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Ancient Monuments Laboratory
Report 1/99

TREE-RING ANALYSIS OF THE BELL TOWER OF THE CHURCH OF ST MARY, PEMBRIDGE, HEREFORDSHIRE

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Summary

The bell tower of the church of St Mary, Pembridge, Herefordshire, is a detached structure approximately 15 m north of the chancel of the church. The four main posts of the tower include redundant notched lap-joints. As a result of the presence of these stylistic features, dates between the eleventh and fourteenth century have been offered for this phase. Later, a major modification, or series of modifications have been carried out upon the structure which have had suggested dates ranging between the fourteenth and seventeenth centuries. This report covers the dendrochronological analysis of 53 oak timbers within the tower and the bellframe that was undertaken in an attempt to clarify the dating of both the earliest surviving timbers and the vaious phases of modification. This analysis indicates that the present structure is the product of a single phase of construction, or more likely a major re-construction dated to AD 1668/9. This construction incorporated re-used timbers which are of early thirteenth-century date and are present throughout the structure whilst a smaller group of re-used sixteenth-century timbers are located in the upper spire.

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TREE-RING ANALYSIS OF THE BELL TOWER OF THE CHURCH OF ST MARY, PEMBRIDGE, HEREFORDSHIRE

Introduction

This document is a technical archive report on the tree-ring analysis of oak timbers from the bell tower of the church of St Mary, Pembridge, Herefordshire (NGR SO392581). It is beyond the dendrochronological brief to describe the building in detail or to undertake the production of detailed drawings. As part of a multifaceted and multidisciplinary study of the building, elements of this report may be combined with detailed descriptions, drawings, and other technical reports at some point in the future to form either a comprehensive publication or an archive deposition on the building. The conclusions may therefore have to be modified in the light of subsequent work.

The bell tower at the church of St Mary, Pembridge, is an unusual detached structure 15 m north of the chancel of the church. There are four major timber elements to the bell tower: a tower, a series of trusses, a spire, and a bellframe (Fig 1). The structure has four massive vertical posts forming the principal corners of a square **tower** rising approximately 10.5 m (Fig 2a). The tower has a large number of integral horizontal, vertical, and X-framed timbers. Around this central tower are a series of twelve **trusses** (Fig 2b), ten of which connect with wall plates on the surrounding octagonal stone wall (Fig 3a). The other two are of slightly different construction and rise from the ground and connect with the wall plates (Fig 3b). The wall and trusses form an ambulatory around the tower. These trusses all rise to meet the main tower at *c* 8 m height, presumably providing increased lateral stability. Above the main tower is a smaller **spire**, rising a further *c* 8 m, which is supported from foundation beams crossing the top of the main tower. The main posts for the spire are jointed to these foundation beams using through-tenons with face pegs. The structure has three separate levels of roof: the lower pent roof above the supporting trusses giving the appearance of a skirt, an upper pent roof atop the main tower surrounding the spire, and the spire's pyramidal roof. A timber **bellframe** with five bells is at the upper level of the tower. Using the modern classification scheme (Pickford 1993, 26 and 53), this is of type 6.A and layout 5.3 (Fig 4). The bellframe appears to be fairly complete and includes a decorated moulding on the heads.

The dating of the bell tower as a whole has been the subject of much speculation over the years. Pevsner (1963, 267) regarded the building as late fourteenth-century in origin, and several other authors follow this opinion. There are four documented recent phases of repair:- 1829, 1898, 1956, and 1982-4, but it is widely assumed that the structure has been subjected to a whole series of undocumented repairs and re-construction phases throughout its life. The presence of notched lap-joints on the four corner posts indicates an early date for these timbers, since evidence from elsewhere in the country suggests a date of between AD 1200 and AD 1350 for this joint type (eg Walker 1998). The date of one of the main posts at Pembridge has previously been subject to dendrochronological analysis. Fletcher (1980, 34) provides a date of 'after 1115' based on the analysis of the sequence from one post, probably measured *in situ* by Dr O Rackham, (op cit, 38, note F7, see also Webster and Cherry 1980, 245). This early date for a post at

Pembridge led to speculation that the posts are re-used from a motte and bailey castle (Higham and Barker 1992).

Pembridge is the westernmost of a cluster of four detached timber belfries that all exhibit structural evidence for an early date. The tower at Mamble, Worcestershire, *c* 35 km east-north-east of Pembridge, has recently been the subject of dendrochronological analysis and the original timbers here were felled between AD 1214 and *c* AD 1255 (Tyers 1996a). There are two other detached timber bell towers at the northern end of the historic counties of Herefordshire and Worcestershire:- Yarpole, *c* 15 km north-east and Knighton-on-Teme, *c* 27 km east-north-east, both are suitable for dendrochronological analysis but neither have been sampled yet.

A comprehensive tree-ring dating programme at Pembridge was requested by David Heath from English Heritage primarily to provide a precise series of dates for the various structural phases. Whilst it was clear that the four main posts were early, and the reliable dating of these was an important component of the study, it was assumed that a number of other modification or repair phases were likely to be identified and dated. An extensive sampling programme was therefore undertaken in an attempt to elucidate the complex history of the structure.

It was hoped that the production of reliable dendrochronological results for the bell tower at Pembridge would

- identify and date some of the undocumented modification phases, leading to new theories and models for the development sequence of the tower
- bring the carpentry techniques, and other cultural features, employed at Pembridge into the typological frameworks established for such items in the rest of the country
- and identify the extent of, and date, the re-used timbers located in the bell tower

Initially 40 samples (from 38 timbers) were obtained from the structure in February 1996, but due to lack of safe access above the bellframe level this phase of the work did not entirely clarify the phases of construction (Tyers *et al* 1997). Subsequently Richard K Morriss and Associates, and Archaeological Investigations Ltd were commissioned by English Heritage to undertake a structural analysis report and to produce a comprehensive drawn survey (Morriss *et al* 1998). The insertion of a scaffold platform in the spire for this work provided an opportunity to obtain a further 16 samples (15 timbers) from both the spire and the upper pent roof in March 1998. This report uses modified versions of some of the new plans and drawings produced as part of the 1998 survey work (Morriss *et al* 1998).

In order to reduce the potential for confusion the sampling locations were recorded with reference to the truss letters (Fig 2b) and the rail numbers (Fig 5) first allocated by Baart (1982).

Methodology

The general methodology and working practises used at the Sheffield Dendrochronology Laboratory are described in English Heritage (1998). The methodology used for this building was as follows.

The dendrochronological sampling programme attempted to obtain cores from as broad a range of timbers, in terms of structural element types, scantling sizes, and carpentry features, as was possible within the terms of the request. Almost all the timbers in the bell tower are of oak (*Quercus* spp.), the only exceptions are from the most recent intervention phases which have introduced some softwood timbers. Note that access to the spire above the foundation beams was safely achieved only after scaffolding had been erected at the top of the tower during the 1998 recording work.

A brief survey identified those timbers with the most suitable ring sequences for analysis. Those with more than 50 annual rings and some survival of the original sapwood and bark-edge were sought.

The most promising timbers were sampled using a 15mm diameter corer attached to an electric drill. The cores were taken as closely as possible along the radius of the timbers so that the maximum number of rings could be obtained for subsequent analysis. In three cases, a second core was taken from the same timber because the first one broke. The core holes were left open. The ring sequences in the cores were revealed by sanding.

The complete sequences of growth rings in the samples that were selected for dating purposes were measured to an accuracy of 0.01mm using a micro-computer based travelling stage (Tyers 1997a). The ring sequences were plotted onto semi-log graph paper to enable visual comparisons to be made between sequences. In addition cross-correlation algorithms (Baillie and Pilcher 1973; Munro 1984) were employed to search for positions where the ring sequences were highly correlated. These positions were checked visually using the graphs and, where these were satisfactory, new mean sequences were constructed from the synchronised sequences. The *t*-values reported below are derived from the original CROS algorithm (Baillie and Pilcher 1973). A *t*-value of 3.5 or over is usually indicative of a good match, although this is with the proviso that high *t*-values at the same relative or absolute position must be obtained from a range of independent sequences, and that these positions are supported by satisfactory visual matching.

All the measured sequences from this assemblage were compared with each other and any found to cross-match were combined to form a site master curve. These, and any remaining unmatched ring sequences were tested against a range of reference chronologies, using the same matching criteria: high *t*-values, replicated values against a range of chronologies at the same position, and satisfactory visual matching. Where such positions are found these provide calendar dates for the ring-sequence.

The tree-ring dates produced by this process initially only date the rings present in the timber. The interpretation of these dates relies upon the nature of the final rings in the sequence. If the sample ends in the heartwood of the original tree, a *terminus post quem (tpq)* for the felling of the tree is indicated by the date of the last ring plus the addition of the minimum expected number of sapwood rings which are missing. This *tpq* may be many decades prior to the real felling date. Where some of the outer sapwood or the heartwood/sapwood boundary survives on the sample, a felling date range can be calculated using the maximum and minimum number of sapwood rings likely to have been present. The sapwood estimates applied throughout this report are a minimum of 10 and maximum of 55 annual rings, where these figures indicate the 95% confidence limits of the range. These figures are applicable to oaks from the British Isles (Hillam *et al* 1987). Alternatively, if bark-edge survives, then a felling date can be directly utilised from the date of the last surviving ring. The dates obtained by the technique do not by themselves necessarily indicate the date of the structure from which they are derived. It is necessary to incorporate other specialist evidence concerning the re-use of timbers and the repairs of structures before the dendrochronological dates given here can be reliably interpreted as reflecting the construction date of phases within the structure.

Results

A total of 56 cores were extracted from 53 timbers that were selected as most suitable for sampling (Table 1; Figs 6-20). The samples were numbered **1-56** inclusive. The samples can be grouped into 8 types according to the structural element represented (Table 2).

Some of the remaining timbers in the structure were rejected for sampling because they contained too few rings, or because they did not have readily accessible sapwood, but often timbers were rejected because of problems of safe access. This factor was particularly relevant for trusses J-L, and for the tower between rails 3 and 5. Many otherwise suitable timbers were rejected for sampling because it was felt they would yield samples that would replicate data from already adequately sampled areas of the structure.

Samples **15**, **26**, **31**, and **47-49** when examined in the laboratory were found to include too few rings for reliable analysis (Table 1). These were rejected for further analysis.

Sequences from 50 samples originating from 47 timbers were measured. These were initially compared with each other, and subsequently these, and a number of working composite chronologies were also compared to dated reference chronologies. Four groups of samples were found that either matched together to form internally consistent groups or were coeval when dated against the reference chronologies. For each of these identified groupings a site mean chronology was calculated, these were named PBT_A, PBT_B, PBT_C, and PBT_D. Tables 3a-d show the internal cross-correlation for these groups whilst Tables 4a-c show the correlation of the mean sequences with dated reference chronologies at the dating position identified for three of the sequences. Sequence PBT_A composed of re-used timbers was dated AD 994-1196 inclusive, PBT_B composed of two re-used timbers is dated AD 1360-1550 inclusive, and PBT_C composed of fresh timber distributed throughout the structure is dated AD1559-1668 inclusive. PBT_D a short 90 year sequence composed of 6 fresh timbers distributed in the trusses could not be dated, despite comparison with data from throughout the British Isles and much of northern Europe. Tables 5a-d list the site mean chronologies.

Interpretation

Early timbers

The 203-year chronology PBT_A is dated AD 994 to AD 1196 inclusive. It was created from ten timbers (11 samples) from three different areas of the structure (Fig 21a). The four main posts include a large number of redundant notched lap-joints and are clearly either re-used from elsewhere, or are the remnant part of a structure that has been extensively modified. Assuming they are contemporary, and hence combining the results for the posts, suggests a felling date range for them of AD 1207-AD 1223. A single re-used rafter from the lower pent roof was also dated and this was felled after AD 1205 but possibly before AD 1250. Five re-used rafters from the upper pent roof are also dated and, if we assume they are contemporary, they provide a combined felling date of AD 1197-AD 1216 inclusive. These rafters are re-used elements clearly identifiable in both the lower pent roof and upper pent roof. They are of quite small scantling, and have smaller peg hole sizes and smaller notched lap-joints compared with those from the main posts. The original function of these rafters is not known but the dendrochronological analysis indicates they were originally part of a structure, or structures, of broadly the same date as the main posts. If all the dated material in group PBT_A is part of a single structure a date of AD 1207-AD 1216 is indicated.

Middle period timbers

The 191-year chronology PBT_B is dated AD 1360 to AD 1550 inclusive. It is constructed from only two samples, both from the upper spire (Fig 21a). There is no convincing match between these timbers (Table 3b), but each timber gives both good visual and statistically significant replicated matches to a wide range of reference data (Table 4b). On the basis of their differing responses and the distribution of their matches to reference data across England and Wales it seems possible that these two timbers are derived from different geographic locations. Sample **52** is definitely re-used since it has redundant joint housings, sample **46** was not noted as re-used at the time of sampling. Sample **52** was thought to end at the heartwood/sapwood boundary, whilst **46** is entirely heartwood. The small number of timbers located of this date, the possible differences in origin, and the uncertainties over the re-used status of one of them indicates that some caution should be used in assuming these two timbers are contemporary. The fairly similar end dates and the significantly greater length of the individual sequences compared with those from PBT_C and PBT_D suggests they may be representative of a small number of mid- or late-sixteenth century re-used timbers in the upper spire.

Later timbers

The 16 timbers (18 samples) that were combined to form the 110-year PBT_C sequence are derived from a variety of locations within the **tower**, supporting **trusses**, **bellframe**, and **spire**. Bark-edge was recorded on four timbers, and probable bark-edge on a fifth. Sapwood was present on all but three timbers, though these three all included heartwood/sapwood boundaries (Fig 21a). The range of heartwood-sapwood transitions is consistent with a group of timbers which were felled at the same time (Baillie 1982, 57), indicating that they were probably contemporary. All the samples with clear bark-edge exhibit no signs of spring growth for AD 1669 and thus the felling of this material appears to have taken place between summer AD 1668 and the early spring of AD 1669. Since timbers were usually felled as required and used green (Rackham 1990, 69), a construction date at this point or shortly afterwards is implied. Datable timbers include **36** and **40** from the **bellframe, 30** and **32** which are the foundation beams for the upper **spire, 20** and **21** from **truss** H, as well as a variety of timbers distributed throughout the **tower** and **spire**. It therefore seems likely that the entire surviving structure was completely rebuilt as part of a single building campaign in or shortly after AD 1668/9. Recent survey of the timber alignments suggests the main posts were not moved as part of this process (Morriss *et al* 1998).

Undated timbers

The six timbers that were combined to form the 90-year PBT_D sequence are derived from the **trusses** (Fig 21b). In the absence of dendrochronological dates the interpretation of this material is difficult. This group of timbers are of similar scantling and conversion types as those in the dated group in PBT_C. Both groups are mostly trimmed halved timbers, with abundant survival of the original bark surface. However they differ in that the PBT_D group has clear signs of trestle sawing, whereas the dated group in PBT_C appear to be pit-sawn.

From the tree-ring evidence the PBT_D material is faster grown, and the parent trees are characterised by being more curved than those in the PBT_C group. The ring sequence exhibits a characteristic growth stress and release cycle which perhaps indicates they are derived from a single woodland unit. A possible interpretation is that although the PBT_C and PBT_D groups are the same date one group is derived from a different woodland unit to the other and were converted into usable timbers by a different process, or different team. This proposal could allow for the material from one of the woodland units being undatable by dendrochronological methods because of some combination of their relative youth, fairly fast growth rate, and perhaps the non-climatic effects of the woodland management regime employed at this woodland.

Discussion

Early timbers

The results for the four corner posts, combined with the survey work indicating they are *in situ*, show there was originally a tower at Pembridge of broadly the same date as the slightly different type of structure now incorporated into Mamble church. No comparative work has yet been done at Yarpole or Knighton-on-Teme. The early thirteenth-century date is probably too late to support the theories that the posts are a re-used tower from the nearby motte.

The poor inter-correlation found between the sequences from the posts may indicate a variety of sources had to be used to obtain them. Since each tree was apparently subject to quite different external influences during its life this may indicate the trees are of hedgerow origin. Their re-use in 1668/9 perhaps indicates that such large timber trees were not common, or that the cost of obtaining such material was significant and it was therefore economically viable to re-use them despite the extra effort involved in cutting new joints *in situ* on seasoned oak timbers.

There is a large redundant joint housing in the north-east corner post. This housing has a highly polished upper surface. A count of the rings visible here suggests that this is where the sequence was derived that was used to obtain the original tree-ring dating for the tower (Fletcher 1980, 34). There are 112 rings here, and the original single dendrochronological date is quoted as using part of an 111 ring sequence (Webster and Cherry 1980, 245). Sample sequence **1+2** has the same end ring as a sequence obtained from measuring the exposed surface since the core site is only a few centimetres above the housing and the grain pattern indicates no rings are gained or lost between the housing and the core site. Sample sequence **1+2** is dated here to end at AD 1189 and there is no evidence to support the previously published dating of this post. Additional points that should be considered here are that the new cores are measured at higher resolution than could be possible *in situ* even today, there is a much denser network of both local and regional reference material of higher quality than was available in the late 1970s and sample sequence **1+2** has higher replicated correlation for this sequence than Fletcher quoted for the measurements supplied from the exposed surface. The dates presented here also reinforce the point, regularly made by dendrochronologists, that buildings should not be dated on the basis of results from a single timber and that reliable work is founded on extensive sampling strategies.

The re-used material in the lower and upper pent roofs is especially intriguing. The dendrochronological dating clearly suggests an early thirteenth-century origin. There are a variety of rafters with a combination of notched lap-, mortise-, and tenon-joints and a distinctive halved lap-joint. It is unfortunately impossible to prove this material derives from the original structure, or even that they are precisely contemporary with the main tower posts.

Sixteenth-century timbers

The samples from the spire identified two timbers, a brace and a rafter that are apparently re-used from a sixteenth-century structure. Visual inspection suggests this material is not abundant anywhere in the structure, and may be confined to the spire, where it is intermingled with thirteenth-century timbers and 1668/9 timbers. The tree-ring sequences from these two samples are longer than almost everything else sampled in the bell tower.

Later timbers

The sampling programme undertaken on the building was originally carried out in the expectation that there were a number of repair and/or modification phases within the structure. The results fail to support such an hypothesis. Instead there is clear indication that the entire tower was rebuilt around 1668/9 and that this was the only major change that occurred before the documented or evident remedial works of 1829, 1898, 1956, and 1982-4. Pembridge bell tower thus seems to be an almost complete example of later seventeenth-century work. This single massive rebuilding could suggest either a functional change to the building, perhaps requiring the construction of the ambulatory wall, or increased structural requirements imposed by augmenting the bell numbers or weights, or possibly that a structural failure occurred in the earlier structure.

It is important to stress that this hypothesis assumes that the group of matched but undated timbers are part of the proven 1668/9 work. The dendrochronological analysis by itself cannot confirm or refute this assumption, instead it requires use of evidence derived from other analyses of the building. This assumption is made here primarily from the undated timbers close structural association with the 1668/9 timbers, the best supporting evidence comes from truss H which has two definite 1668/9 timbers, and one PBT_D type timber. The outer adzed surfaces of both the PBT_C and PBT_D timbers show abundant evidence of notch-and-chop tool marks where the notching has been over vigorous or the chopping has been underdone, this has previously been observed on seventeenth-century woodwork. A tool signature study may help clarify whether the same group of tools were used on both groups.

Subsequent visual inspection shows that the other trusses appear to include some timbers identical to both the types in truss H. It is slightly unfortunate that only the PBT_D type timbers were reliably matched together, four other samples from the trusses were not matched to either group. Subsequent visual inspection of the tower and trusses suggests the sampling of this material has given a slightly false impression of the distribution of the PBT_D type timbers since there are pit sawn and trestle sawn timbers intermingled throughout the tower and trusses in such a way as to be otherwise indistinguishable. It is possible that the trestle sawn timbers were originally slightly smaller than the pit sawn timbers and that the latter were preferentially used for horizontal members of the tower with the former more likely to occur in the X-bracing.

Conclusion

The dendrochronological analysis of timbers from Pembridge has revealed the extensive presence of re-used timbers throughout the structure, but highlighted a comprehensive reconstruction of the structure in AD 1668/9. The analysis of the Pembridge timbers provides an example of dendrochronology simplifying the interpretation of a structure by eliminating a number of prior assumptions for which no structural evidence exists. It would be nice to have the opportunity to examine the towers at Yarpole and Knighton to see if the phases of modification at the four towers show signs of being driven by common external events such as fashions in bell ringing or competition between parishes or are driven in each case by local events, such as structural failure.

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Figure 1

East-west cross-section of the tower showing the various structural elements referred to in the report (after Morriss *et al* 1998)

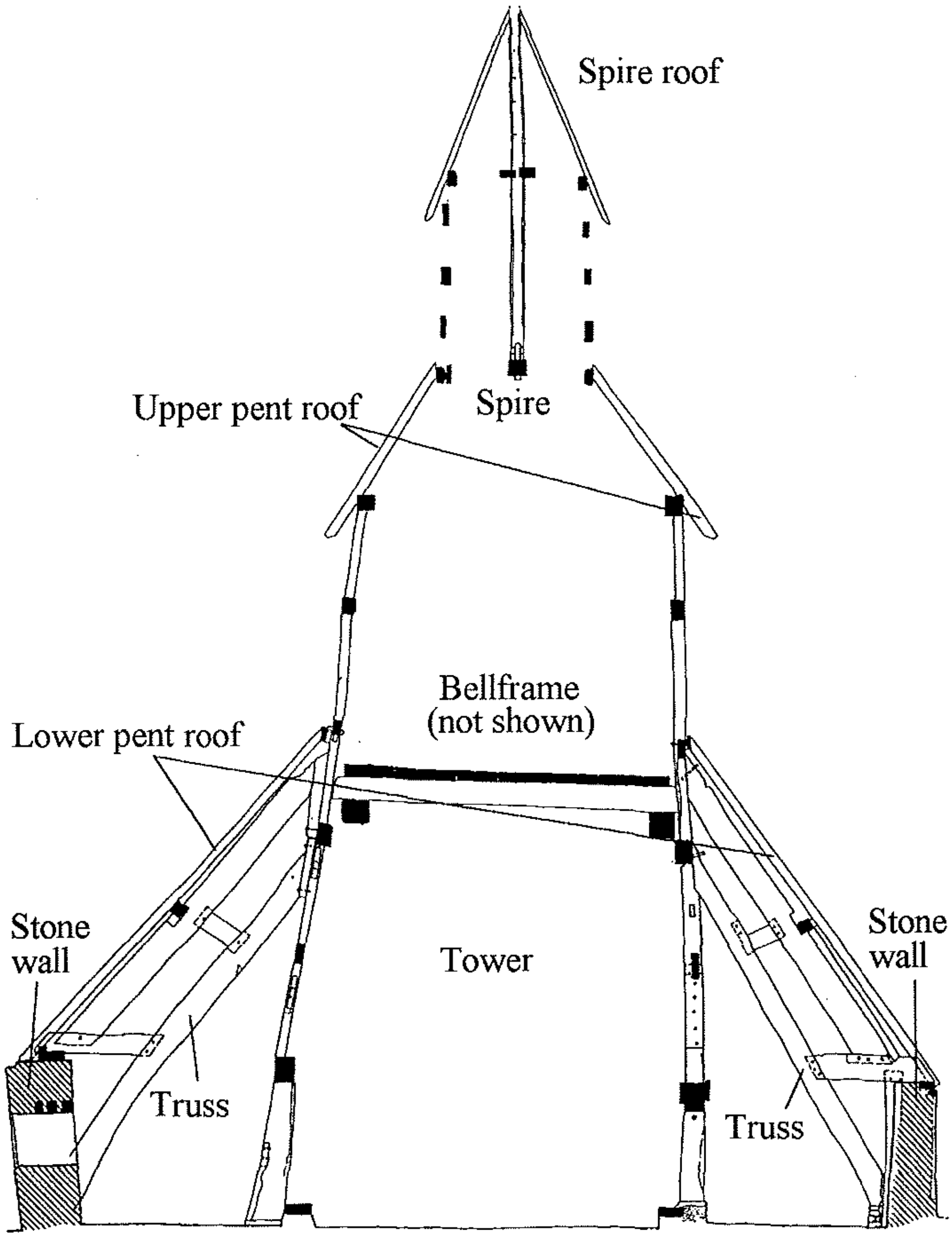


Figure 2a

Ground level plan of the tower (after Morriss *et al* 1998)

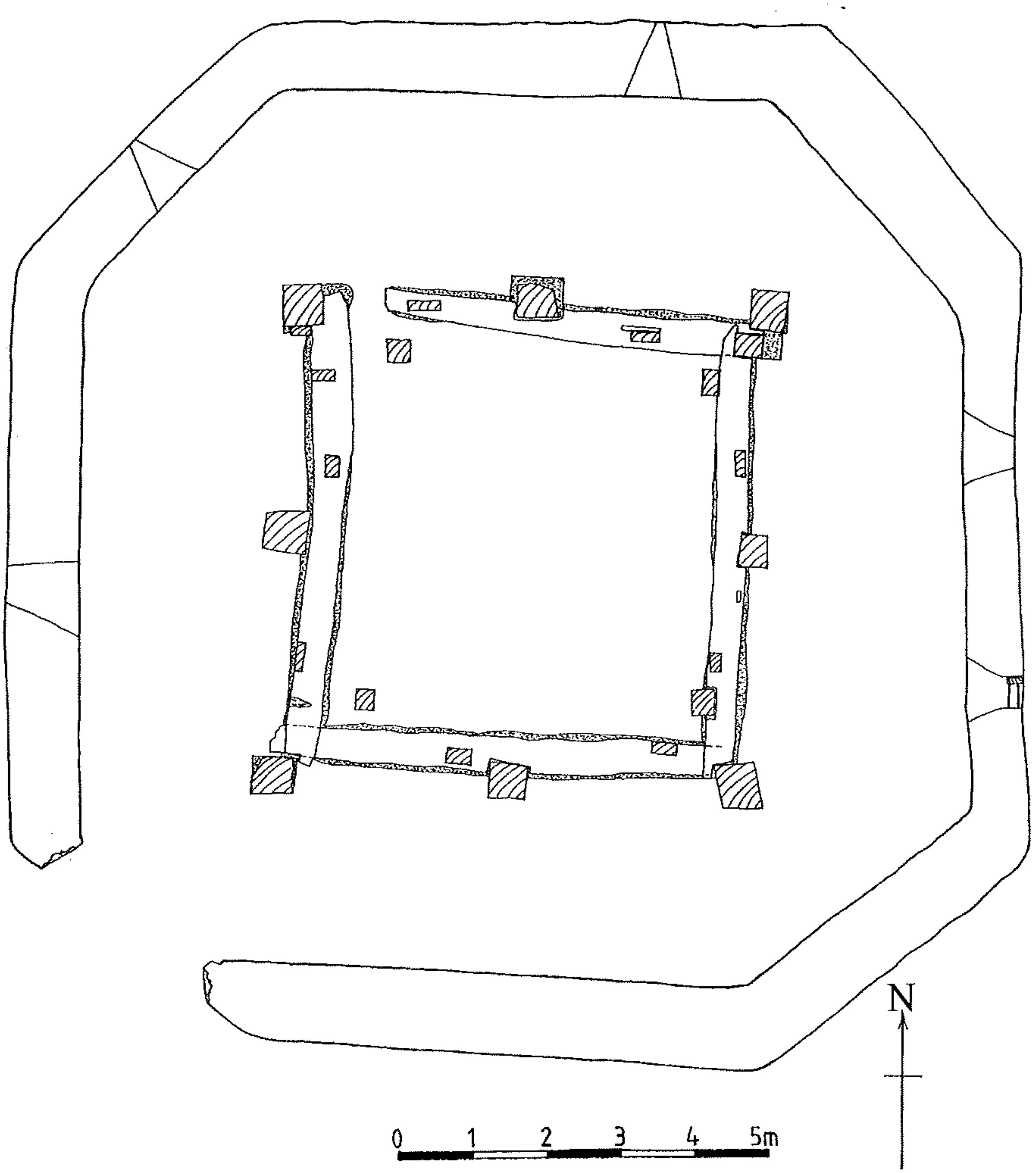


Figure 2b

A sketch plan of the bell tower showing the supporting trusses with the Baart truss numbering scheme followed in this report.

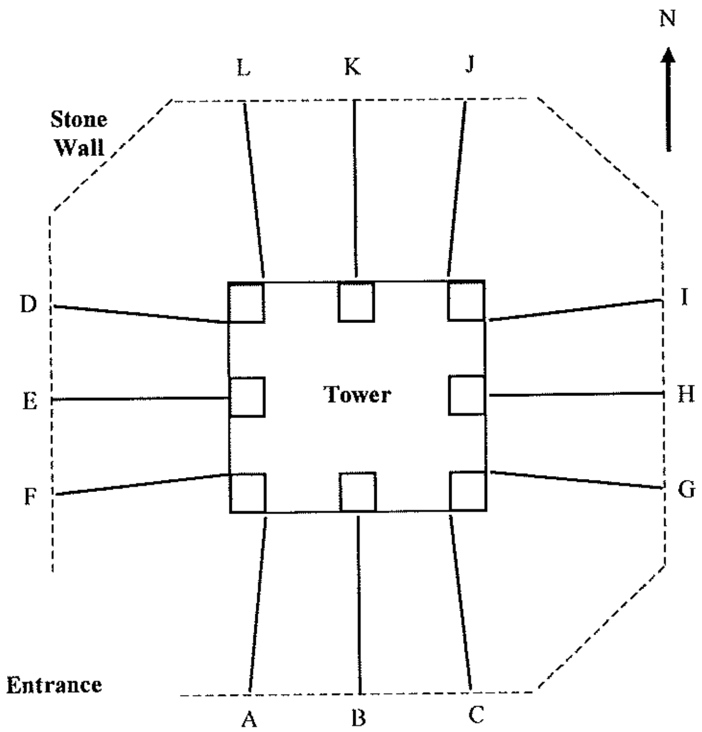


Figure 3 a) Truss K, showing the typical form of trusses (excepting trusses E and H), and the terminology used in the report, b) Truss E showing the form of trusses E and H and the terminology used in the report, after Morriss *et al* (1998)

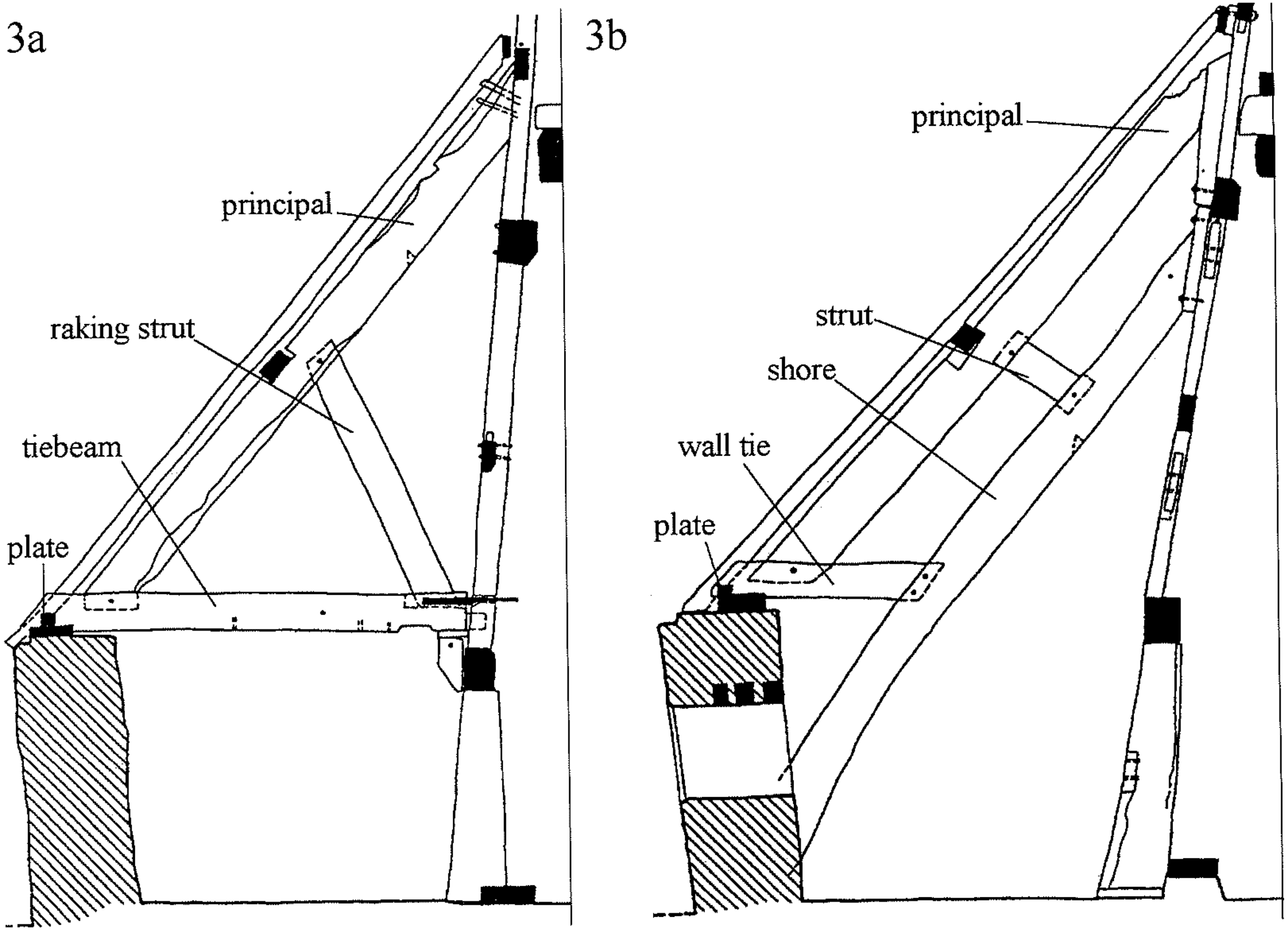


Figure 4

Plan of the bellframe, showing its form (after Morriss *et al* 1998)

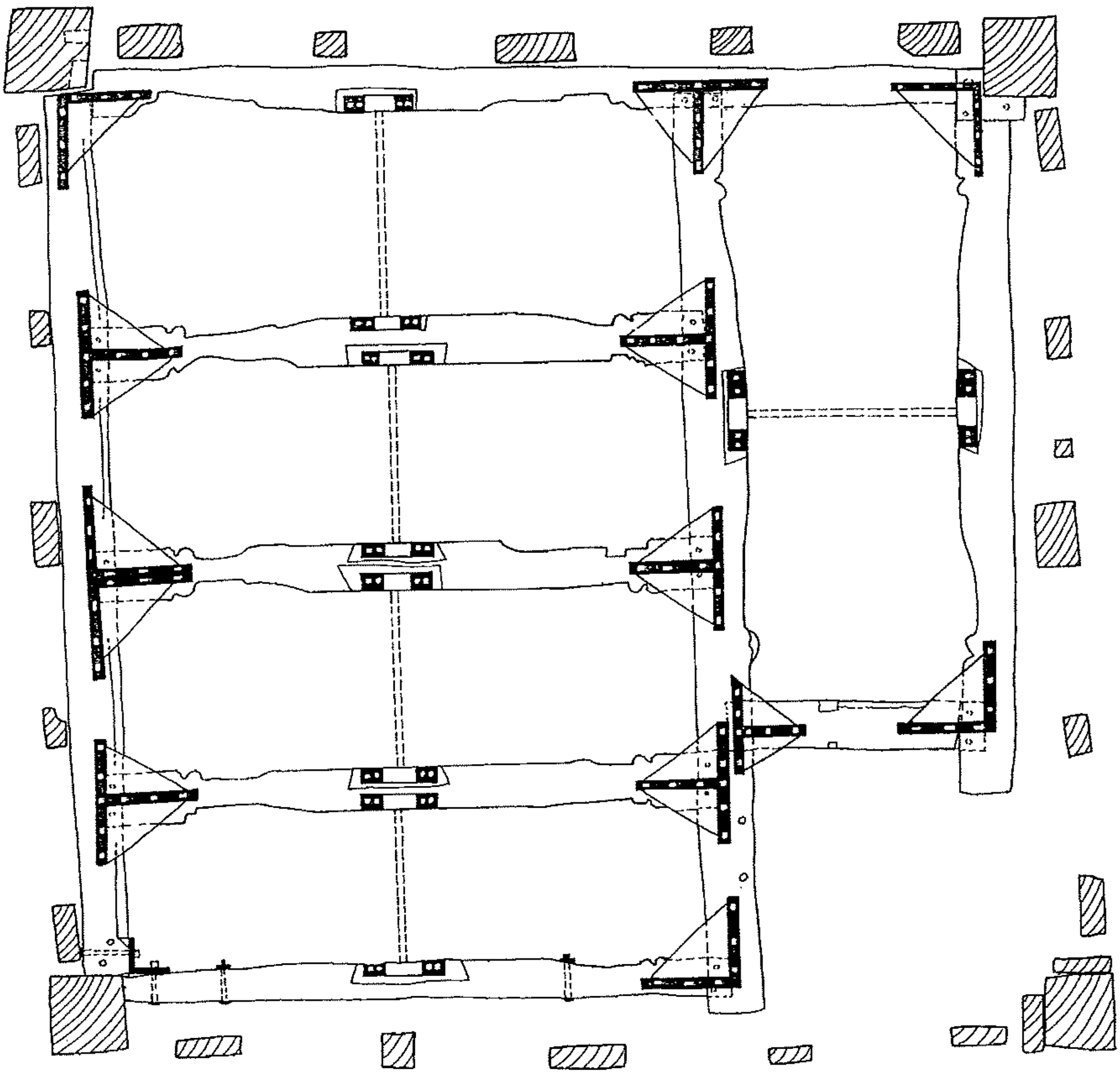
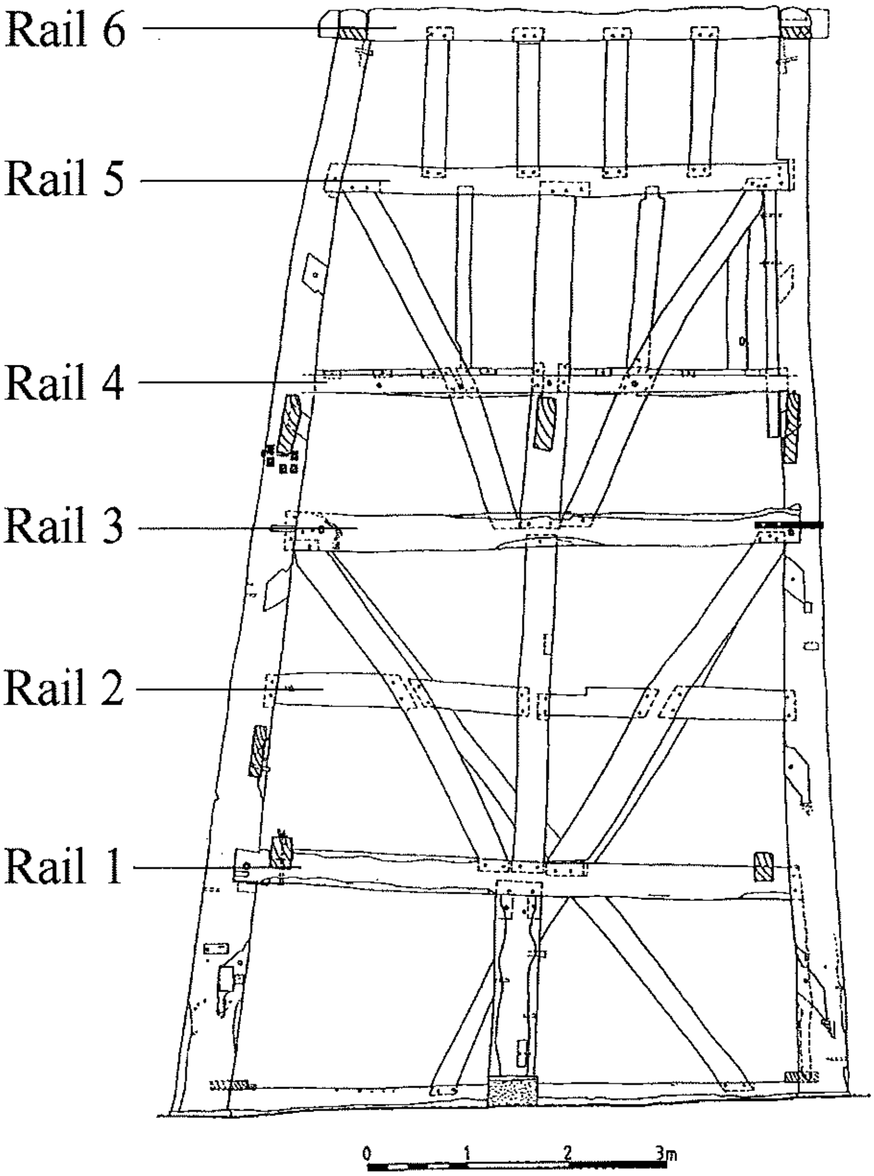


Figure 5

The west side of the tower showing the Baart rail numbering scheme followed in this report (after Morriss *et al* 1998)



<u>Figure 6</u> Ground floor plan showing location of samples **1-9** inclusive, after Morriss *et al* (1998)

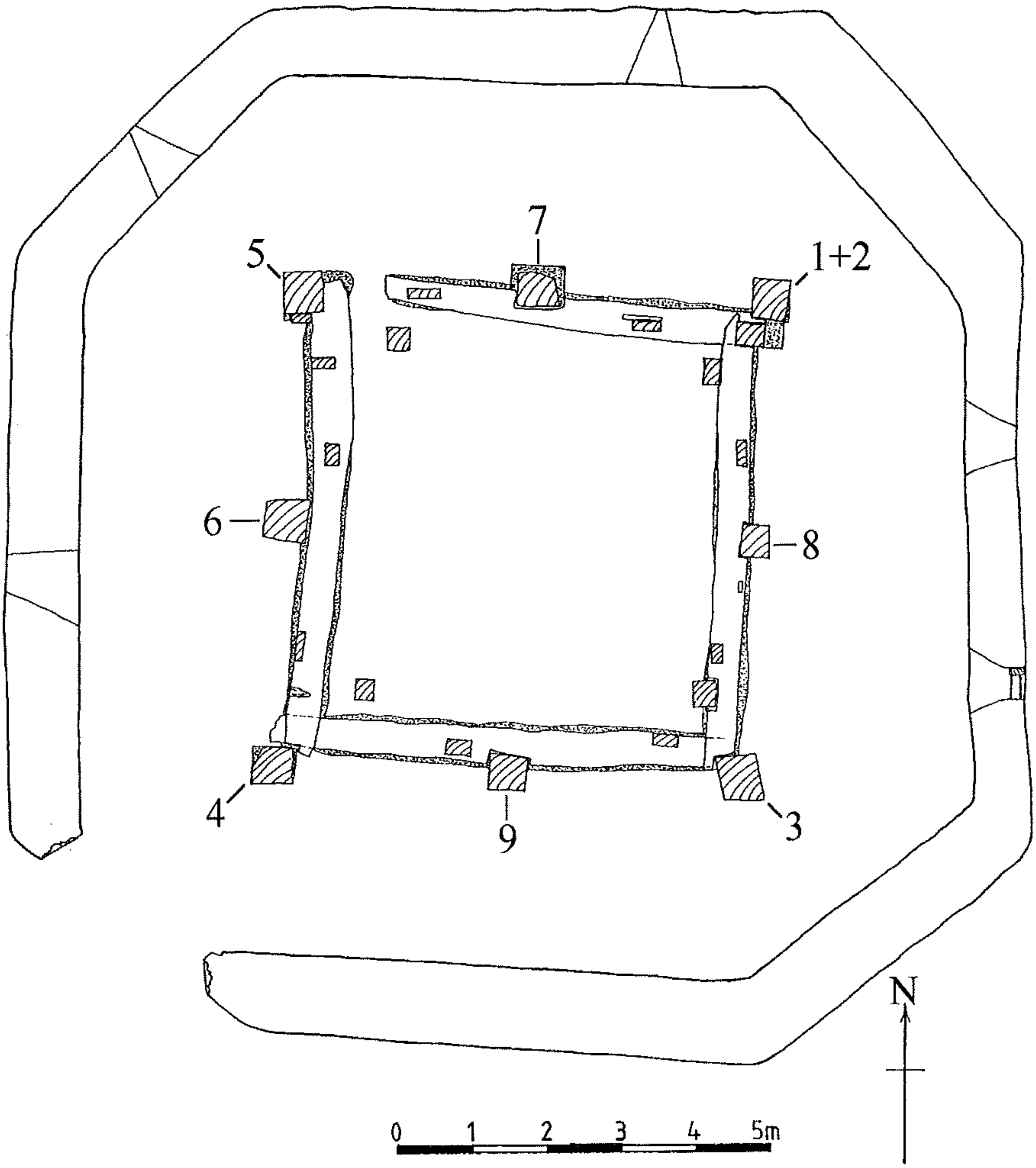


Figure 7 South elevation of the tower showing location of samples **3**, **4**, **9-11** inclusive, **34**, and **35**, after Morriss *et al* (1998)

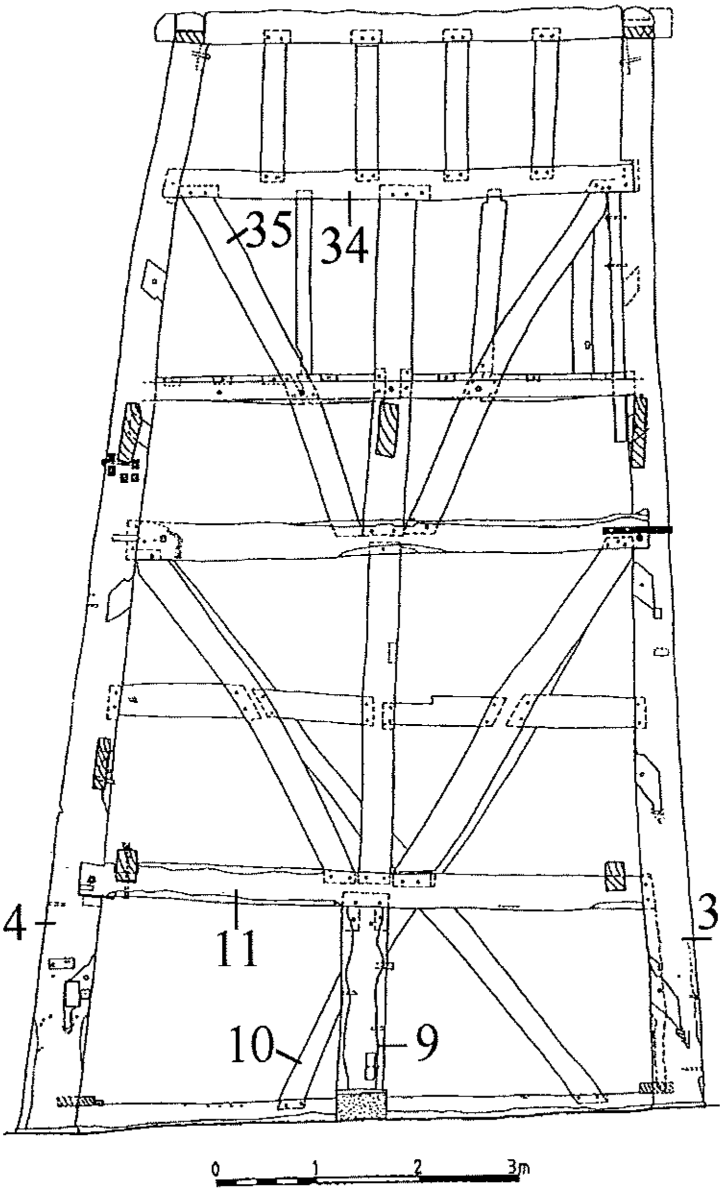


Figure 8 West elevation of the tower showing location of samples **4-6** inclusive, **26**, **30**, **32**, **37** and **38**, after Morriss *et al* (1998)

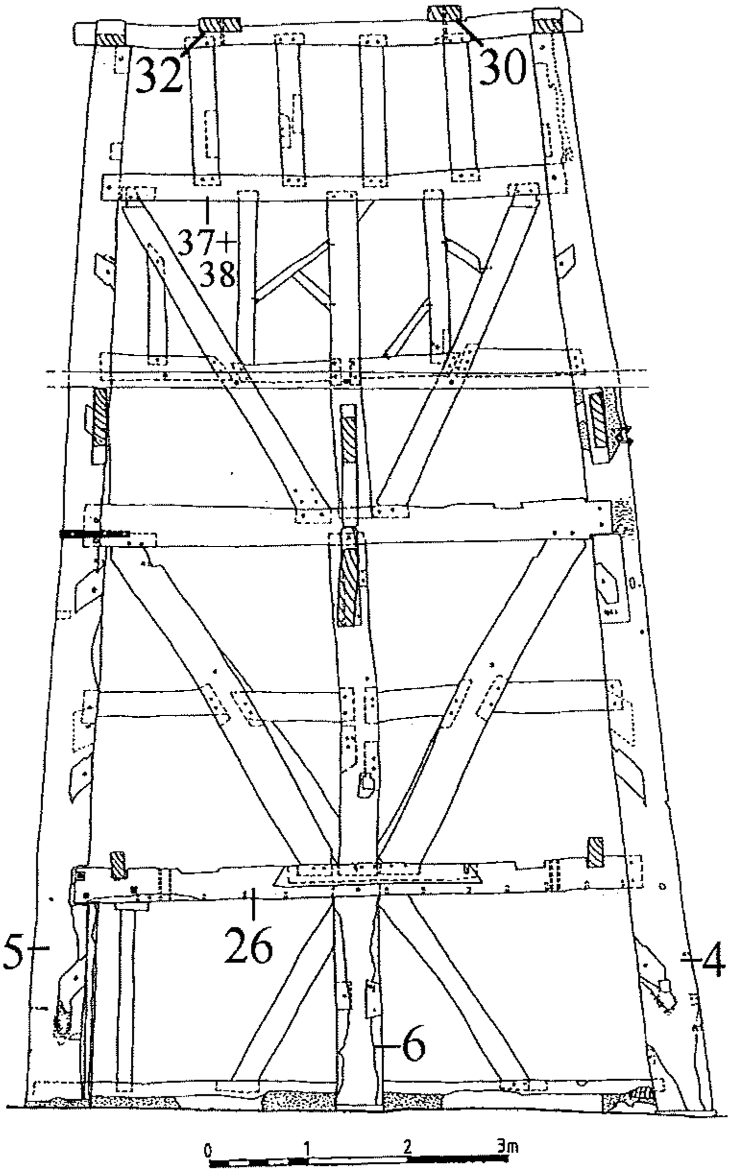


Figure 9 North elevation of the tower showing location of samples **1**, **2**, **5**, **7**, **23** and **33**, after Morriss *et al* (1998)

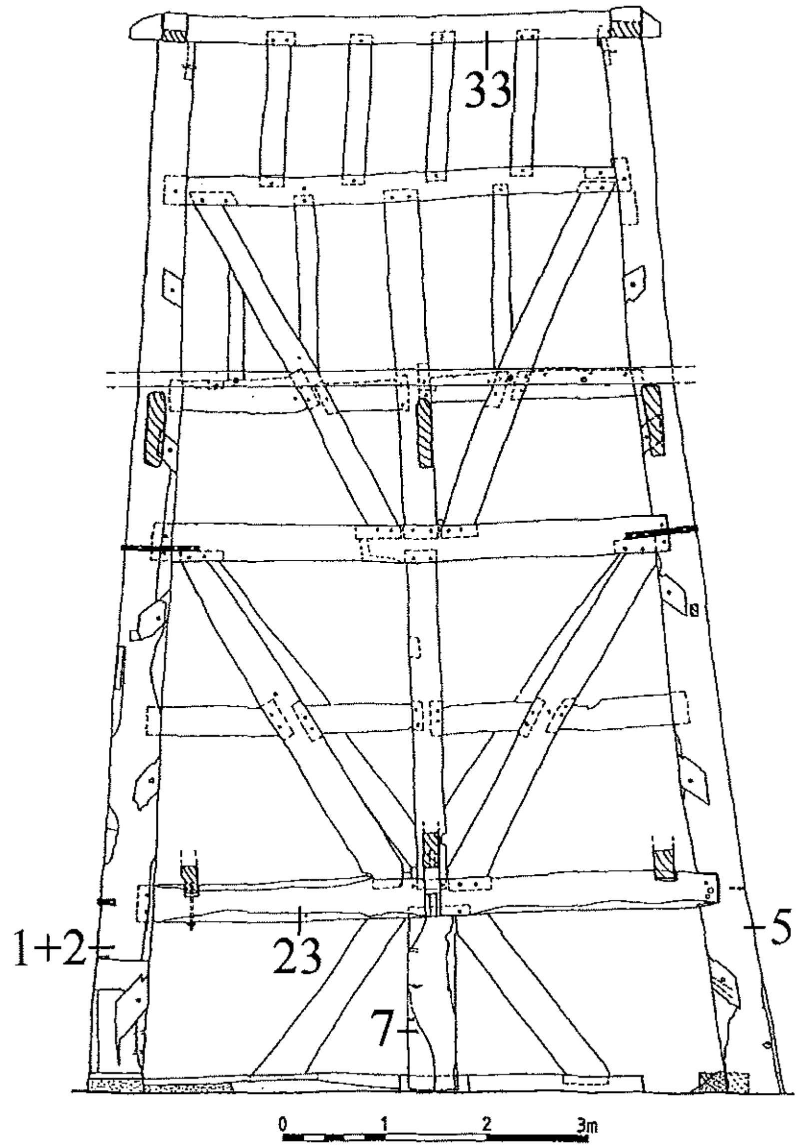


Figure 10 East elevation of the tower showing location of samples **1-3** inclusive, **8**, and **28-32** inclusive, after Morriss *et al* (1998)

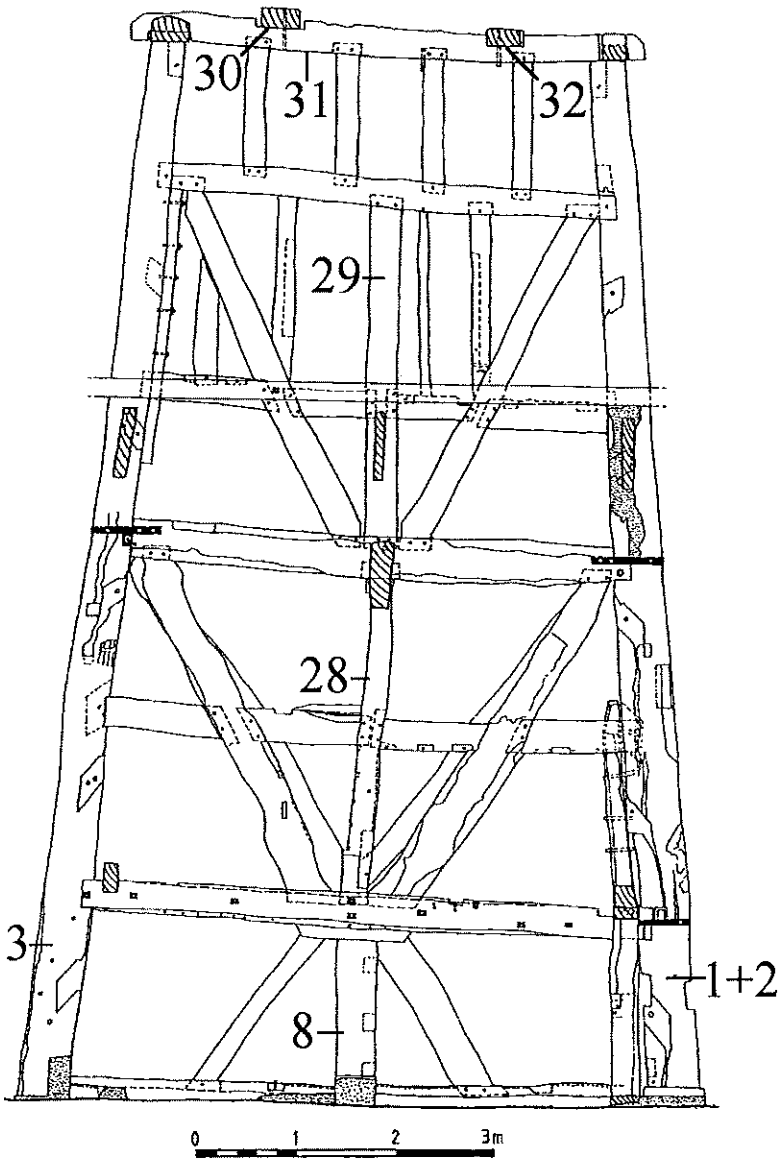


Figure 11 Plan of the bellframe showing location of samples **36**, **39**, and **40**, after Morriss *et al* (1998)

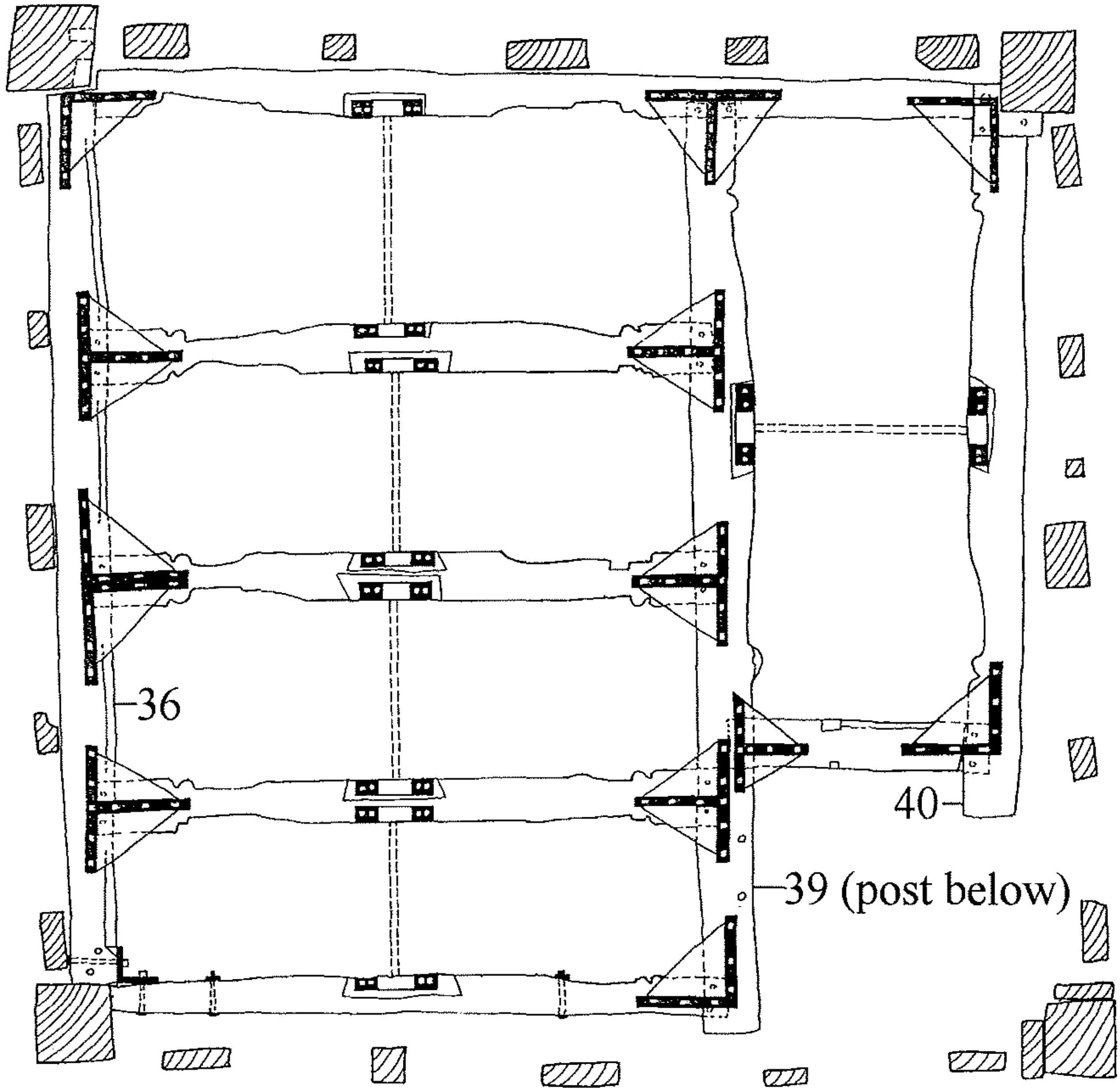


Figure 12 South elevation of the spire showing location of samples **30**, **31**, **43-46** inclusive, and **48**, after Morriss *et al* (1998)

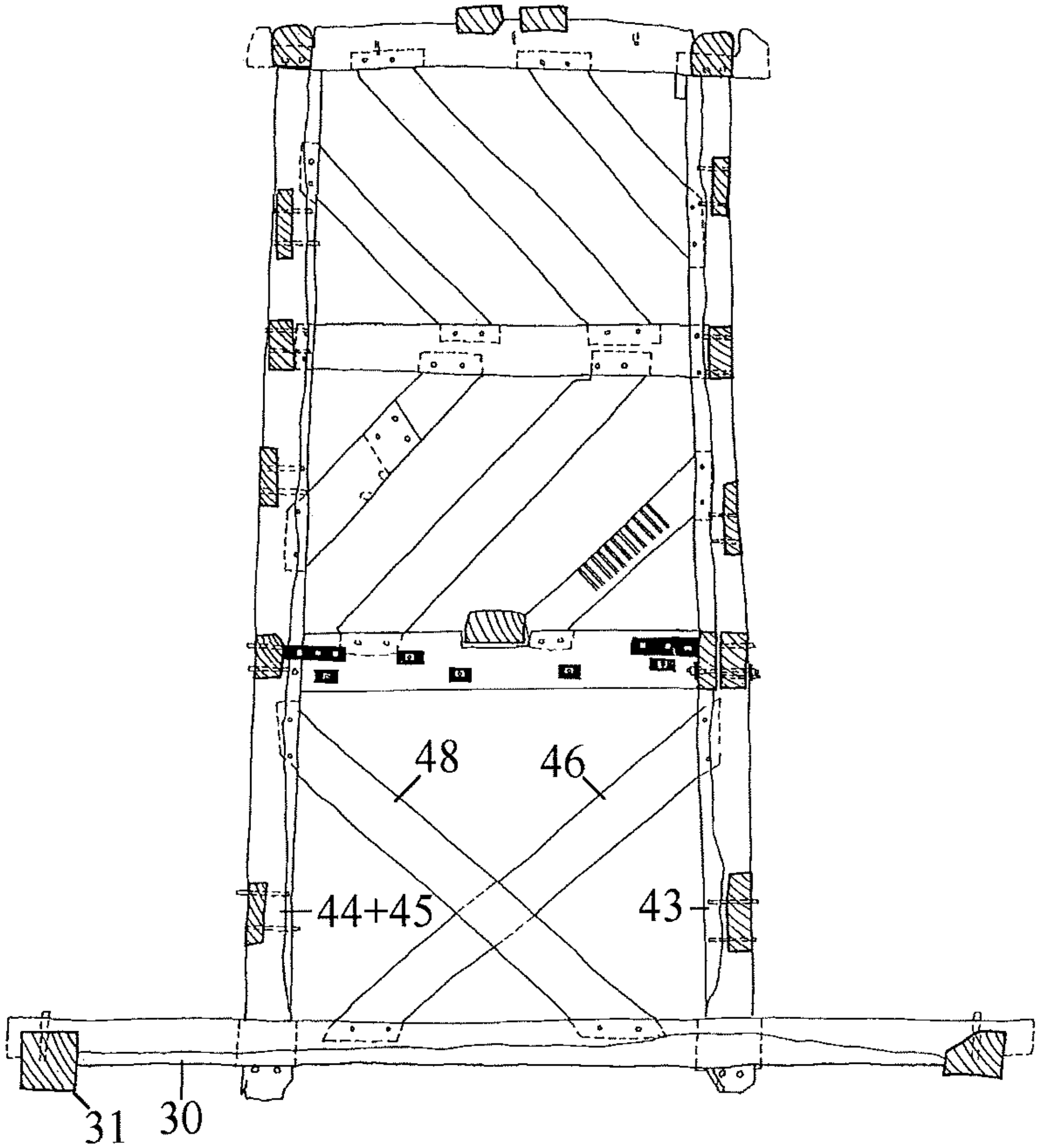


Figure 13 West elevation of the spire showing location of samples **30**, **32**, **42**, **43**, and **49**, after Morriss *et al* (1998)

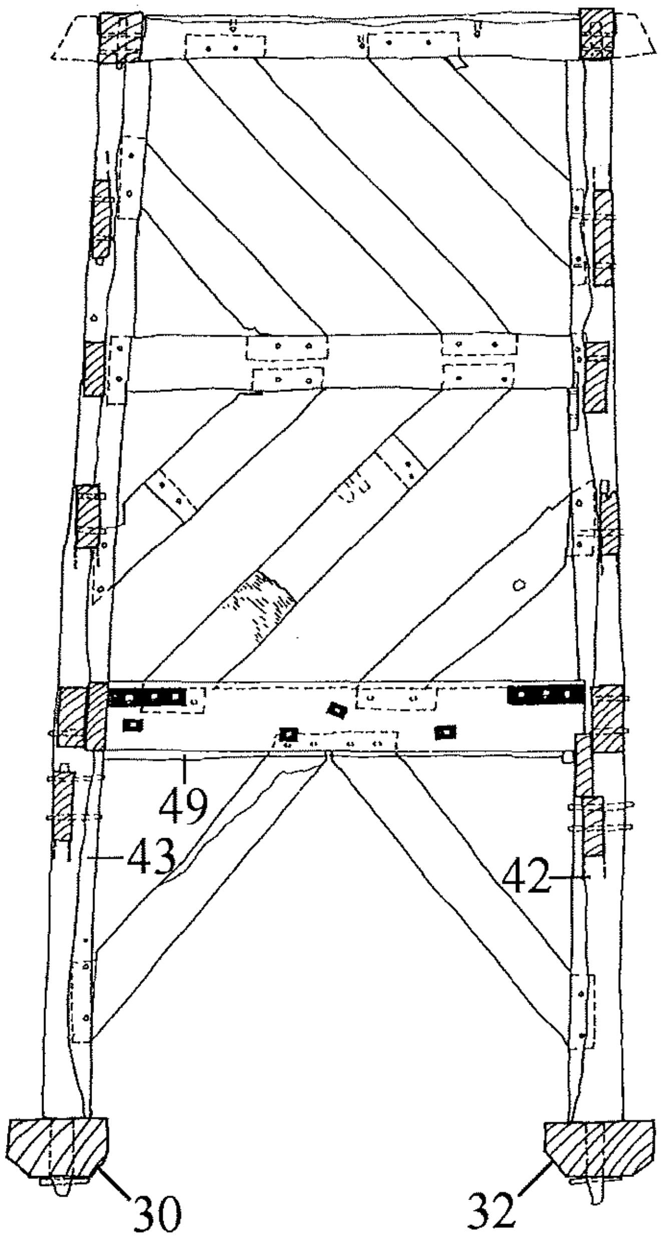


Figure 14 North elevation of the spire showing location of samples **31**, **32**, **41**, and **42**, after Morriss *et al* (1998)

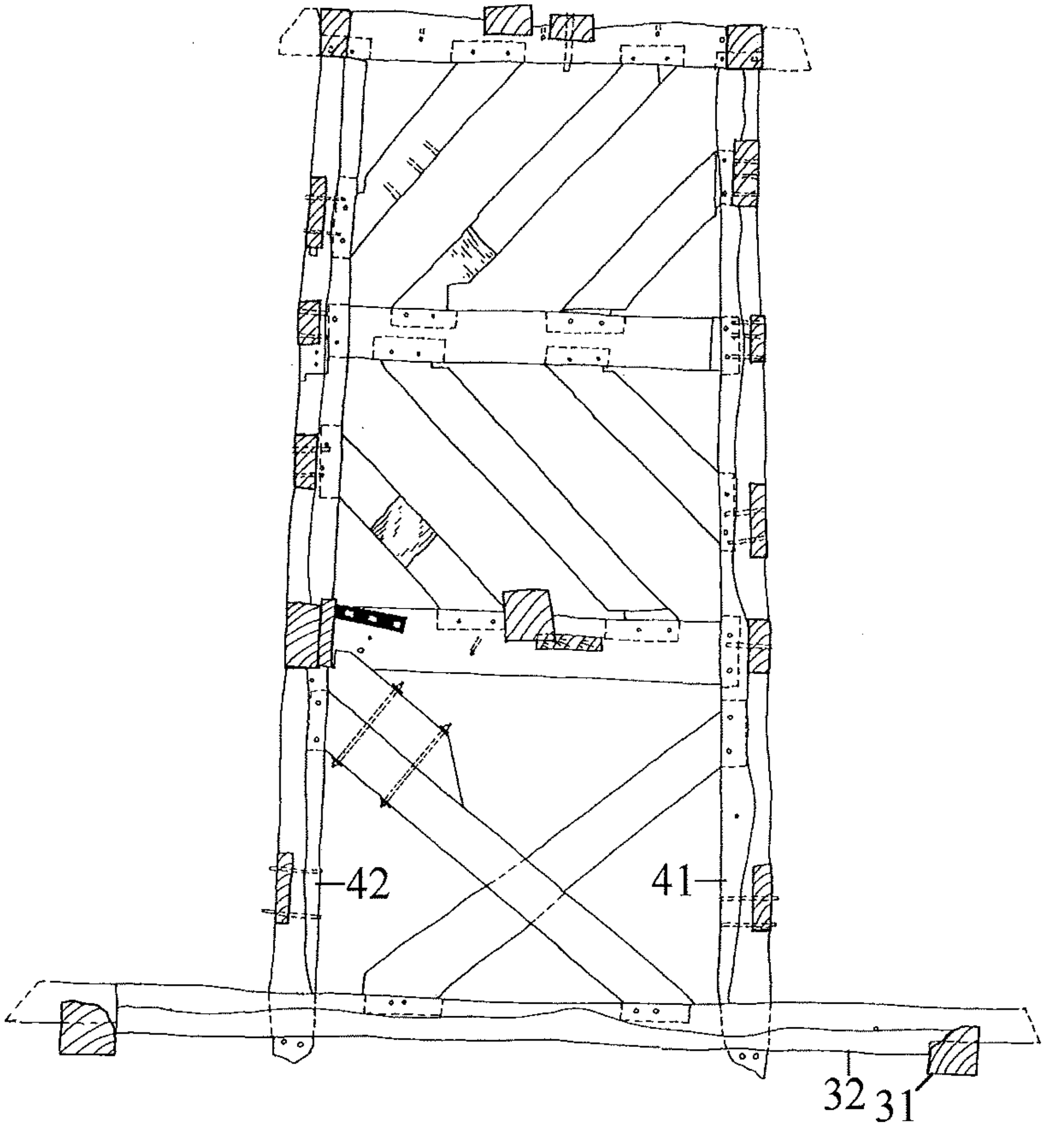


Figure 15 East elevation of the spire showing location of samples **30**, **32**, **41**, **44**, **45**, and **47**, after Morriss *et al* (1998)

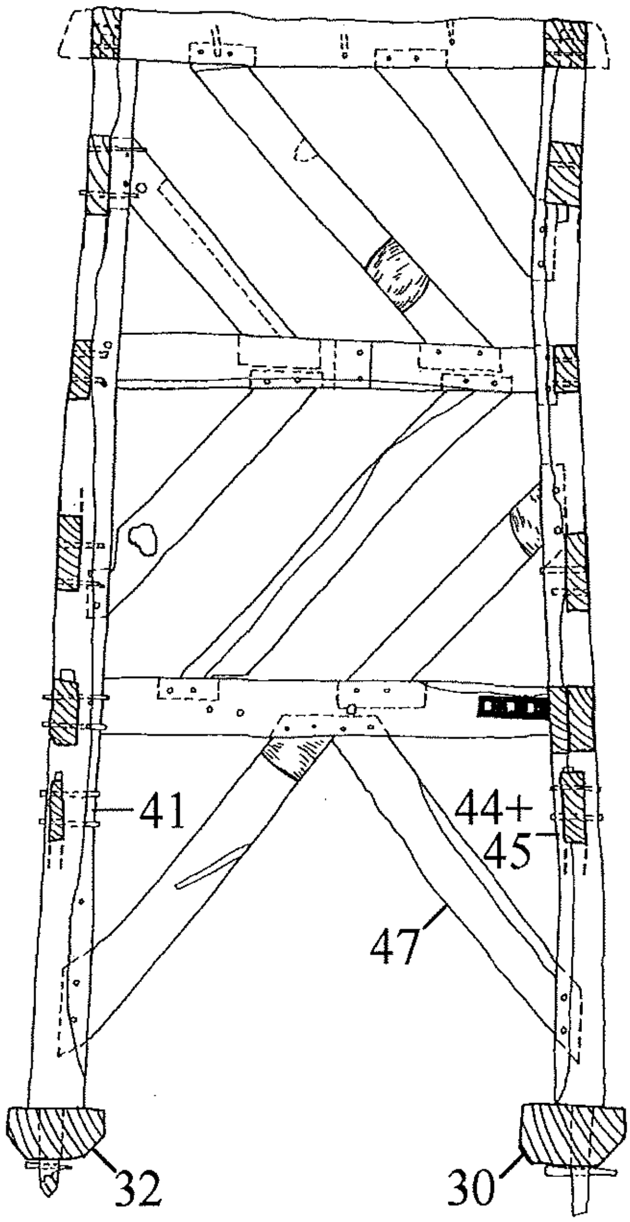


Figure 16 Trusses A, B, C, D, and F showing location of samples **12-15** inclusive, **18**, **19**, **24**, and **27**, after Morriss *et al* (1998) truss K.

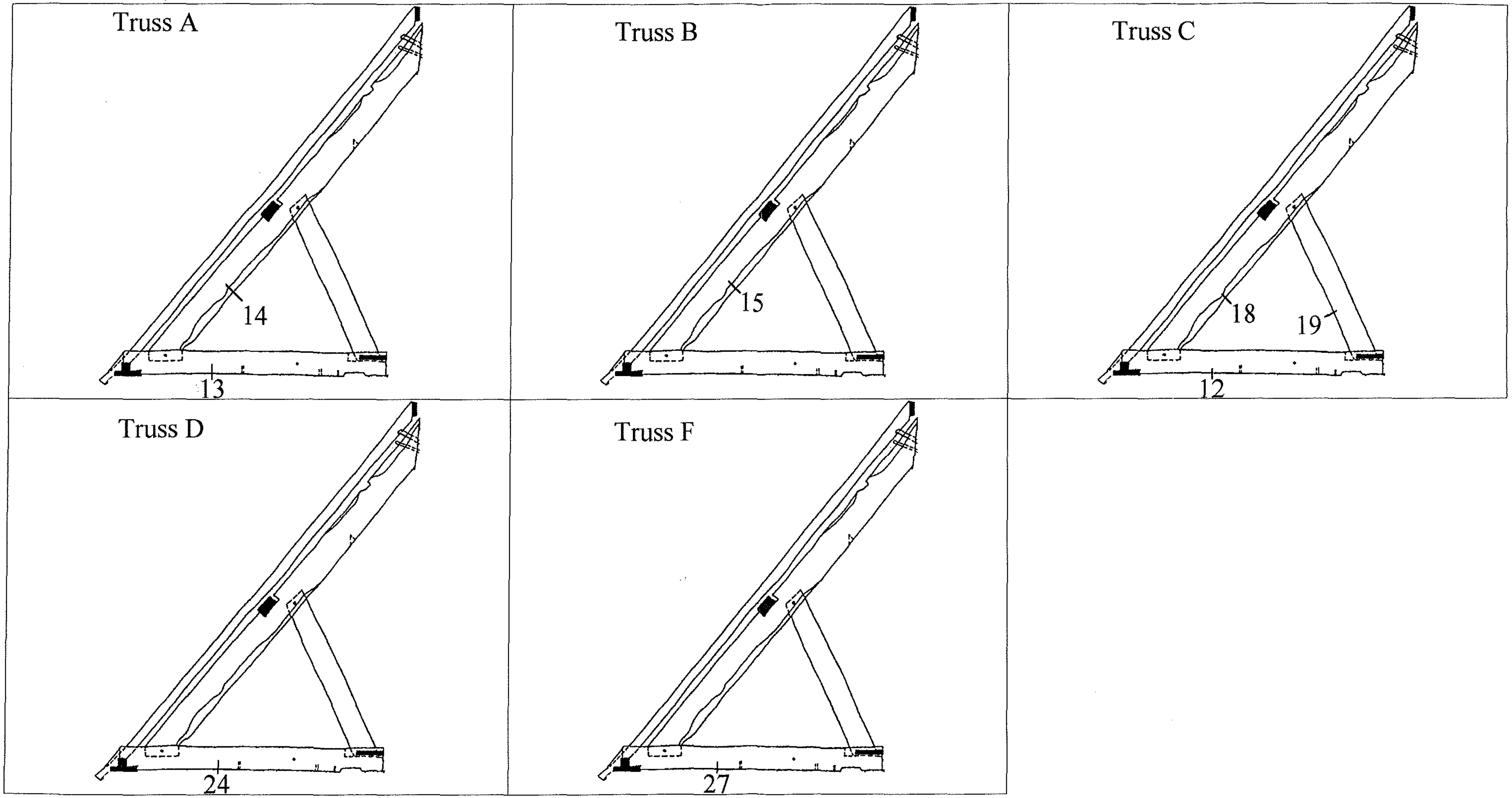


Figure 17 Trusses E, and H showing location of samples **20-22** inclusive, and **25**, after Morriss *et al* (1998)

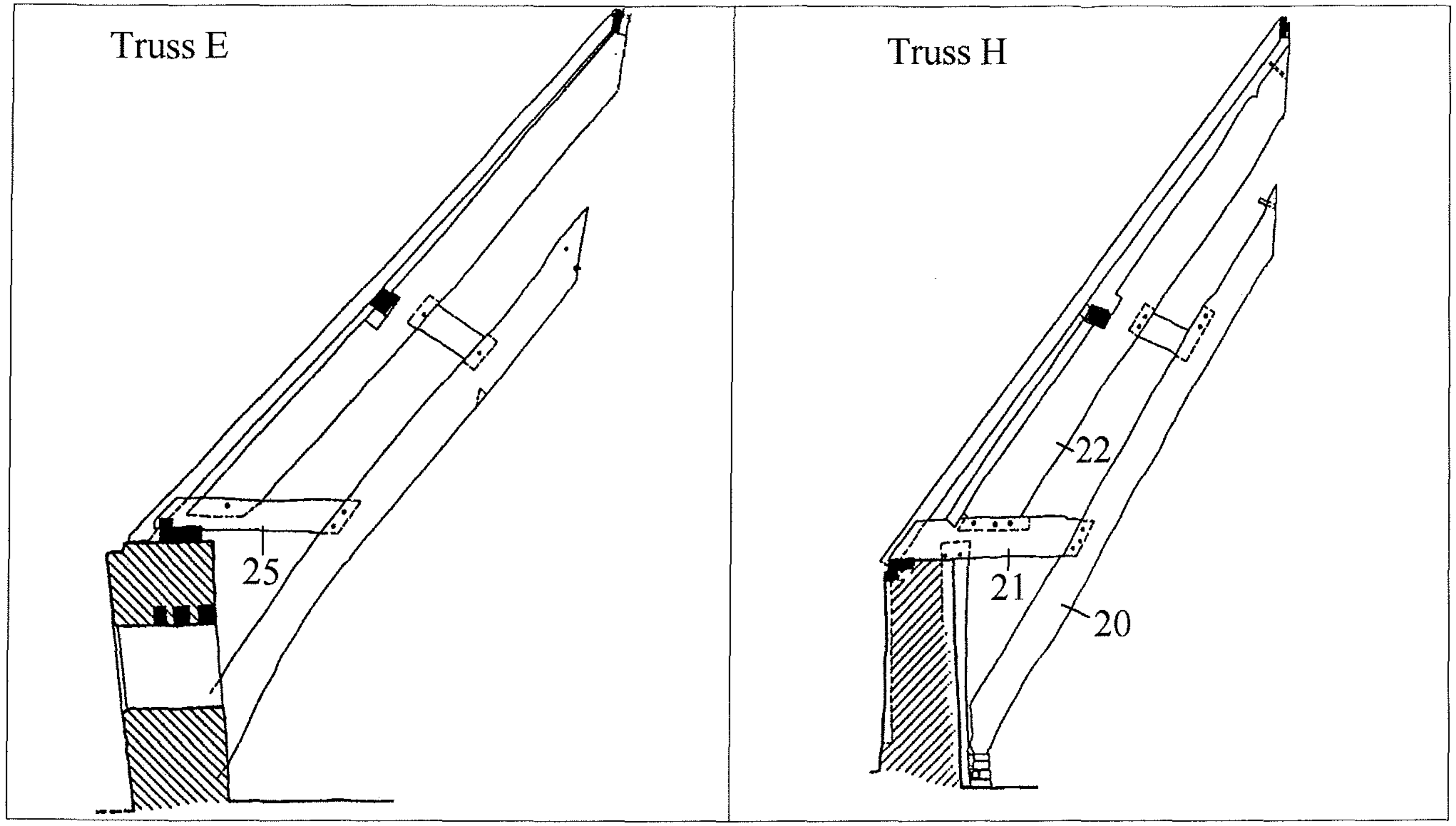


Figure 18 Sketch of lower pent roof south side, showing location of samples **16** and **17**

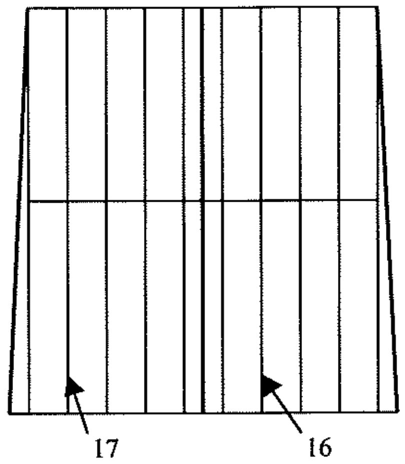


Figure 19 Sketch of upper pent roof east side, showing location of sample **50**

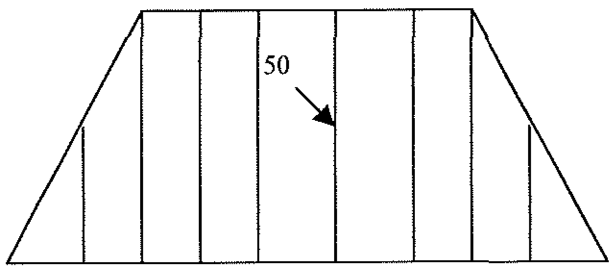


Figure 20 Sketch of Upper pent roof north side, showing location of samples **51-56**

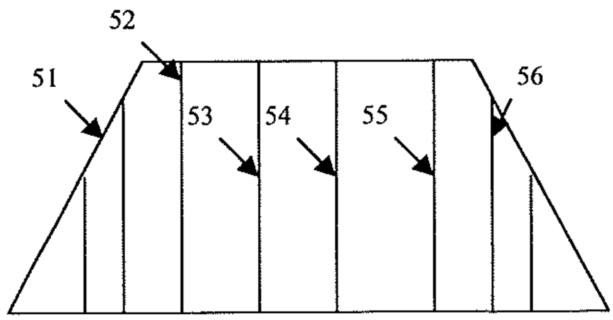


Figure 21a

Bar diagram showing the chronological positions of the 28 dated timbers (31 samples), grouped by date and structural element. The felling period for each sequence is also shown. For key see next page

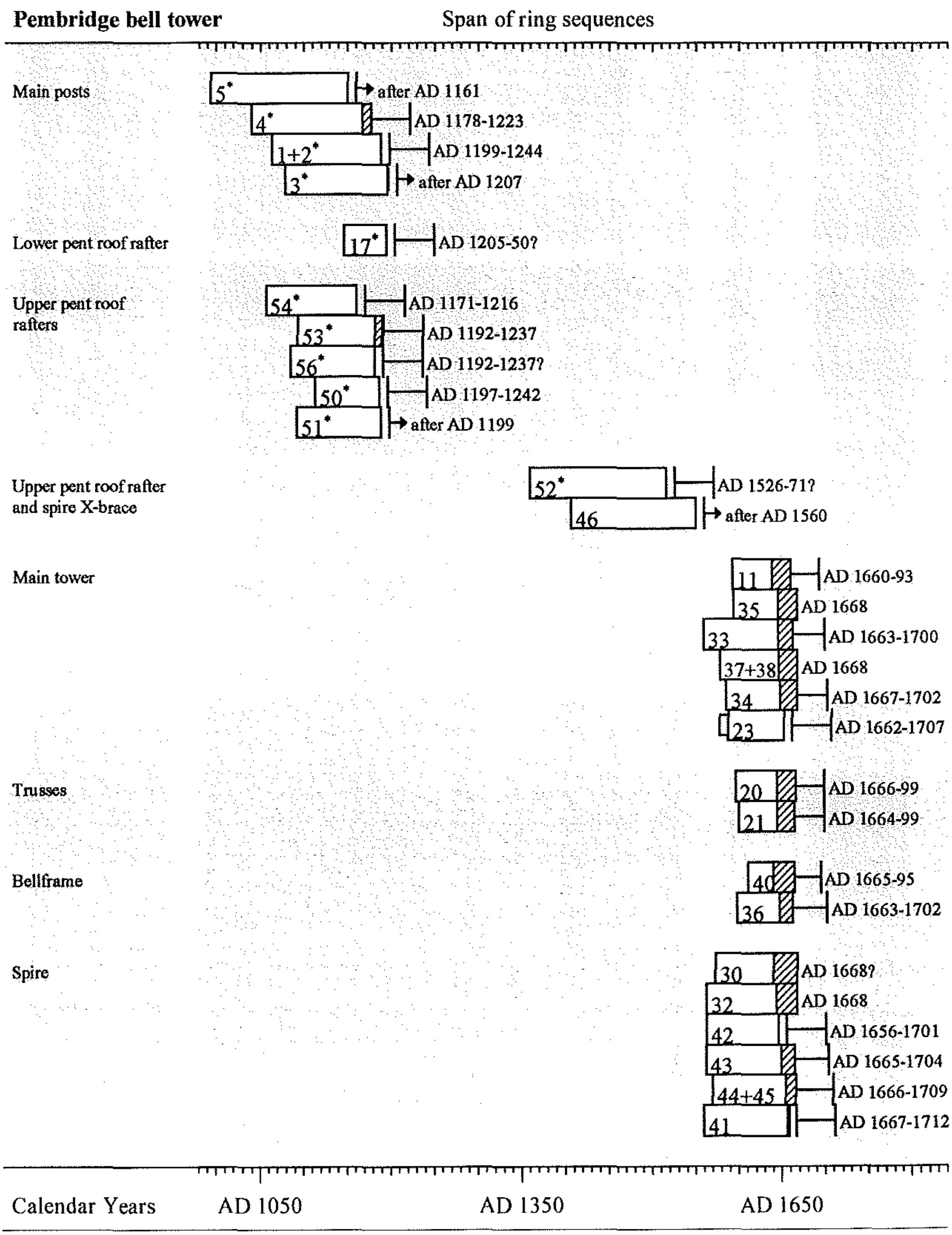
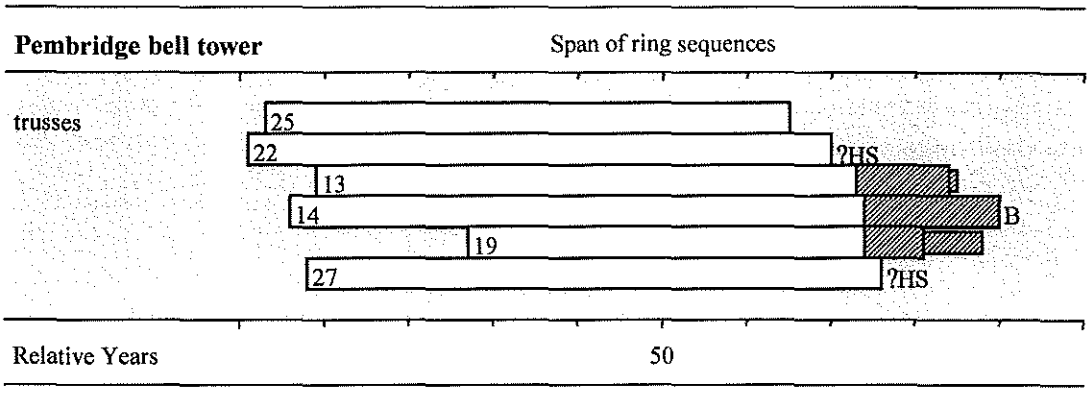


Figure 21b

Bar diagram showing the relative positions of the matched but undated timbers derived from the bell tower



KEY

heartwood
sapwood
unmeasured heartwood
unmeasured sapwood
?HS possible heartwood/sapwood boundary
B bark boundary
* re-used timber

Table 1

List of samples, grouped by area of sampling

Area of sampling	Sub-area of sampling	Core No	Origin of core	Total rings	Sapwood rings	ARW mm/year	Date of sequence	Felling period
Main Tower	Corner posts	**1**	Tower NE corner post	86	h/s	2.14	AD 1104-1189	} AD 1199-1244
	" " "	**2**	Tower NE corner post *repeat core*	123	?h/s	2.54	AD 1064-1186	}
	" " "	**3**	Tower SE corner post	118+1	h/s	2.38	AD 1079-1196	AD 1207-52
	" " "	**4**	Tower SW corner post	139	10	1.71	AD 1040-1178	AD 1178-1223
	" " "	**5**	Tower NW corner post	158	-	1.88	AD 994-1151	after AD 1161
	Centre posts	**6**	Tower W central post lower	87	-	3.44	-	-
	" " "	**7**	Tower N central post lower	51	?h/s	2.69	-	-
	" " "	**8**	Tower E central post lower	70	?h/s	2.30	-	-
	" " "	**28**	Tower E central post middle	72	?h/s	2.85	-	-
	" " "	**29**	Tower E central post upper	49	12	3.99	-	-
	" " "	**9**	Tower S central post lower	68	h/s	3.14	-	-
	X framing	**10**	Tower S inner X-frame	72	13	3.11	-	-
	" " "	**35**	Tower S upper X-frame	75	23+b	1.72	AD 1594-1668	AD 1668/9
	Rails	**11**	Tower S rail 1	69	22	1.68	AD 1592-1660	AD 1660-93
	" "	**23**	Tower N rail 1	65	h/s	2.52	AD 1588-1652	AD 1662-1707
	" "	**26**	Tower W rail 1	-	-	-	-	-
	" "	**34**	Tower S rail 5	83	20	2.12	AD 1585-1667	AD 1667-1702
	" "	**37**	Tower W rail 5	56	21+b	2.19	AD 1613-1668	} AD 1668/9
	" "	**38**	Tower W rail 5 *repeat core*	91	23+b	2.25	AD 1578-1668	}
	" "	**31**	Tower E rail 6	-	-	-	-	-
	" "	**33**	Tower N rail 6	105	18	2.30	AD 1559-1663	AD 1663-1700
Trusses	-	**13**	Truss A tiebeam	76	11	3.43	*	-
		14	Truss A principal	85	16+b	2.11	*	-
		15	Truss B principal	-	-	-	-	-
		12	Truss C tiebeam	81	20+b	2.15	-	-
		18	Truss C principal	57	-	3.18	-	-
		19	Truss C strut	55	7	2.13	*	-
		24	Truss D tiebeam	77	16+b	2.43	-	-
		25	Truss E wall tie	63	-	3.05	*	-
		27	Truss F tiebeam	69	?h/s	3.50	*	-
		20	Truss H shore	71	22	2.36	AD 1596-1666	AD 1666-99
		21	Truss H wall tie	65	20	2.21	AD 1600-1664	AD 1664-99
		22	Truss H principal	70	?h/s	2.22	*	-
Lower roof	-	**16**	Lower pent roof rafter west of truss B	77	h/s	1.11	-	-
		17	Lower pent roof rafter east of truss B	49	?h/s	1.66	AD 1147-1195	AD 1205-50
Bellframe	-	**36**	bellframe W upper plate	66	16	2.02	AD 1598-1663	AD 1663-1702
		39	bellframe post	65	h/s	1.62	-	-
		40	bellframe E head	55	25	1.65	AD 1611-1665	AD 1665-95
Spire	Support beams	**30**	Spire S foundation beam	96	28+?b	2.25	AD 1573-1668	AD 1668/9?
	" " "	**32**	Spire N foundation beam	106	24+b	1.81	AD 1563-1668	AD 1668/9
	Corner posts	**41**	Spire NE corner post	100	2	2.05	AD 1560-1659	AD 1667-1712
	" " "	**42**	Spire NW corner post	84	h/s	2.36	AD1563-1646	AD 1656-1701
	" " "	**43**	Spire SW corner post	104	16	2.35	AD1562-1665	AD 1665-1704
	" " "	**44**	Spire SE corner post	76	-	2.60	AD1570-1645	} AD 1666-1709
	" " "	**45**	Spire SE corner post *repeat core*	65	12	1.56	AD1602-1666	}
	X bracing	**46**	Spire X-brace south side	144	-	1.64	AD1407-1550	after AD 1560
	" " "	**47**	Spire X-brace east side	-	-	-	-	-
	" " "	**48**	Spire X-brace south side	-	-	-	-	-
	Rail	**49**	Spire rail west side	-	-	-	-	-
Upper roof	-	**50**	Spire pent roof E rafter	74	h/s	1.64	AD1114-1187	AD 1197-1242
		51	Spire pent roof NW hip rafter	97	-	1.24	AD1093-1189	after AD 1199
		52	Spire pent roof N rafter	157	?h/s	1.20	AD1360-1516	AD 1526-71?
		53	Spire pent roof N rafter	97	8	1.07	AD1094-1190	AD 1192-1237
		54	Spire pent roof N rafter	105	h/s	1.27	AD1057-1161	AD 1171-1216
		55	Spire pent roof N rafter	87	22+b	1.56	-	-
		56	Spire pent roof N rafter	97	?h/s	1.49	AD1086-1182	AD 1192-1237?

Key:
Total rings = all measured rings, +value means additional rings were only counted, the felling period column is calculated using these additional rings.
sapwood rings: h/s = heartwood/sapwood boundary, ?h/s possible heartwood/sapwood boundary, b = bark-edge, ?b = possible bark-edge
ARW = average ring width of the measured rings
Date of sequence: * = sequences matched together to form the undated PBT_D sequence

Table 2

Summary showing the structural function of the sampled timbers

Structural element	Sample numbers	Description
Tower: corner posts	**1-5**	Five cores from the four main posts; samples **1** and **2** are from same timber (Figs 6-10).
Tower: intermediate posts	**6-9**	Four cores from four posts. All four lower sections of the intermediate posts may be re-used (Figs 6-10).
Lower pent roof rafters	**16** and **17**	Several rafters were observed in the lower roof that included notched lap-joints and were thus assumed to be re-used. Two were sampled (Fig 18).
Tower: rails and X-bracing	**10-11**, **23**, **26**, **28-29**, **31**, **33-35**, **37**, and **38**	12 cores from 11 timbers distributed throughout the central tower; samples **37** and **38** are from the same timber (Figs 7-10).
Trusses	**12-15**, **18-22**, **24-25**, and **27**	12 cores from 12 timbers from the supporting trusses (Figs 16-17)
Bellframe	**36**, **39** and **40**	Three timbers from the bellframe (Fig 11)
Upper spire: support beams, corner posts, rail, and X-bracing	**30**, **32**, and **41-49**	11 cores from 10 timbers distributed throughout the upper spire, samples **44** and **45** are from the same timber (Figs 12-15).
Upper pent roof rafters	**50-56**	Several rafters were observed in the upper roof that included notched lap-joints and some other joints. Seven were sampled including some with no evidence of re-use (Figs 19-20).

Table 3a

t-value matrix for the re-used timbers forming the chronology PBT_A.
KEY: - = *t*-values under 3.0, \ = no overlap

	3	4	5	17	50	51	53	54	56
1+2	3.13	-	-	-	-	-	3.22	-	-
3		-	-	4.83	3.12	-	4.75	-	3.48
4			4.89	-	-	4.57	3.20	3.81	3.68
5				\	-	-	-	-	-
17					-	3.36	3.21	-	-
50						-	4.64	4.34	-
51							4.95	5.20	6.51
53								3.90	4.00
54									5.13

Table 3b

t-value matrix for the re-used timbers forming the chronology PBT_B.
KEY: - = *t*-value under 3.0

	52
46	-

Table 3c

t-value matrix for the later dated timbers forming the chronology PBT_C.
KEY: - = *t*-values under 3.0

	20	21	23	30	32	33	34	35	36	37+38	40	41	42	43	44+45
11	4.79	3.72	-	3.93	3.29	3.94	5.00	3.03	4.09	5.22	5.05	3.70	-	5.11	4.39
20		3.33	3.55	4.08	4.98	8.34	3.63	5.65	4.46	7.05	6.82	4.25	3.62	5.16	4.67
21			4.59	6.53	6.31	4.85	4.06	4.42	4.67	5.63	5.70	-	-	4.79	4.47
23				5.12	4.30	3.30	3.43	4.76	-	4.74	3.68	-	-	-	-
30					8.28	5.41	4.11	5.48	4.52	6.29	4.78	5.88	-	5.76	3.86
32						6.70	5.31	5.66	5.89	4.51	5.71	3.98	-	4.60	4.64
33							4.26	6.28	5.11	5.40	9.01	4.17	-	4.48	4.70
34								3.39	3.99	4.72	3.67	-	-	3.67	3.12
35									4.03	5.58	4.53	3.44	-	4.00	3.03
36										4.75	3.28	2.44	-	5.25	4.42
37+38											6.47	6.22	4.65	7.85	5.48
40												4.09	3.39	5.64	5.31
41													8.14	9.48	7.58
42														6.78	8.11
43															10.19

Table 3d

t-value matrix for the undated timbers forming the chronology PBT_D.
KEY: - = *t*-value under 3.0

	14	19	22	25	27
13	4.77	3.32	4.76	3.35	6.40
14		5.13	10.30	5.41	4.79
19			6.89	3.55	-
22				5.16	4.67
25					3.23

Table 4a

Dating the mean sequence PBT_A, AD 994-1196 inclusive. *t*-values with independent reference chronologies

Area	**Reference chronology**	***t*-values**
Avon	Bristol Bridge (Hillam 1984)	8.69
	Bristol, Dundas Wharf (Nicholson and Hillam 1987)	11.30
Cambridgeshire	Peterborough Cathedral (Tyers in prep)	11.28
Gloucestershire	Gloucester Blackfriars (Hillam and Groves 1993)	8.46
	Siddington Tithe Barn (Groves and Hillam 1992)	6.74
Herefordshire	Hereford City mean (Tyers 1996b)	8.81
	Bordesley Abbey (Brown 1993)	8.31
Staffordshire	Stafford, St Mary and Eastgate (Groves pers comm)	7.18
Worcestershire	Mamble Church A (Tyers 1996a)	6.10
	Droitwich, Upwich 2 (Groves and Hillam 1997)	7.21
Yorkshire	Beverley, Eastgate (Groves 1992)	9.14
Wales	Magor Pill Wreck (Nayling 1998)	8.96

Table 4b

Dating the sixteenth century timbers, sample **46** AD 1407-1550 inclusive, sample **52** AD 1360-1516 inclusive. *t*-values with independent reference chronologies

Area	**Reference chronology**	Sample **46**	Sample **52**
Gloucestershire	Gloucester, Mercer's Hall (Howard *et al* 1996)	5.89	4.65
Herefordshire	Kings Pyon Barn (Groves and Hillam 1993)	4.07	5.74
	Hereford City mean (Tyers 1996b)	4.87	7.59
	Dore Abbey 2 (Tyers and Boswijk 1998)	4.77	4.83
Somerset	Lancin Farmhouse (Tyers 1994)	5.22	3.71
Staffordshire	Sinai Park (Tyers 1997b)	5.73	3.59
Worcestershire	Lower Sapey Church (Tyers 1995)	4.89	4.68
	Manor Farm, Lower Wick (Bridge 1981)	3.10	5.88
	Bayton (Bridge 1996)	5.45	4.06
Yorkshire	Nostell Priory (Tyers 1998)	3.74	3.84
	Bayhall, Huddersfield (Boswijk and Tyers 1998)	4.05	4.70
Wales	Welsh Border Houses (Siebenlist-Kerner 1978)	6.05	4.39

Table 4c

Dating the PBT_C chronology, AD 1559-1668 inclusive. *t*-values with independent reference chronologies

Area	**Reference chronology**	***t*-values**
Herefordshire	Tupsley (Tyers 1997c)	4.51
	Dore Abbey 2 (Tyers and Boswijk 1998)	5.82
Lincolnshire	Lincoln, Vicars Court (Hillam and Groves 1996)	4.78
Nottinghamshire	Sherwood (Briffa *et al* 1986)	5.99
Staffordshire	Sinai Park (Tyers 1997b)	6.17
Worcestershire	Droitwich, Upwich 3 (Groves and Hillam 1997)	6.98
Yorkshire	Featherstone (Hillam 1978)	5.89
Wales	Anglesey, Hafoty (Hillam and Groves 1992)	4.59
N Ireland	Belfast (Baillie 1977)	6.21

Table 5a

Ring-width data from site master PBT_A, dated AD 994-1196 inclusive

Date	Ring widths (0.01mm)										No of samples									
AD 994				337	533	255	268	237	228	215				1	1	1	1	1	1	1
AD 1001	188	180	227	263	214	173	164	268	210	174	1	1	1	1	1	1	1	1	1	1
	154	189	253	149	340	246	271	215	155	208	1	1	1	1	1	1	1	1	1	1
	171	268	206	181	125	193	220	215	227	260	1	1	1	1	1	1	1	1	1	1
	244	175	255	264	360	241	375	322	246	336	1	1	1	1	1	1	1	1	1	2
	310	316	283	243	269	257	277	237	285	212	2	2	2	2	2	2	2	2	2	2
AD 1051	203	207	220	153	271	227	247	241	291	272	2	2	2	2	2	2	3	3	3	3
	363	315	278	292	258	295	247	209	226	238	3	3	3	4	4	4	4	4	4	4
	228	220	181	145	204	192	189	230	211	196	4	4	4	4	4	4	4	4	5	5
	161	184	193	181	281	272	248	238	217	193	5	5	5	5	5	6	6	6	6	6
	242	236	235	207	238	216	199	205	202	191	6	6	7	8	8	8	8	8	8	8
AD 1101	163	158	160	171	197	181	148	186	129	107	8	8	8	8	8	8	8	8	8	8
	120	125	126	145	156	180	151	144	103	149	8	8	8	9	9	9	9	9	9	9
	146	154	168	160	151	126	122	137	98	105	9	9	9	9	9	9	9	9	9	9
	123	135	126	133	165	112	110	134	127	147	9	9	9	9	9	9	9	9	9	9
	168	177	134	128	175	169	137	146	163	144	9	9	9	9	9	9	10	10	10	10
AD 1151	144	142	187	145	155	173	180	181	193	221	10	9	9	9	9	9	9	9	9	9
	151	158	144	148	157	139	158	166	170	153	9	8	8	8	8	8	8	8	8	8
	158	148	132	119	113	140	105	132	174	134	8	8	8	8	8	8	8	8	7	7
	152	199	217	159	165	182	188	118	147	187	7	7	6	6	6	6	6	5	5	3
	197	209	255	166	133	264					2	2	2	2	2	1				

Table 5b

Ring-width data from site master PBT_B, dated AD 1360-1550 inclusive

Date	Ring widths (0.01mm)										No of samples									
AD 1360										170										1
	209	150	200	183	108	121	153	155	193	199	1	1	1	1	1	1	1	1	1	1
	124	122	145	146	157	163	115	152	203	137	1	1	1	1	1	1	1	1	1	1
	101	104	79	84	119	158	96	106	130	88	1	1	1	1	1	1	1	1	1	1
	152	88	129	109	112	148	139	162	144	193	1	1	1	1	1	1	1	1	1	1
AD 1401	135	130	164	109	138	96	216	301	271	220	1	1	1	1	1	1	2	2	2	2
	143	189	163	188	212	234	241	214	132	211	2	2	2	2	2	2	2	2	2	2
	190	170	217	200	254	205	178	190	231	223	2	2	2	2	2	2	2	2	2	2
	206	266	195	203	209	232	168	197	127	138	2	2	2	2	2	2	2	2	2	2
	142	111	129	202	160	193	156	144	145	122	2	2	2	2	2	2	2	2	2	2
AD 1451	140	146	132	190	169	163	150	143	118	157	2	2	2	2	2	2	2	2	2	2
	124	113	136	116	114	134	131	110	126	117	2	2	2	2	2	2	2	2	2	2
	102	96	102	128	161	152	133	141	140	120	2	2	2	2	2	2	2	2	2	2
	148	110	159	104	81	67	76	73	72	62	2	2	2	2	2	2	2	2	2	2
	58	57	73	71	68	99	84	58	87	107	2	2	2	2	2	2	2	2	2	2
AD 1501	89	87	83	85	77	70	73	67	70	81	2	2	2	2	2	2	2	2	2	2
	75	98	97	95	82	92	98	83	126	127	2	2	2	2	2	2	1	1	1	1
	203	177	155	109	102	125	113	169	116	116	1	1	1	1	1	1	1	1	1	1
	116	97	107	108	147	164	164	174	171	197	1	1	1	1	1	1	1	1	1	1
	188	242	168	104	122	140	189	176	154	143	1	1	1	1	1	1	1	1	1	1

Table 5c

Ring-width data from site master PBT_C, dated AD 1559-1668 inclusive

Date	Ring widths (0.01mm)										No of samples									
AD 1559									436	363									1	2
	493	421	369	478	391	329	322	272	430	434	2	3	5	5	5	5	5	5	5	6
	485	404	424	458	372	336	341	323	329	465	6	6	7	7	7	7	7	8	8	8
	362	396	365	405	359	346	319	288	361	251	8	8	8	8	9	9	9	10	10	10
	280	342	274	306	327	270	264	265	248	234	10	11	11	12	12	13	13	14	14	15
AD 1601	259	244	283	313	221	250	247	251	222	221	15	15	15	15	15	15	15	15	15	15
	244	194	202	178	170	137	177	224	173	216	16	16	16	16	16	16	16	16	16	16
	198	262	223	156	124	149	180	196	231	191	16	16	16	16	16	16	16	16	16	16
	165	197	181	124	171	116	144	206	158	181	16	16	16	16	16	16	16	16	16	16
	188	139	126	88	106	129	127	146	154	144	16	16	16	16	16	16	15	15	15	15
AD 1651	132	82	78	80	147	145	118	122	124	147	15	15	14	14	14	14	14	14	14	13
	133	140	156	155	144	153	114	113			12	12	12	10	9	7	5	4		

Table 5d

Ring-width data from site master PBT_D, undated

Ring widths (0.01mm)										No of samples									
371	332	544	516	568	548	514	491	584	755	1	1	2	2	2	3	3	4	5	5
553	507	463	471	592	487	557	476	398	350	5	5	5	5	5	5	5	5	5	5
434	561	467	274	184	233	193	172	184	177	5	5	5	5	5	5	6	6	6	6
219	242	218	235	121	133	162	198	335	233	6	6	6	6	6	6	6	6	6	6
244	366	363	269	172	163	246	300	276	254	6	6	6	6	6	6	6	6	6	6
244	193	233	248	173	158	178	118	175	194	6	6	6	6	6	6	6	6	6	6
174	184	179	164	148	161	173	147	131	158	6	6	6	6	6	5	5	5	5	5
182	192	167	187	170	169	175	141	203	189	4	4	4	4	4	4	3	3	3	3
198	246	235	174	263	395	347	229	340	423	3	2	2	2	1	1	1	1	1	1