of Exeter Cathedral

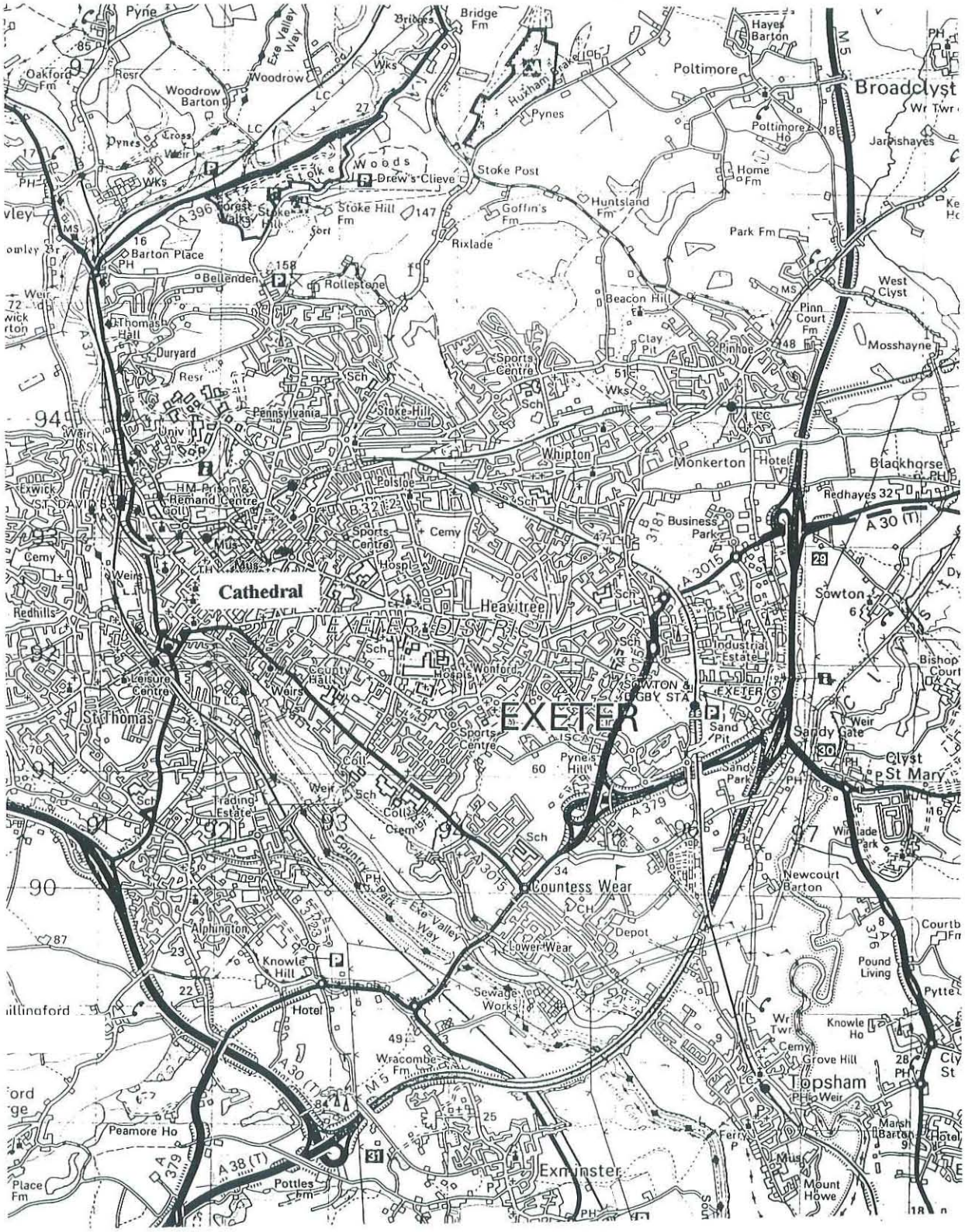


Figure 2: Simplified plan of Exeter Cathedral

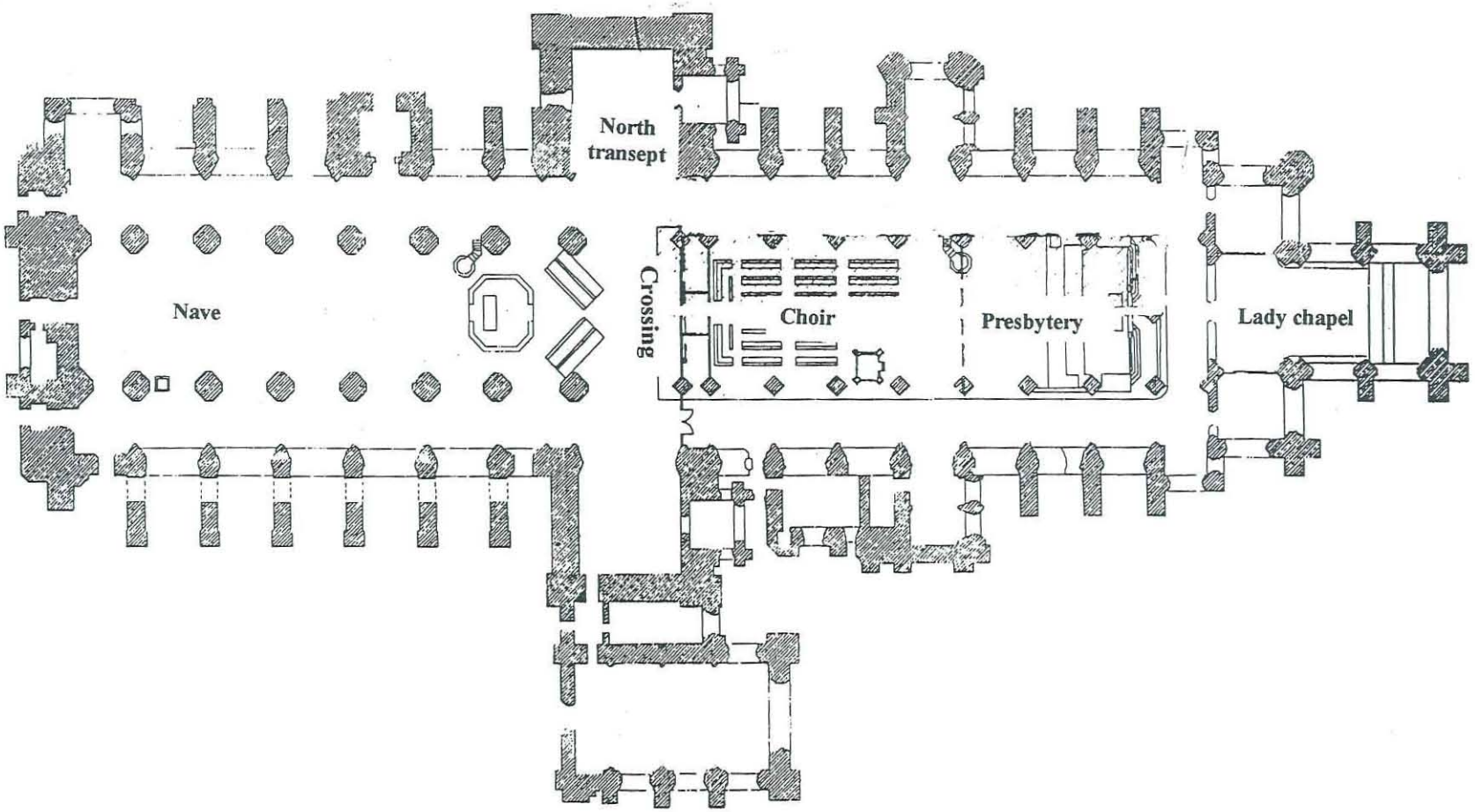


Figure 3a: Illustration of a typical truss from the Choir roof (after Hewett 1980)

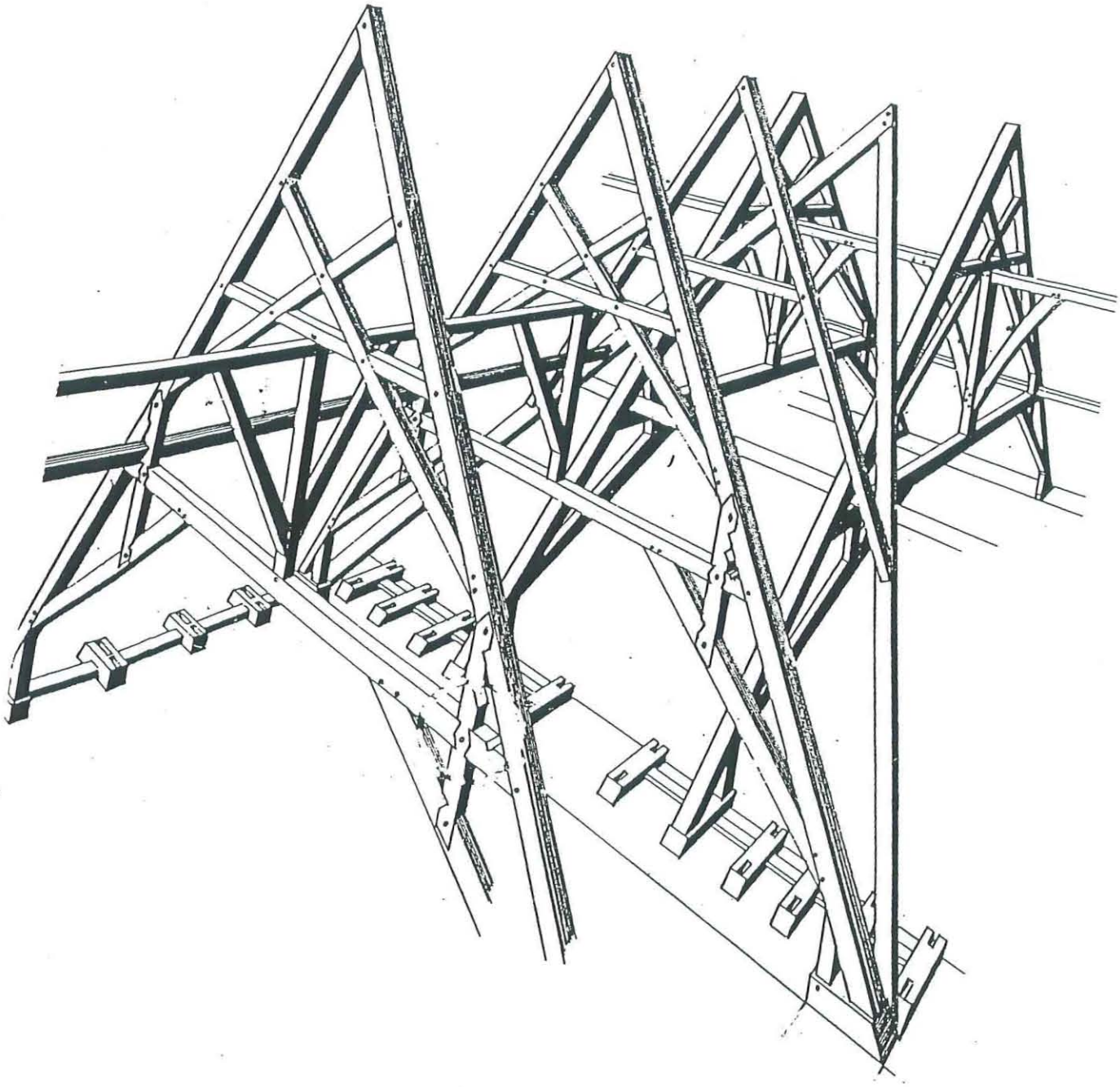


Figure 3b: Illustration of a typical truss from the North transept roof (after Hewett 1980)

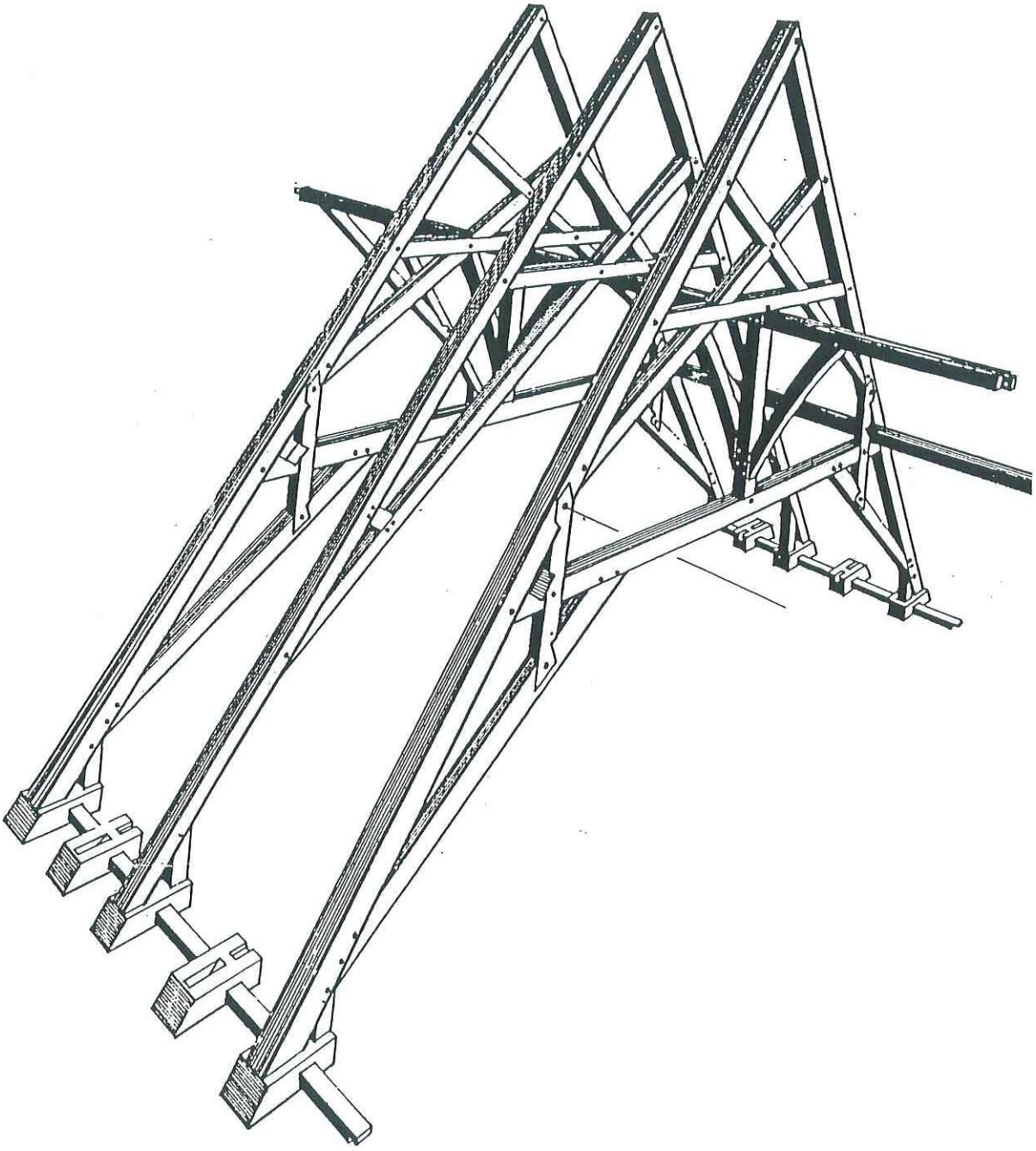


Figure 4: Drawing of a typical frame with the elements named (after Watts 1998)

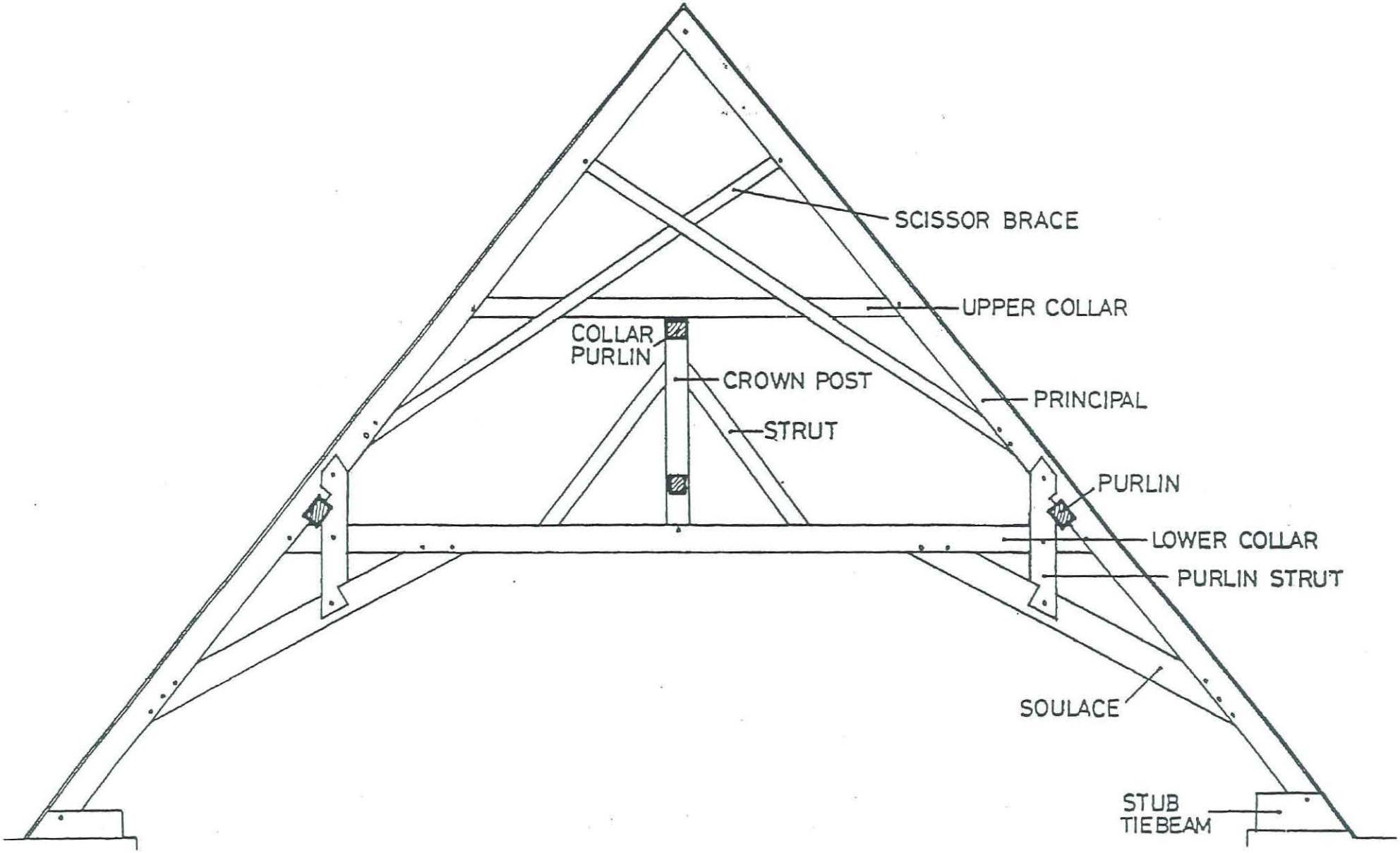


Figure 5: Long section of the Presbytery/Choir roof showing the degree of racking (after Brown 1999)

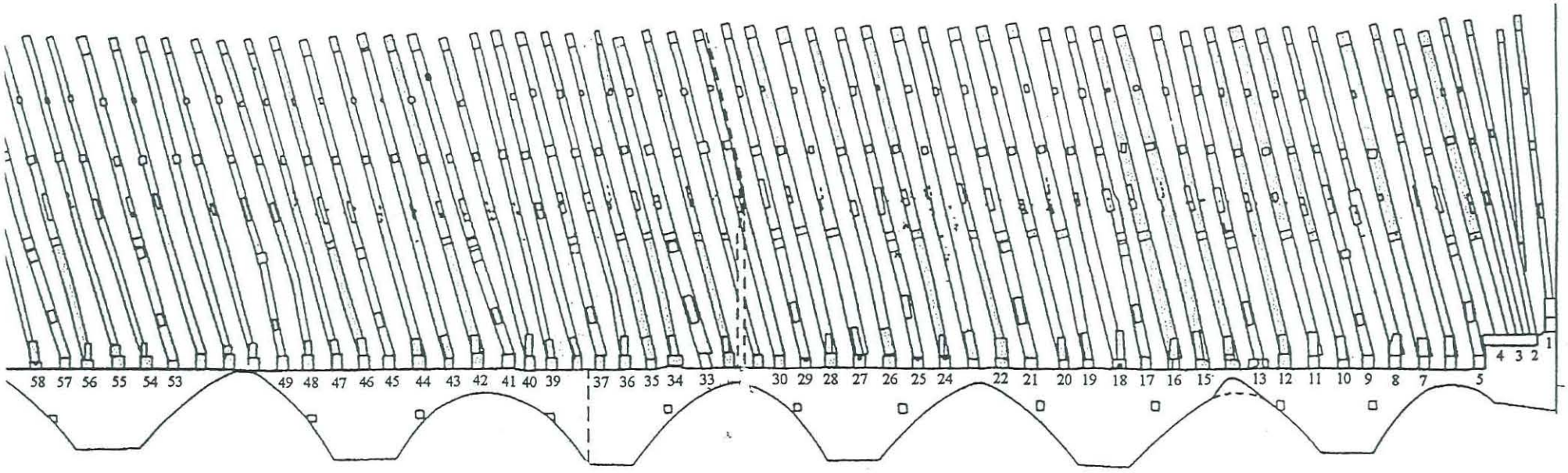
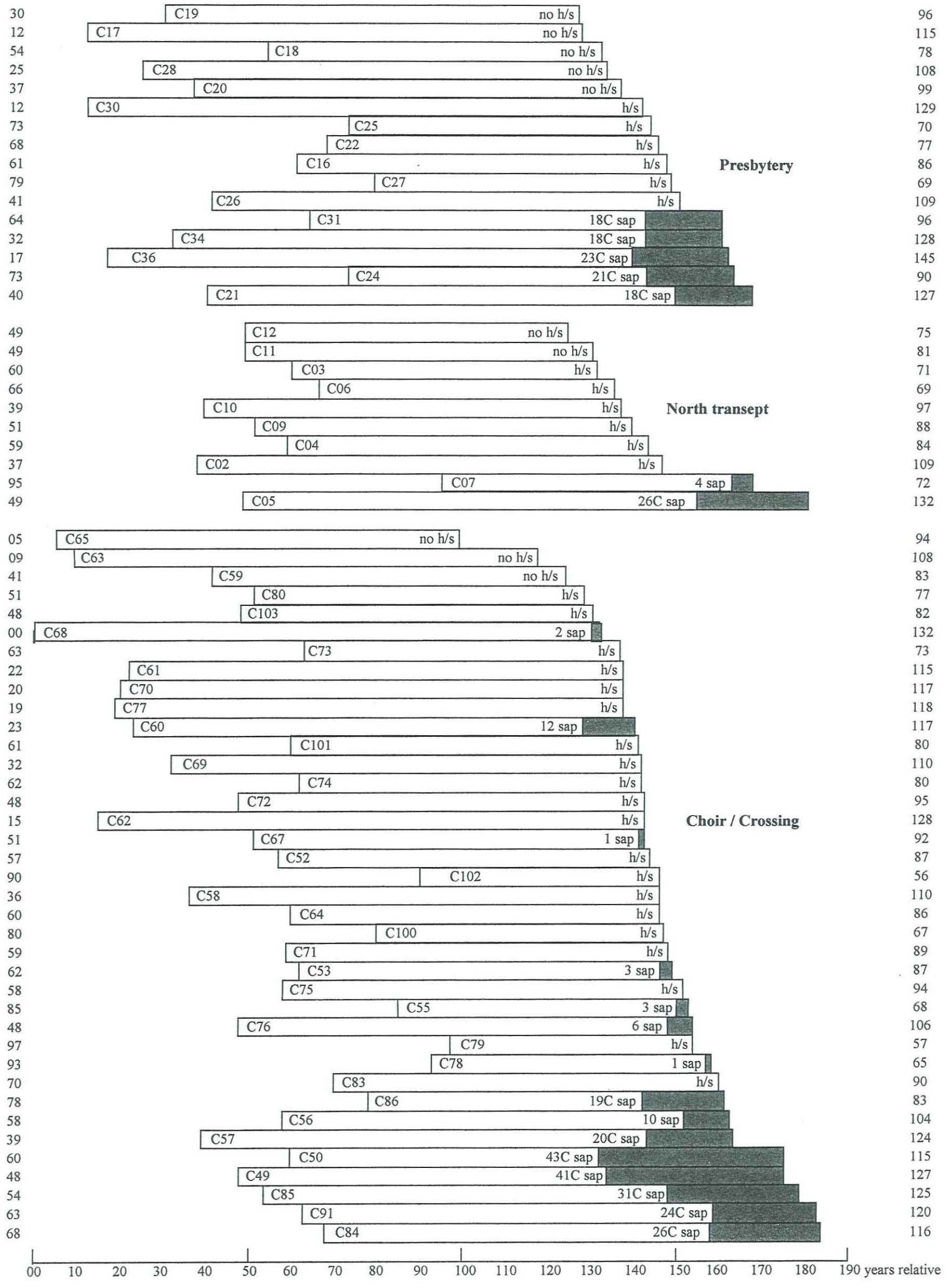
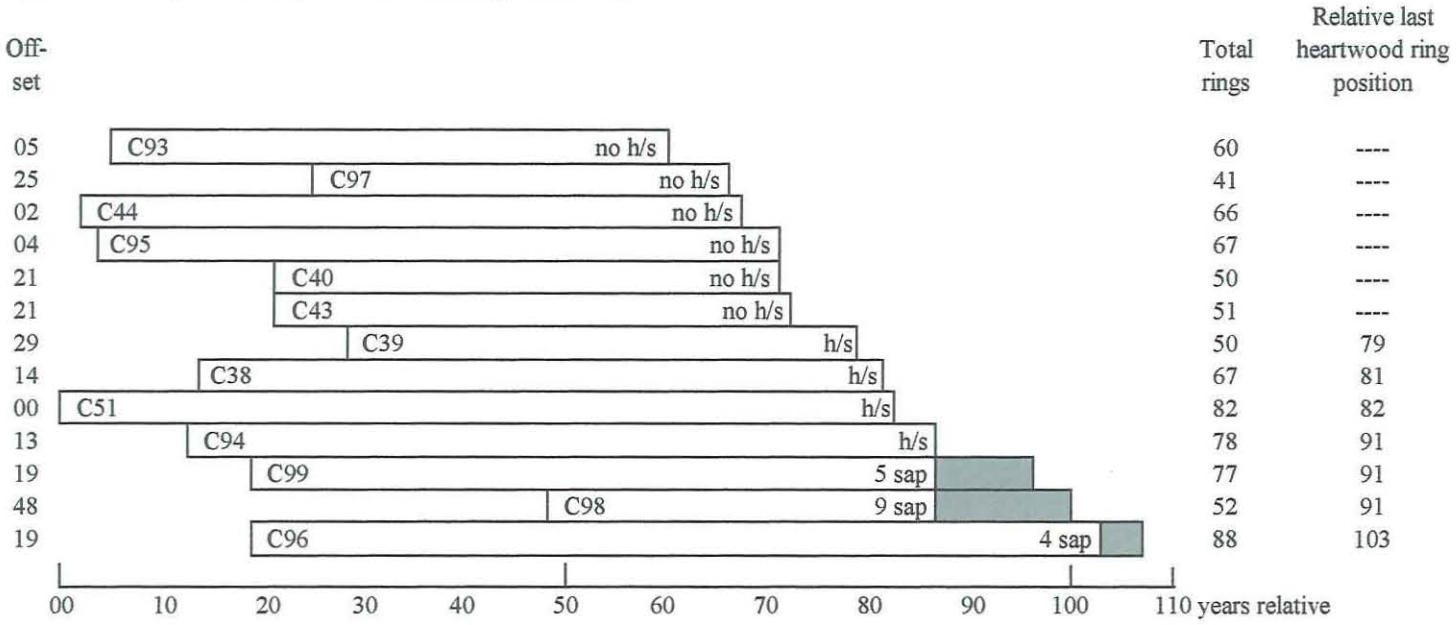


Figure 6: Bar diagram of samples in site chronology EXTCSQ01, shown by sampling area



Off-set			Total rings	Relative last heartwood ring position
30	C19	no h/s	96	----
12	C17	no h/s	115	----
54	C18	no h/s	78	----
25	C28	no h/s	108	----
37	C20	no h/s	99	----
12	C30	h/s	129	141
73	C25	h/s	70	143
68	C22	h/s	77	145
61	C16	h/s	86	147
79	C27	h/s	69	148
41	C26	h/s	109	150
64	C31	18C sap	96	142
32	C34	18C sap	128	142
17	C36	23C sap	145	139
73	C24	21C sap	90	142
40	C21	18C sap	127	149
49	C12	no h/s	75	----
49	C11	no h/s	81	----
60	C03	h/s	71	131
66	C06	h/s	69	135
39	C10	h/s	97	136
51	C09	h/s	88	139
59	C04	h/s	84	143
37	C02	h/s	109	146
95	C07	4 sap	72	163
49	C05	26C sap	132	154
05	C65	no h/s	94	----
09	C63	no h/s	108	----
41	C59	no h/s	83	----
51	C80	h/s	77	128
48	C103	h/s	82	130
00	C68	2 sap	132	130
63	C73	h/s	73	136
22	C61	h/s	115	137
20	C70	h/s	117	137
19	C77	h/s	118	137
23	C60	12 sap	117	128
61	C101	h/s	80	141
32	C69	h/s	110	142
62	C74	h/s	80	142
48	C72	h/s	95	143
15	C62	h/s	128	143
51	C67	1 sap	92	142
57	C52	h/s	87	144
90	C102	h/s	56	146
36	C58	h/s	110	146
60	C64	h/s	86	146
80	C100	h/s	67	147
59	C71	h/s	89	148
62	C53	3 sap	87	146
58	C75	h/s	94	152
85	C55	3 sap	68	150
48	C76	6 sap	106	148
97	C79	h/s	57	154
93	C78	1 sap	65	157
70	C83	h/s	90	160
78	C86	19C sap	83	142
58	C56	10 sap	104	152
39	C57	20C sap	124	143
60	C50	43C sap	115	132
48	C49	41C sap	127	134
54	C85	31C sap	125	148
63	C91	24C sap	120	159
68	C84	26C sap	116	158

Figure 7: Bar diagram of samples in site chronology EXTCSQ02



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

Figure 8: bar diagram of samples in site chronology EXTCSQ03

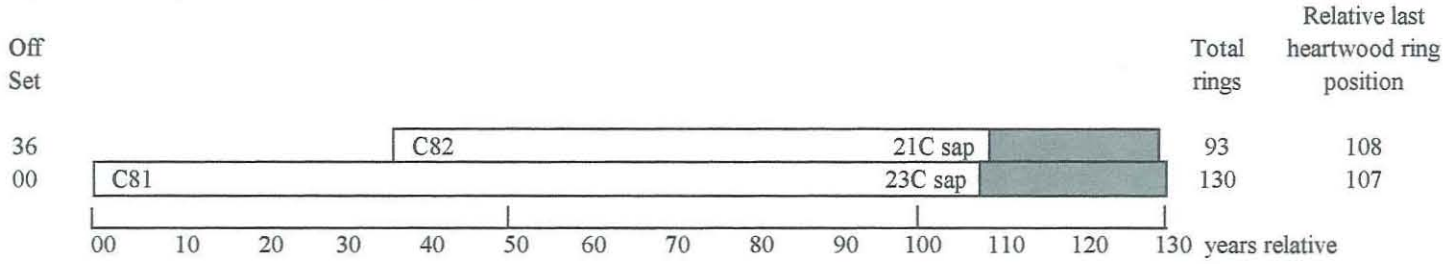
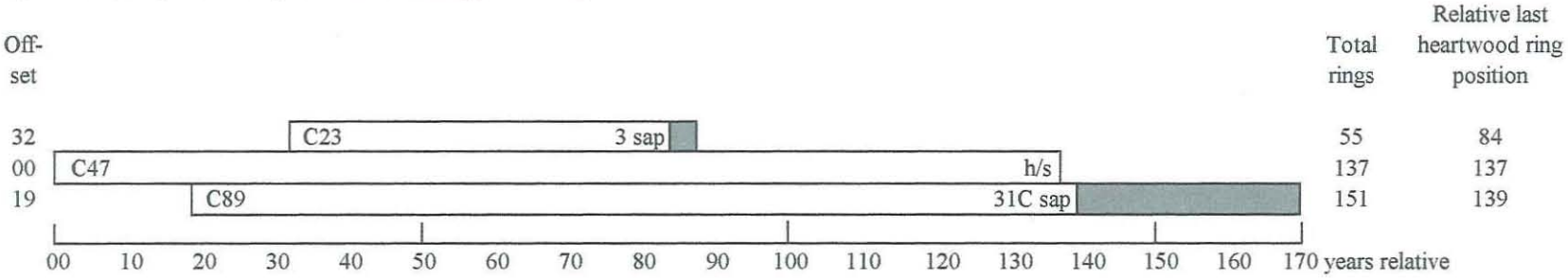


Figure 9: bar diagram of samples in site chronology EXTCSQ04



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

Figure 10: bar diagram of samples in site chronology EXTCSQ05

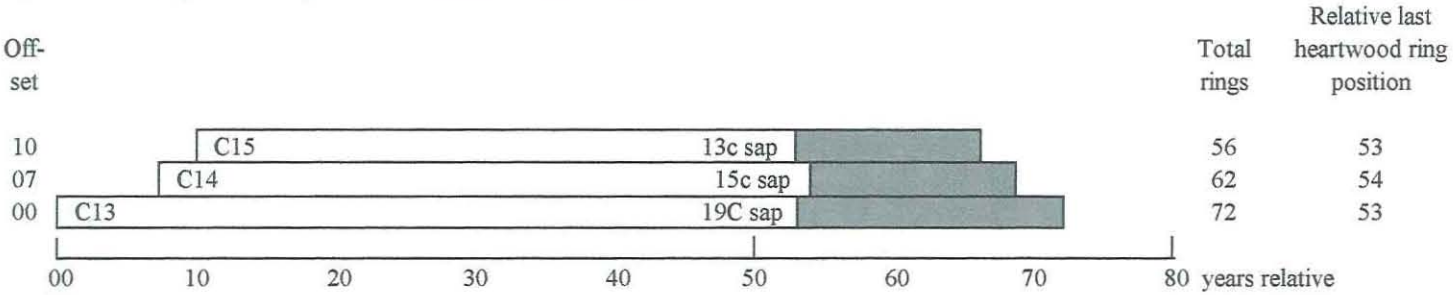
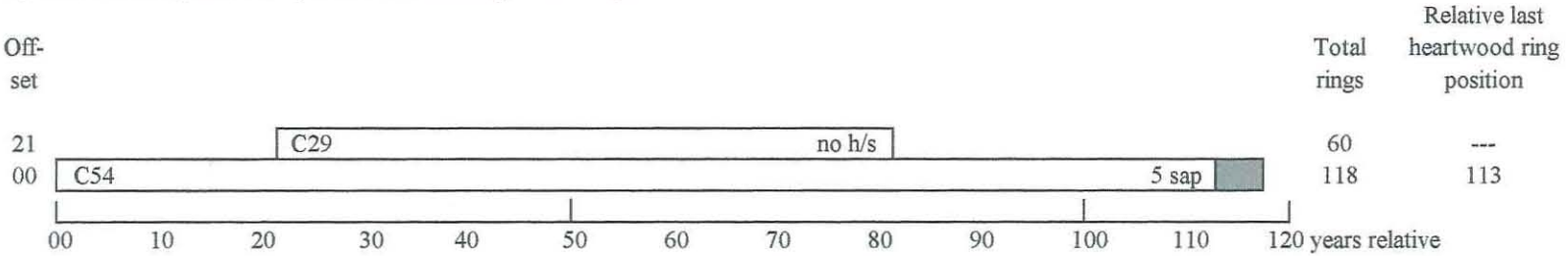


Figure 11: bar diagram of samples in site chronology EXTCSQ06



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 12: Bar diagram of samples in site chronology EXTCSQ07

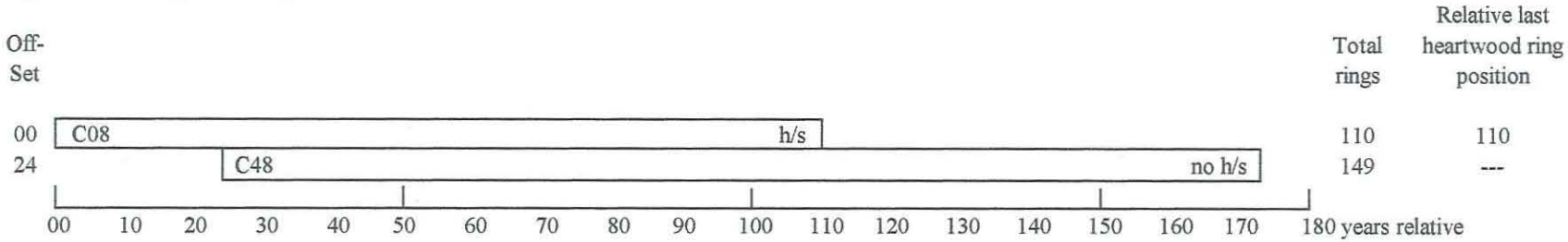
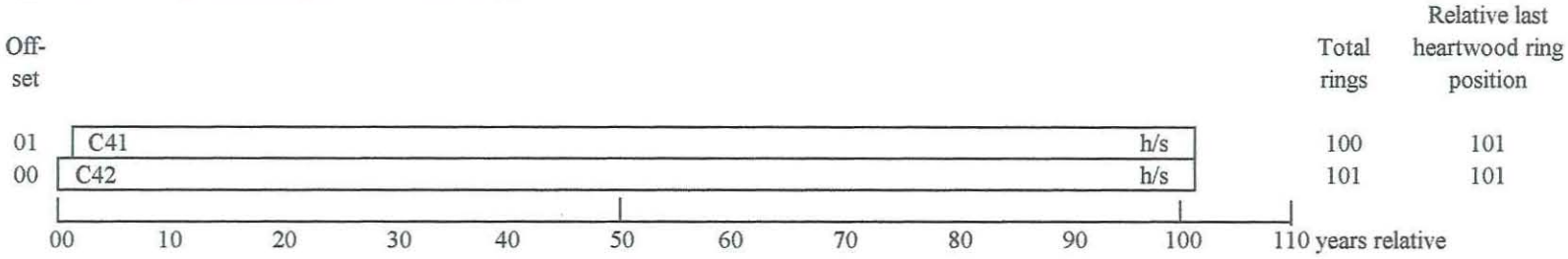


Figure 13: Bar diagram of samples in site chronology EXTCSQ08



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

Figure 14a: Drawing of frame 1 of the north transept, viewed from the north, to show sample locations

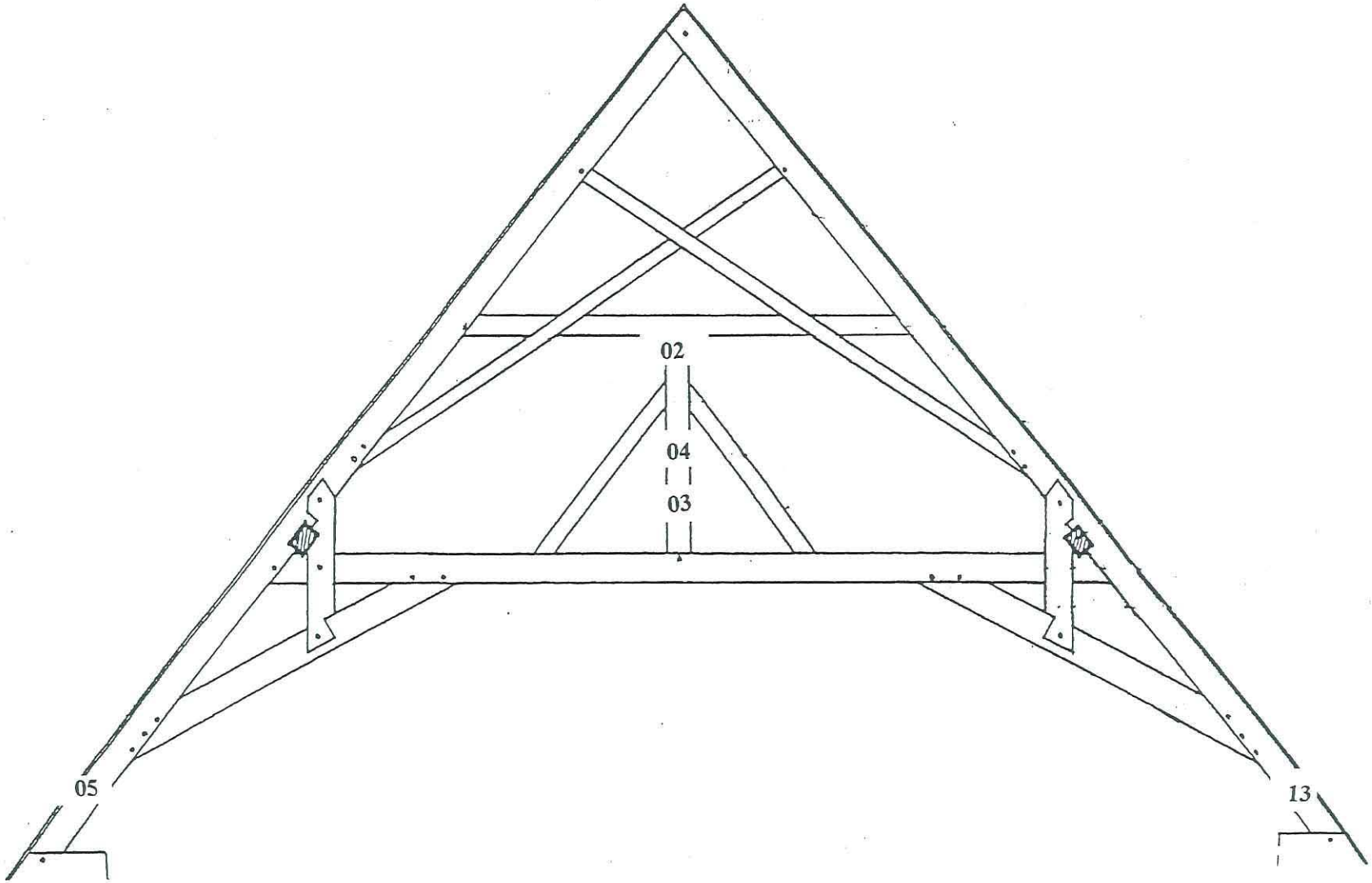


Figure 14b: Drawing of frame 1 of the north transept, viewed from the south, to show sample locations

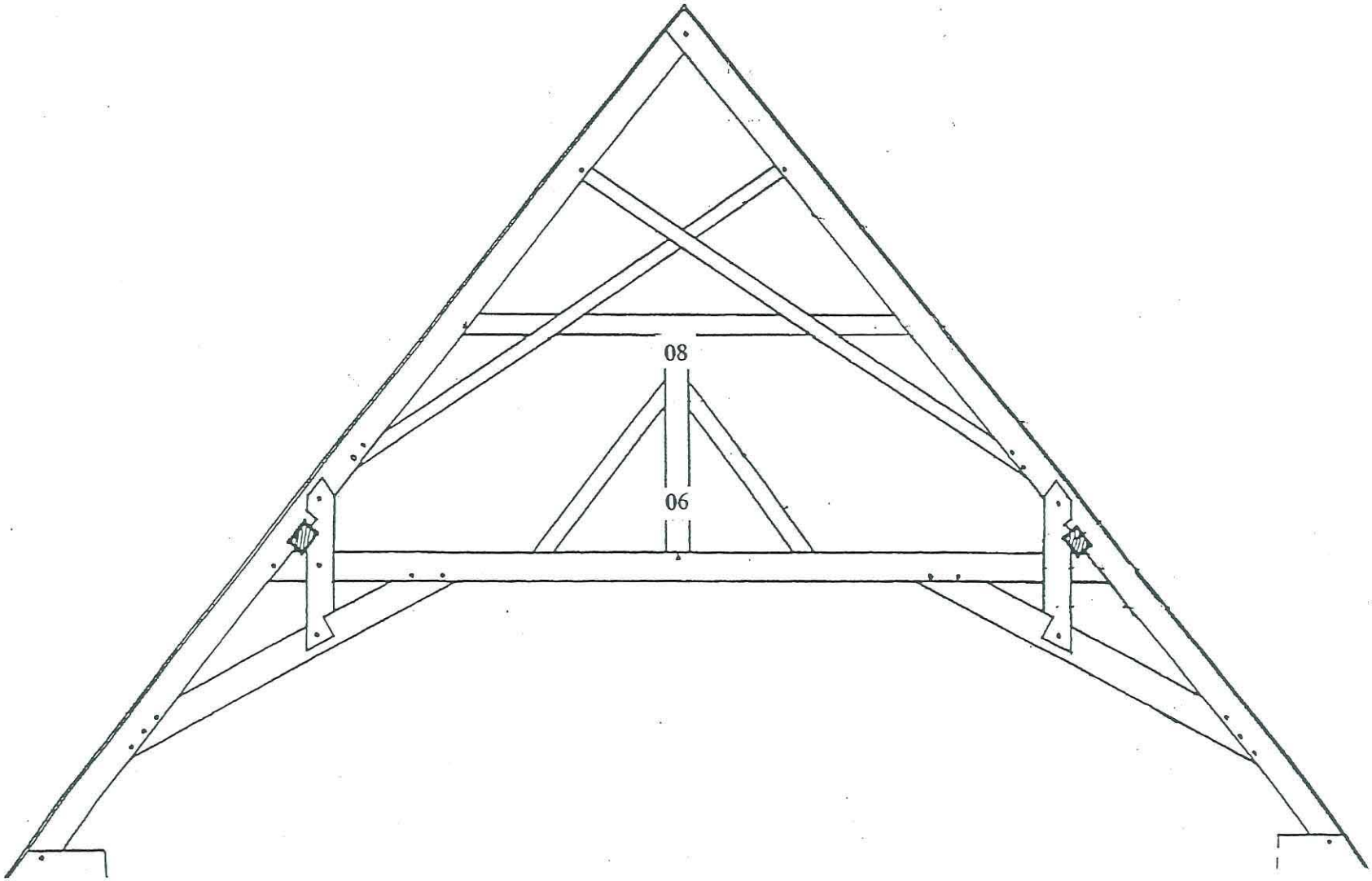


Figure 14c: Drawing of frame 2 of the north transept, viewed from the north, to show sample locations

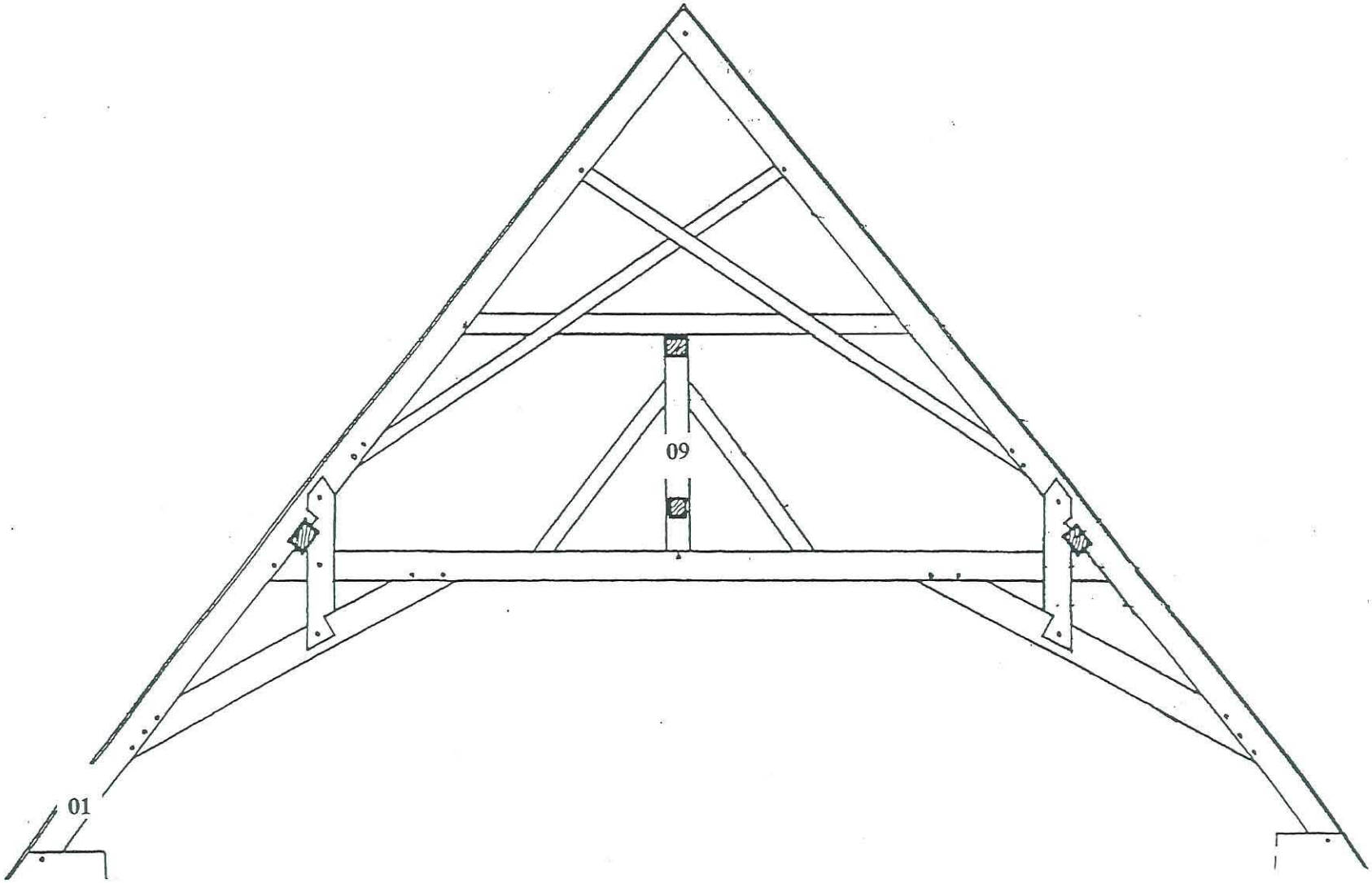


Figure 14d: Drawing of frame 2 of the north transept, viewed from the south, to show sample locations

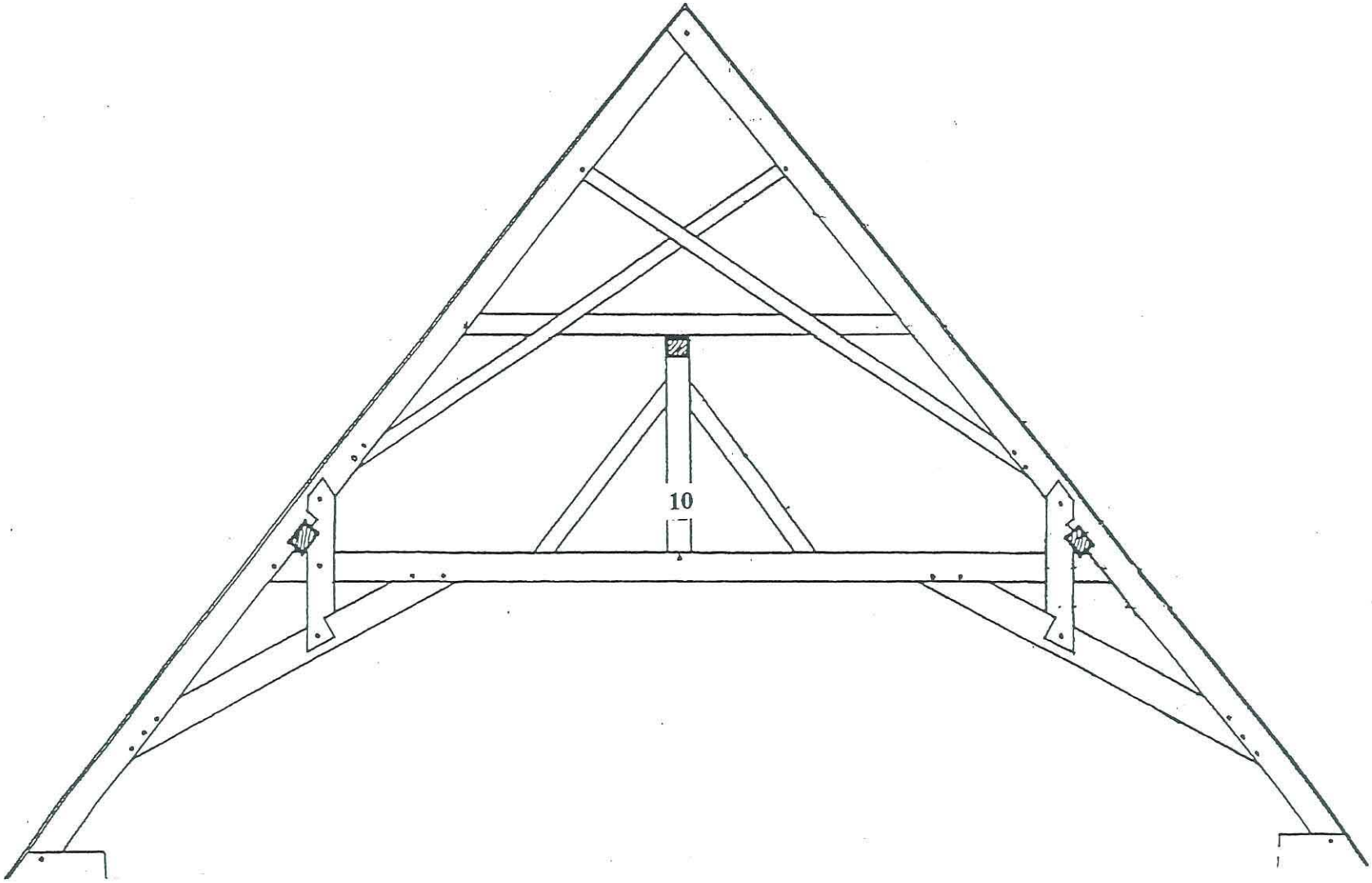


Figure 14e: Drawing of frame 5 of the north transept, viewed from the north, to show sample locations

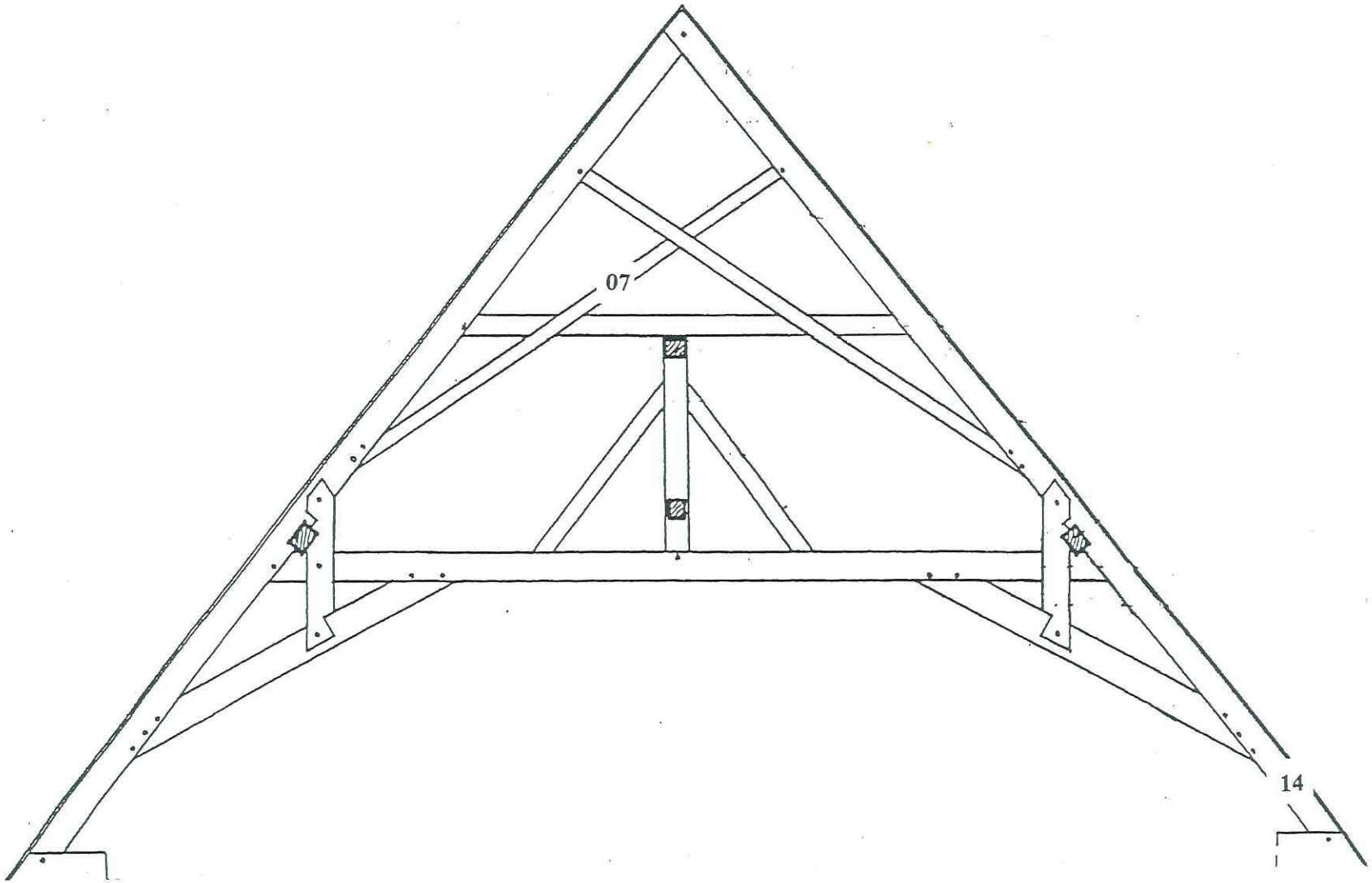


Figure 14f: Drawing of frame 9 of the north transept, viewed from the north, to show sample locations

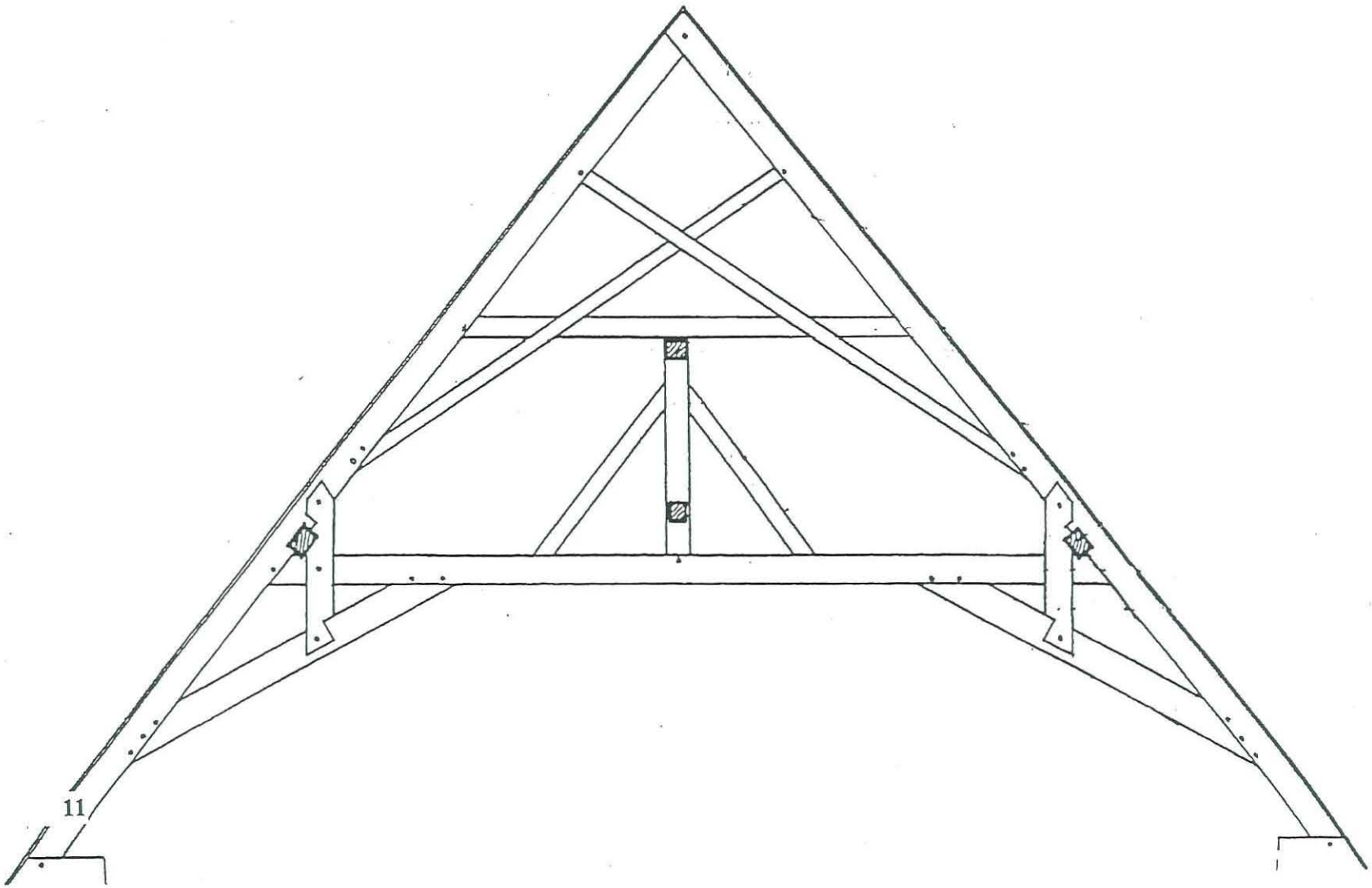


Figure 14g: Drawing of frame 10 of the north transept, viewed from the north, to show sample locations

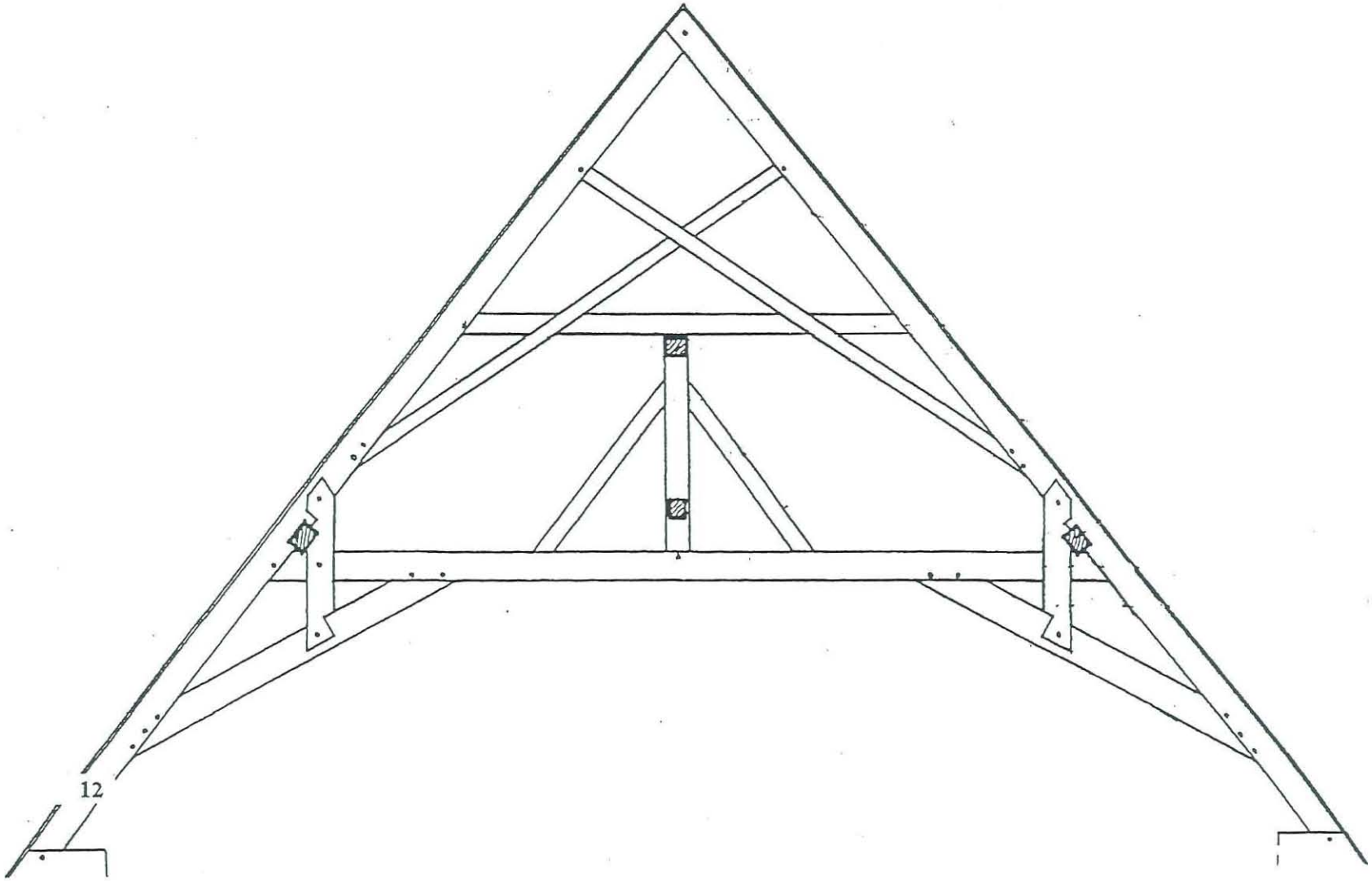


Figure 14h: Drawing of frame 6 of the north transept, viewed from the north, to show sample locations

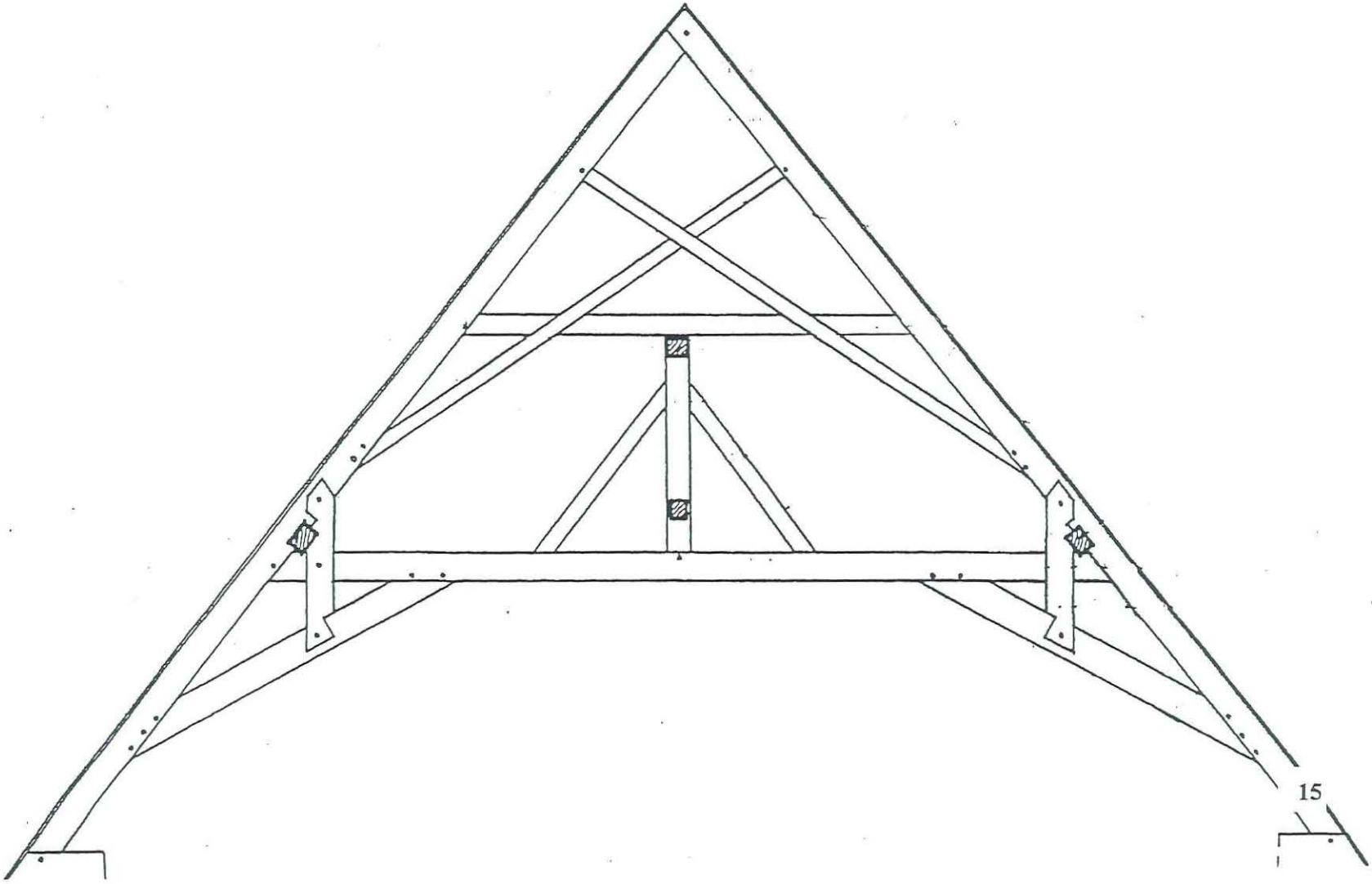


Figure 15a: Drawing of frame 5 of the Presbytery, viewed from the east, to show sample locations

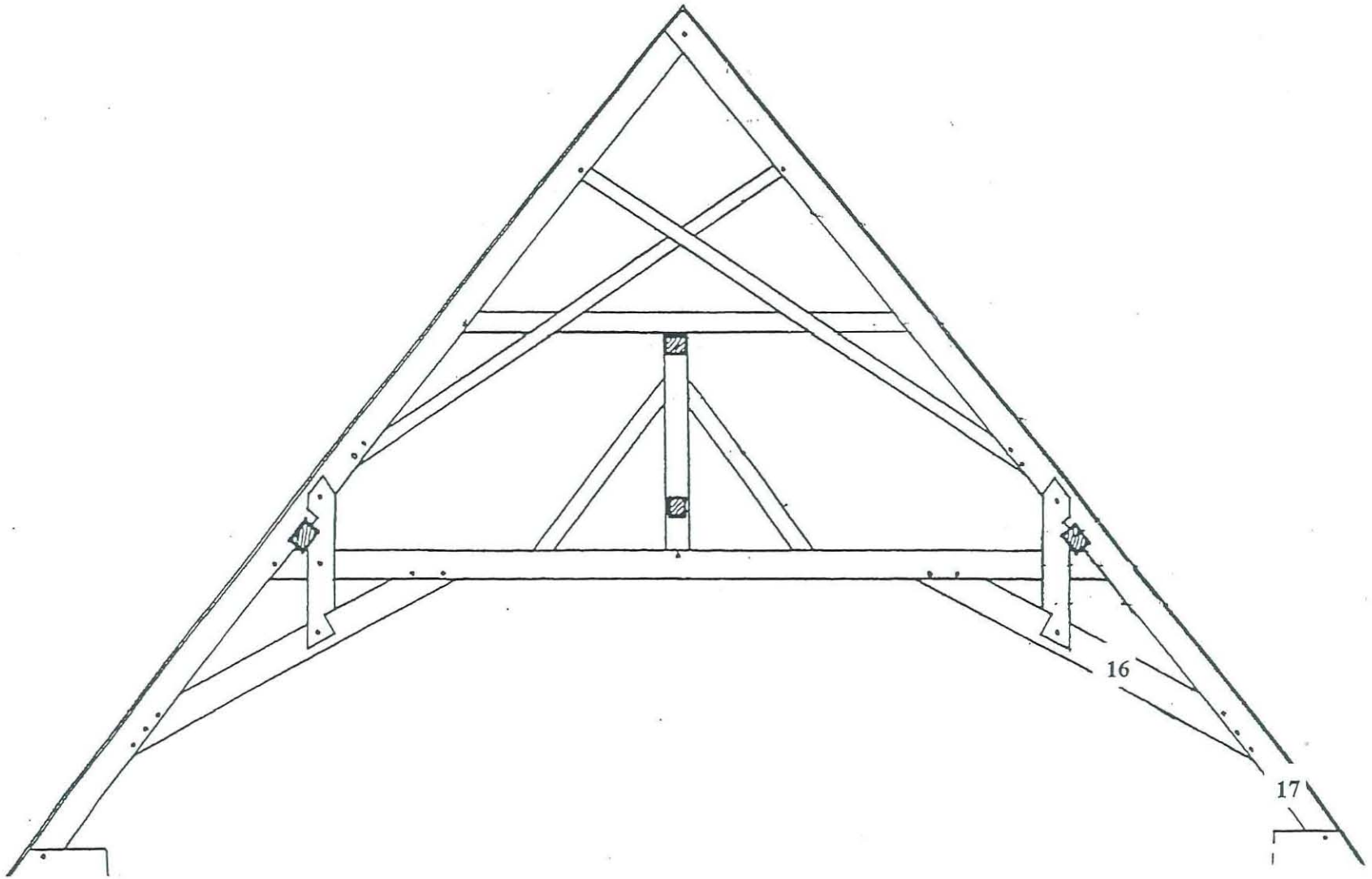


Figure 15b: Drawing of frame 8 of the Presbytery, viewed from the east, to show sample locations

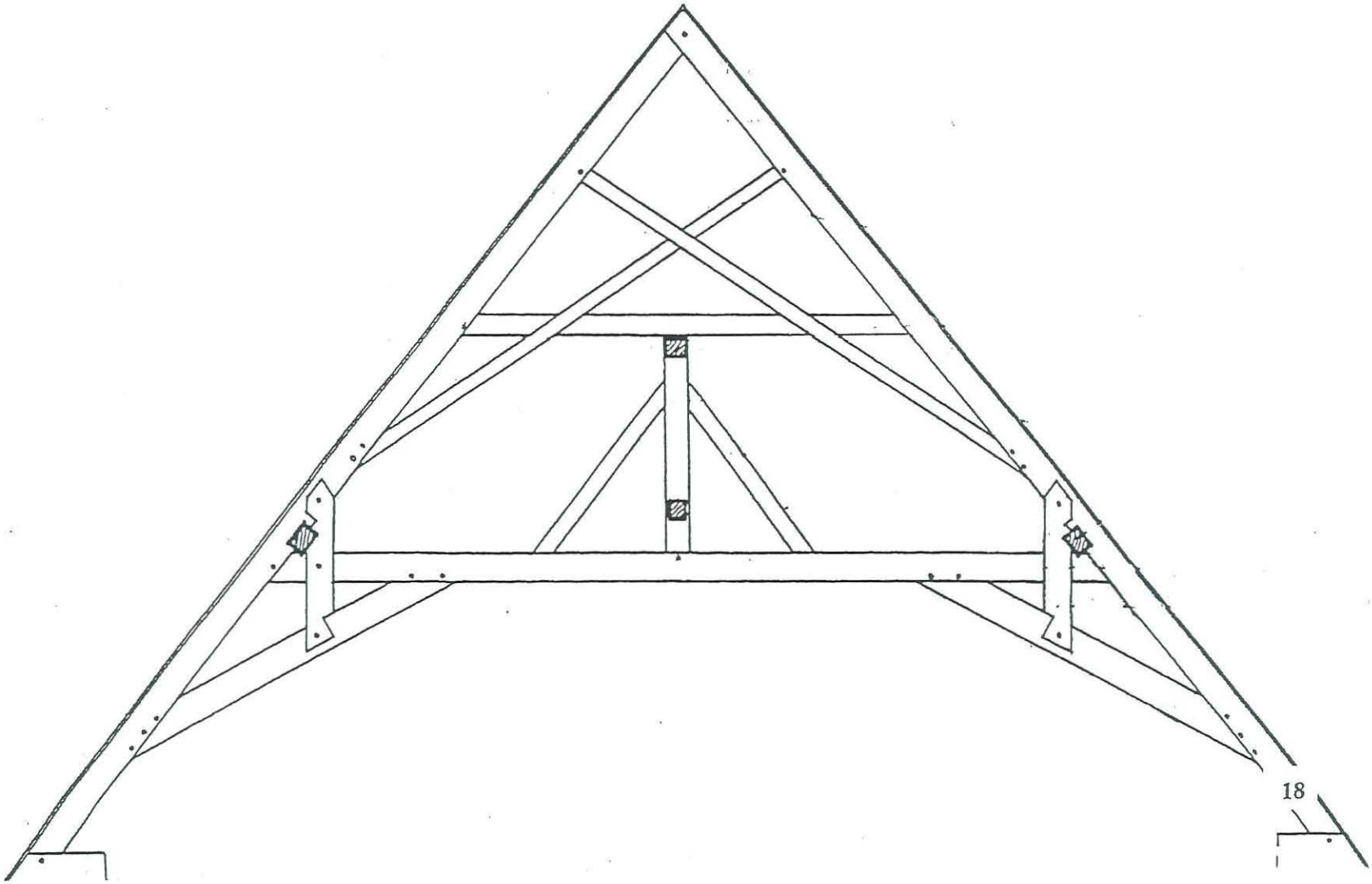


Figure 15c: Drawing of frame 9 of the Presbytery, viewed from the east, to show sample locations

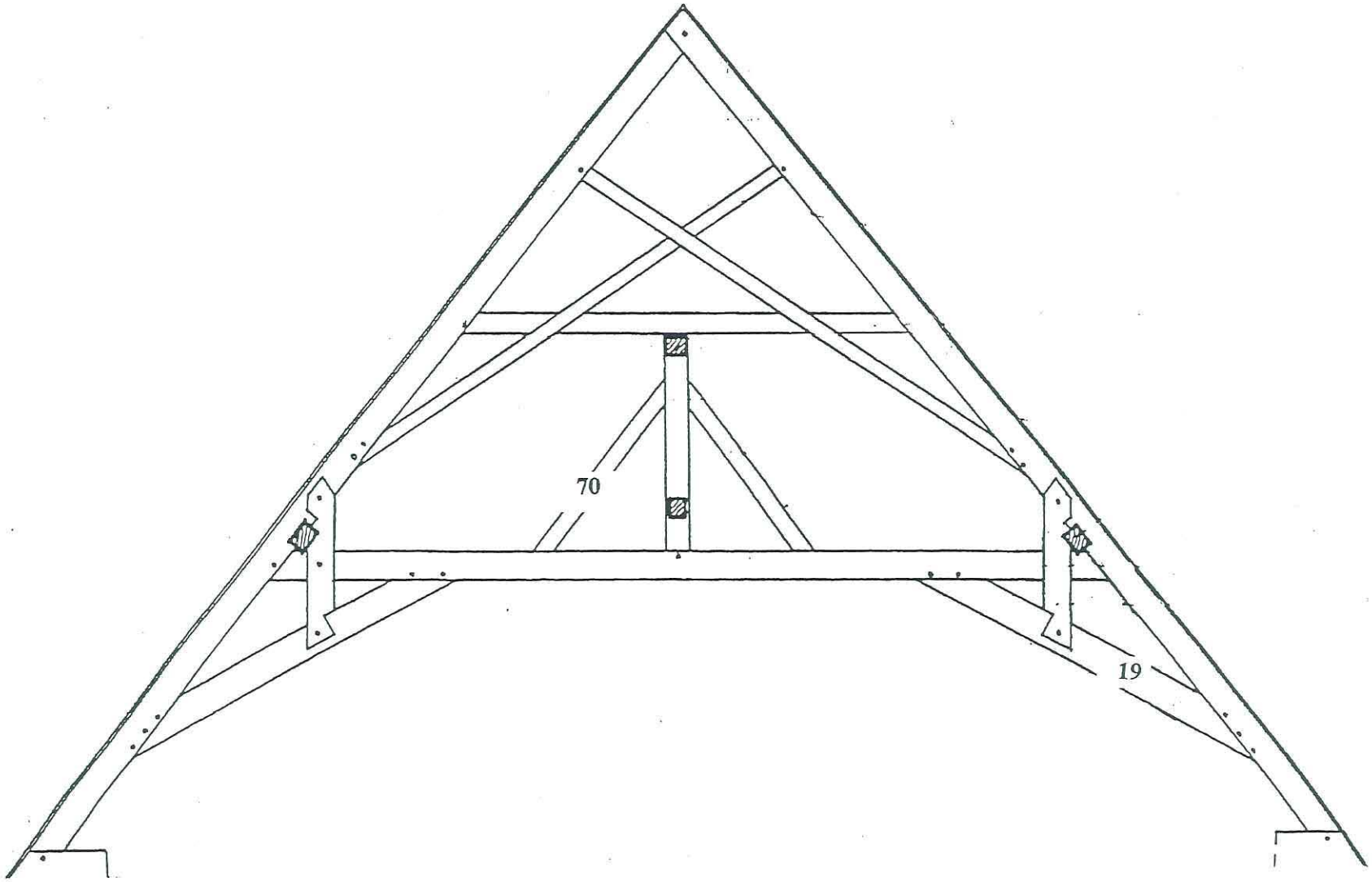


Figure 15d: Drawing of frame 10 of the Presbytery, viewed from the east, to show sample locations

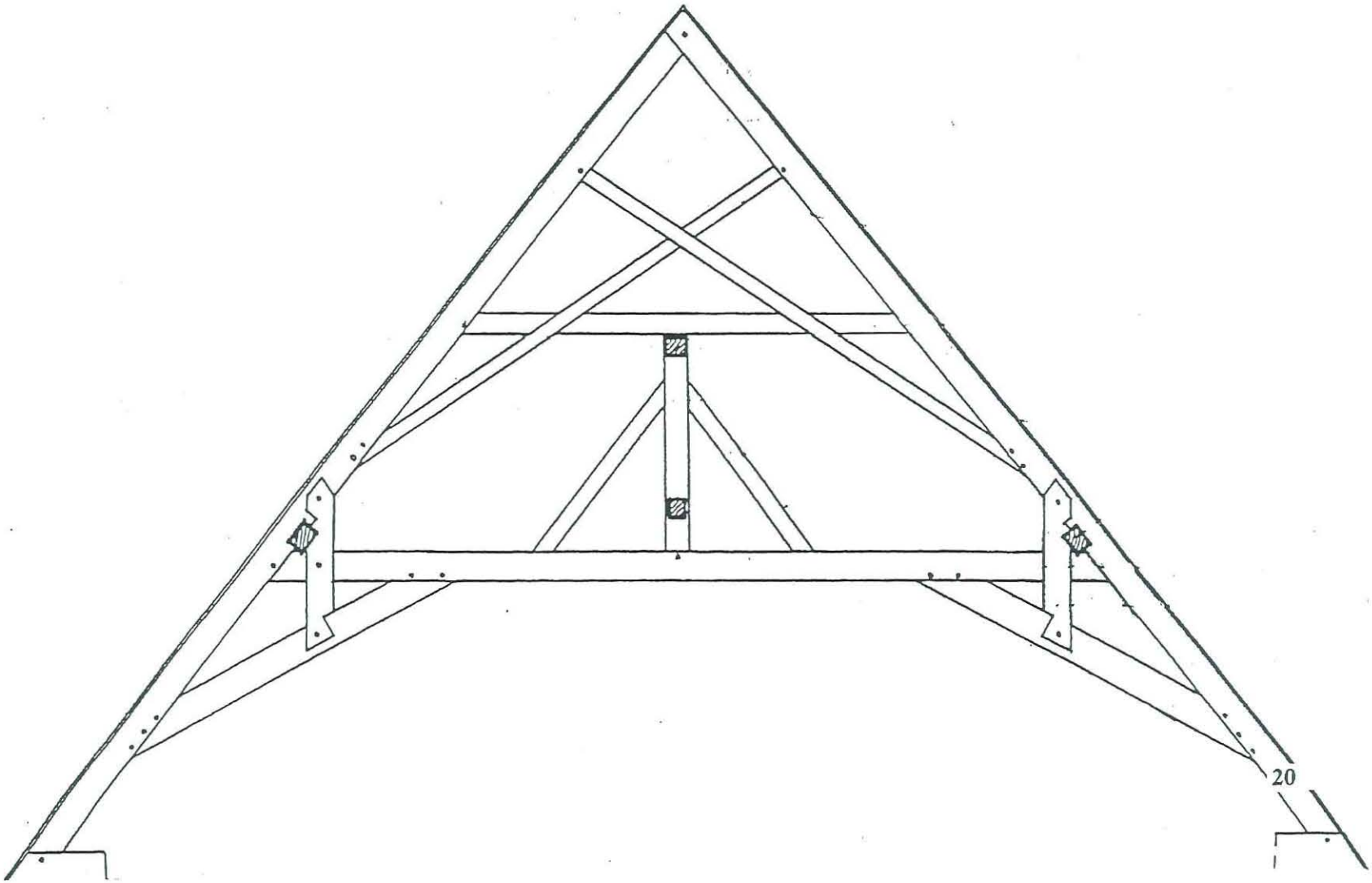


Figure 15e: Drawing of frame 11 of the Presbytery, viewed from the east, to show sample locations

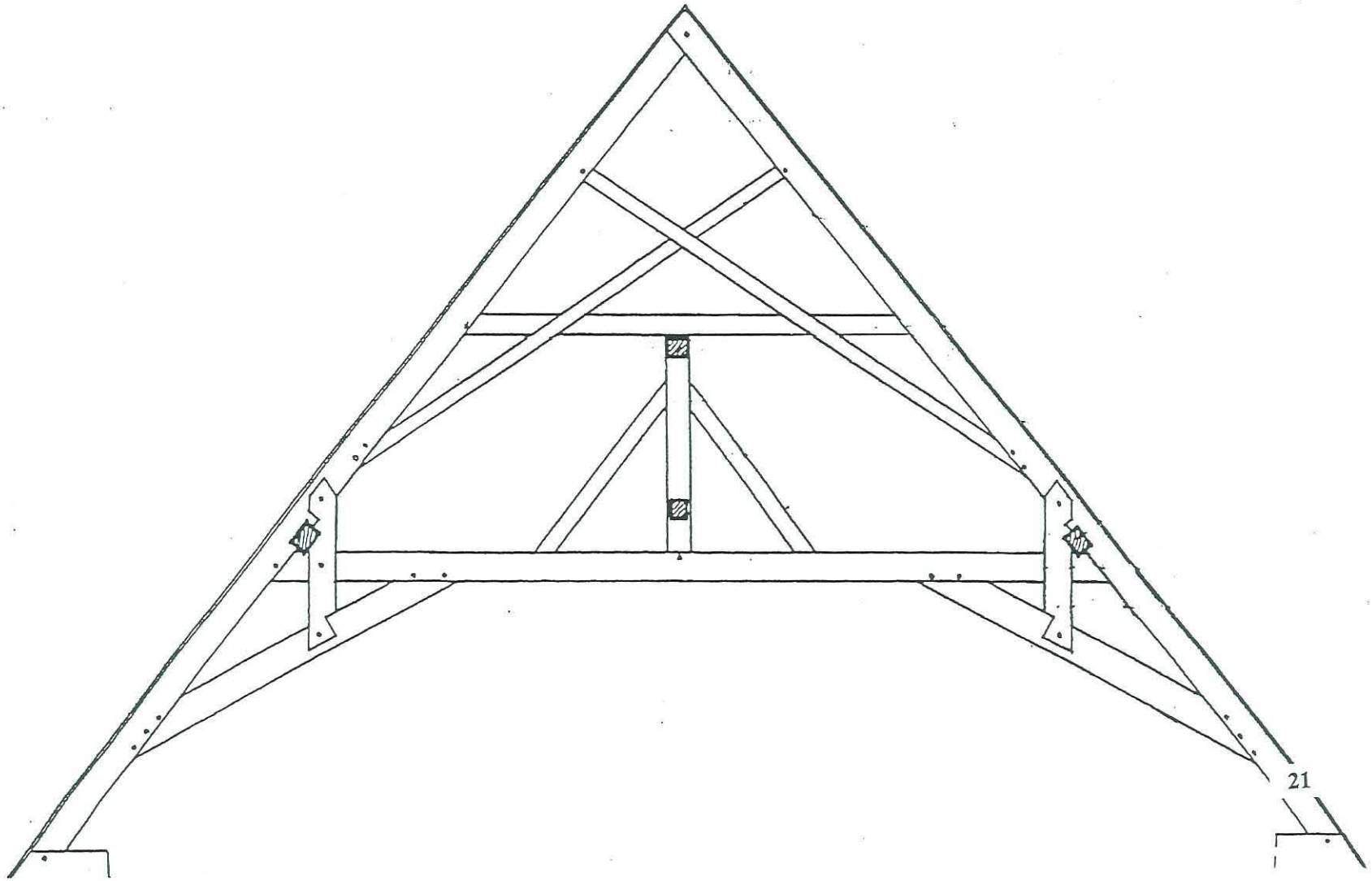


Figure 15f: Drawing of frame 13 of the Presbytery, viewed from the east, to show sample locations

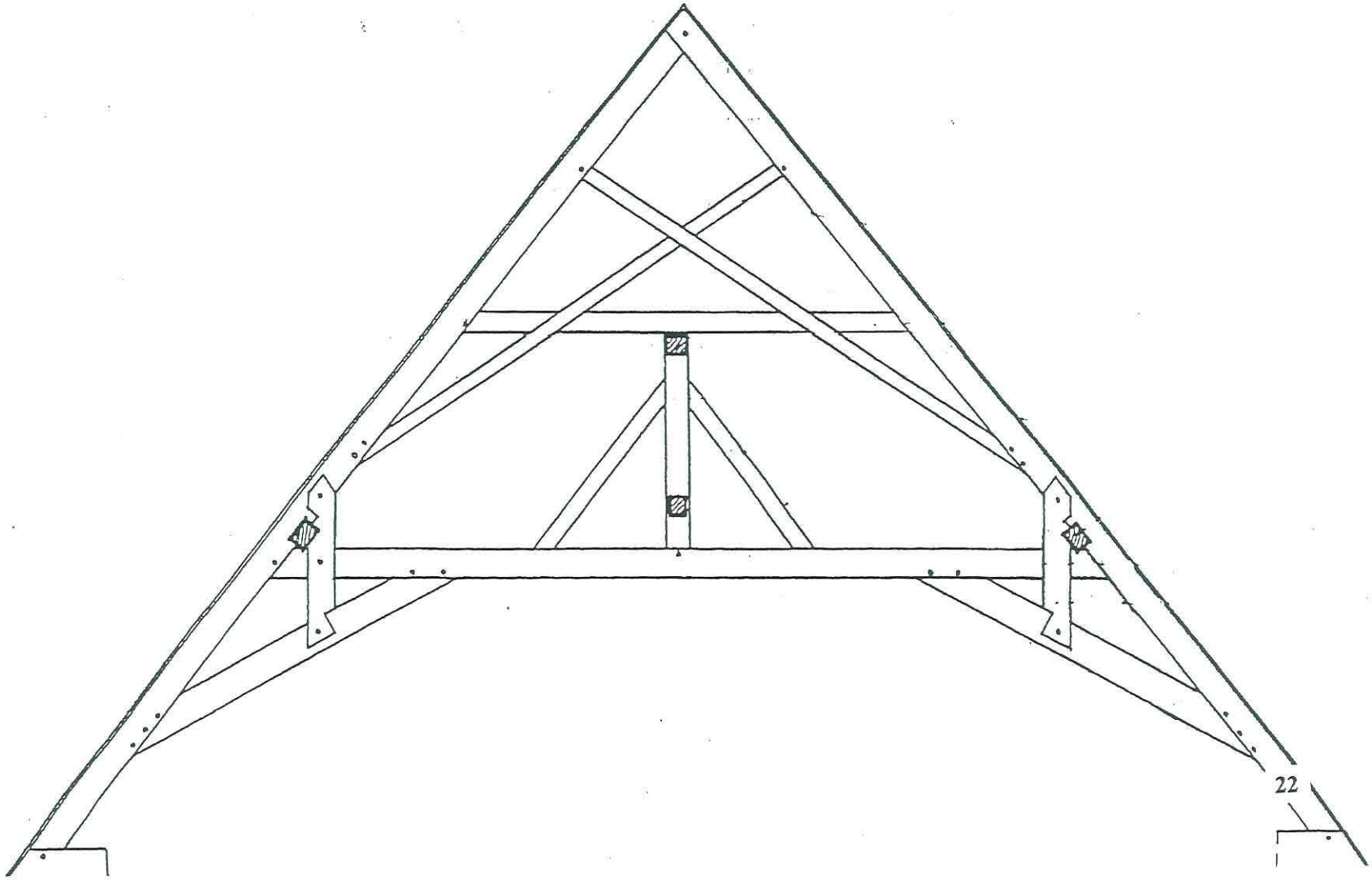


Figure 15g: Drawing of frame 14 of the Presbytery, viewed from the east, to show sample locations

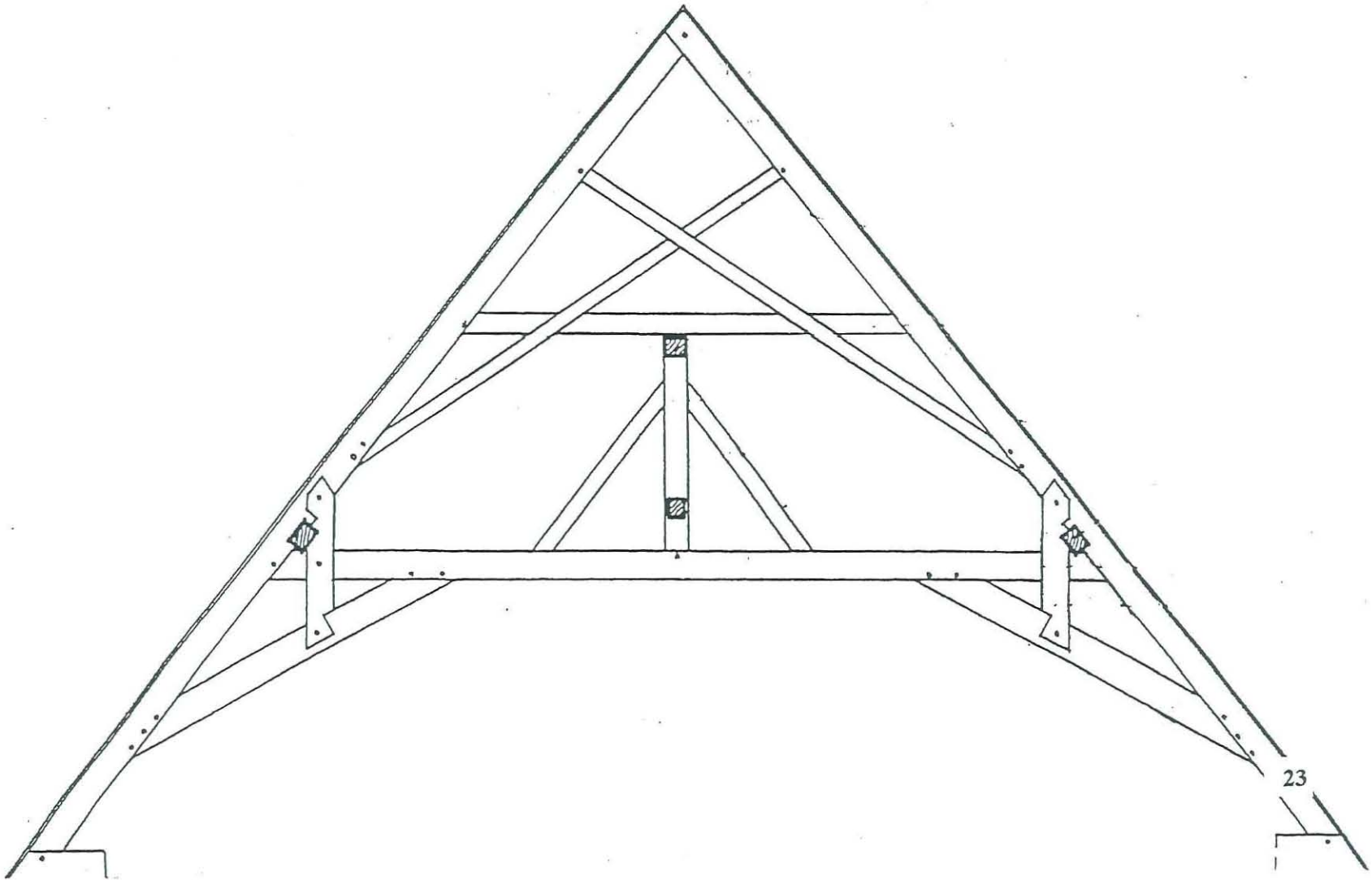


Figure 15h: Drawing of frame 15 of the Presbytery, viewed from the east, to show sample locations

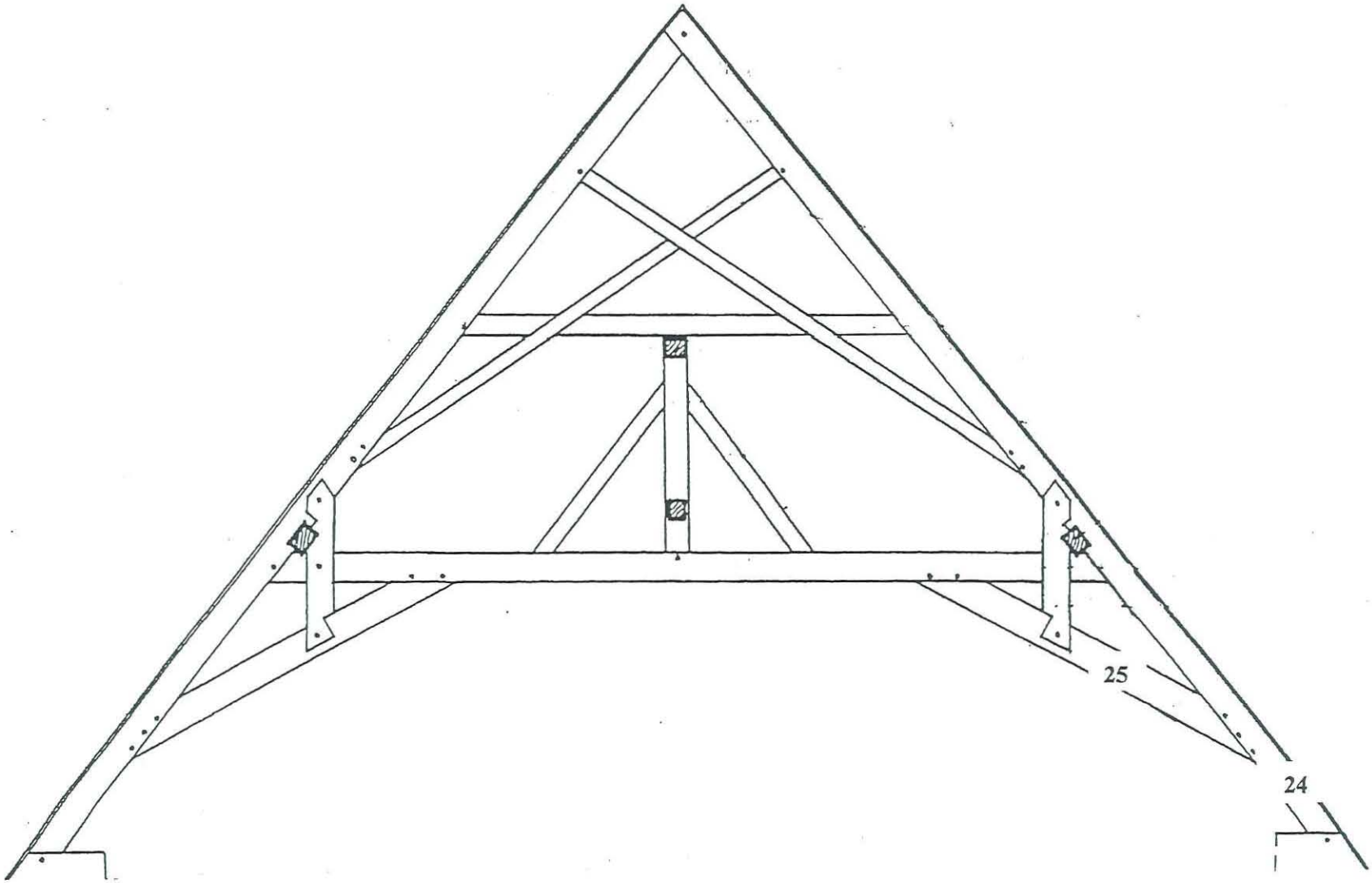


Figure 15i: Drawing of frame 16 of the Presbytery, viewed from the east, to show sample locations

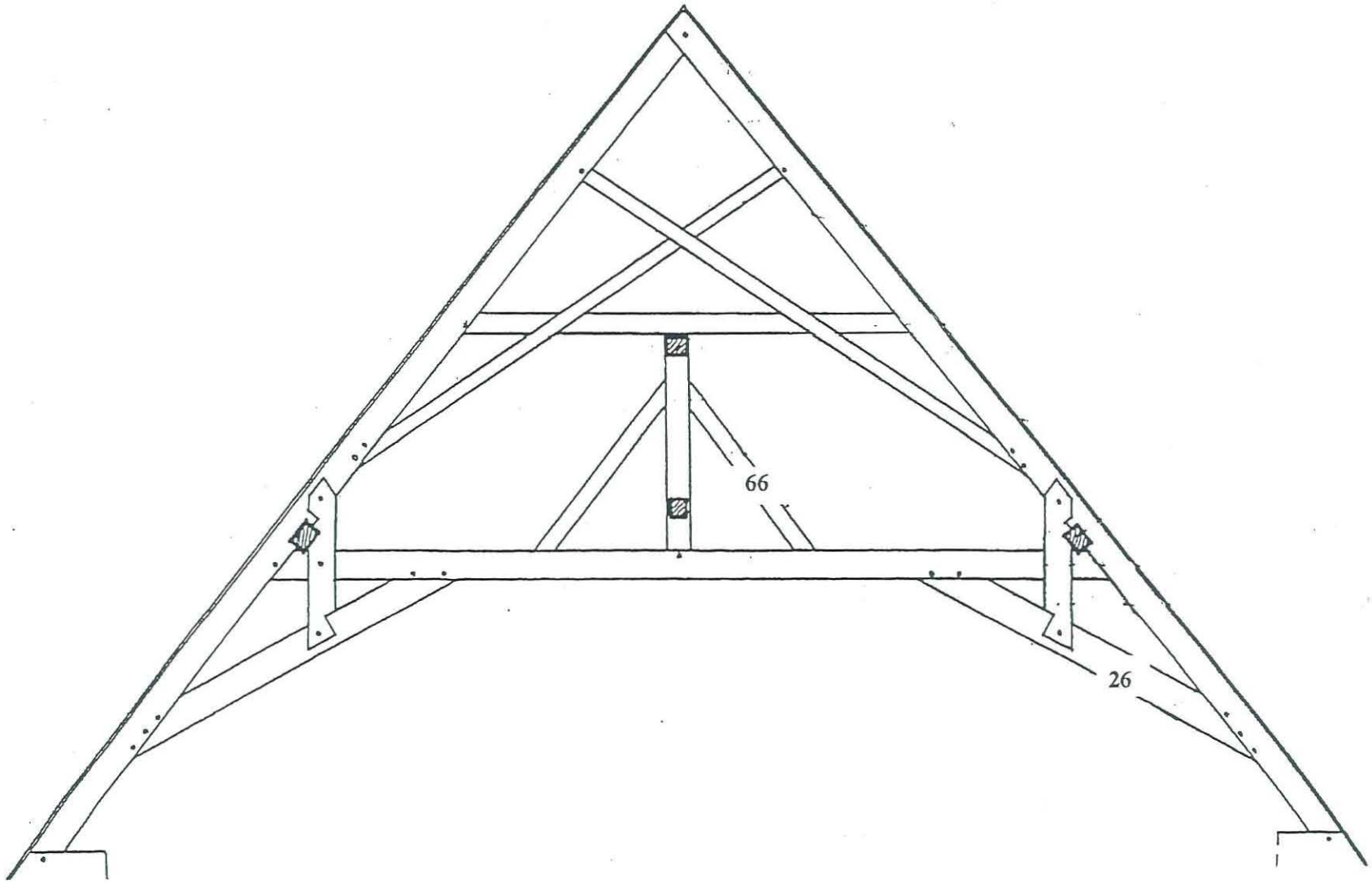


Figure 15j: Drawing of frame 17 of the Presbytery, viewed from the east, to show sample locations

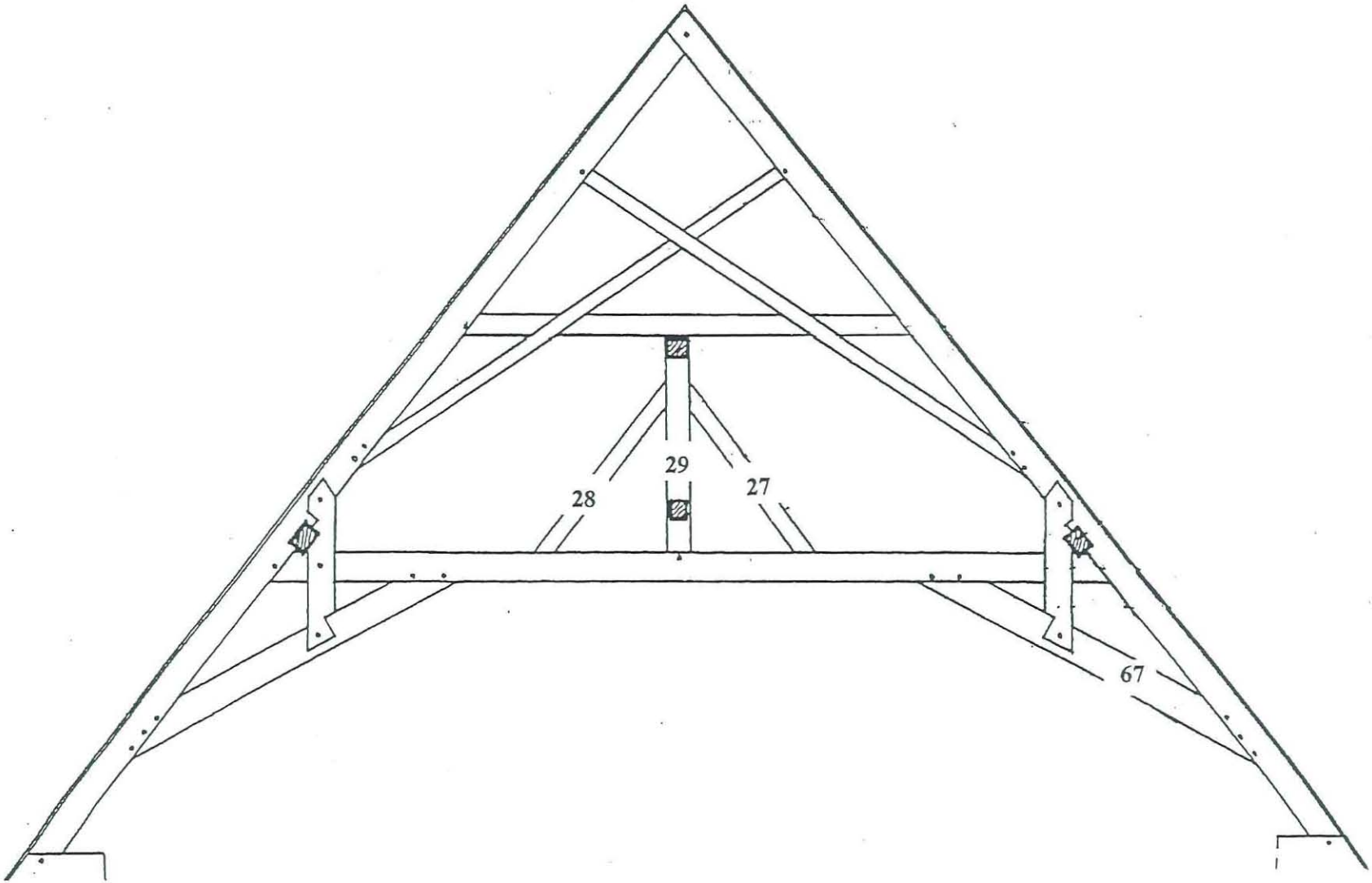


Figure 15k: Drawing of frame 24 of the Presbytery, viewed from the east, to show sample locations

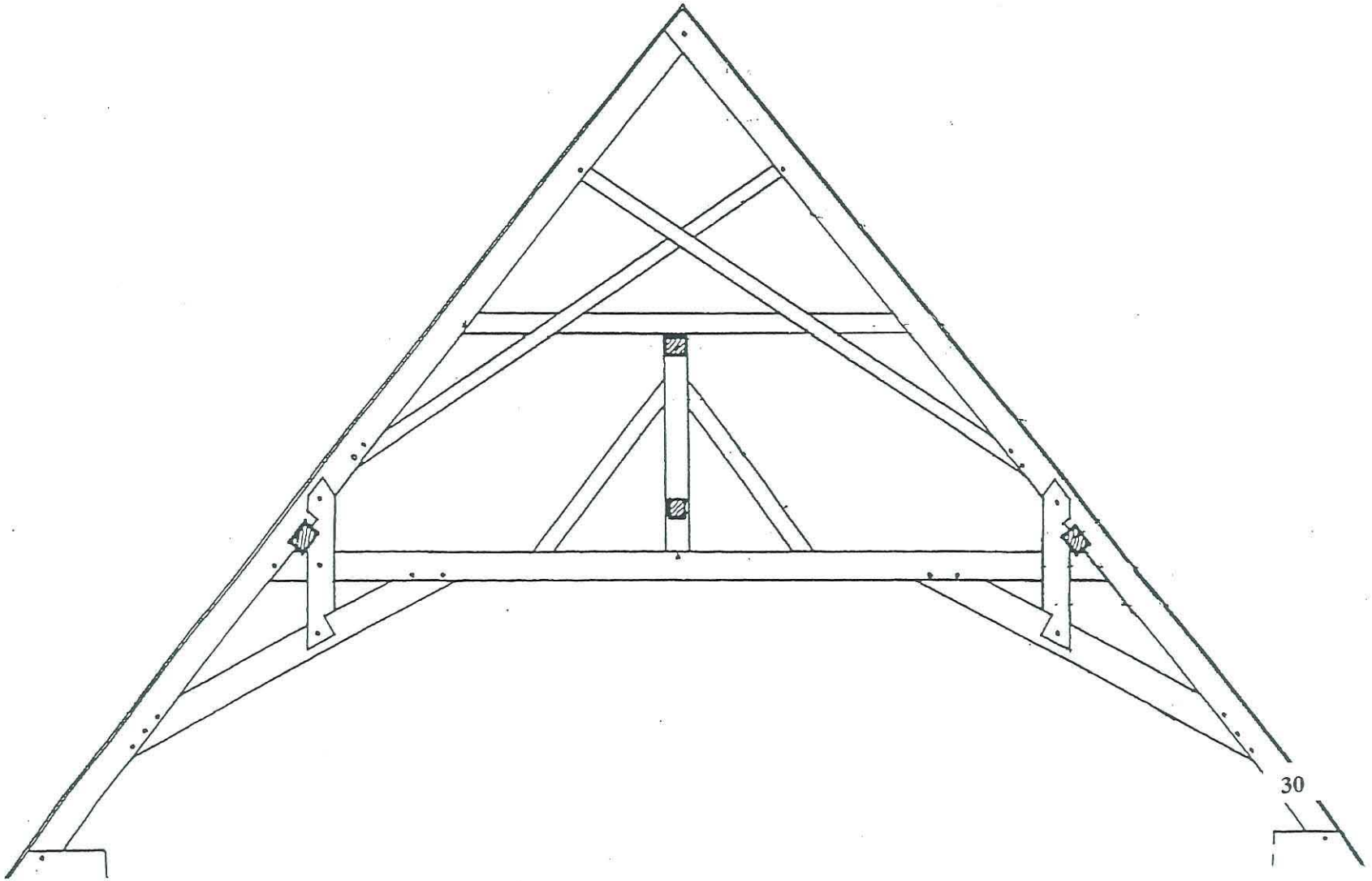


Figure 15l: Drawing of frame 1 of the Presbytery, viewed from the east, to show sample locations

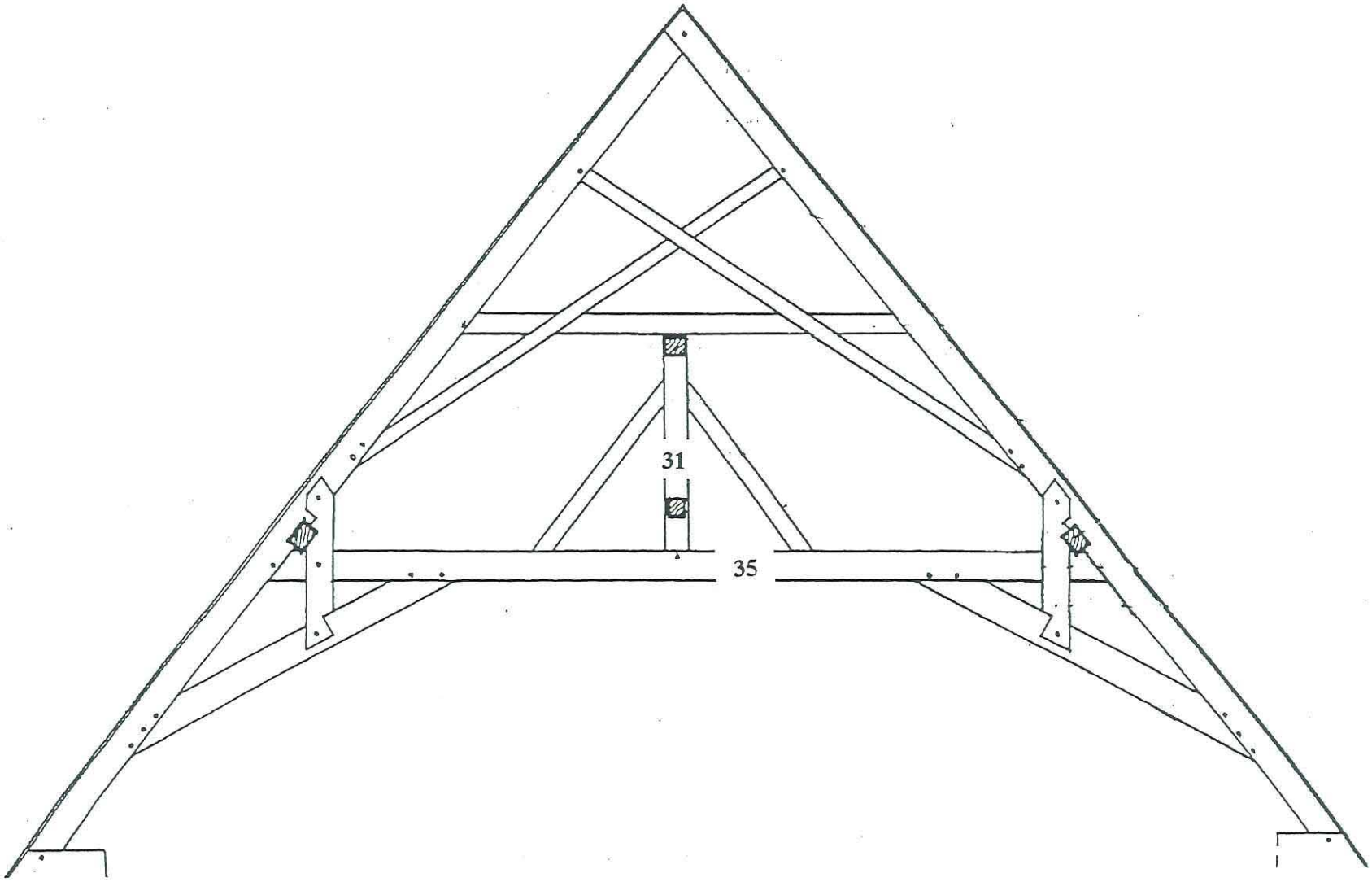


Figure 15m: Drawing of frame 27 of the Presbytery, viewed from the east, to show sample locations

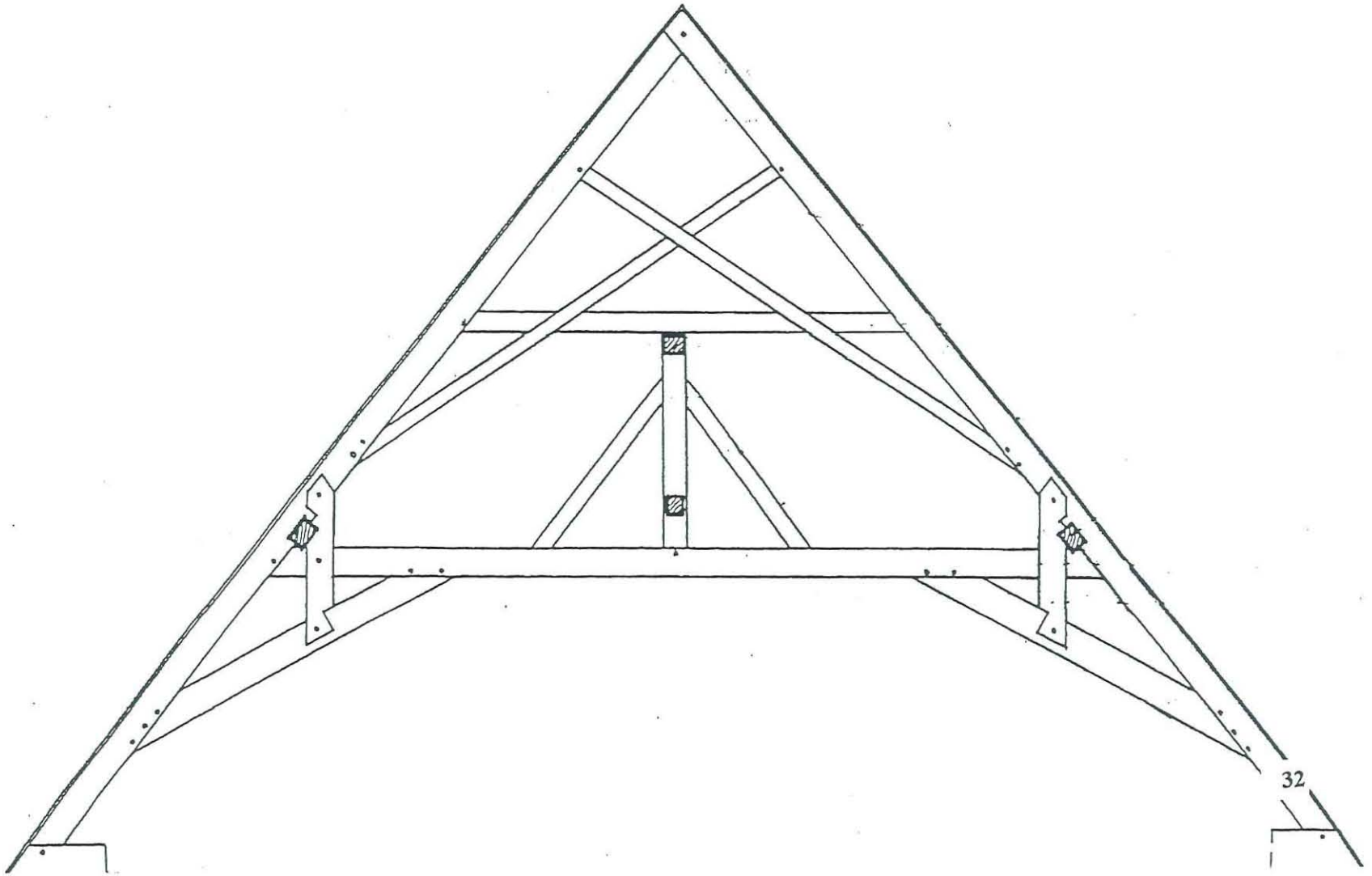


Figure 15n: Drawing of frame 7 of the Presbytery, viewed from the east, to show sample locations

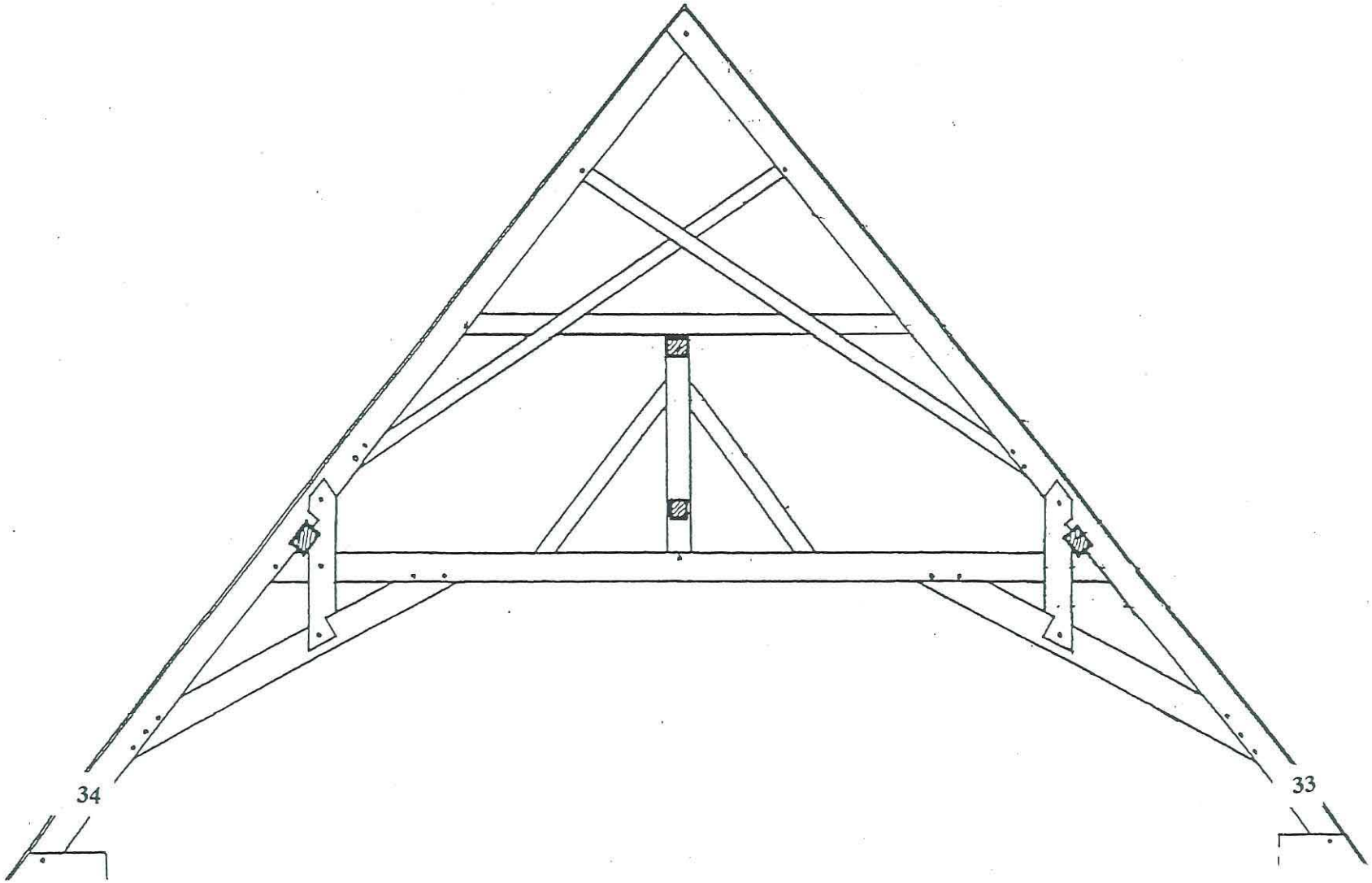


Figure 15o: Drawing of frame 29 of the Presbytery, viewed from the east, to show sample locations

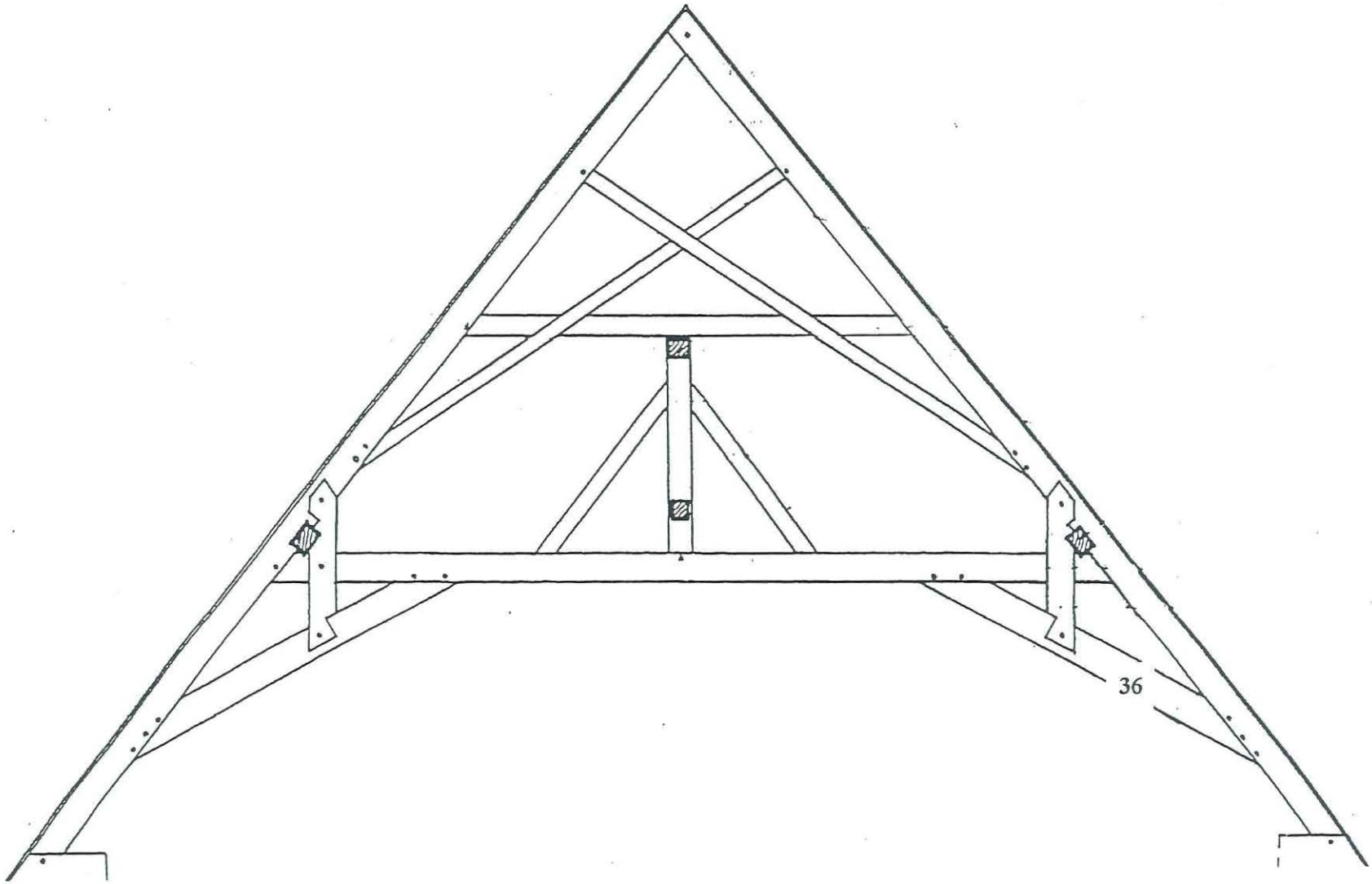


Figure 15p: Drawing of frame 26 of the Presbytery, viewed from the east, to show sample locations

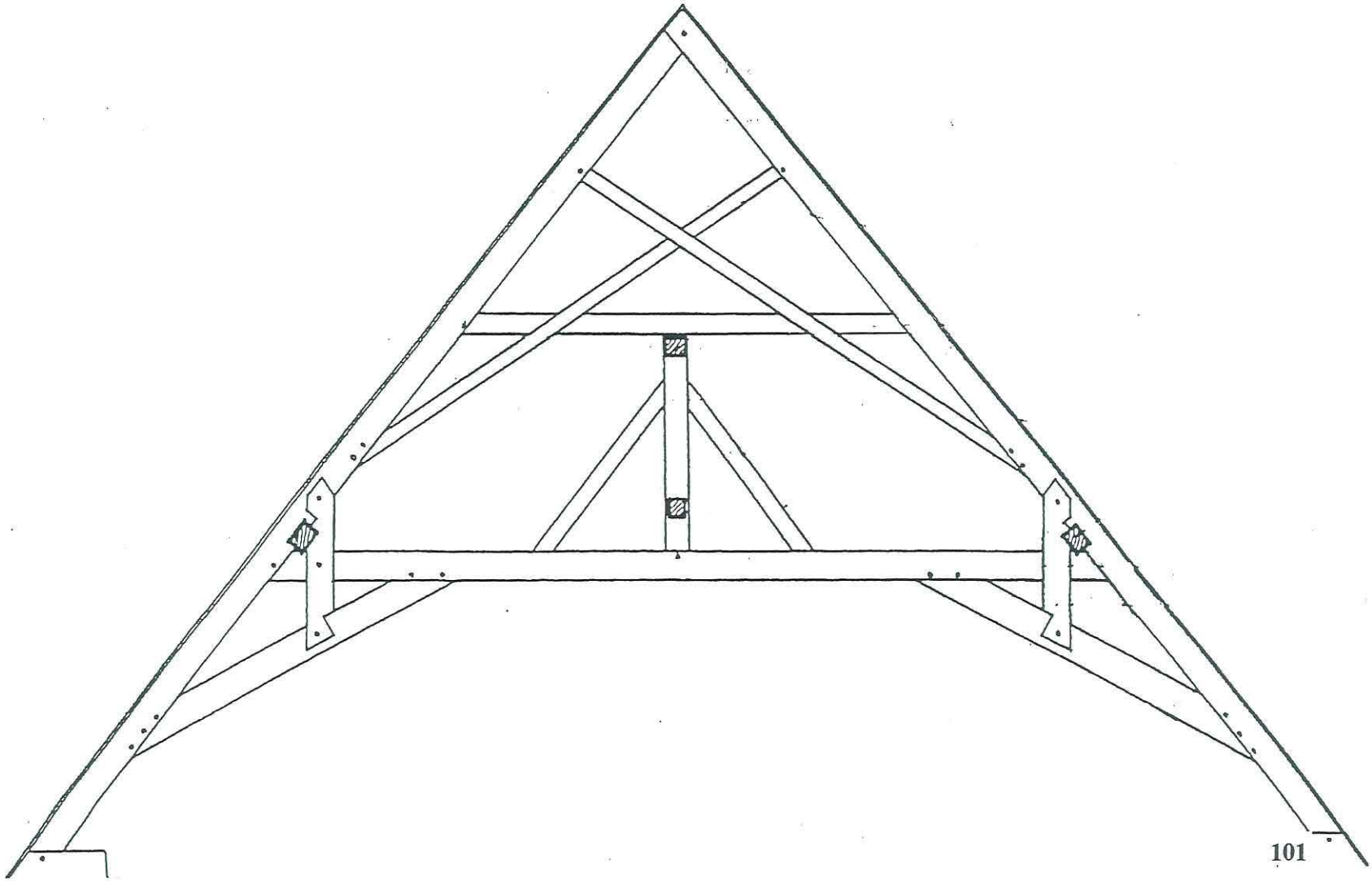


Figure 15q: Drawing of frame 23 of the Presbytery, viewed from the east, to show sample locations

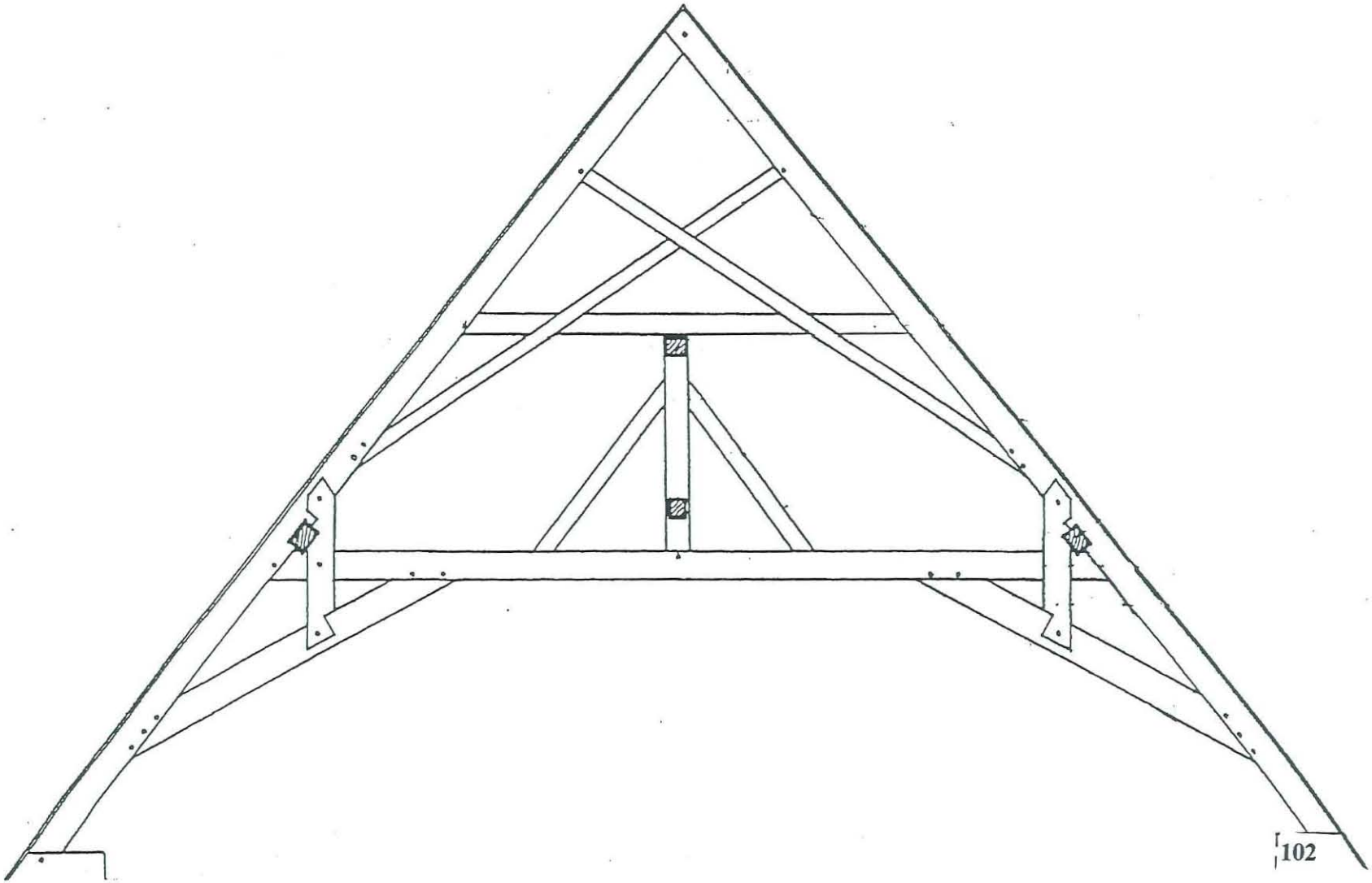


Figure 15r: Drawing of frame 22 of the Presbytery, viewed from the east, to show sample locations

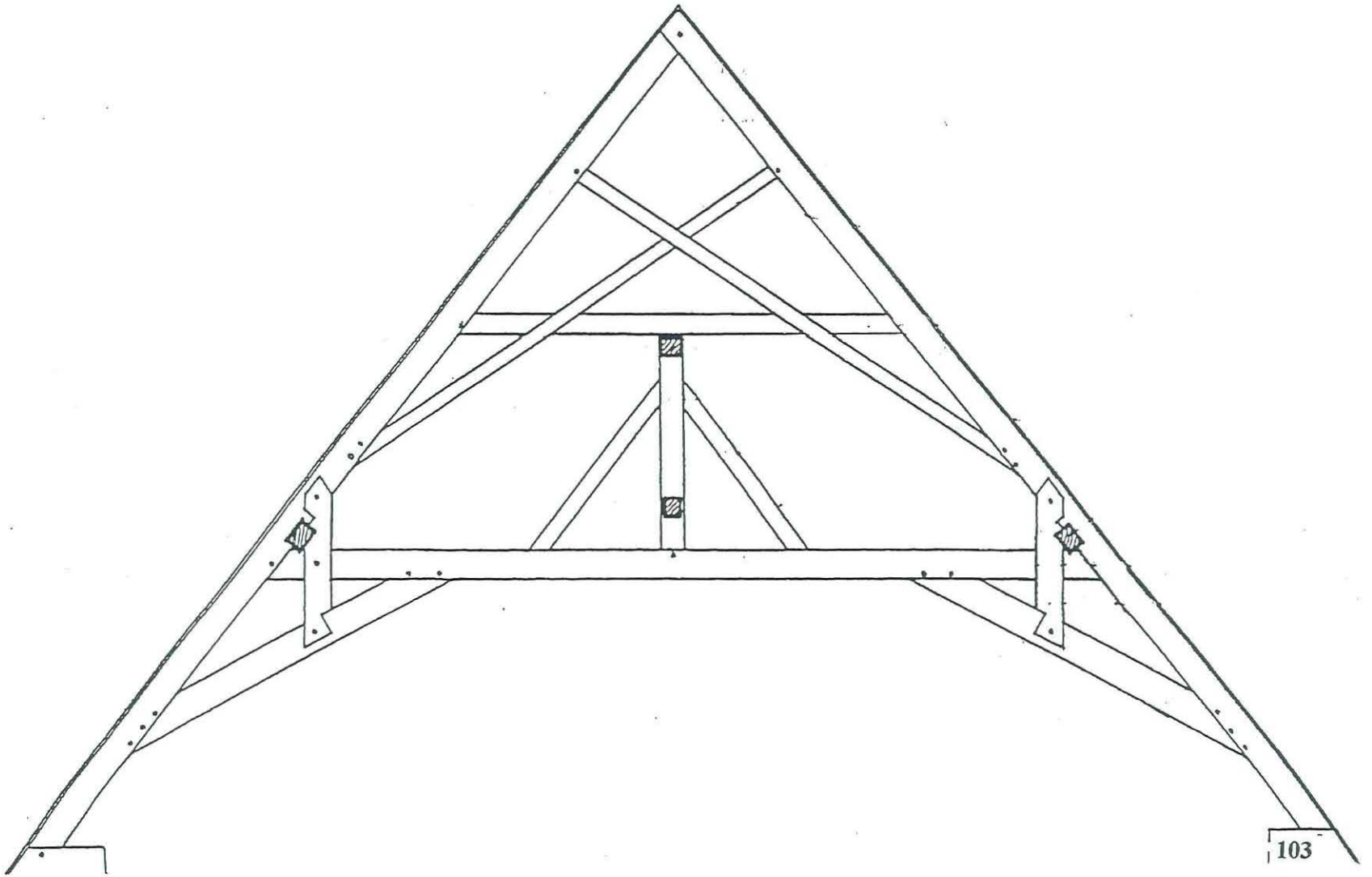


Figure 15s: Drawing of frame 15 of the Presbytery, viewed from the east, to show sample locations

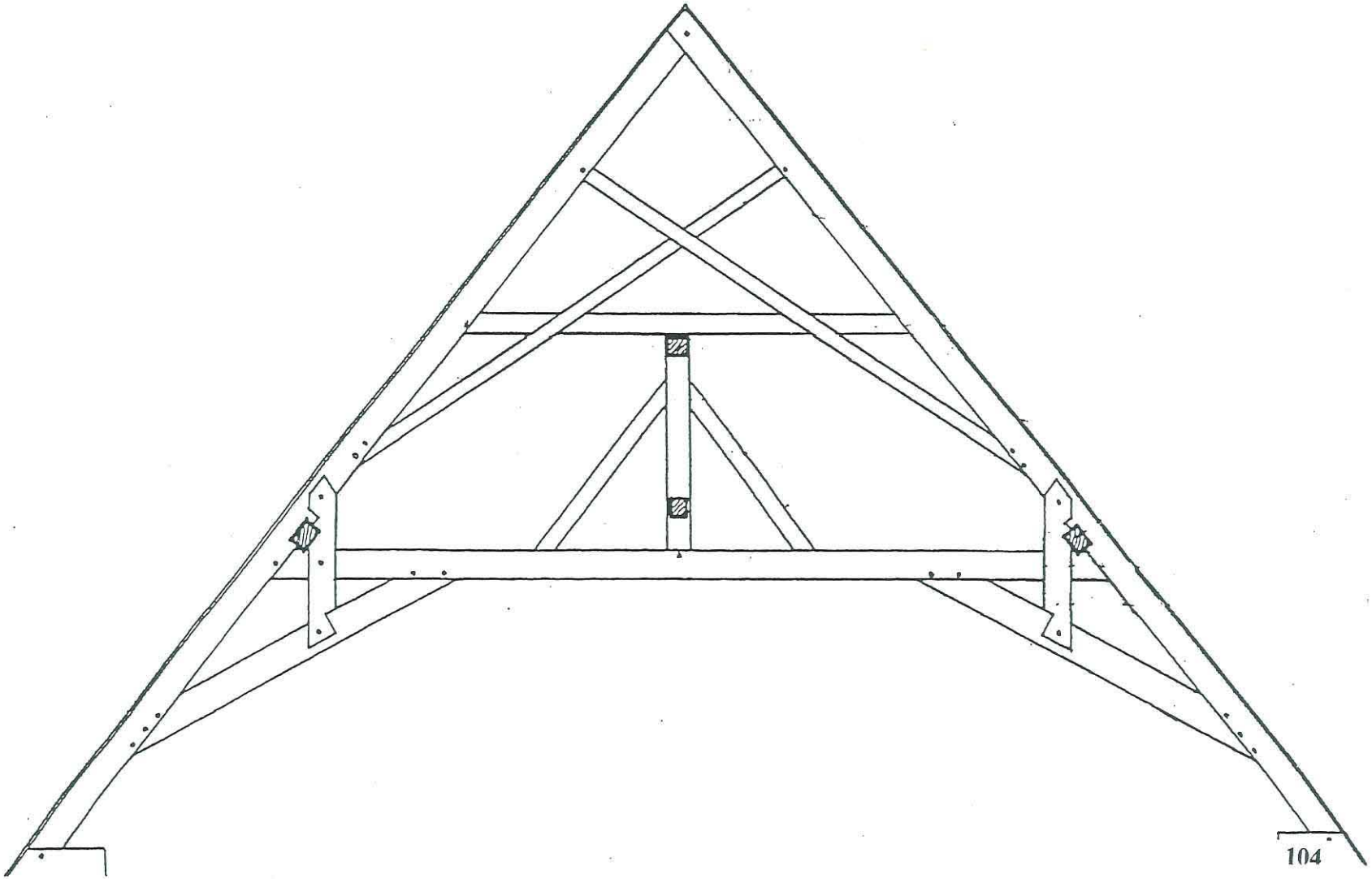


Figure 16: Drawing to show position of samples from the repair timbers

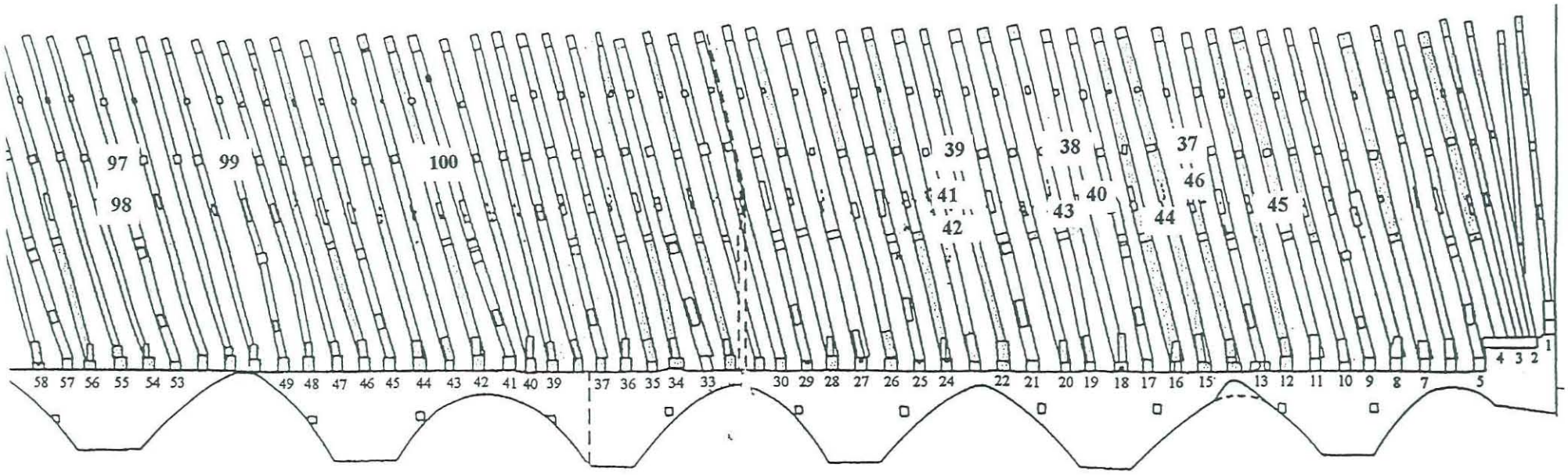


Figure 17a: Drawing of frame 42 of the Choir and crossing, viewed from the east, to show sample locations

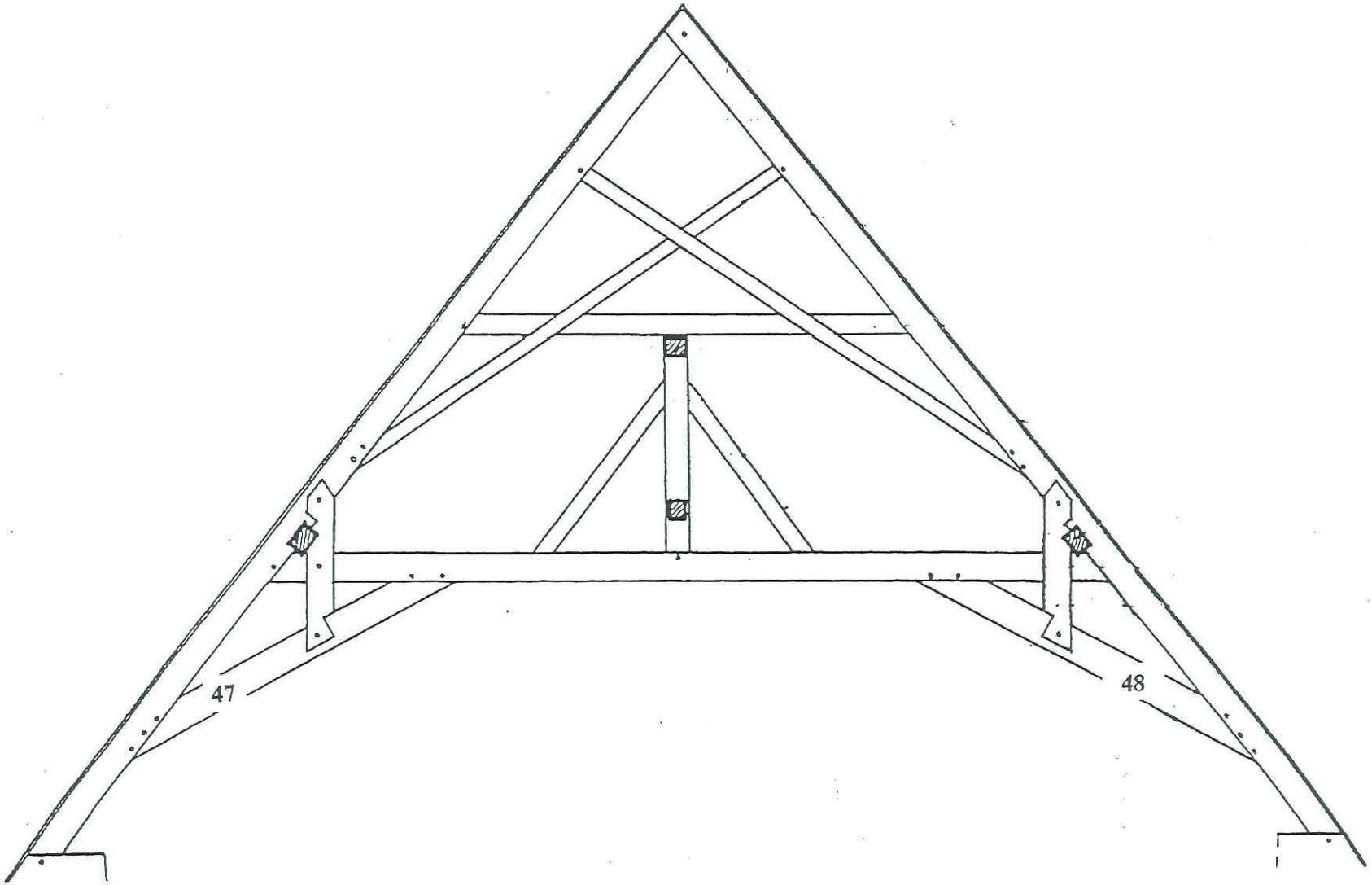


Figure 17b: Drawing of frame 41 of the Choir and crossing, viewed from the east, to show sample locations

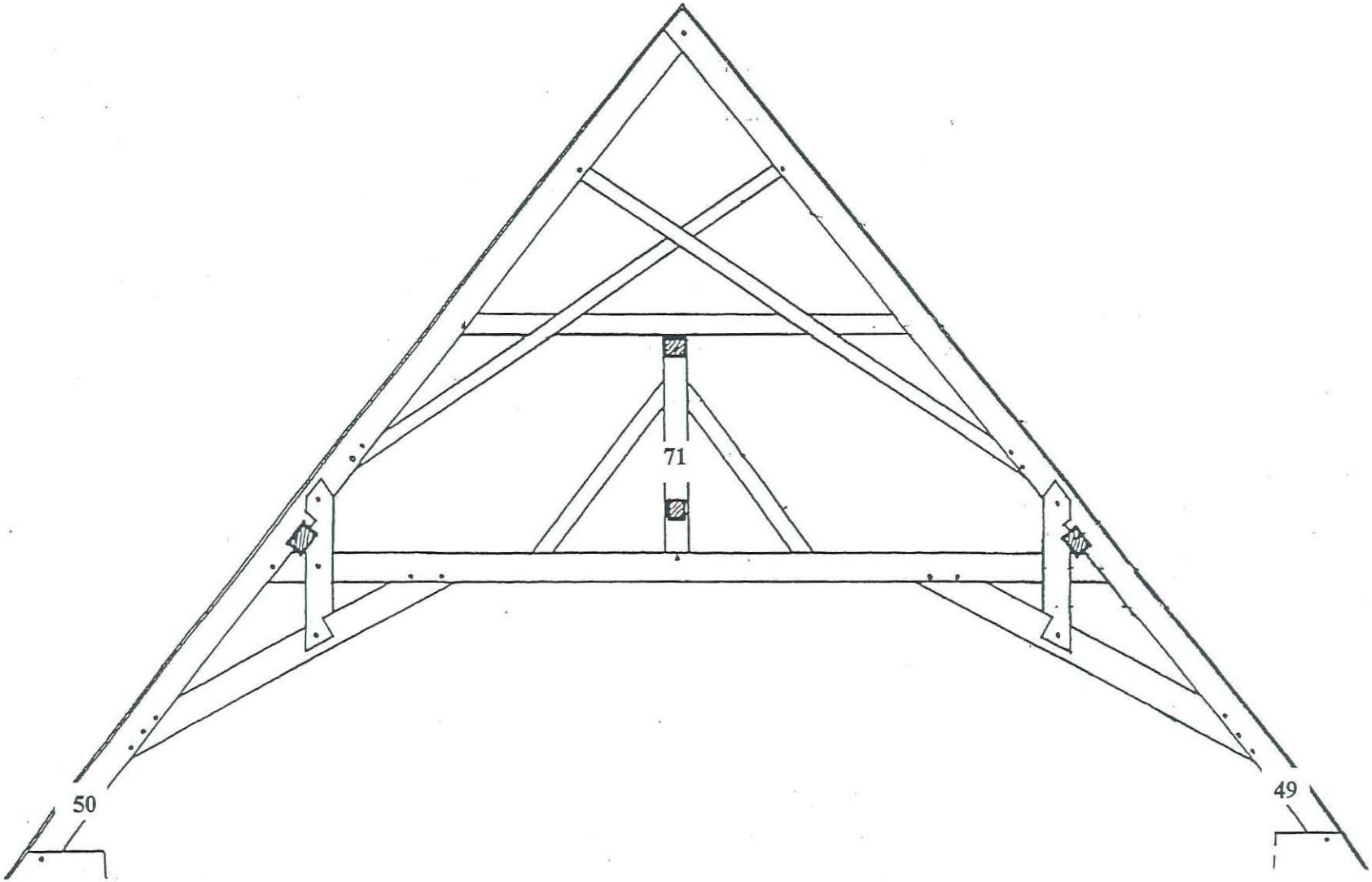


Figure 17c: Drawing of frame 68 of the Choir and crossing, viewed from the east, to show sample locations

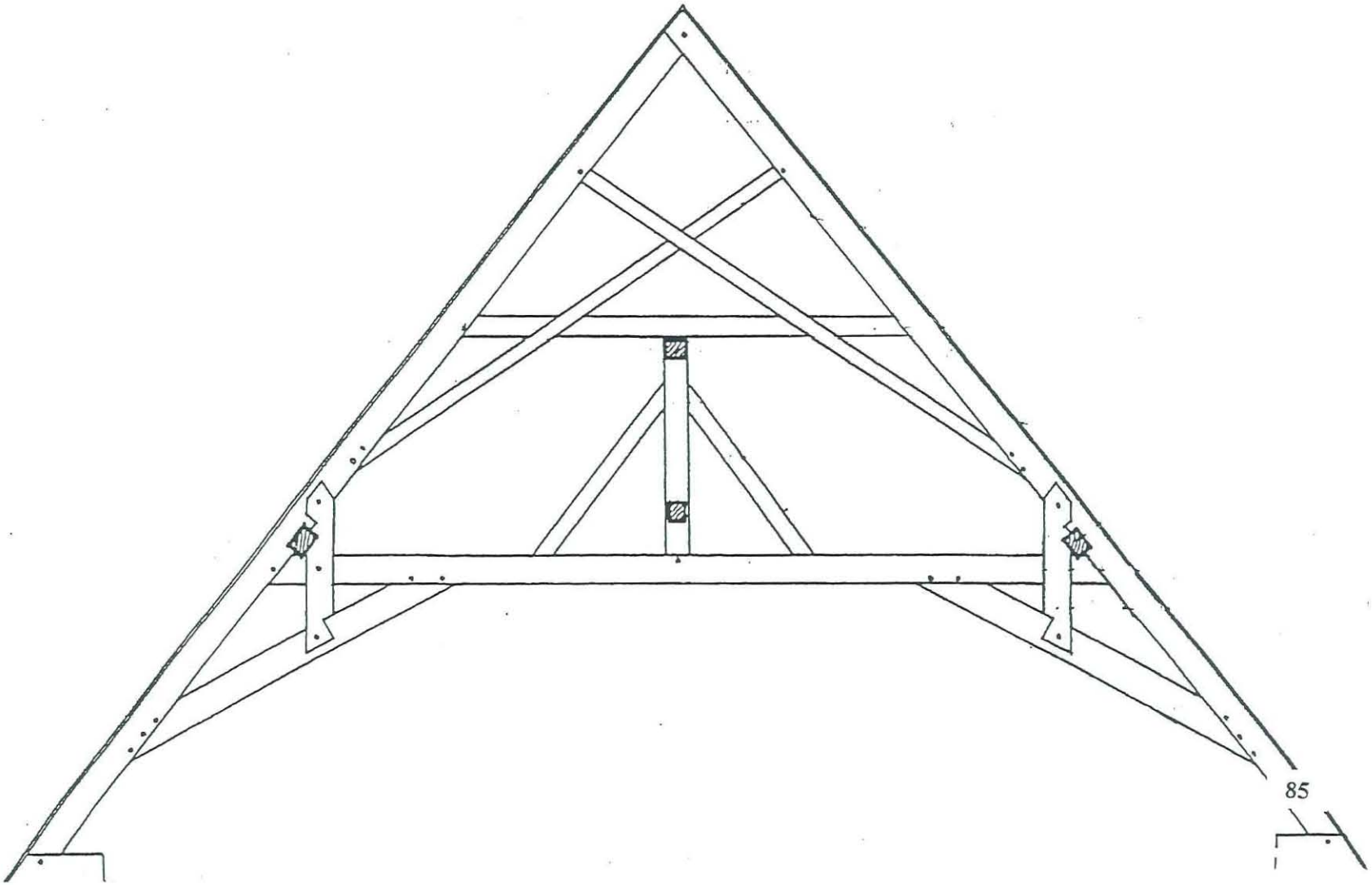


Figure 17d: Drawing of frame 47 of the Choir and crossing, viewed from the east, to show sample locations

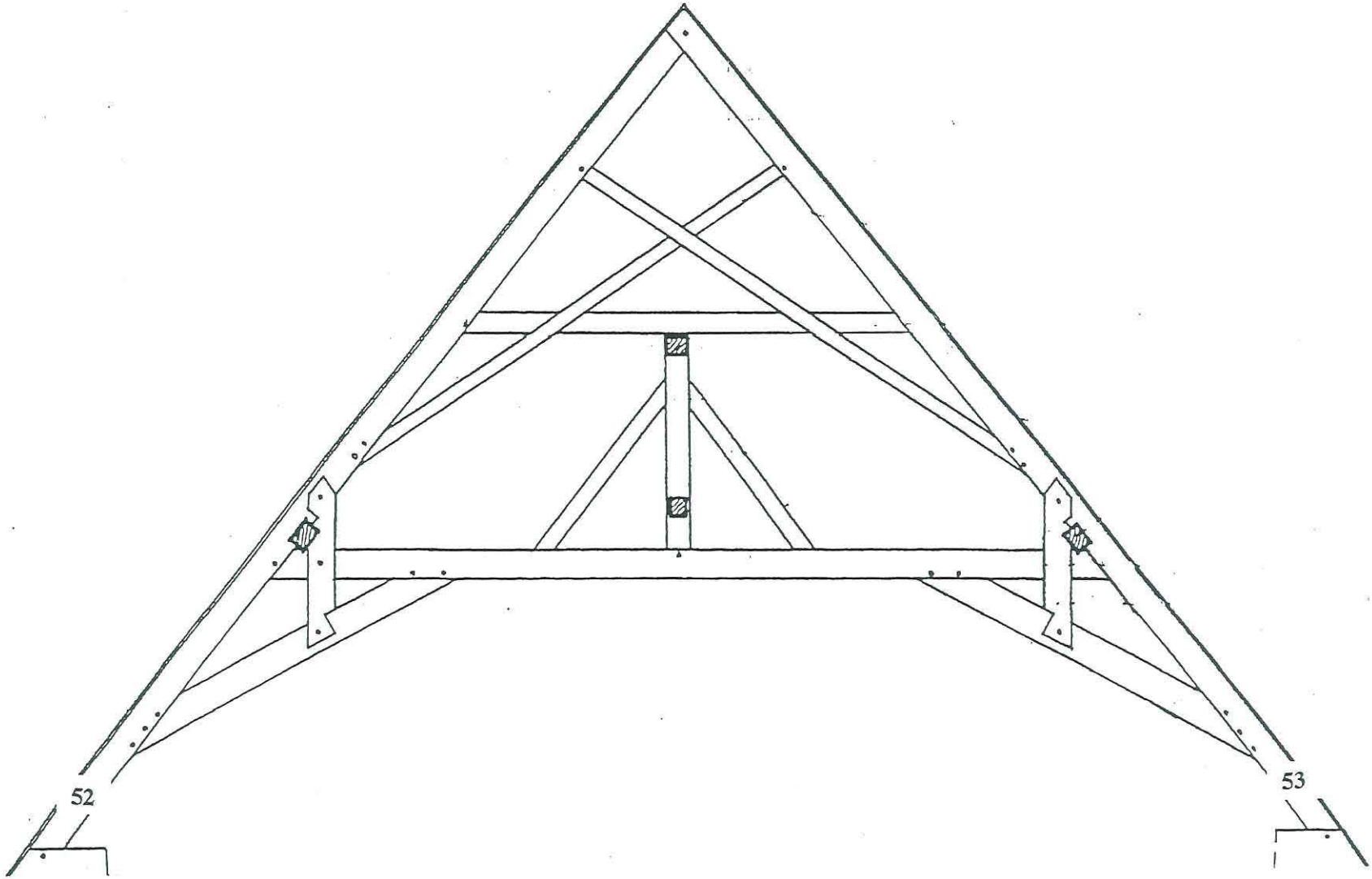


Figure 17e: Drawing of frame 45 of the Choir and crossing, viewed from the east, to show sample locations

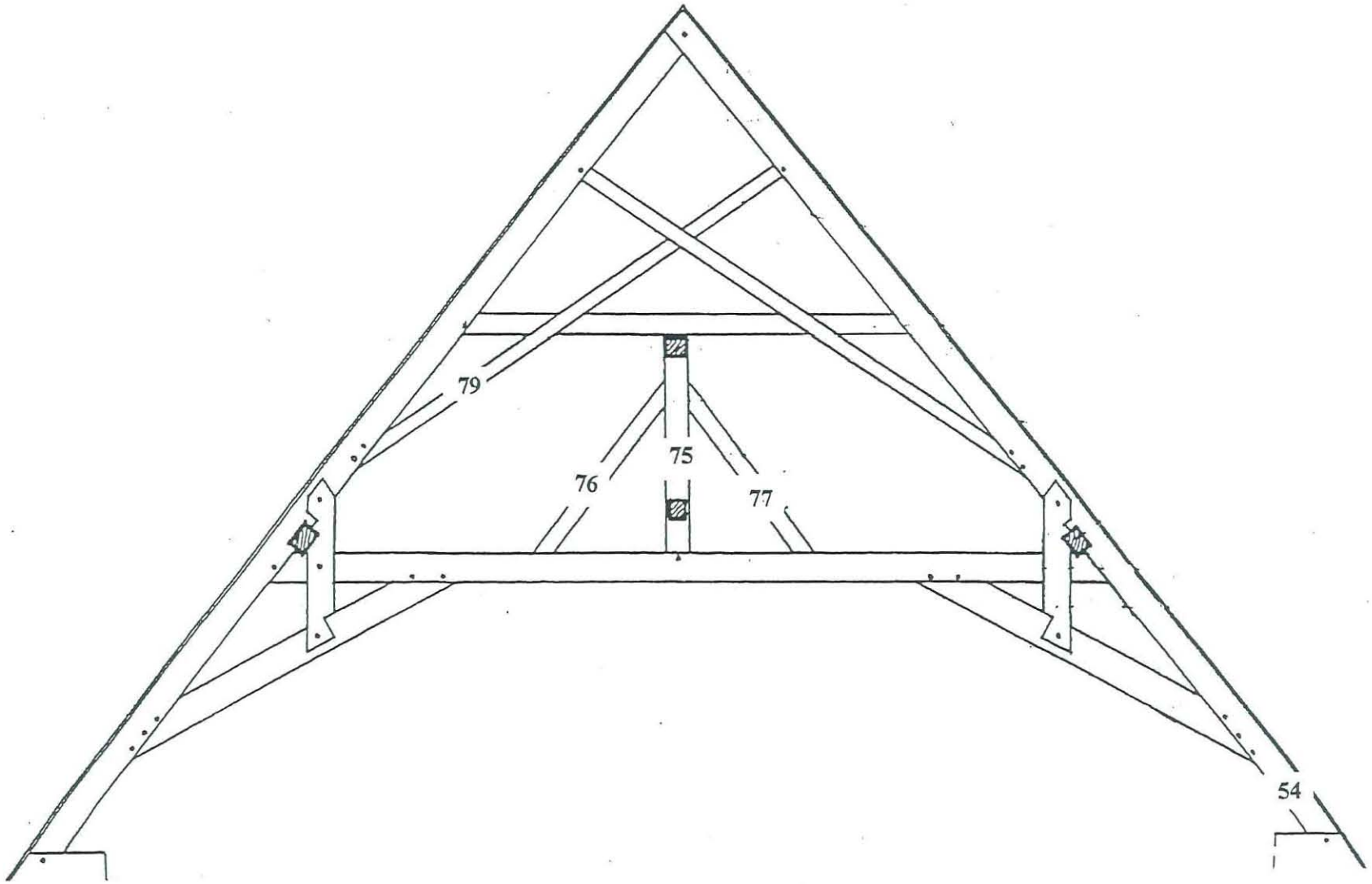


Figure 17f: Drawing of frame 56 of the Choir and crossing, viewed from the east, to show sample locations

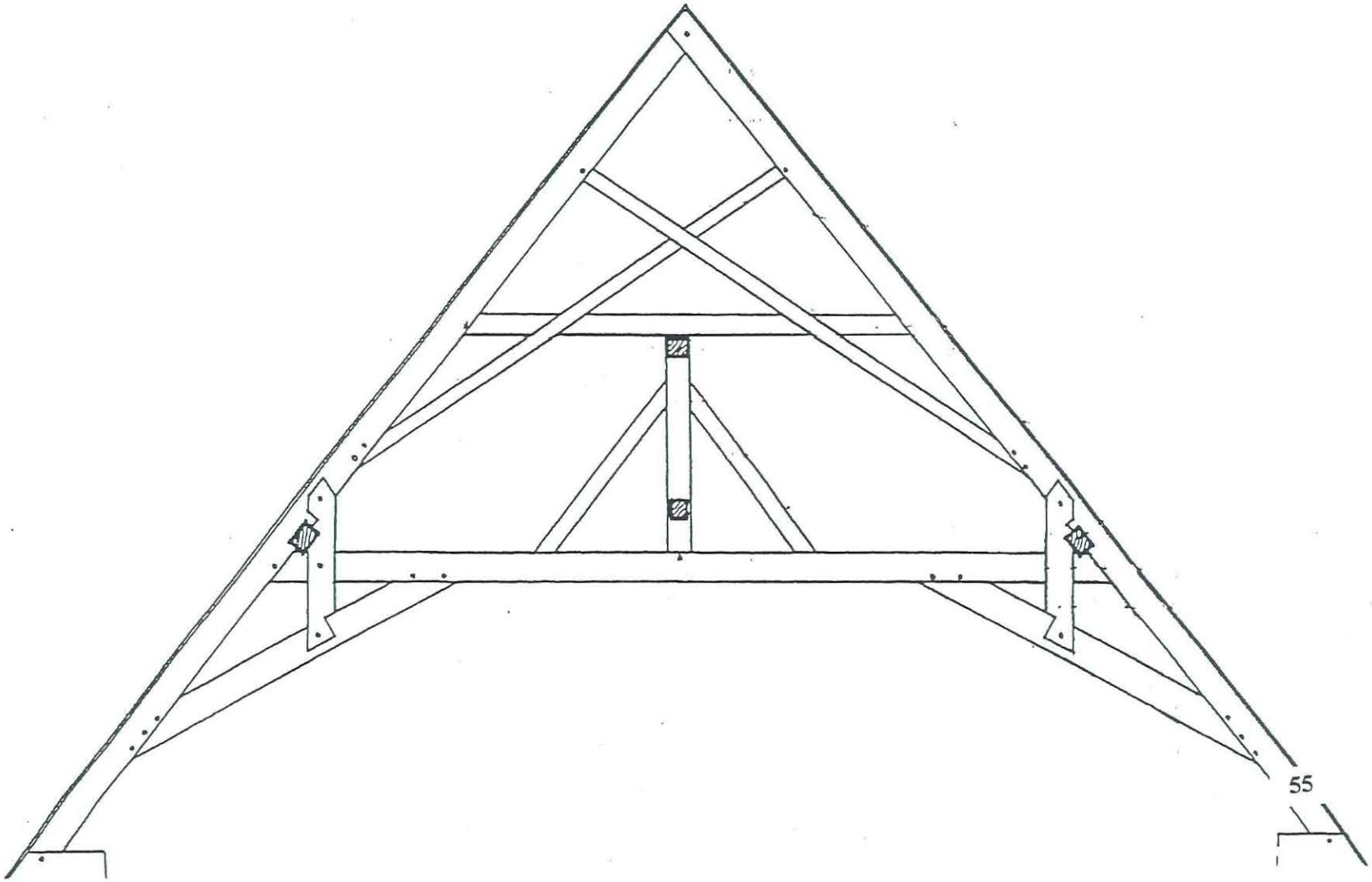


Figure 17g: Drawing of frame 57 of the Choir and crossing, viewed from the east, to show sample locations

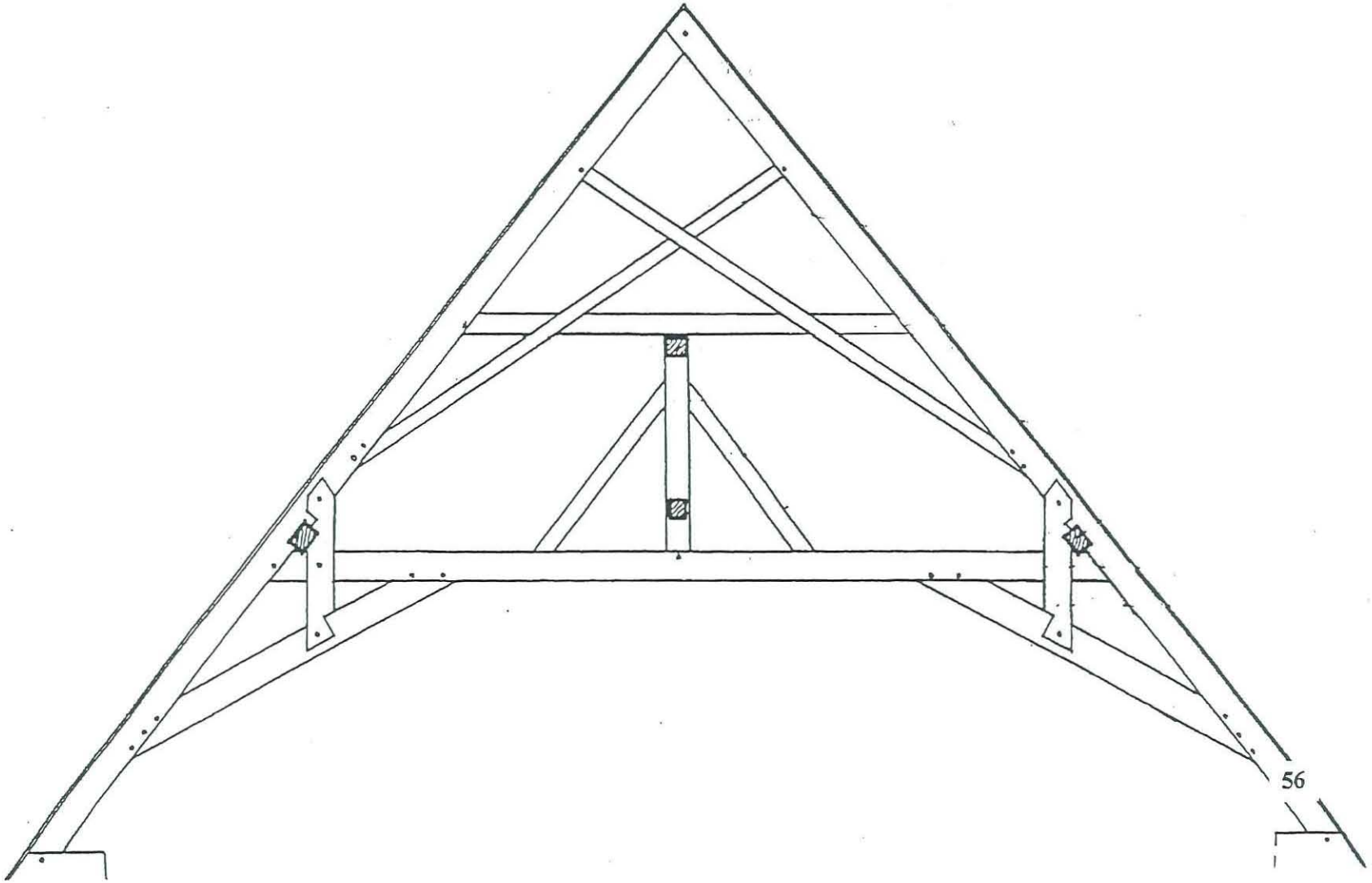


Figure 17h: Drawing of frame 53 of the Choir and crossing, viewed from the east, to show sample locations

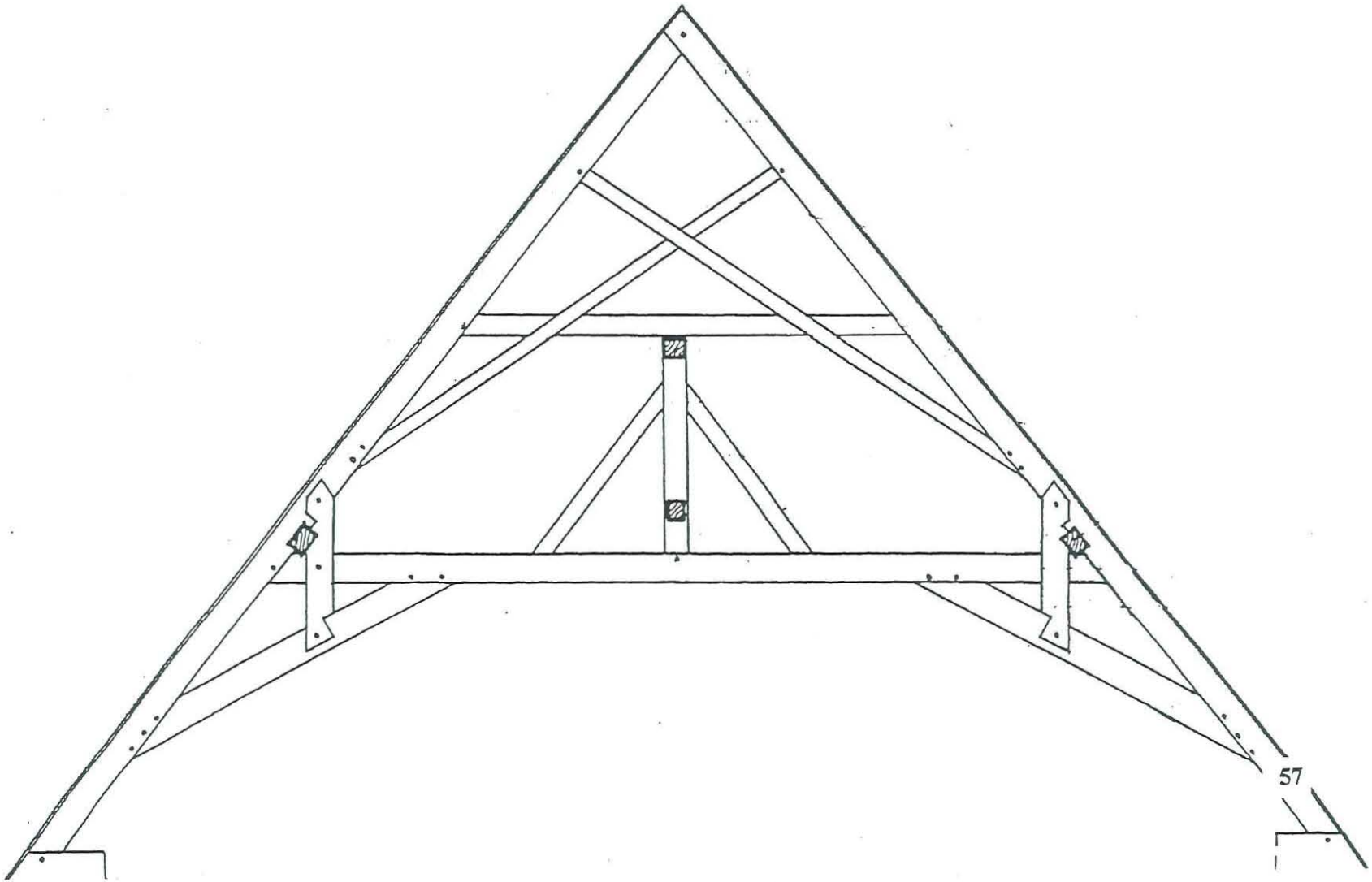


Figure 17i: Drawing of frame 49 of the Choir and crossing, viewed from the east, to show sample locations

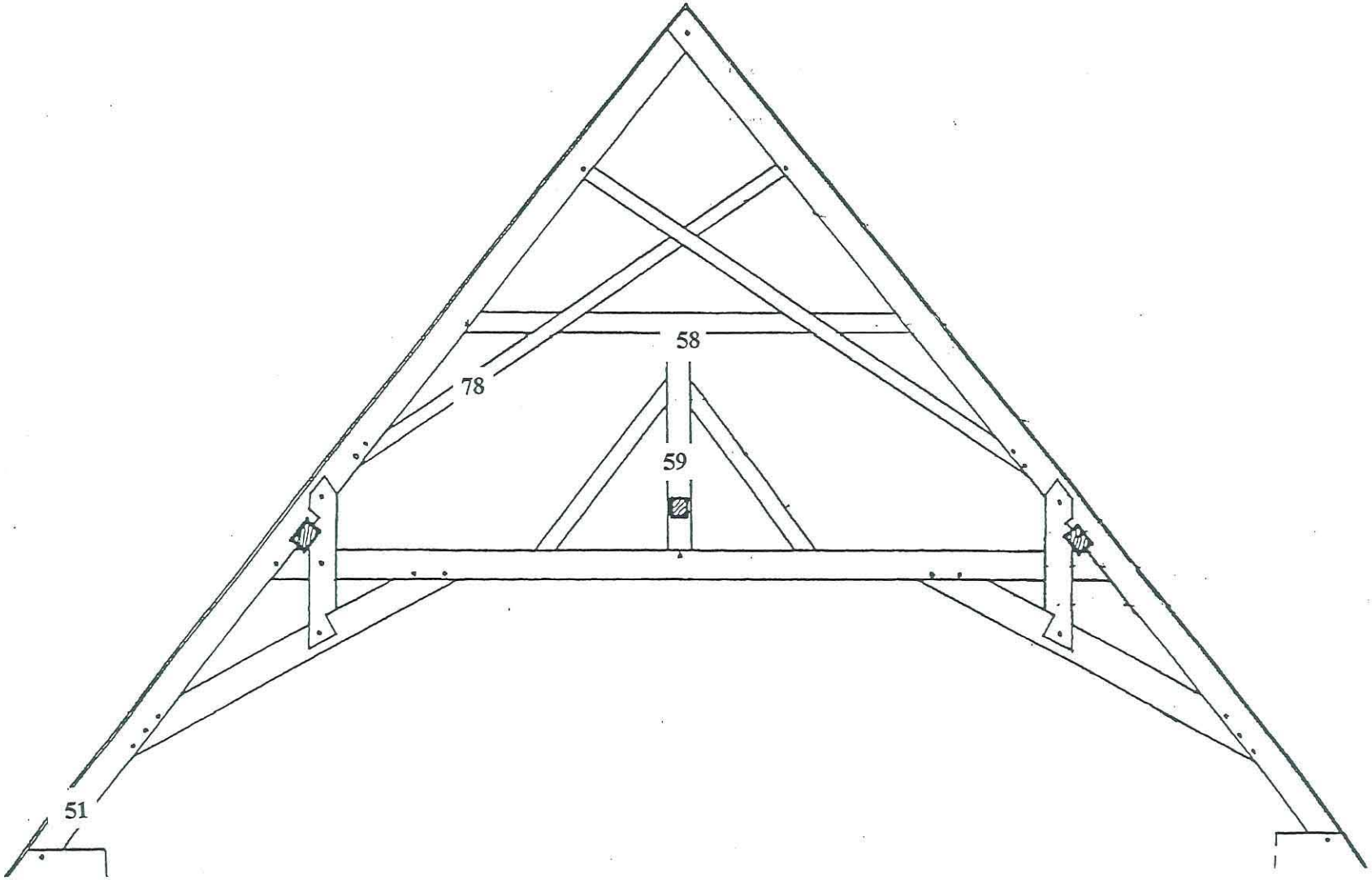


Figure 17j: Drawing of frame 21 of the Choir and crossing, viewed from the east, to show sample locations

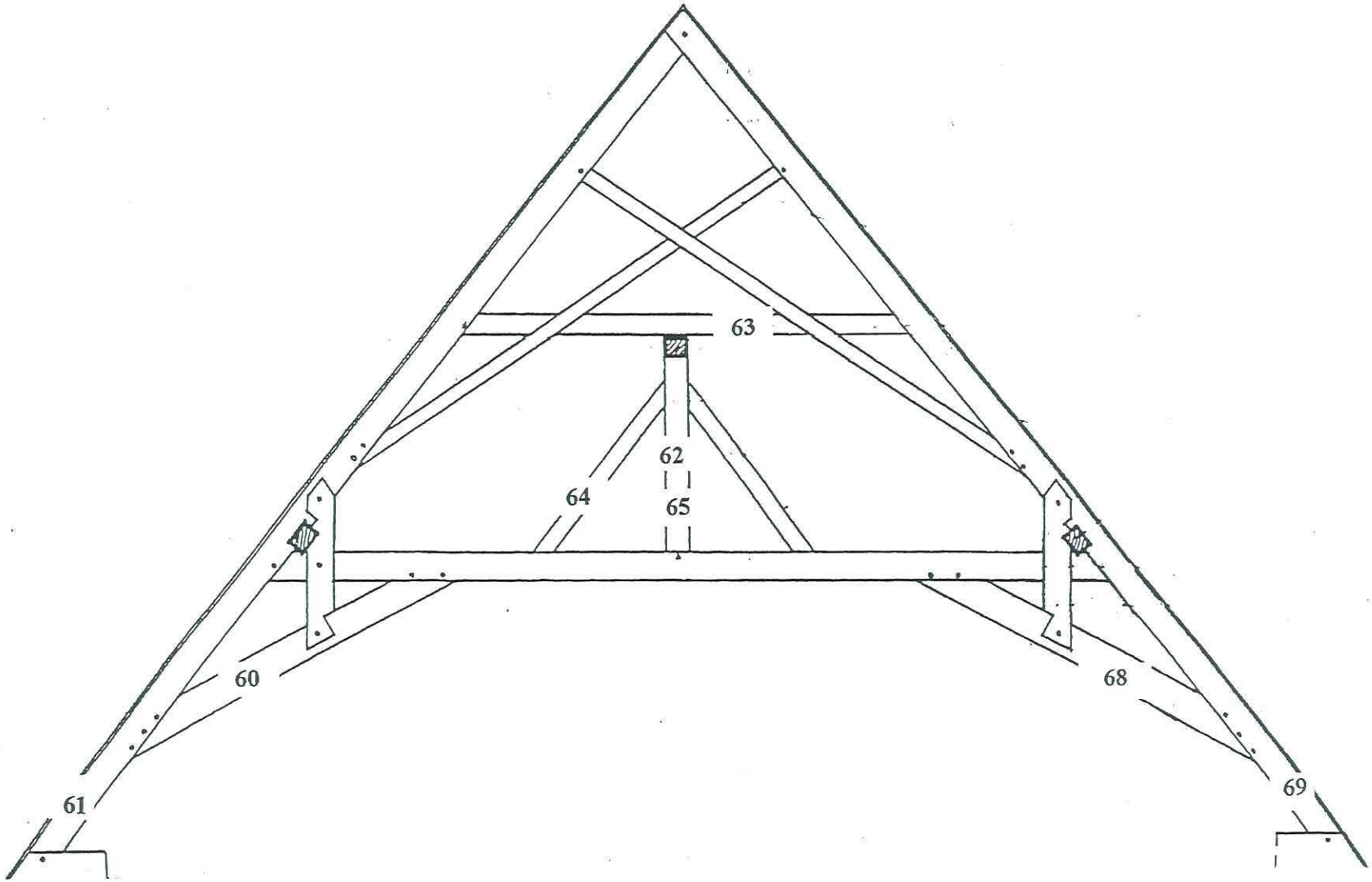


Figure 17k: Drawing of frame 37 of the Choir and crossing, viewed from the east, to show sample locations

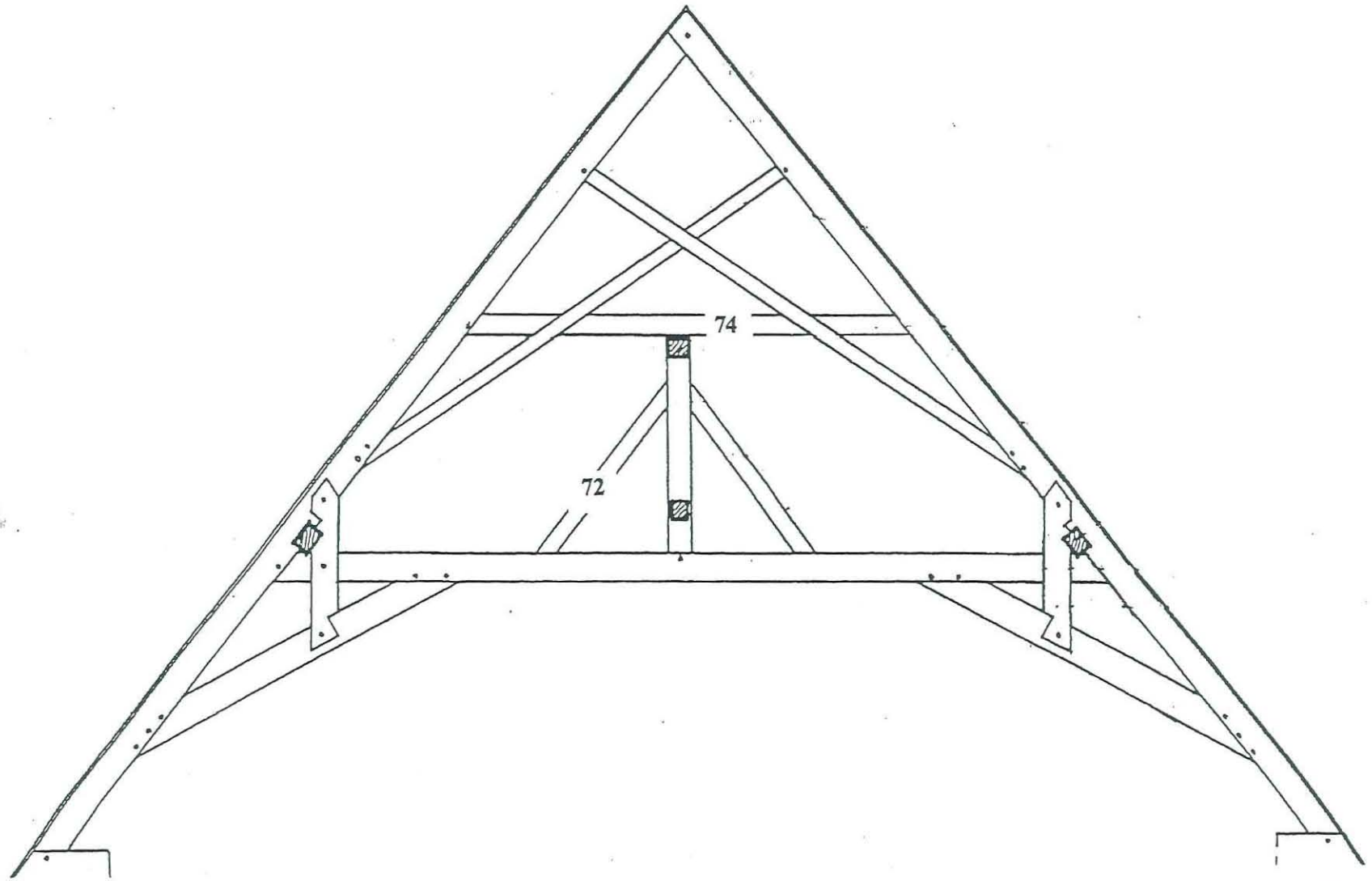


Figure 17l: Drawing of frame 36 of the Choir and crossing, viewed from the east, to show sample locations

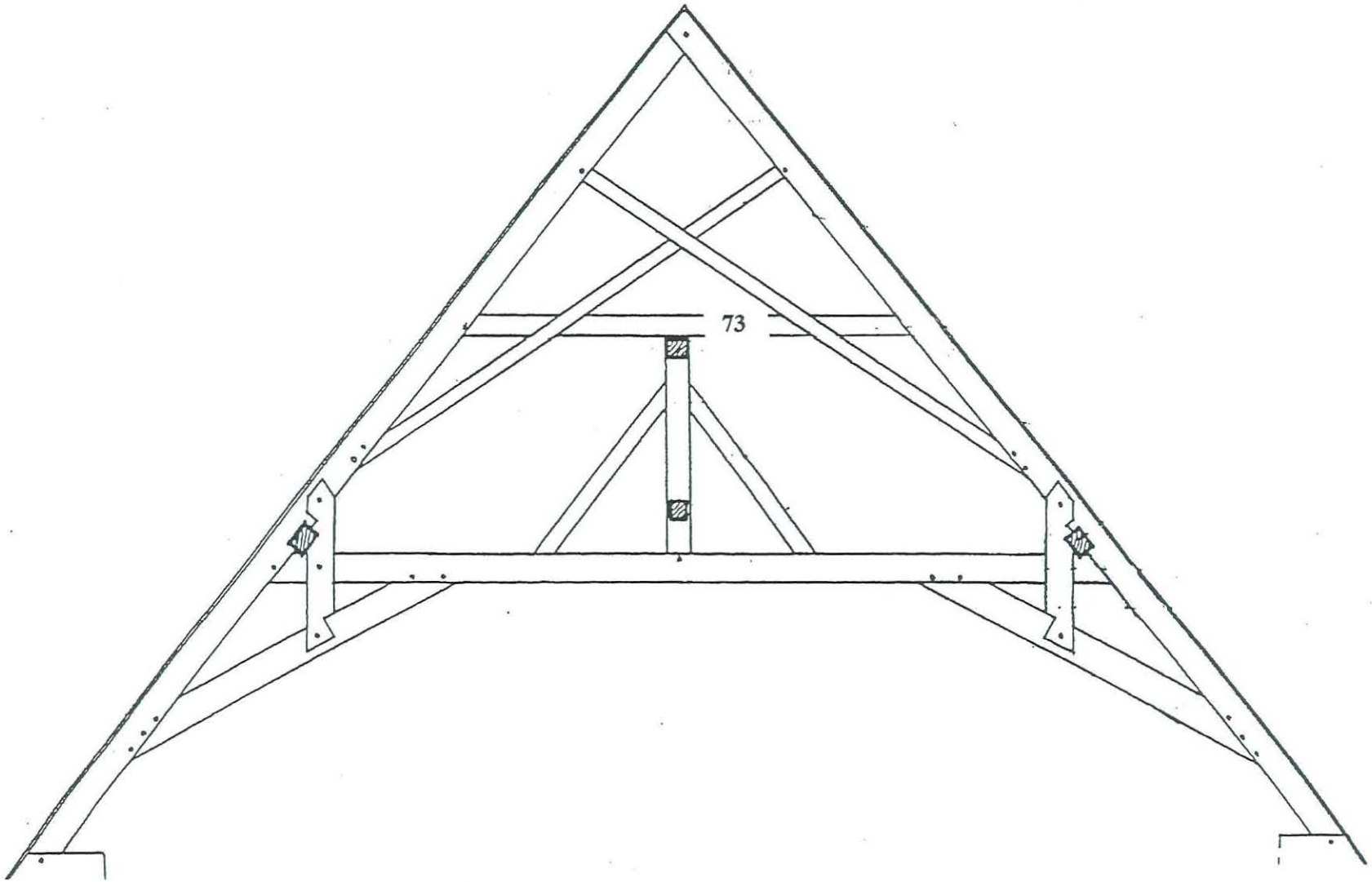


Figure 17m: Drawing of frame 44 of the Choir and crossing, viewed from the east, to show sample locations

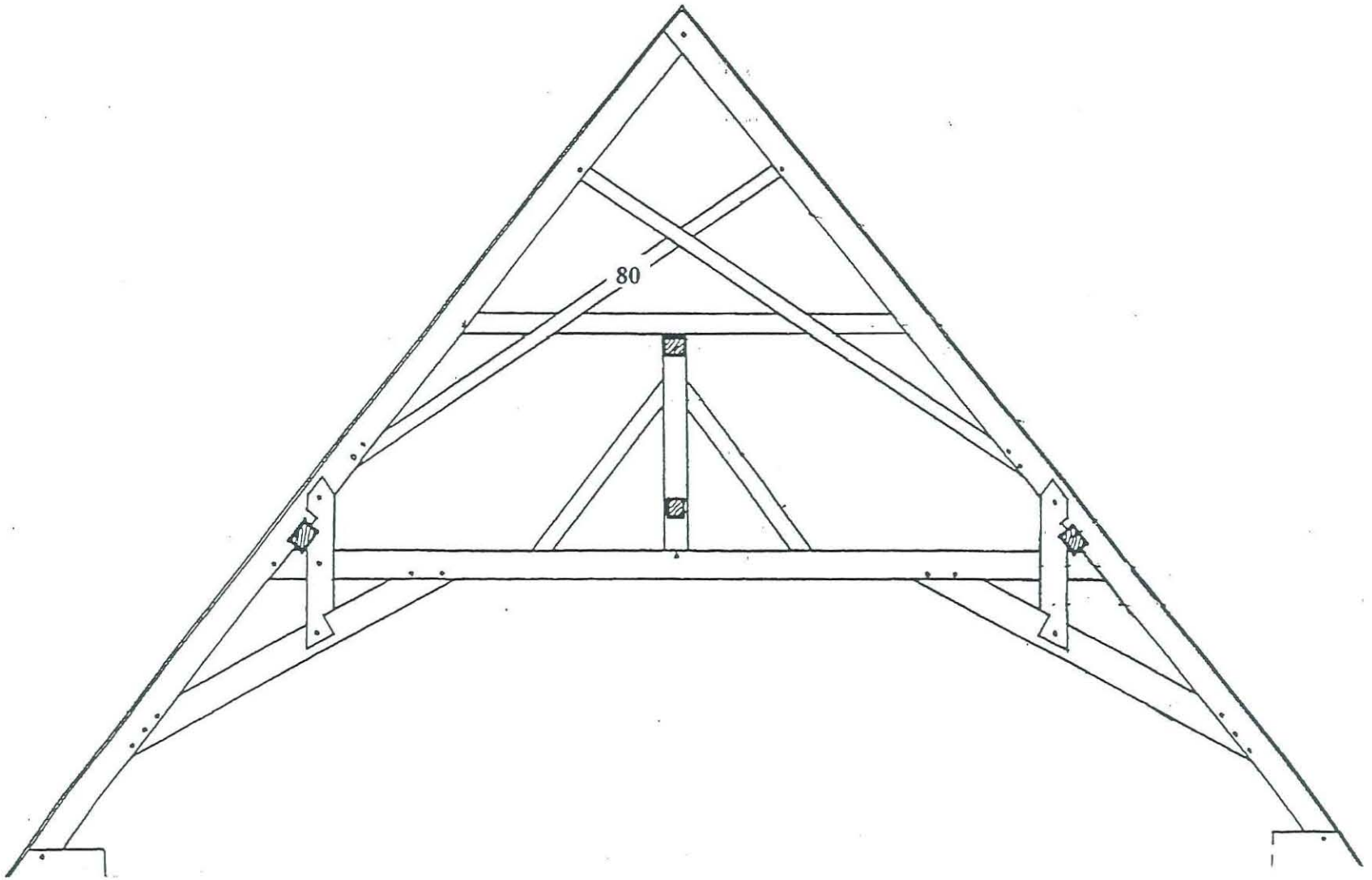


Figure 17n: Drawing of frame 69 of the Choir and crossing, viewed from the east, to show sample locations

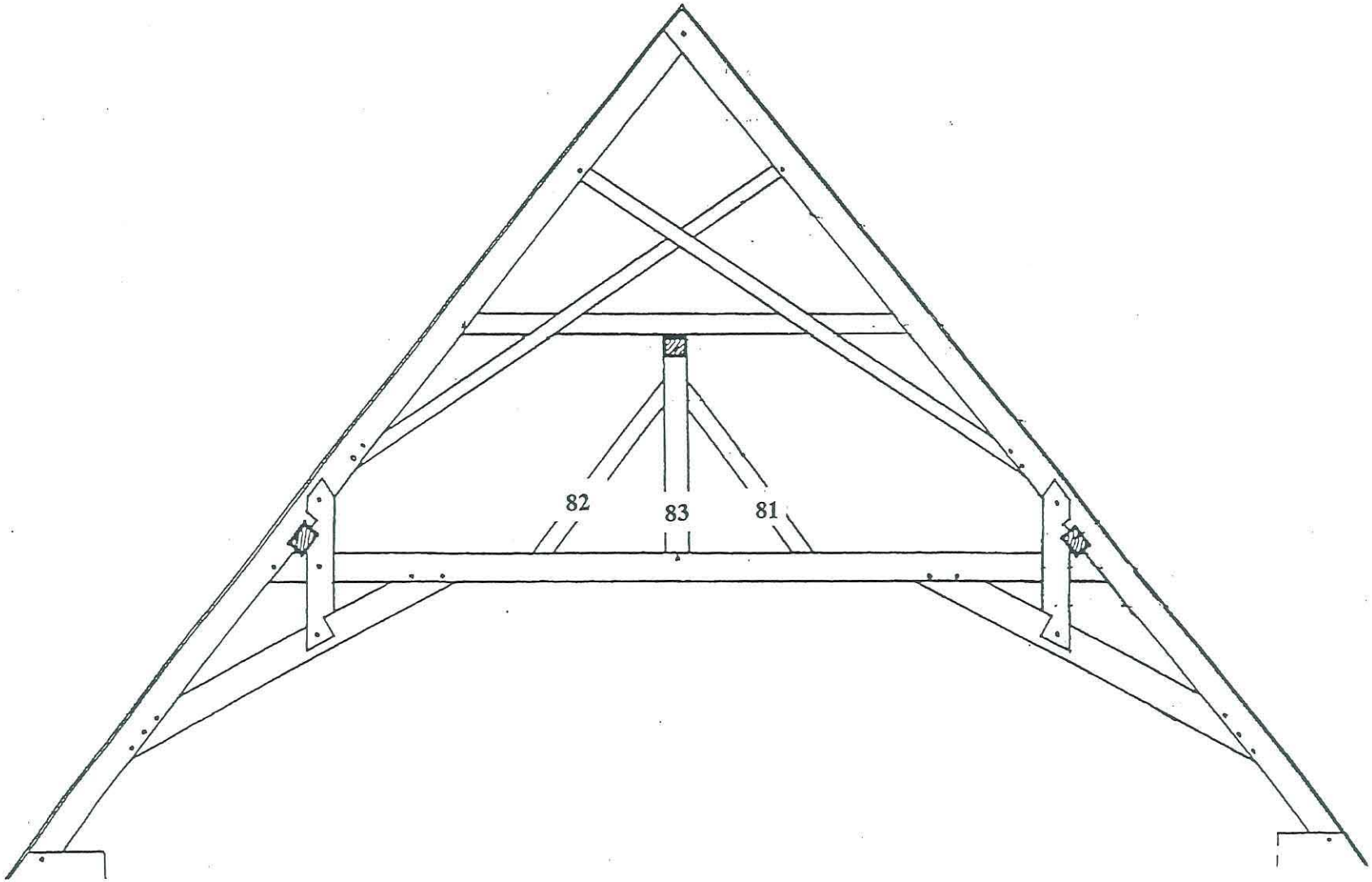


Figure 17o: Drawing of frame 66 of the Choir and crossing, viewed from the east, to show sample locations

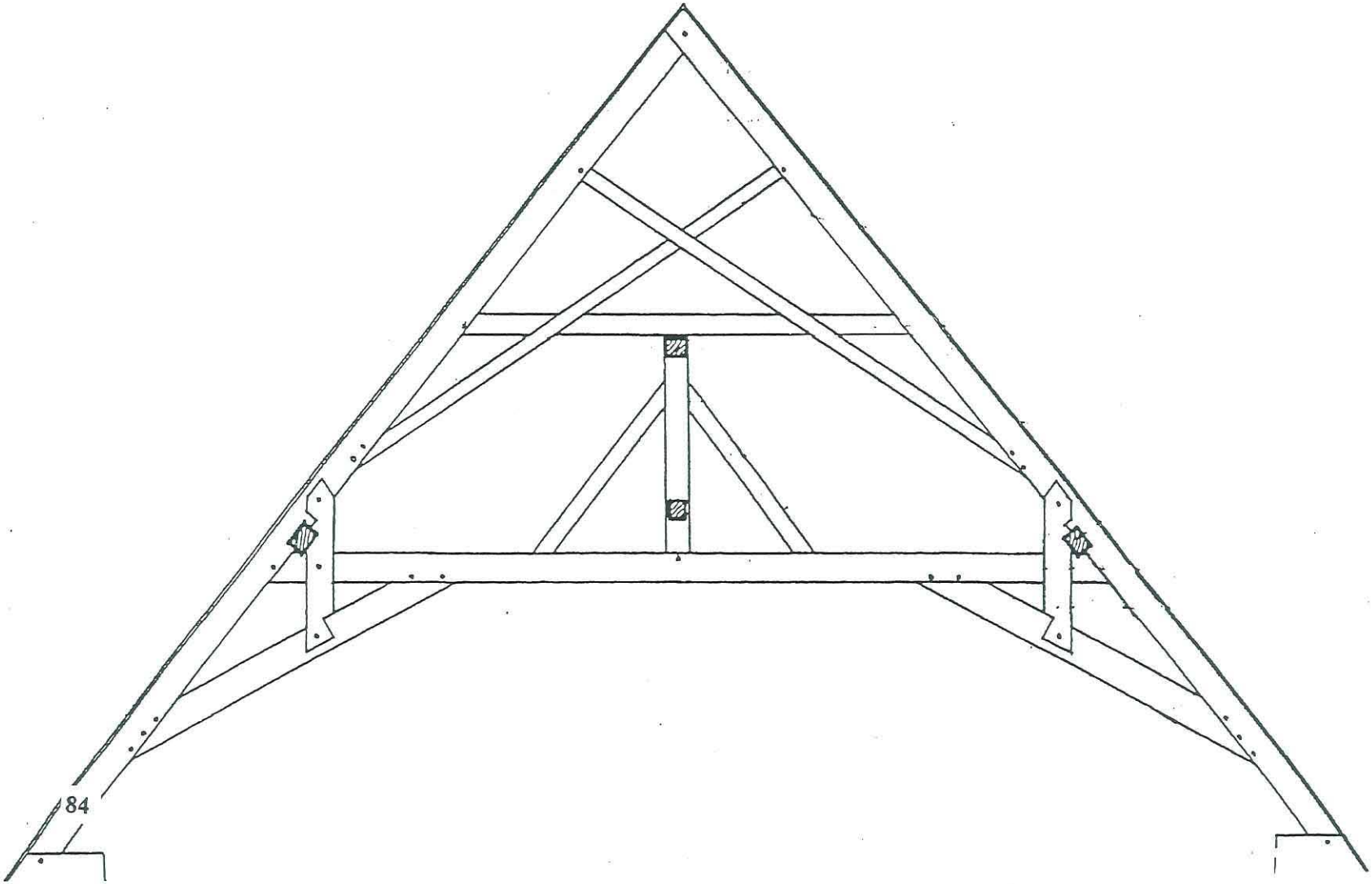


Figure 17p: Drawing of frame 71 of the Choir and crossing, viewed from the east, to show sample locations

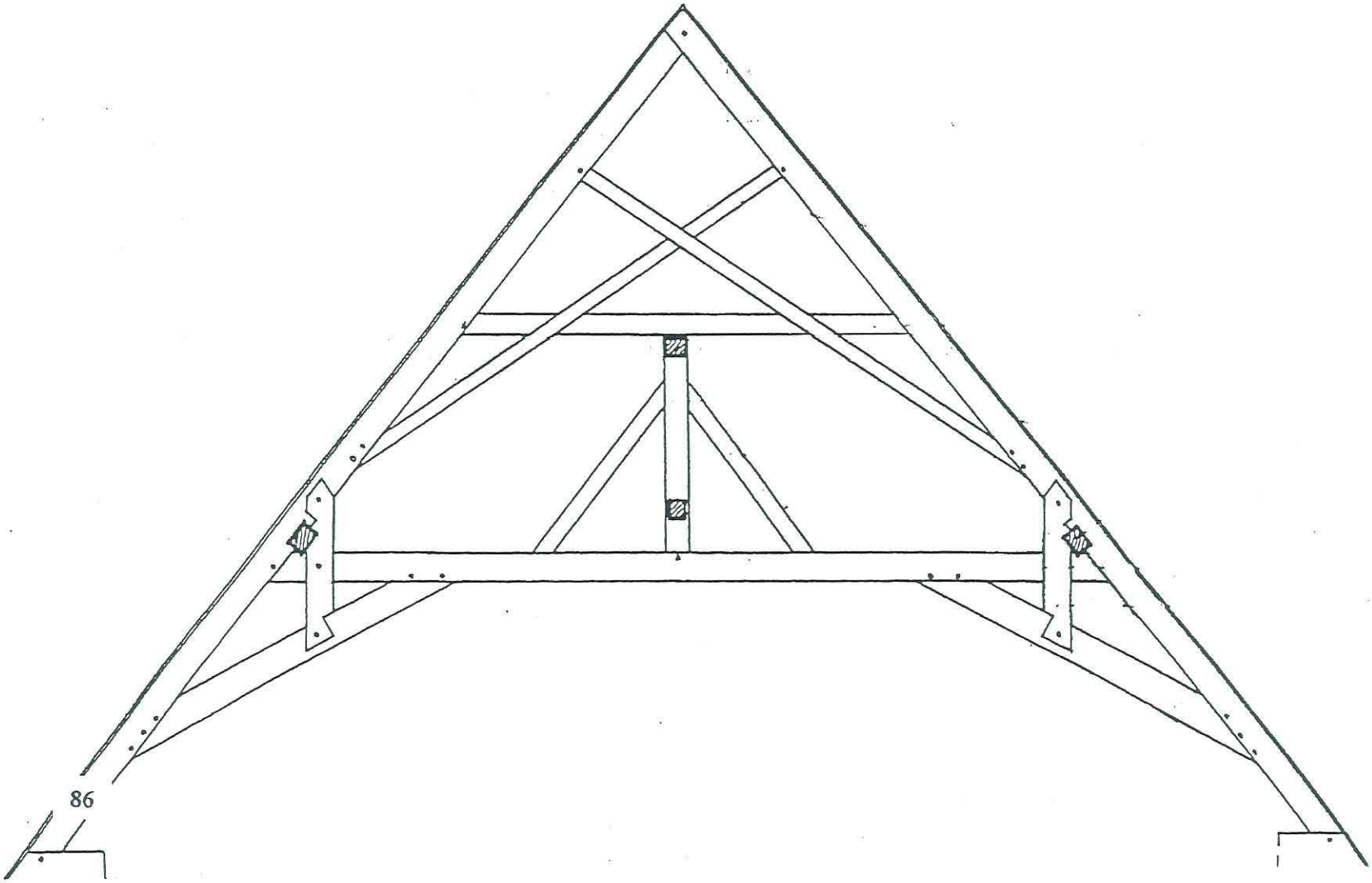


Figure 17q: Drawing of frame 65 of the Choir and crossing, viewed from the east, to show sample locations

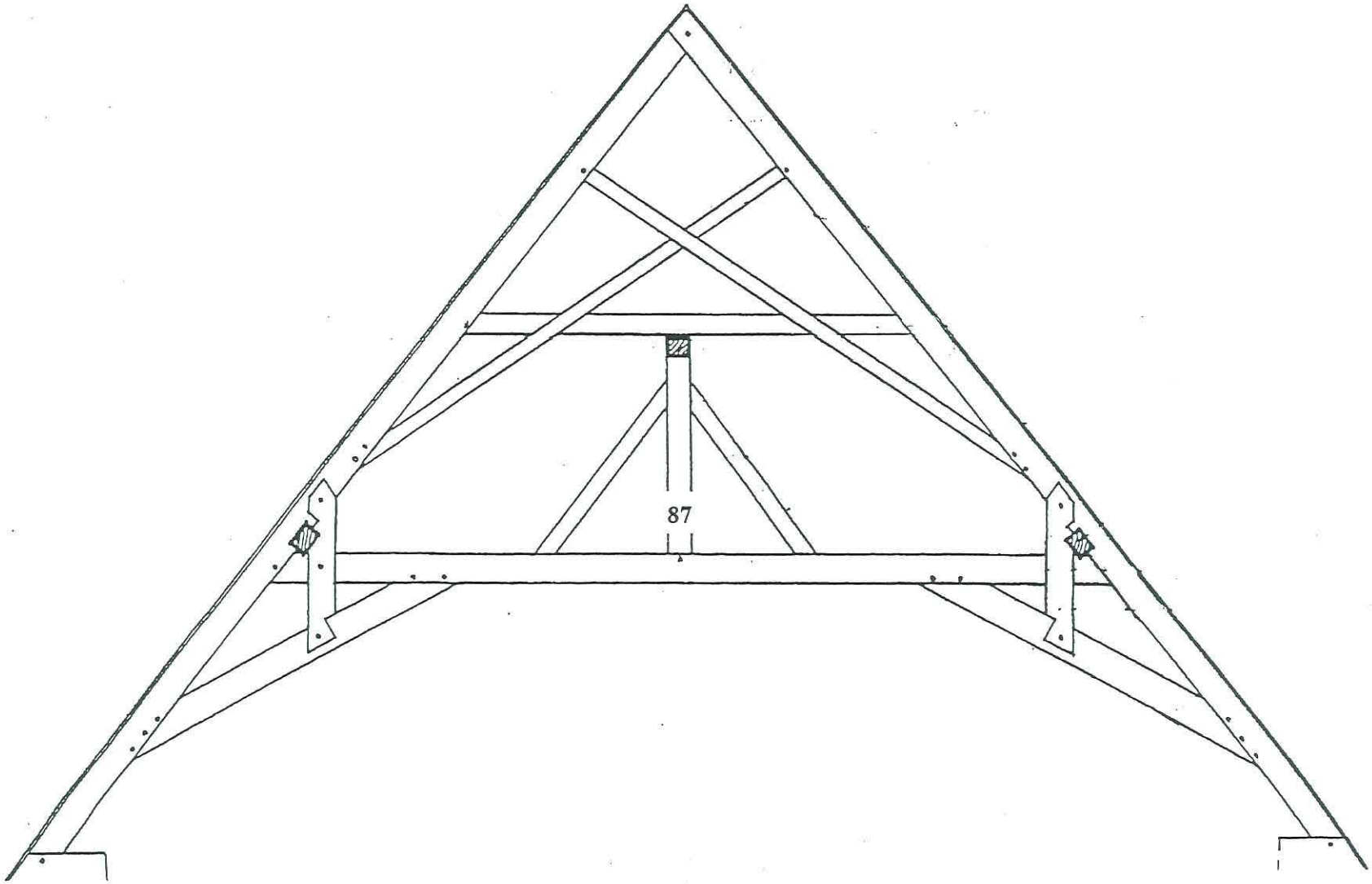


Figure 17r: Drawing of frame 63 of the Choir and crossing, viewed from the east, to show sample locations

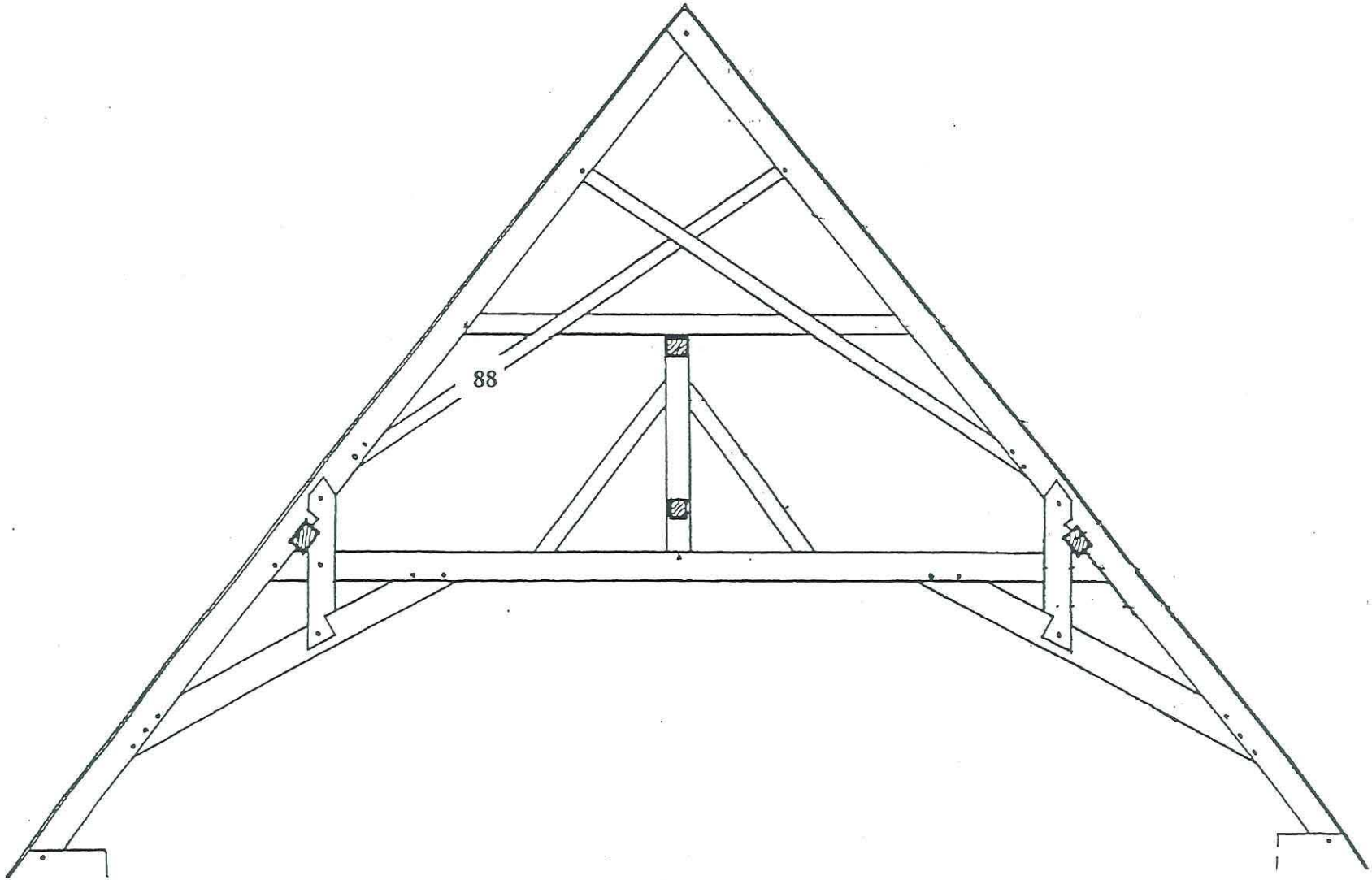


Figure 17s: Drawing of frame 64 of the Choir and crossing, viewed from the east, to show sample locations

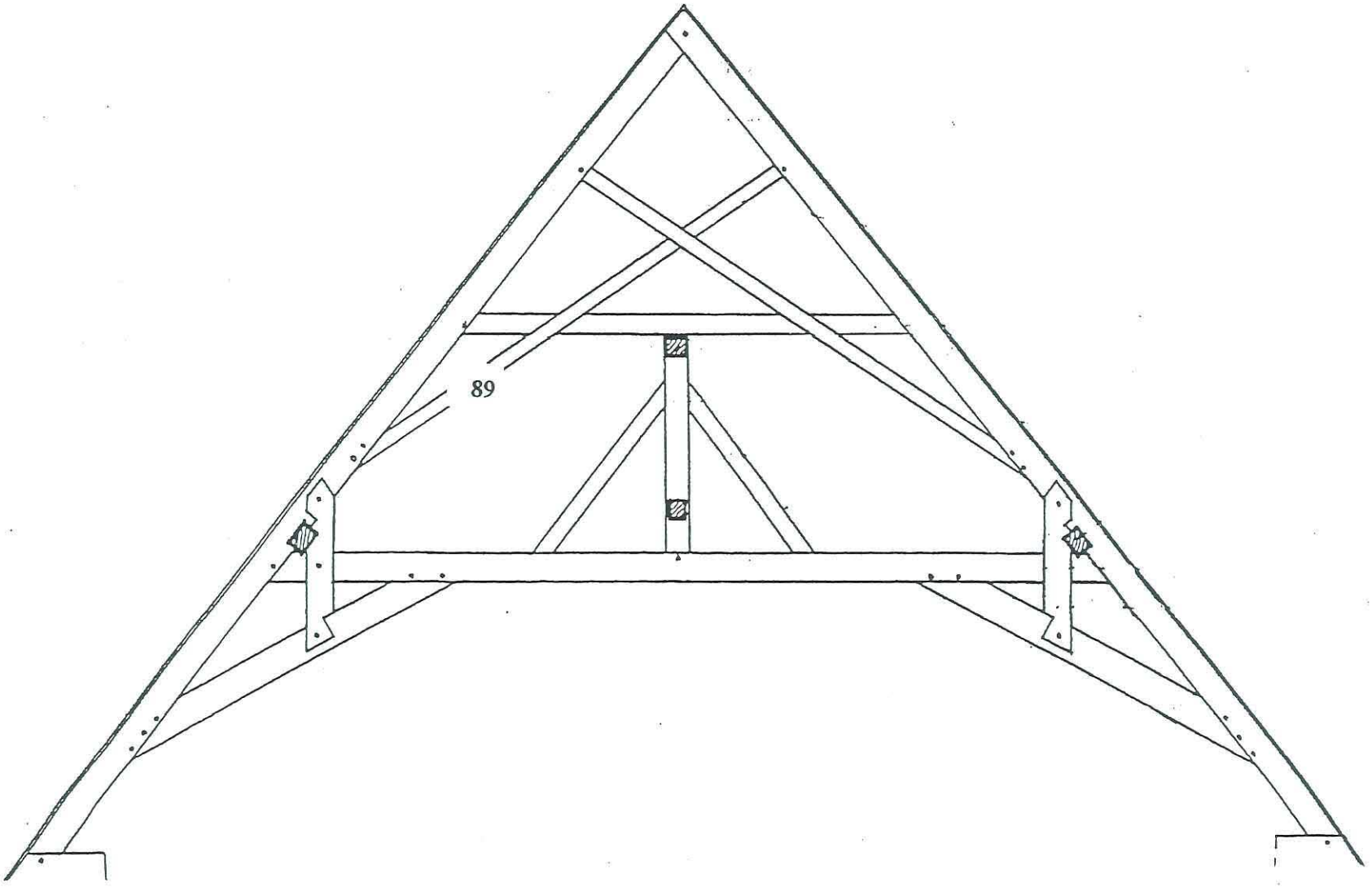


Figure 17t: Drawing of frame 72 of the Choir and crossing, viewed from the east, to show sample locations

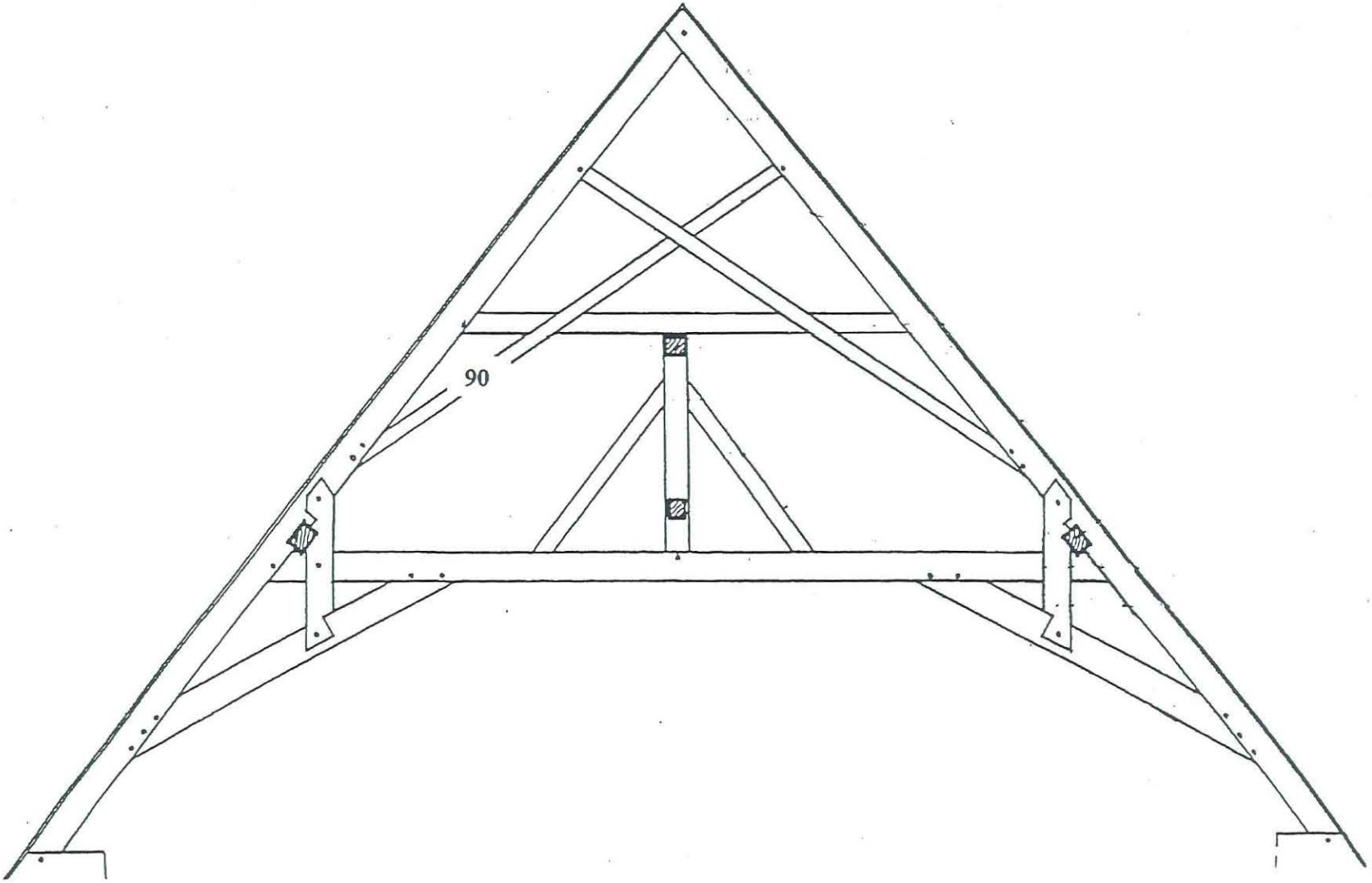
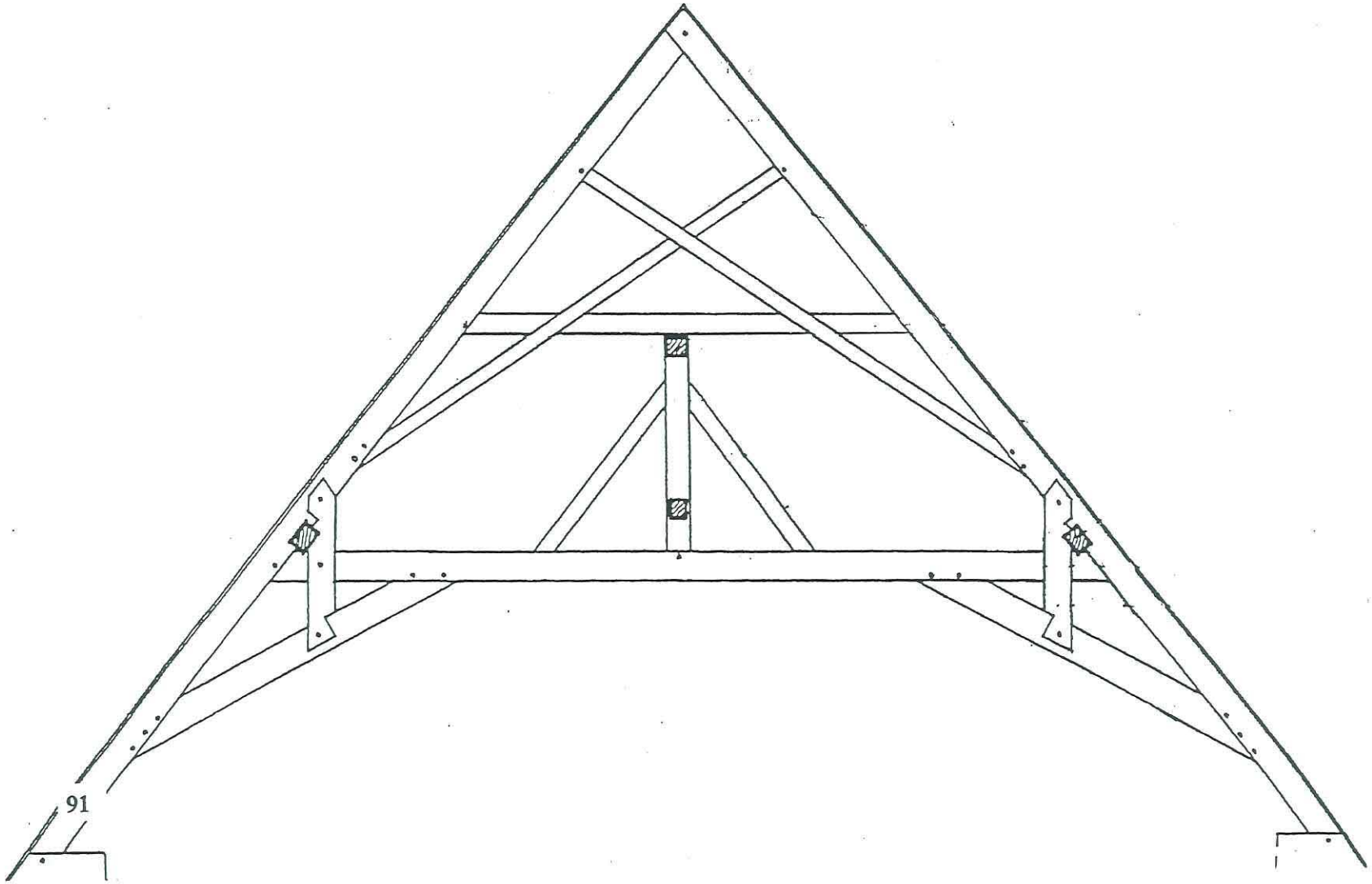


Figure 17u: Drawing of frame 74 of the Choir and crossing, viewed from the east, to show sample locations



Data of measured samples – measurements in 0.01 mm units

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100 113 83 108 108 82 111 91 97 111 132 114 121 86 94 110 79 56 67 86
58 46 54 48 90 58 71 86
EXT-C01B 68
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221 118 159 134 80 90 120 108 99 69 57 77 74 85 95 135 143 99 85 117
106 109 77 118 106 89 105 99 95 117 120 104 124 91 83 114 84 61 52 76
58 51 48 62 91 61 74 89
EXT-C02A 109
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106 159 154 174 81 113 88 86 88 67 59 103 120 152 135 101 102 64 98 120
192 146 130 104 99 84 98 94 87 119 102 112 91 54 65 110 121 186 132 171
167 164 77 64 84 94 90 81 132 134 115 111 100 95 104 110 81 104 109 114
123 136 139 118 114 82 94 85 81 170 148 123 112 102 128 94 123 122 102 102
101 133 133 122 158 167 86 102 148
EXT-C02B 109
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110 180 142 171 86 112 87 78 74 71 50 106 111 152 130 103 106 64 91 112
194 146 122 104 90 82 104 95 97 122 103 107 97 71 62 114 119 201 138 179
163 160 73 67 67 105 83 75 133 139 110 124 98 86 115 107 80 99 111 120
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87 148 116 127 172 150 94 108 135
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113 128 156 183 116 143 138 107 98 114 140 212 143 156 194 176 62 121 112 113
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73 110 131 209 138 144 164 143 148 163 173
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251 230 298 191 205 136 222 236 169 166 97 141 163 194 185 182 184 191 216 184
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110 85 108 114
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96 78 98 117

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66 73 70 58 79 81 39 56 72 115 62 102 91 80 72 93 92 109 118 150
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190 229 166 169 176 114 178 286 280 291 220 155 150 148 123 129 116 183 162 168
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137 128 89 64 91 81 84 99 84 77 84 100
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EXT-C07B 72
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142 143 105 149 214 152 213 210 156 129 133 103 140 176 197 268 175 162 175 144
96 85 114 169 162 218 284 208 182 195 139 139
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186 152 227 134 81 102 106 92 98 87 124 180 156 159 109 115 89 99 96 121
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122 116 149 127 165 136 187 185 147 111 144 130 103 64 80 113 75 77 95 103
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139 124 124 123 85 104 95 94 122 110

EXT-C09A 88
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96 105 101 119 125 127 154 159 128 132 113 101 75 87 103 76 125 151 132 105
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297 253 171 130 133 161 230 155 224 231 168 179 135 157 180 203 121 156 173 210
177 144 211 189 118 132 131 108 109 87 97 80 68 107 102 144 148 135 90 124
94 81 94 69 92 91 99 58 73 90 84 89 93 141 103 78 68 78 93 173
164 144 150 127 85 93 121 124 128 153 191 209 176 154 130 109 158 142 134 112

108 119 125 99 102 77 127 124 118 122 202 156 117 112 131 115
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207 130 211 184 122 122 124 124 108 82 100 71 80 98 112 143 140 129 98 126
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169 154 251 237 308 196 180 136 129 137 138 193 213 232 140 156
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EXTC103B 58
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93 108 101 158 88 274 167 133 214 128 137 187 178 146 202 229 139 281 218 216
160 316 196 198 194 319 454 390 264 351 315 277 248 256 269 179 125 186

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151 181 185 226 220 279 130 211 228 205 237 222 342 298 139 157 192 118 144 114
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

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

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

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

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

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

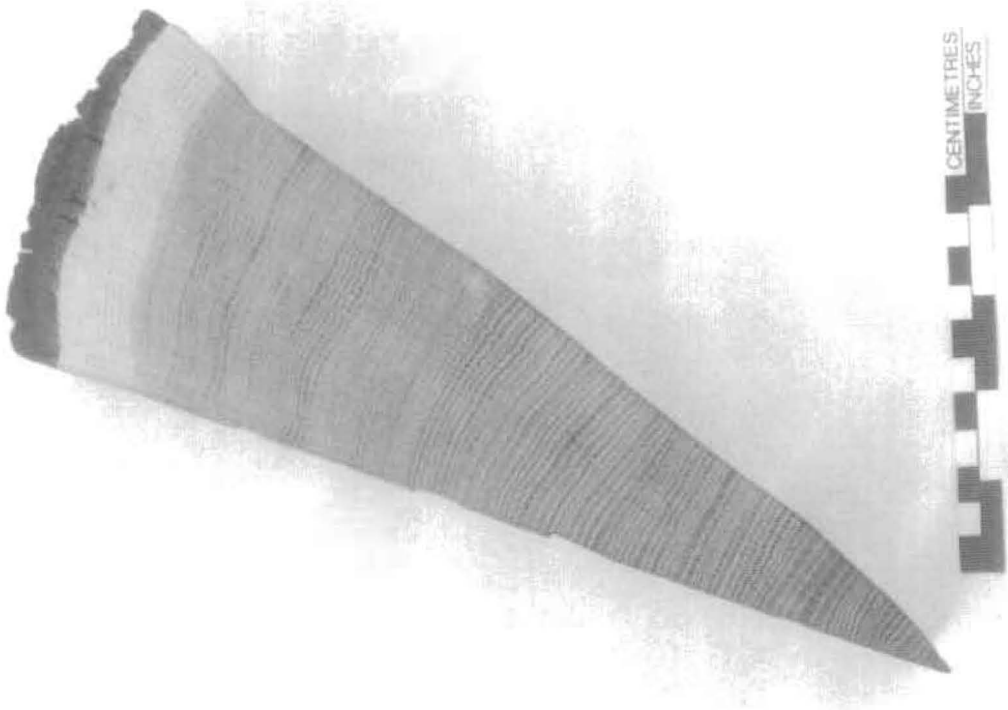

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

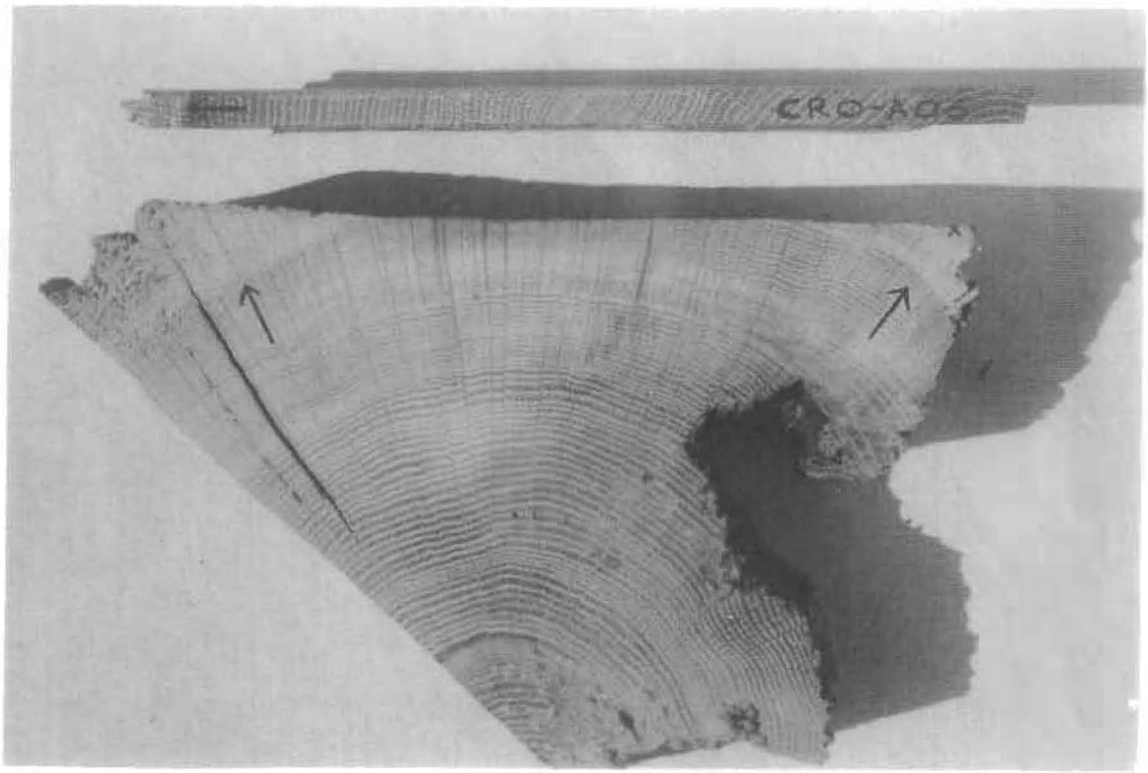

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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

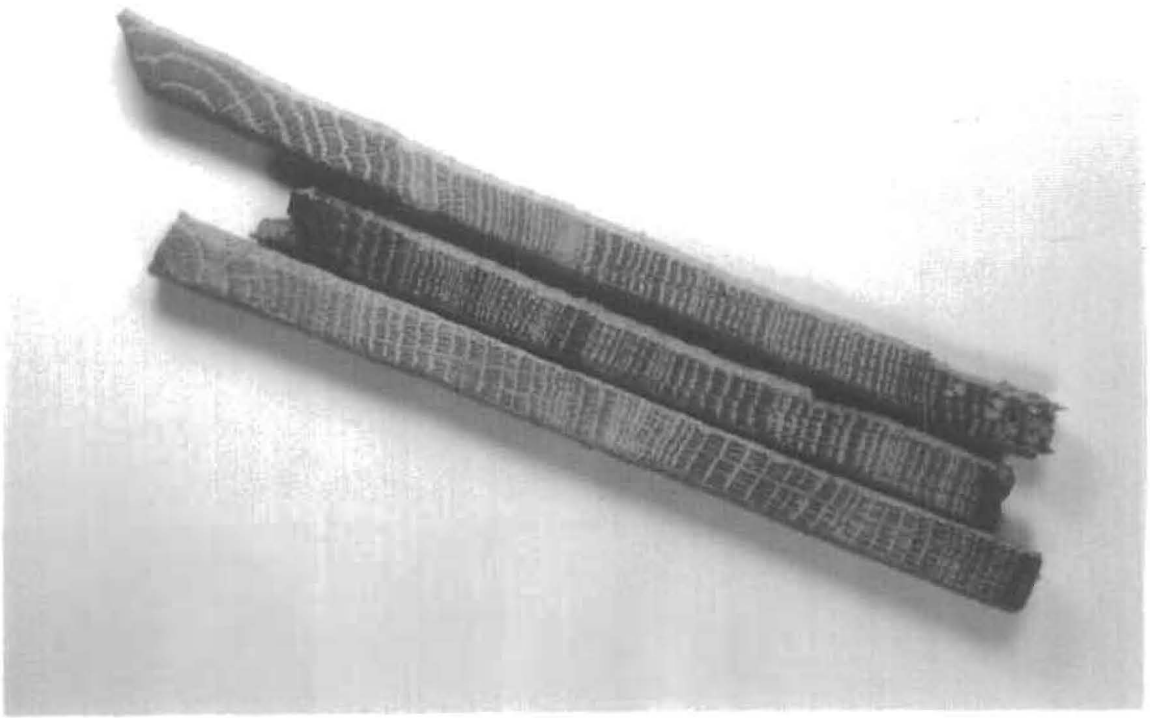

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

T-value/Offset Matrix

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

Bar Diagram

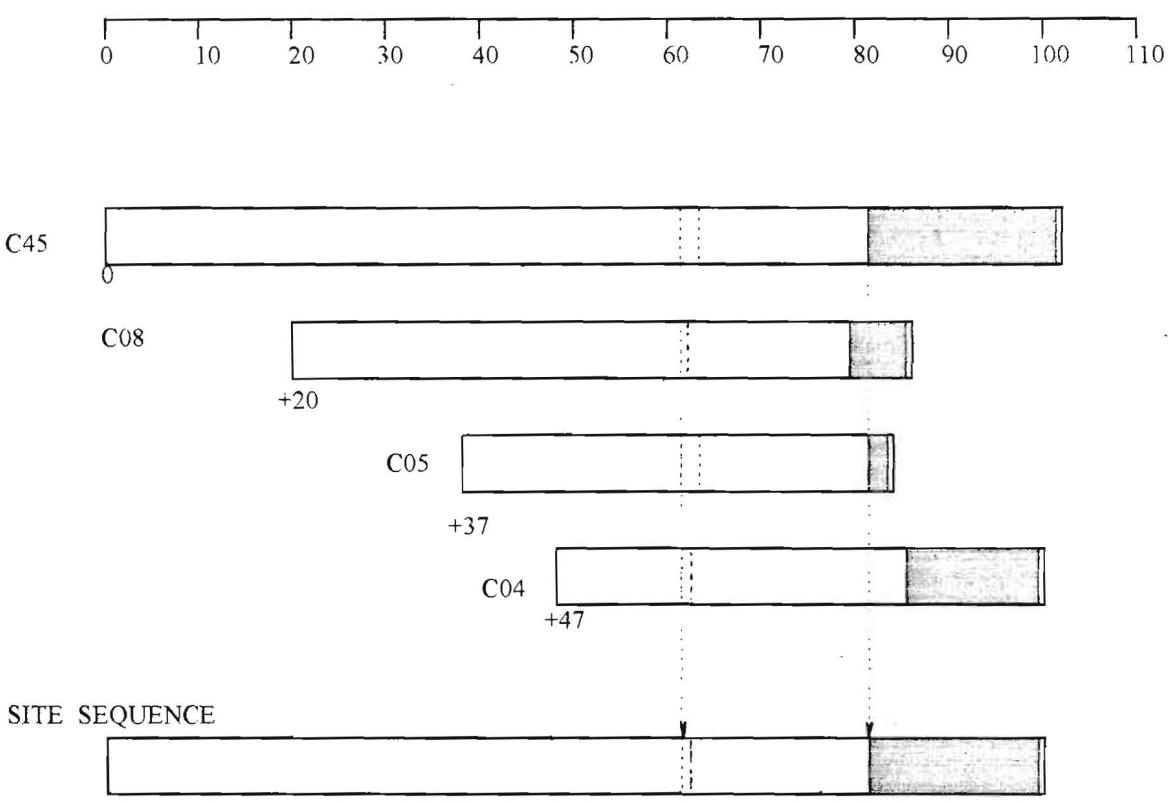

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions *(offsets)* to each other at which they have maximum correlation as measured by the *t-values.*

The *t-value offset* matrix contains the maximum t-values below the diagonal and the offsets above it. Thus, the maximum t-value between C08 and C45 occurs at the offset of +20 rings and the t-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

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

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

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

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

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

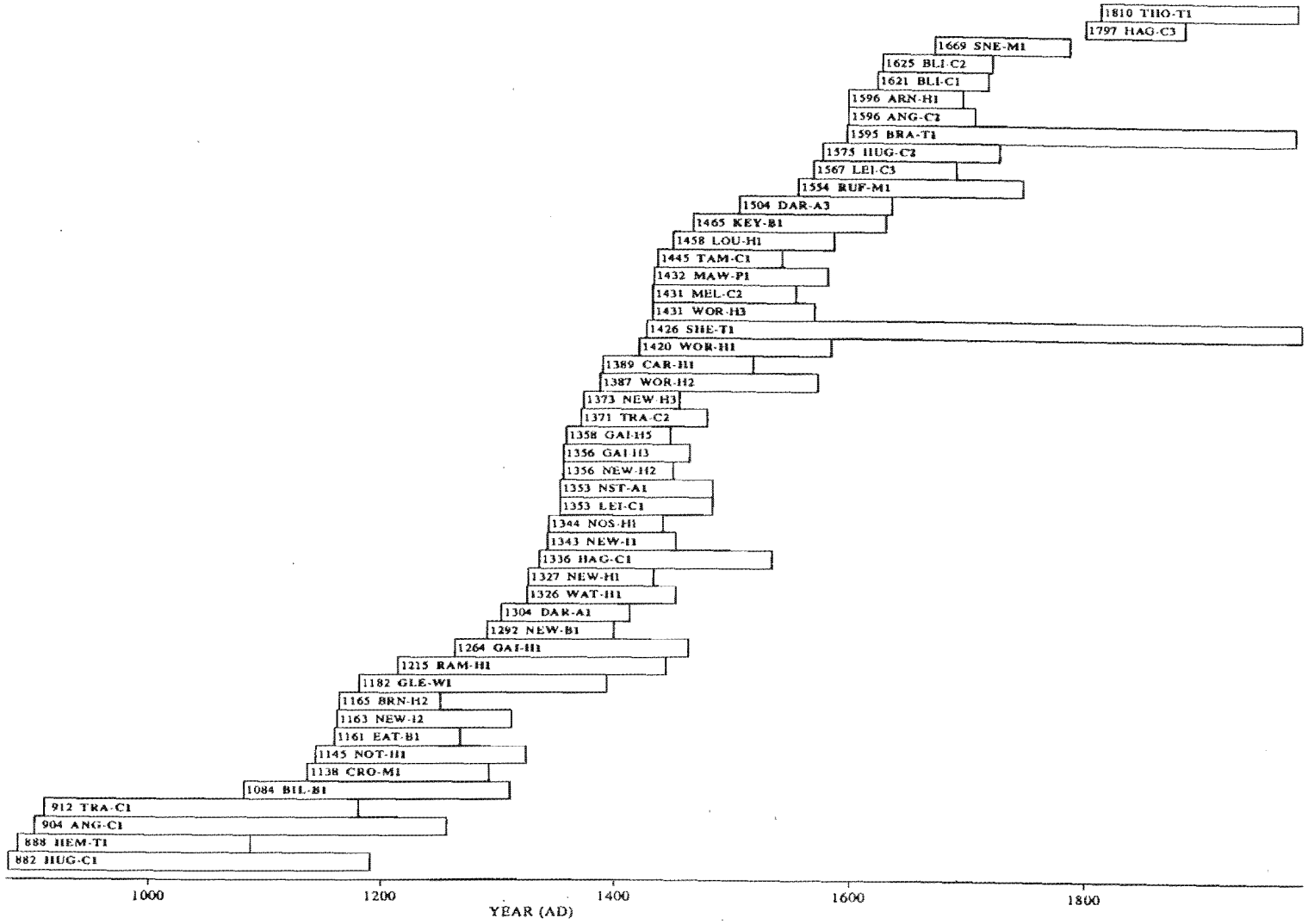

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

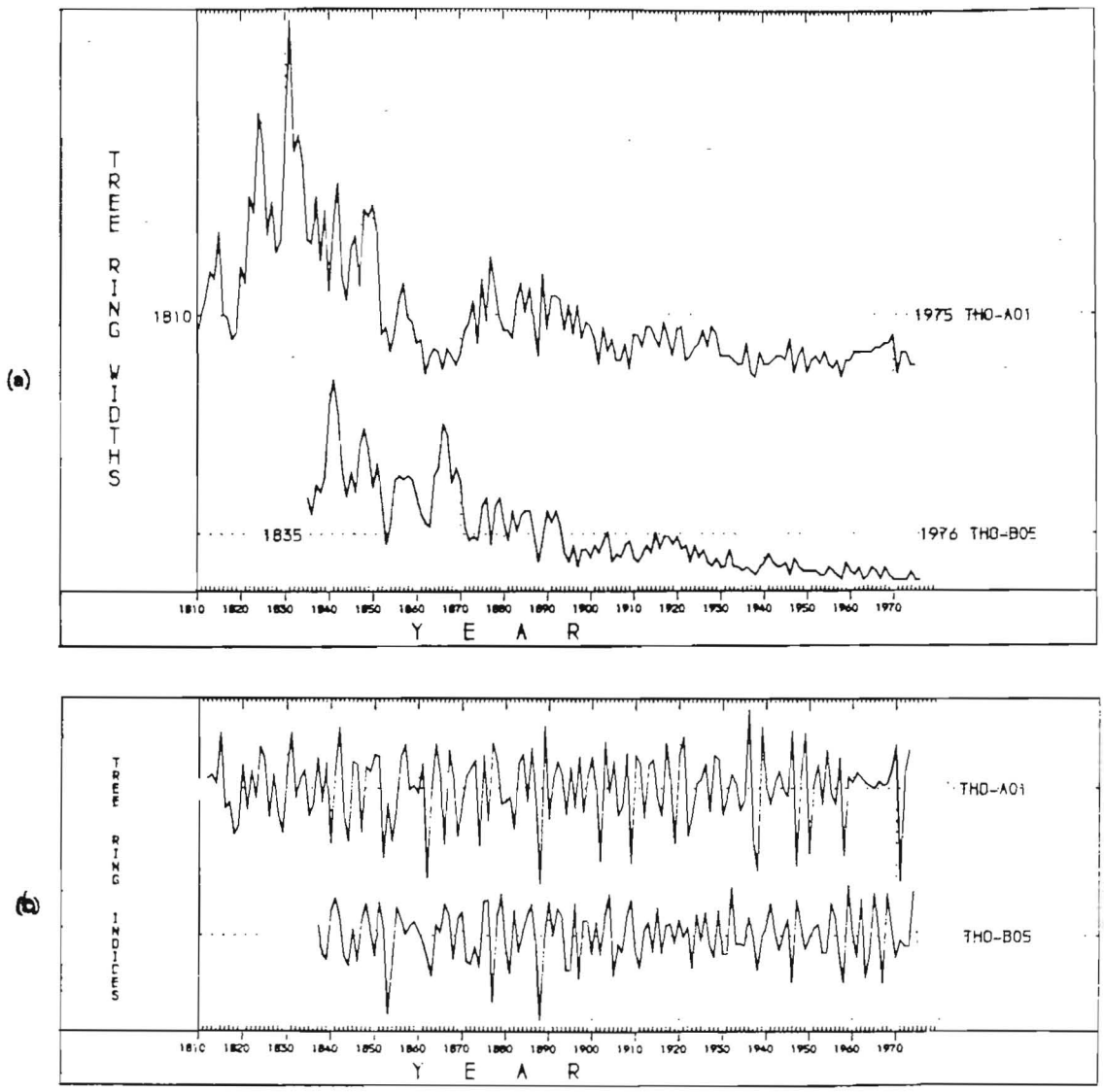

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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

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

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