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TREE-RING ANALYSIS OF OAK TIMBERS FROM PETERBOROUGH CATHEDRAL, PETERBOROUGH, CAMBRIDGESHIRE: STRUCTURAL TIMBERS FROM THE NAVE ROOF AND NORTH-WEST PORTICO

ENGLISH HERITAGE

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Summary

Tree-ring analysis was undertaken on samples from 74 structural timbers from two areas of the roof of Peterborough Cathedral. The results confirm the interpretation, based on documentary and structural evidence, of the construction sequence of the nave and north-west portico. The nave roof appears to be the product of a building campaign of the late-twelfth century, although the far west end of the nave includes some timbers from the early thirteenth-century. The north-west portico has a surviving remnant of an early thirteenth-century roof which is of broadly similar date to the later timbers at the west end of the nave.

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Introduction

This document is a technical archive report on the tree-ring analysis of timbers from Peterborough Cathedral, Peterborough, Cambridgeshire. It is beyond the dendrochronological brief to describe the sampled parts of the building in great detail or to undertake the production of detailed drawings. As part of a multifaceted and multidisciplinary study of the painted ceiling of the nave, 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 presented here may therefore have to be modified in the light of subsequent work.

Peterborough Cathedral lies in the centre of Peterborough (NGR TL194987), and is now in the modern county of Cambridgeshire, though traditionally in the Soke of Peterborough, part of Northamptonshire. A Benedictine Abbey was established on the site *c* AD 960. The present cathedral building, built between *c* AD 1118 and *c* AD 1238 (Higham 1990), is one of the finest surviving and most complete twelfth- and thirteenth-century structures in England. The nave ceiling consists of a unique series of painted panels which are the subject of a 7 to 10 year restoration programme partially funded by English Heritage. As part of this two separate but linked dendrochronology projects have been commissioned at the request of David Heath, English Heritage Cathedral Architect. The first project, and the subject of this report, is the analysis of the joists and other medieval oak timbers that are above the ceiling boards or in related roofs. The purpose of this project is twofold: to test our current understanding of the chronology and structural development of the roof, based on documentary evidence and surviving structural evidence; and to construct a strong reference chronology from the cathedral timbers that may assist the successful execution of the second project. The second of these projects concerns attempts to tree-ring date and provenance the painted boards (Groves forthcoming). The timing of, and the likelihood of success of, this longer term project will be determined primarily by the availability of access to the underside and end-grain of the boards during the long conservation programme.

A short description of the areas of sampling, and an attempt to explain the various numbering schemes in use in the nave is incorporated here to assist the clarity of this report. The nomenclature and numbering scheme of Donald Mackreth, Cathedral Archaeologist, are followed throughout this report.

The nave roof

The details of the construction of the nave roof were being recorded at the time this report was being compiled. A draft preliminary report by Donald Mackreth and a series of verbatim comments made by Hugh Harrison and Bob Chapell during the period of sampling were used to compile the following description.

The present roof of the nave (Fig 1) consists of 26 trusses, numbered 1 to 26 east-west by Mackreth. These are of pine and date from a major re-construction in the nineteenth or twentieth centuries of all the high roofs of the cathedral following extensive infestation by death-watch and woodworm beetles. These trusses are of scissor-brace construction with three collars (Fig 2). It is widely assumed that these are a reflection of the design of the roof they replaced. The westernmost 26th truss is inaccessible within a modern firewall. Documentary evidence, in the form of the Peterborough version of *The Anglo-Saxon Chronicle* which continues through to AD 1153 (Garmonsway 1972) and the *Chronicle of Hugh Candidus* which continues through to AD 1177 (Mellows 1997), suggest the original nave, and possibly its roof, was constructed over an extended period of the twelfth century, starting at the east end. The surviving structural medieval oak timbers are directly attached to the painted boards and appear to be the truncated part of the lowest collar and the truncated sections of the north and south scissor-braces of a scissor-braced common-rafter roof (Fig 2). In total there are 81 truncated collars and 81 pairs of truncated north and south braces directly above the painted ceiling. These are numbered 1 to 81 from the east, by Mackreth (Fig 3). The westernmost 81st set are inaccessible within the modern firewall. Randomly throughout the length of the nave these three elements have been replaced by curious laminated softwood beams, presumably as part of the documented nineteenth- or twentieth-century repair works.

Two other numbering sequences also need explaining. The nave is often referred to as of 10 bays, based on the vaulting below. These bays are numbered 1 to 10 from the east and, for example, results in the panel restoration project normally referring to itself as beginning in bay 1 (Fig 3). The decorated scheme of the ceiling consists of diamond sets of boards, with two diamonds down the centre-line for each bay of the nave. Hence there are 20 diamond sets down the centre-line of the nave. These are numbered 1 to 20 from the east in most descriptions (Fig 3). The bays, the diamond panels, and the 81 truncated trusses all form part of a coherent modular construction. For example the diamond panels are aligned with the truncated collars above, with the junctions between the centre line diamond panels directly under a collar in a number sequence of 1,5,9, etc,..., 77, 81. The collars in the number sequence 1, 9, 17, etc, ..., 73, 81 are aligned with the bays in the stonework below (Fig 3).

In contrast, the spacing of the 26 modern trusses does not respect the spacing of the collars or bays. In some parts of the roof they inhibit access to the truncated medieval trusses.

The north-west portico

There are eight fairly complete trusses of a roof perhaps similar in design to the lost parts of the nave roof in the north-west portico (Figs 1 and 4). These are thought on documentary and structural grounds to be of similar date to the panels themselves, although there is some suggestion they are truncated, and possibly re-used from elsewhere in the cathedral (Reuter 1964; Hewett 1985). No numbering scheme was known to be in use in this area at the time of sampling. For reference purposes the trusses were labelled NW1-NW8 from the east.

Initial Objectives

The objectives of the sampling request were twofold:

i) To test our current understanding of the chronology and structural development of the roof, based on documentary evidence and surviving structural evidence.

ii) To assist the successful analysis of the ceiling boards a sufficiently large sample size should be obtained from the structural timbers to enable the construction of a chronology that is reliable and well replicated. This objective is predicated on the assumption that the painted boards were derived from a similar area as the structural elements. This assumption cannot be addressed until the analysis of the boards gets underway.

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 240 support timbers from truncated trusses 1 to 80, and the surviving timbers from the eight north-west portico trusses were assessed for their potential to provide dendrochronological dates. The three timbers in the 81st truss were inaccessibly embedded in the modern firewall.

In the nave this process involved climbing out to the joint at each end of each truncated collar where it passes the truncated scissor brace. For each of these, where the end was not covered by the later softwood planking, the end-grain was cleaned with a toothbrush so that the potential of the material to produce viable tree-ring samples could be assessed. The laminated pine timbers were excluded from this process. Most of the collars also have a central joint housing for an original vertical timber which, after cleaning, also allowed easy assessment of the cross-section and numbers of rings in the collars. Although there were no consistent redundant housings on the truncated scissors there were a variety of places where the joints had been cut back and therefore allowed easy assessment. The north-west portico timbers were similarly assessed although their more complete character meant that assessment usually relied purely upon the visible surface features rather than on later cuts or redundant housings.

A selection of the most promising timbers from both the nave roof and the north-west portico 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 the nave the later softwood trusses restricted access to a great many of the timbers. In addition the presence of a unique ceiling directly under the timbers and the necessity of downward sampling towards it, whilst perched over an 25 metre drop certainly provided a more interesting sampling environment than many. All sampling on the truncated nave elements had to be undertaken in a downward direction which, due to increased problems of saw-dust clogging the corers, generally leads to a lower success rate than upward or level coring angles. Here, perhaps due to the dry and warm atmosphere there were few problems evident. 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 1997). 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 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.

A further important element of the tree-ring analysis of buildings and archaeological assemblages is the identification of 'same tree' groups within the sampled material. Inspection of timbers, both in buildings and archaeological sites, often suggests that the patterns of knots or branching in timbers are so similar that they appear to be derived from a single tree. Tree-ring analysis is often used to support these suggestions. The identification of 'same tree' groups is based on a combination of high levels of matching between samples, extremely similar longer term growth trends, and individual anatomical anomalies within the timbers. High *t*-values are not by themselves necessarily indicative of two series being derived from a single tree. Conversely low *t*-values do not necessarily exclude the possibility. It is the balance of a range of information that provides the evidence.

Results

Assessment

Nave

Some of the medieval timbers have modern sections scarf-jointed in, so there are in reality more than 240 elements in total. It was determined that 67 of the 240 timbers are entirely modern replacements. 43 of the remainder were assessed as having too low a number of rings for successful dendrochronological analysis, and 20 of the remainder were noted as either being difficult to access (here the principal problem is the modern trusses are in the way of the correct coring angle) or knotty (thus it is potentially difficult to get complete cores, or datable sequences, from these timbers). This leaves *c* 110 oak structural elements, of presumed medieval date, of some potential dendrochronological use.

Overall the timbers are derived from quartered or halved trees. The trees are of a quite slow-grown nature and are remarkably straight grained. The surviving collar lengths are around 8 metres, but it seems likely these were 10 to 11 metres long prior to truncation.

The oak timbers throughout the nave included visible heartwood/sapwood boundaries, but very little sapwood and no observed bark-edge. This is doubtless a result of the beetle infestations that prompted the re-construction in pine. No later oak insertions were identified, although a number of oak timbers apparently similar to and possibly re-used from the nave roof are present, particularly as common rafters at the east end of the nave. These were thought to be too slight for coring. The softwood timbers of the re-construction were not within the brief for this analysis.

North-west portico

These timbers were also derived from long, straight, slow-growing trees similar to those of the nave. Some of the surviving scissor-braces are 7 or 8 metres long. The reconstruction by Reuter suggests the principal rafters would have been 9 to 10 meters long (Reuter 1964, 182). The oak timbers throughout the north-west portico included identifiable heartwood/sapwood boundaries but again very little surviving sapwood. The later oak structure, a series of four supporting purlins, included two timbers of marginal suitability for tree-ring analysis.

Summary of assessment

The paucity of sapwood and absence of surviving bark-edge throughout meant there would be no opportunity to assign precise calendar dates to the construction of any part of the roof.

Consultation with colleagues led to the decision to sample fairly extensively across the entire nave with, if survival of suitable timbers allowed, a concentration in bays 1 and 10 and in the middle of the roof, *c* bays 5 and 6. This was to try and determine if there was a difference of construction date between the different ends. The north-west portico scissor-braced trusses were to be sampled to allow for an extension of the sequence up to the likely construction date of the panels. Finally there is little dendrochronological literature relating to how extensive a sampling programme is required to yield a 'strong' tree-ring sequence. Each site, local area, and group of trees brings a number of disparate and unique factors to such an exercise and no clearly defined rules have been identified. Replication levels appropriate for objective ii) were thus somewhat difficult to set but it was eventually agreed to attempt to obtain *c* 70 cores. Allowing for normal sampling failure and cross-dating success this number of cores was intended to produce around 50 dated timbers, allowing the construction of a robust sequence for subsequent use in the board project.

Refined objectives

Nave

iii) test the broad accuracy of the construction sequence identified from documentary and structural evidence and likely period of construction activity of the nave roof. This to be achieved by concentrating on timbers with heartwood/sapwood boundaries and, if the surviving remnants and difficulties of access allow, a concentration in bay 1, bays 5-6, and bay 10

iv) attempt to sample at least 60 timbers

v) check a later undocumented roof replacement is not what is present

vi) construct a 'strong' sequence in order to assist with the dating of the ceiling boards.

North-west portico

i) extend the reference data out to the most likely period of construction of the painted ceiling

ii) test documentary and other evidence that this is a later structure

iii) attempt to sample at least 10 timbers

In addition sampling this extensively within a relatively tightly phased structure potentially creates data useful in addressing the following questions:

i) if there is a clearly defined mixture of sources for the timbers this may help illustrate characteristics of the monastic economy, such as the habit of gifting the monastic orders trees for structural projects. If not it may illustrate the nature of some of the monastic land holdings

ii) if a foreign origin for the timbers is indicated this would identify international trade in timber at an early date

iii) the numbers of samples, and the general presence of quartered and halved timbers should identify some level of same-tree usage. Such data may help calculate the number of missing timbers in the lost structure, and the acreage of woodland required for the construction of the roof

iv) the data may illuminate statistical issues relating to tree-ring chronology construction and replication

<u>Dating the timbers</u>

The sampling programme obtained samples from 74 oak timbers (*Quercus* spp.) labelled **1** to **74** (Table 1). These can be divided into 60 from the nave roof, 12 from the north-west portico trusses, and two from the north-west portico later support purlins. The coring operation was carried out from the west, due to the inconvenience of working in bay 1 during the restoration work. A disadvantage of this is that the core numbering sequence primarily runs west to east, in opposition to the majority of the numbering schemes in use in the roof.

Four samples were of no further use: sample **5** from a north-west portico support purlin, samples **16** and **27** from the nave in bay 10, and sample **62** from bay 2. The remainder were measured. All 70 measured samples had more than 75 rings. Four had some sapwood, whilst 31 samples were complete to, or probably complete to, the heartwood/sapwood boundary. Two timbers, samples **19** and **60**, had anatomical anomalies preventing the entire ring sequence being obtained. These were both measured in 2 segments suffixed with an inner and outer label (eg **19in**, **19out**). Nine timbers were sampled twice, usually due to fragmentation problems with the first core. The second cores were suffixed with a B code (eg **20** and

20B). Where both cores had measurable sequences a composite sequence was created by averaging the sequences, these were suffixed with an M code (eg **20M**). Table 2 summarises the sampling by area, showing the attempt to concentrate at the ends and mid-point of the nave.

The 70 successfully sampled and measured series were initially compared with each other. Sixty-nine sequences were found that matched together to form an internally consistent group (Table 3a-c). A 339-year site mean chronology was calculated, named 'PCRStructural' (Fig 5; Table 4). The site mean was then compared with dated reference chronologies from throughout the British Isles and northern Europe. Table 5 shows the correlation of the mean sequences at the dating position identified for the sequence, AD 887-1225 inclusive.

Sample **6**, the only one of the measured north-west portico support purlins, did not match the rest of the material that forms the 'PCRStructural' sequence. This sequence was compared with dated reference chronologies from throughout the British Isles and northern Europe without any dating being obtained. The support purlins are thought to be a later modification to the north-west portico trusses.

Interpretation

The 339-year chronology 'PCRStructural' is dated AD 887 to AD 1225 inclusive. It was created from 69 timbers of which four had some sapwood and a further 30 were complete to either the heartwood/sapwood boundary or the possible heartwood/sapwood boundary. Two features are clearly visible from inspection of the bar diagram (Fig 5) which depicts the span of ring sequences obtained arranged in date order divided up into the different bays and other sampling areas. Firstly the north-west portico structure is slightly later than the majority of the timbers from the nave roof, and secondly there are some timbers present in bays 9 and 10 which are broadly contemporary with the north-west portico structure, and clearly later than the bulk of the material from the roof. First however we should examine the dating evidence from the nave roof.

Nave

There are dated timbers from all ten bays, and there are timbers with heartwood/sapwood boundaries from seven bays, the exceptions being 3, 8, and 10. There are only two timbers with sapwood, sample **63** in bay 2 and sample **32** in bay 9. It is clearly impossible under these circumstances to determine the precise felling date of any timber or the precise construction date of any part of the structure. Instead fairly broad felling date ranges can be applied to each bay. Fig 6 shows felling date ranges calculated for each bay, assuming the contemporaneity of the felling period for the timbers within each bay, but deliberately <u>excluding</u> 2 samples each from bays 9 and 10 (see below).

Is the roof the product of a single building campaign?

The date ranges calculated from each bay may be taken to suggest the whole original nave roof was constructed between AD 1180 to AD 1188. This however assumes both that the entire roof was the product of a single intensive building campaign, and that the usual assumptions of the use of green, rather than stockpiled, timbers are appropriate (Rackham 1990, 69). However before accepting this suggestion it is important to re-iterate that the absence of sapwood prevents precise dating being obtained from any one timber and that the varying survival of sapwood and varying sampling density along the roof automatically creates different degrees of dating precision for each bay. It may also be inappropriate to assume the absence of stockpiling for complex ecclesiastical building programmes (see discussion below).

The tree-ring evidence could indicate that bays 1, 5, and 7 are a decade or so earlier than the others, although there is no structural reason why bays 5 and 7 should be any different in date from bay 6. The situation is more complex for bay 1, where structural and documentary evidence indicates this is the first completed part of the nave structure (Mackreth pers comm). Excluding the bay 1 data from the calculations yields a date range of AD 1180-89 for bays 2 to 10, whilst bay 1 alone has a AD 1169-88 construction date. Hence, the data cannot be reliably used to imply bay 1 is earlier than the rest of the structure, and all the results provide is somewhat equivocal evidence for an extended period of construction.

The later nave timbers in the western bays

However there is no doubt that there are three, or possibly four, timbers from bays 9 and 10 which do not appear to be contemporary with the rest of the nave roof..

Samples **19** and **24** from bay 10, sample **32** from bay 9, and possibly sample **34M** from bay 9 produced noticeably later sequences. Sample **19** was felled after AD 1222, **24** after AD 1206, **32** between AD 1211 and AD 1256, whilst **34M** was felled between AD 1186 and AD 1231. Assuming these are contemporary indicates a common felling period for the first three of AD 1222-56, or if all four are contemporary a felling date range of AD 1222-31. Sample **34M** cannot clearly be identified as part of either this group or the nave roof construction. Subsequent examination of these timbers failed to observe differences in surface tool-marks or other evidence to distinguish between them and the apparently earlier timbers in the same bays.

North-west portico

Two samples here included sapwood, whilst six others were complete to the heartwood/sapwood boundary. Assuming these are contemporary indicates a common felling period of AD 1225-1230 for these timbers.

Discussion

The dates outlined above provide strong supporting evidence for the structural analysis of Donald Mackreth (pers comm). The stonemasons marks in the nave indicate a disturbance at the extreme west end of the nave walls, interpreted as part of the construction of the new west front and towers. This work involved the taking down of the original west front and some parts of the westernmost nave walls. Taking down the westernmost nave would clearly have disturbed any pre-existing roof structure over it. The tree-ring evidence appears to suggest that although the original timbers were mostly re-usable it was also necessary to incorporate fresh timbers during the re-roofing. This has resulted in four timbers being identified in bays 9 and 10 which are likely to be contemporary with the re-construction of the end section of the nave, although the majority of the timbers are contemporary with the rest of the nave roof and probably derived from original roof timbers. The trusses in the north-west portico appear to be contemporary with this disturbance. Assuming the ceiling was inserted only after all of this construction work was completed appears to suggest that the earliest possible date for the ceiling is AD 1222-1231. The structural evidence from the stone work suggests the nave was intended to be stone vaulted but that movement in the walls from the weight prevented the completion of the scheme (Mackreth pers comm). Hence, the unique ceiling was only conceived after the failure of the stone vaulting.

The chronology constructed from the tree-ring data is unusually robust, over 12000 individual tree-rings were measured from the cores. The resultant master chronology matches well to tree-ring chronologies from across Europe as well as to virtually every contemporaneous data set from England and Wales. However the best matches (Table 4) are mostly to other eastern and central English data and there seems little doubt that the timbers were derived from somewhere within this area and in all probability not too far from Peterborough. The unexpected dating of all 69 measured sequences from the early medieval roof timbers has produced a better replicated data set than was originally requested. Although this achievement must be partly a reflection of the great length of the sequences derived from many of the samples, it may also be an indication that a common or at least remarkably similar woodland area was exploited for all the sampled nave and north-west portico timbers. If this is the case a single woodland type or area was continually exploited for long straight slow-grown timbers for 40 to 60 years for the construction of these cathedral roofs. The *Chronicle of Hugh Candidus* lists two papal bulls of 1146 (Mellows 1997, 52-57) which appear to list the monastic holdings at that time and notes (op cit, 52, fn 3) the small difference between these lists and the holdings of the monastery at the time of its dissolution in 1539. This offers the intriguing possibility that some documents in the archives may indicate where the roof timbers came from.

There are several other aspects of the analysis that have some relevance for the interpretations. Firstly, a broad sapwood estimate has been used for the calculation of the felling date ranges despite some evidence that a narrower range is appropriate in many areas of the country (eg Miles 1997, 46; English Heritage 1998, 11). The 10-55 year sapwood range of Hillam *et al* (1987) has been used here because the more recent work arguing for narrower sapwood estimates has been using data from timbers that are generally both faster grown and from less long-lived trees than those present in the Peterborough roofs. Hollstein (1980, 34) and Hillam *et al* (1987, 169) both presented evidence that tree-age has some influence on total sapwood numbers, whilst the latter reference also suggested that average growth-rate has some influence. It is clearly inappropriate to utilise a sapwood estimate primarily derived from young fast-growing trees on the Peterborough roof timbers since these are both exceptionally long-lived and unusually slow-grown and one must expect them to have a different sapwood range. The calculation of possibly spurious narrow felling date ranges for each bay, by use of a tight sapwood estimate could lead to entirely false conclusions about the phasing of the roof construction. This potential pitfall is avoided by using the broad sapwood estimate.

The Peterborough Cathedral roof tree-ring results have many aspects of similarity to the results obtained from Lincoln Cathedral (summarised in Simpson and Litton 1996). For example at Lincoln the absence of sapwood also prevents precise felling dates being assigned to most parts of the early roofs and there is extensive re-use of earlier timbers in later structures. What is clearly indicated at Lincoln that is not apparent, but should be considered a possibility, at Peterborough is the presence of stockpiled timbers. At Lincoln there is evidence for the first-use of some timbers that were felled up to 40 years earlier. If there were such material at Peterborough this could in theory allow for the construction of the entire nave ceiling to be dated around AD 1220-30, but using 90% or more stockpiled timbers from 40 years before. Fortunately such a suggestion is not tenable at Peterborough due to the later felled material being restricted to an area where masonry evidence suggests there was a period of later disturbance. This evidence argues for the identified re-use being restricted to a small area of the roof, with the majority of the roof earlier and undisturbed.

Statistical evidence suggests that the chronology is more than adequately replicated. Figure 7 shows that the average *t*-values of the PCRStructural sequence against a large number of reference chronologies no longer increase after the inclusion of any 40 of the dated sequences, and may possibly decline. This feature may simply relate to mathematical rounding error, but may be an indication that there is a poorly understood feature of the balance of local and regional characteristics within a well replicated tree-ring data set. There is a frustrating paucity of other large groups of contemporaneous single structure data with which to compare the observed trend in the correlation behaviour of the composite sequence with increasing levels of replication.

The level of internal correlation between the entire data set, the consistent use of long-lived and slow-grown trees, and the consistent use of quarters or halves of such trees may all be taken to indicate a single common woodland resource was exploited over a 50-year period to provide the timbers for the roofs of the nave and portico. This conclusion is potentially supported by statistical analysis of the tree-ring series using cluster methods (Hans-Hubert Leuschner and Thomas Reimer pers comm), principal components analysis (John Spain pers comm), and the Litton-Zainodin grouping procedure (eg Litton and Zainodin 1991) which all fail to indicate there are any consistent sub-groupings within the data. Such a conclusion is perhaps evidence contrary to the frequently assumed occurrence of gifts of trees from major benefactors from the King downwards for ecclesiastical projects of this scale which should yield clearly differentiated sources of timber. Although some care should be taken with negative evidence I think the very small number of 'same-tree' matches within the measured sequences despite the large number of samples is probably indicative of the number of timbers now lost from the original medieval roof. This presumably originally had principal rafters, collars, purlins, wind braces, and vertical struts that are all now lost.

The value of the PCRStructural sequence to tree-ring analysis of the painted ceiling will only be known when the tree-ring sequences have been obtained and analysed from the boards (Groves forthcoming).

Conclusion

The dendrochronological analysis of timbers from the roof of Peterborough have demonstrated the general accuracy of the documentary evidence relating to the cathedrals construction, and validated the interpretation of the surviving structural evidence put forward by Donald Mackreth as a result of his analysis of the stonemasons marks. It is hoped the resultant data set has some potential for assisting in the dating of the painted boards. Even if this is not the case, if for example the boards and structural timbers are from different source areas, it has yielded an extremely well replicated tree-ring data set of value for future dendrochronological research.

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References

Baillie, M G L, 1977 Dublin Medieval Dendrochronology, *Tree-Ring Bulletin*, **37**, 13-20

Baillie, M G L, 1982 *Tree-ring dating and archaeology*, London

Baillie, M G L, and Pilcher, J R, 1973 A simple crossdating program for tree-ring research, *Tree Ring Bulletin*, **33**, 7-14

Brown, D, 1993 Dendrochronological analysis, in *A Medieval Industrial Complex and its Landscape: the Metalworking Watermills and Workshops of Bordesley Abbey* (G G Astill), CBA Res Rep, **92**, 242-5

Bush, P, 1997 *The Painted Ceiling of Peterborough Cathedral*, Peterborough

English Heritage, 1998 *Guidelines on producing and interpreting dendrochronological dates*, London

Garmonsway, G N, 1972 *The Anglo-Saxon Chronicle*, new edn, London

Groves, C, 1990 *Tree-ring analysis of medieval bridge timbers from Willaston moated site, near Nantwich, Cheshire, 1990*, Anc Mon Lab Rep, **79/90**

Groves, C, 1992 Tree-ring analysis of timbers, in *Excavations at 33-35 Eastgate, Beverley, 1983-86* (D H Evans and D G Tomlinson), *Sheffield Excavation Rep*, **3**, 256-65

Groves, C, forthcoming *Tree-ring analysis of oak timbers from Peterborough Cathedral, Peterborough, Cambridgeshire: timbers from the painted nave ceiling*, Anc Mon Lab Rep

Groves, C, and Hillam, J, 1985 *Beverley: Dyer Lane 1982, Dendrochronology,* Anc Mon Lab Rep, **4691**

Hewett, C, 1985 *English Cathedral and Monastic Carpentry*, Chichester

Higham, J, 1990 *Peterborough Cathedral*, Andover

Hillam, J, 1984 *Bristol Bridge dendrochronology: analysis of the reused boat timbers,* Anc Mon Lab Rep, **4168**

Hillam, J, and Groves, C, 1993 *Tree-ring analysis of oak timbers from the south range of the Blackfriars Priory, Gloucester, Gloucestershire*, Anc Mon Lab Rep, **26/93**

Hillam, J, Morgan, R A, and Tyers, I, 1987 Sapwood estimates and the dating of short ring sequences, in *Applications of tree-ring studies: current research in dendrochronology and related areas* (ed R G W Ward), BAR Int Ser, **333**, 165-85

Hollstein, E, 1980 *Mitteleuropäische Eichenchronologie*, Mainz

Laxton, R R, and Litton, C D, 1988 *An East Midlands master tree-ring chronology and its use for dating vernacular buildings*, University of Nottingham, Dept of Classical and Archaeological Studies, Monograph Series, **III**

Litton, C D, and Zainodin, H J, 1991 Statistical models of Dendrochronology, *J Arch Sci*, **18**, 429-40

Mellows, W T (ed), 1997 *The Peterborough Chronicle of Hugh Candidus*, revised edn, Peterborough

Miles, D M, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architect*, **28**, 40-56

Munro, M A R, 1984 An improved algorithm for crossdating tree-ring series, *Tree Ring Bulletin*, **44**, 17-27

Nayling, N, 1998 Oak Dendrochronology, in *Magor Pill medieval wreck* (N Nayling) CBA Res Rep, **115**, 116-22

Nicholson, R, and Hillam, J, 1987 Tree-ring analysis of medieval oak timbers from Dundas Wharf, Redcliffe Street, Bristol, *Trans Bristol and Gloucs Archaeol Soc*, **105**, 133-45

Rackham, O, 1990 *Trees and woodland in the British Landscape*, 2nd edn, London

Reuter, R, 1964 Addendum: Scissor-Braced Trusses at Peterborough Cathedral, 182-3, in Fletcher, J M, and Spokes, P S, The Origin and Development of Crown-Post Roofs, *Medieval Archaeology*, **8**, 152-83

Simpson, W G, and Litton, C D, 1996 *Dendrochronology in Cathedrals* 183-209, in Tatton-Brown, T, and Munby, J, *The Archaeology of Cathedrals*, Oxford University Committee for Archaeology Monograph, **42**

Tyers, I, 1996a *The tree-ring analysis of Six secular buildings from the City of Hereford*, Anc Mon Lab Rep, **17/96**

Tyers, I, 1996b *Tree-ring analysis of the tower of St John the Baptist Church, Mamble, Hereford and Worcester*, Anc Mon Lab Rep, **22/96**

Tyers, I, 1997 *Dendro for Windows program guide*, ARCUS Rep, **340**

Tyers, I, forthcoming *Tree-ring analysis of the bell tower of the Church of St Mary, Pembridge, Herefordshire* Anc Mon Lab Rep

Figure 1 Plan of cathedral showing the nave and the north west portico

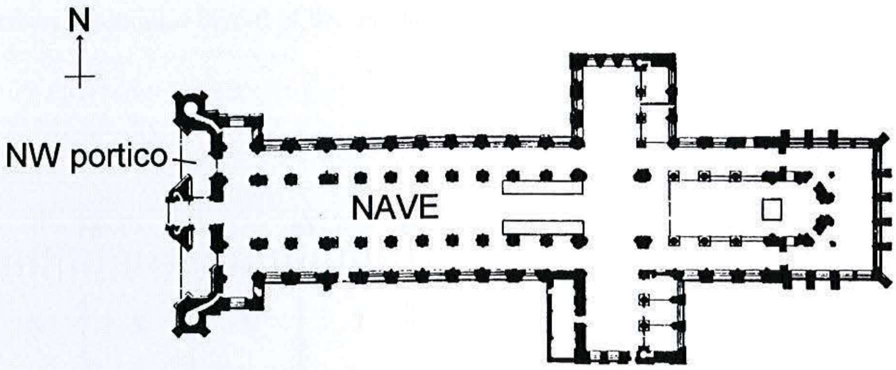


Figure 2 A typical truss from the nave showing the modern truss layout, the positions of the truncated collars and scissor-braces of the original trusses, and the location of the painted panelling (after Marshall Sisson and Partners diagram)

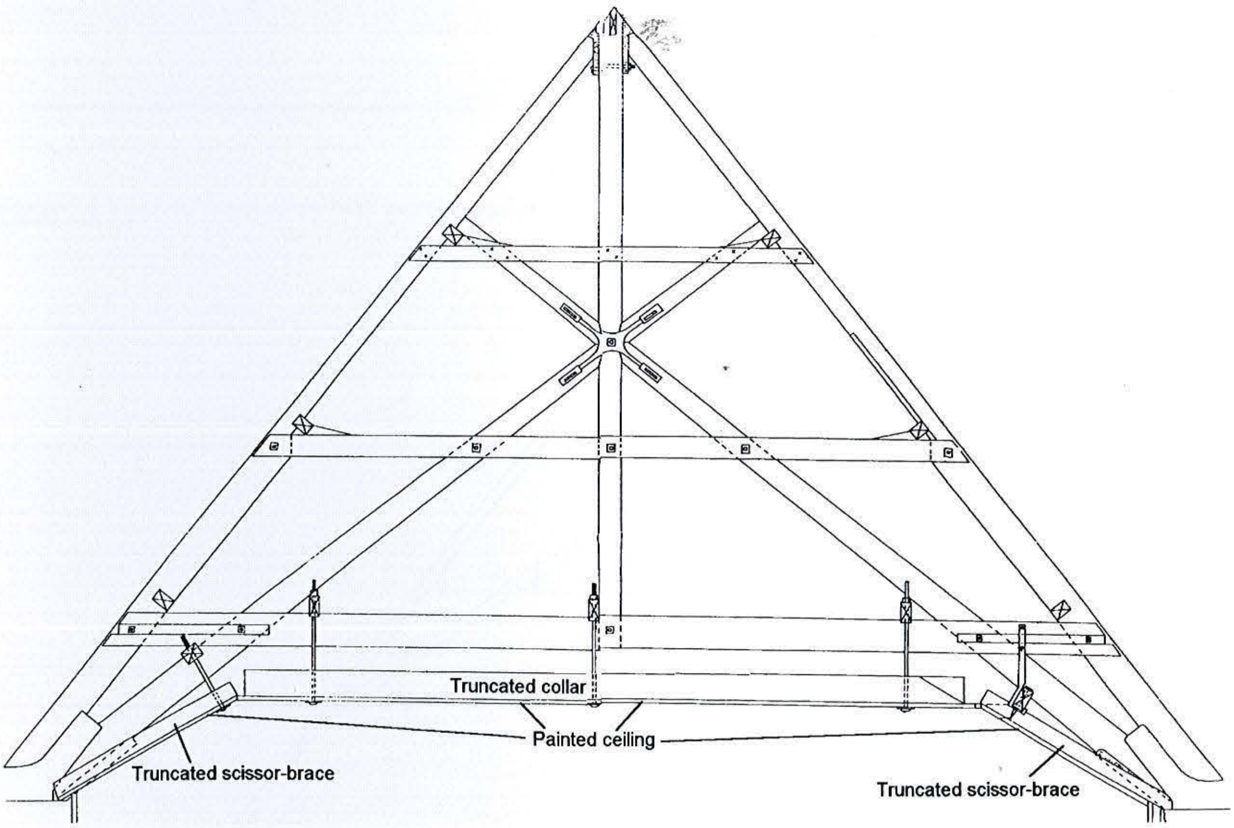


Figure 3 Plan of the ceiling showing the diamond layout of the painted panels, the central panel numbering scheme, and the relative positions of the bay and original truss numbering scheme used in this report, showing the coherent modular layout of the medieval elements of the roof (diamond layout after Bush 1997)

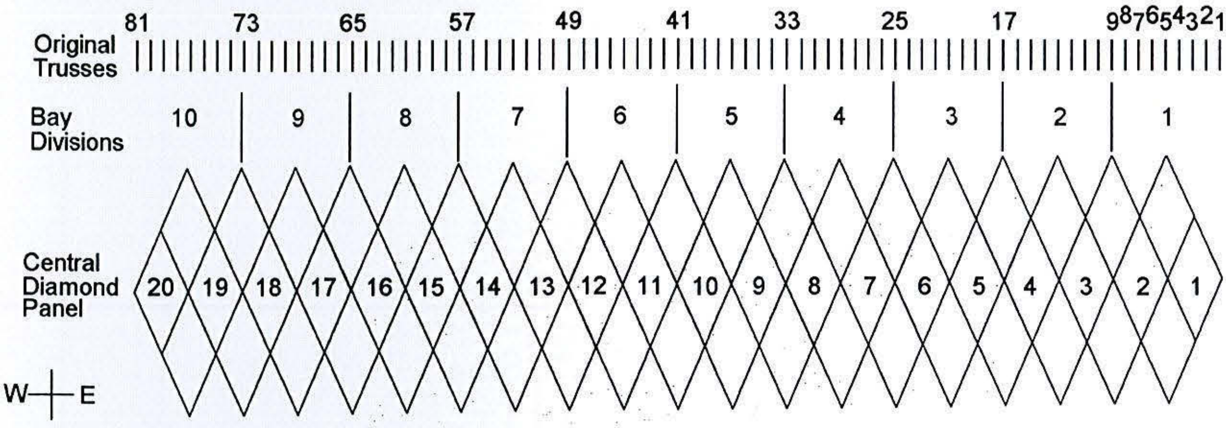


Figure 4 Typical truss from NW portico (after Reuter 1964)

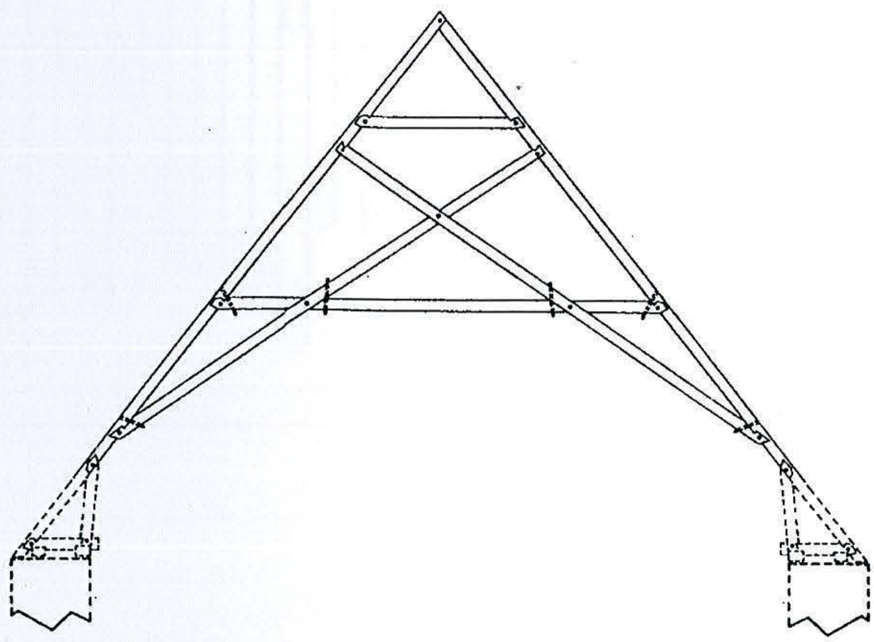


Figure 5 Bar diagram showing the chronological positions of the 69 dated timbers

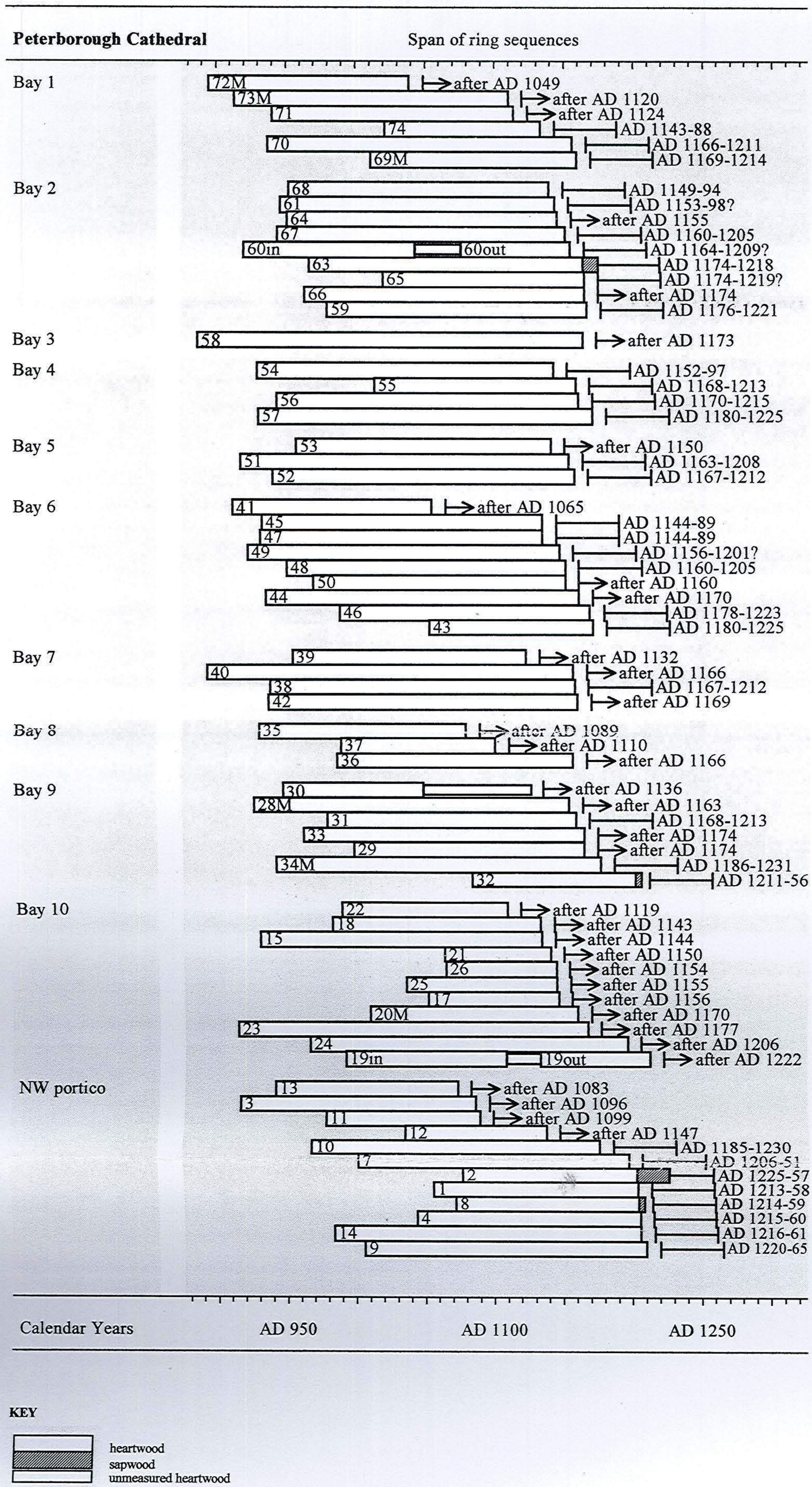
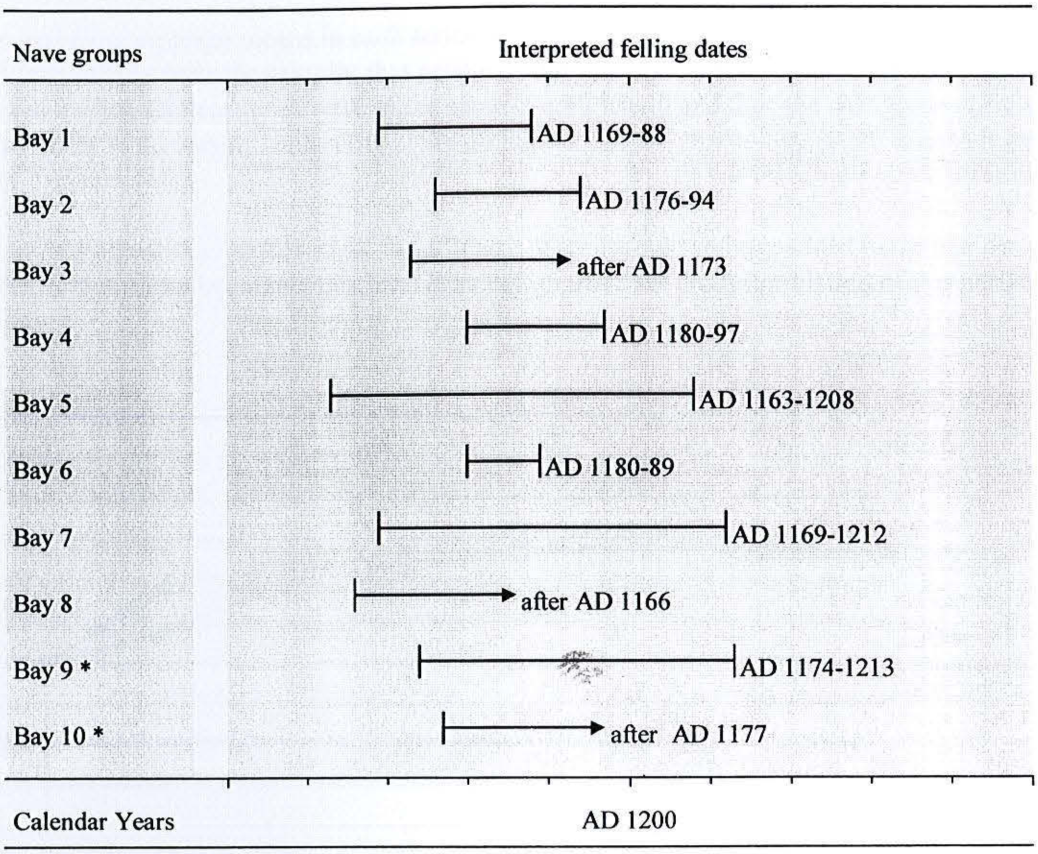


Figure 6

The felling date ranges calculated for each bay, assuming the contemporaneity of the felling period for the timbers within each bay, but deliberately excluding 2 samples each from bays 9 and 10 (see discussion)

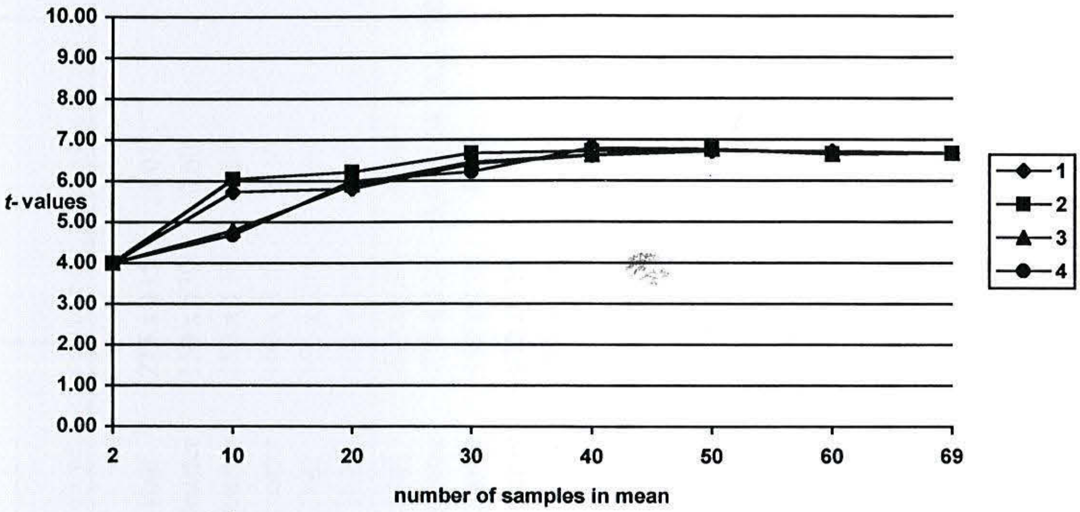


* excluding two samples

Figure 7 One aim of the analysis was to produce a strong chronology for subsequent work on the painted ceiling, it is too early to judge the success of this objective since the analysis of the ceiling boards is at a preliminary stage. This diagram shows the average *t*-values of Peterborough Cathedral chronologies of different replication and with different components against an arbitrary collection of 119 English and Welsh reference tree-ring chronologies that overlap the Peterborough chronology.

The two and 69 component means in each series are identical. The initial two timbers were not randomly selected instead they were the samples that produced the first and last rings of the chronology. This was done to ensure that all data series were of the same overall length and thus the changes in correlation relate to improvement in the quality, judged by cross-correlation, of the chronology rather than to increasing length of the chronology.

Note there is a plateau in *t*-values in all cases after *c* 40 timbers have been added to the site chronology, this indicates that sampling above this level does not improve the cross-correlation of this particular site chronology.



KEY

Series 1 and 2 are where the samples for inclusion were selected at random

Series 3 is where samples were ordered by their correlation to the overall site mean. The highest values were selected first

Series 4 is where samples were ordered by their correlation to the East Midlands Master sequence (Laxton and Litton 1988). The highest values were selected first

Table 1 List of samples, grouped by area of sampling (KEY overleaf)

Area	Core No	Origin of core	Total rings	Sapwood rings	Cross-section of tree	Cross-section size (mm)	ARW mm/year	Date of sequence	Felling period
Nave bay 1	**69M**	Collar 9	149	h/s	Half	215 x 115	1.01	AD 1011 - 1159	AD 1169-AD 1214
	70	Collar 8	220	h/s	Quarter	150 x 130	0.60	AD 937 - 1156	AD 1166-AD 1211
	71	South scissor 7	175	-	Quarter	150 x 130	1.14	AD 940 - 1114	after AD 1124
	72M	North scissor 3	145	-	Quarter	160 x 120	1.36	AD 895 - 1039	after AD 1049
	73M	Collar 3	198	-	Half	155 x 105	0.64	AD 913 - 1110	after AD 1120
	74	Collar 2	113	h/s	Half	190 x 150	0.90	AD 1021 - 1133	AD 1143-AD 1188
Nave bay 2	**59**	Collar 16	187	h/s	Half	220 x 125	0.60	AD 980 - 1166	AD 1176-AD 1221
	60	Collar 14 *	124+32+79	h/s?	Quarter	170 x 125	0.95/0.58	AD 920 - 1043/AD 1076 - 1154	AD 1164-AD 1209?
	61	North scissor 14	198	h/s?	Quarter	150 x 130	0.86	AD 946 - 1143	AD 1153-AD 1198?
	62	South scissor 15	-	-	Quarter	170 x 135	-	not measured	-
	63	North scissor 13	208	11	Quarter	170 x 125	1.02	AD 967 - 1174	AD 1174-AD 1218
	64	Collar 13	195	-	Quarter	190 x 120	0.61	AD 951 - 1145	after AD 1155
	65	South scissor 11	145	h/s?	Quarter	165 x 115	1.05	AD 1020 - 1164	AD 1174-AD 1219?
	66	South scissor 12	201	-	Quarter	165 x 125	0.79	AD 964 - 1164	after AD 1174
	67	Collar 11	207	h/s	Half	210 x 120	0.68	AD 944 - 1150	AD 1160-AD 1205
	68	Collar 10	188	h/s	Half	190 x 120	0.72	AD 952 - 1139	AD 1149-AD 1194
Nave bay 3	**58**	Collar 22	277	-	Quarter	205 x 120	0.78	AD 887 - 1163	after AD 1173
Nave bay 4	**54**	Collar 33	213	h/s	Quarter	245 x 115	0.73	AD 930 - 1142	AD 1152-AD 1197
	55	Collar 30	145	h/s	Quarter	190 x 120	1.01	AD 1014 - 1158	AD 1168-AD 1213
	56	Collar 29	217	h/s	Half	220 x 125	0.62	AD 944 - 1160	AD 1170-AD 1215
	57	Collar 27	240	h/s	Half	205 x 110	0.76	AD 931 - 1170	AD 1180-AD 1225
Nave bay 5	**51**	Collar 40	236	h/s	Quarter	190 x 115	0.84	AD 918 - 1153	AD 1163-AD 1208
	52	Collar 38	217	h/s	Quarter	220 x 125	0.78	AD 941 - 1157	AD 1167-AD 1212
	53	Collar 37	183	-	Quarter	210 x 120	0.73	AD 958 - 1140	after AD 1150
Nave bay 6	**41**	Collar 49	144	-	Half	200 x 130	1.04	AD 912 - 1055	after AD 1065
	43	North scissor 49	118	h/s	Quarter	150 x 140	1.44	AD 1053 - 1170	AD 1180-AD 1225
	44	South scissor 49	225	-	Quarter	160 x 150	0.86	AD 936 - 1160	after AD 1170
	45	Collar 47	202	h/s	Half	200 x 130	0.56	AD 933 - 1134	AD 1144-AD 1189
	46	Collar 45	180	h/s	Half	210 x 140	0.70	AD 989 - 1168	AD 1178-AD 1223
	47	Collar 44	203	h/s	Half	200 x 115	0.61	AD 932 - 1134	AD 1144-AD 1189
	48	Collar 42	200	h/s	Quarter	190 x 120	0.71	AD 951 - 1150	AD 1160-AD 1205
	49	Collar 43	224	h/s?	Quarter	180 x 140	0.89	AD 923 - 1146	AD 1156-AD 1201?
	50	South scissor 45	181	-	Quarter	140 x 120	0.88	AD 970 - 1150	after AD 1160
Nave bay 7	**38**	Collar 57	219	h/s	Quarter	210 x 120	0.94	AD 939 - 1157	AD 1167-AD 1212
	39	Collar 56	168	-	Quarter	210 x 130	0.99	AD 955 - 1122	after AD 1132
	40	Collar 52	263	-	Quarter	210 x 130	0.88	AD 894 - 1156	after AD 1166
	42	Collar 50	222	-	Half	205 x 130	0.64	AD 938 - 1159	after AD 1169
Nave bay 8	**35**	Collar 64	149	-	Quarter	210 x 135	0.96	AD 931 - 1079	after AD 1089
	36	Collar 62	170	-	Quarter	210 x 120	1.17	AD 987 - 1156	after AD 1166
	37	Collar 61	111	-	Quarter	215 x 130	0.81	AD 990 - 1100	after AD 1110
Nave bay 9	**28M**	Collar 73	227	-	Half	165 x 160	0.78	AD 927 - 1153	after AD 1163
	29	Collar 71	166	-	Quarter	230 x 140	1.41	AD 999 - 1164	after AD 1174
	30	Collar 70	102+77	-	Half	220 x 115	0.79	AD 948 - 1049	after AD 1136
	31	Collar 69	179	h/s	Quarter	200 x 120	1.18	AD 980 - 1158	AD 1168-AD 1213
	32	South scissor 68	122	4	Quarter	140 x 140	1.25	AD 1084 - 1205	AD 1211-AD 1256
	33	Collar 67	202	-	Quarter	210 x 105	0.87	AD 963 - 1164	after AD 1174
	34M	Collar 66	234	h/s	Quarter	230 x 110	0.88	AD 943 - 1176	AD 1186-AD 1231
Nave bay 10	**15**	South scissor 75	204	-	Quarter	160 x 140	0.94	AD 931 - 1134	after AD 1144
	16	Collar 76	-	-	Quarter	170 x 150	-	not measured	-
	17	Collar 75	95	-	Quarter	160 x 140	1.49	AD 1052 - 1146	after AD 1156
	18	North scissor 77	151	-	Quarter	170 x 145	0.98	AD 983 - 1133	after AD 1143
	19	North scissor 76 *	117+24+80	-	Quarter	170 x 155	0.83/0.87	AD 992 - 1108/AD 1133 - 1212	after AD 1222
	20M	North scissor 75	151	-	Quarter	135 x 130	0.90	AD 1010 - 1160	after AD 1170
	21	North scissor 74	77	-	Quarter	150 x 135	1.46	AD 1064 - 1140	after AD 1150
	22	Collar 80	120	-	Half	185 x 170	1.28	AD 990 - 1109	after AD 1119
	23	Collar 79	254	-	Quarter	190 x 145	0.92	AD 914 - 1167	after AD 1177
	24	Collar 78	231	-	Quarter	190 x 160	0.96	AD 966 - 1196	after AD 1206
	25	North scissor 78	110	-	Quarter	160 x 150	1.41	AD 1036 - 1145	after AD 1155
	26	North scissor 77	80	-	Quarter	145 x 140	1.76	AD 1065 - 1144	after AD 1154
	27	South scissor 77	-	-	Quarter	150 x 130	-	not measured	-

* samples **19** and **60** include two measurable sections, see the text for discussion, this table records the separate lengths, growth-rates and dates for each section.

Table 1 (continued) List of samples, grouped by area of sampling

Area	Core No	Origin of core	Total rings	Sapwood rings	Cross-section of tree	Cross-section size (mm)	ARW mm/year	Date of sequence	Felling period
NW portico	**1**	NW4 north principal	148	h/s	Quarter	145 x 145	1.11	AD 1056 - 1203	AD 1213-AD 1258
	2	NW5 north principal	149	23	Quarter	150 x 145	0.88	AD 1077 - 1225	AD 1225-AD 1257
	3	NW6 north principal	171	-	Quarter	170 x 165	1.01	AD 916 - 1086	after AD 1096
	4	NW3 north principal	162	h/s	Quarter	140 x 135	0.99	AD 1044 - 1205	AD 1215-AD 1260
	5	North support truss east post	-	-	Quarter	185 x 185	-	not measured	-
	6	North support truss top plate	100	-	Quarter	180 x 150	1.44	undated	-
	7	NW6 collar	195	h/s	Quarter	175 x 160	0.84	AD 1002 - 1196	AD 1206-AD 1251
	8	NW5 collar	137	4	Quarter	170 x 150	1.23	AD 1072 - 1208	AD 1214-AD 1259
	9	NW4 collar	205	h/s	Quarter	160 x 140	0.87	AD 1006 - 1210	AD 1220-AD 1265
	10	NW2 collar	208	h/s	Quarter	140 x 125	0.49	AD 968 - 1175	AD 1185-AD 1230
	11	NW3 south scissor	112	-	Quarter	140 x 125	1.64	AD 978 - 1089	after AD 1099
	12	NW2 south scissor	103	-	Quarter	140 x 120	1.10	AD 1035 - 1137	after AD 1147
	13	NW2 south principal	133	-	Quarter	150 x 130	0.99	AD 941 - 1073	after AD 1083
	14	NW4 south principal	223	h/s	Quarter	170 x 135	0.69	AD 984 - 1206	AD 1216-AD 1261

Key to Table 1:

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.

ARW = average ring width of the measured rings

Table 2

Summary showing the structural function of the sampled timbers

Area	Sample numbers	Description
North-west portico trusses	**1** to **4**, and **7** to **14**	Six principal rafters, four collars, and two scissor braces from trusses NW2 to NW6 inclusive
North-west portico supports	**5** and **6**	Two cores from two of the support purlins
Nave Bay 10	**15** to **27**	Eight truncated scissors and five truncated collars
Nave Bay 9	**28** to **34**	One truncated scissor and six truncated collars
Nave Bay 8	**35** to **37**	Three truncated collars
Nave Bay 7	**38** to **40**, **42**	Four truncated collars
Nave Bay 6	**41**, **43** to **50**	Three truncated scissors and six truncated collars
Nave Bay 5	**51** to **53**	Three truncated collars
Nave Bay 4	**54** to **57**	Four truncated collars
Nave Bay 3	**58**	One truncated collar
Nave Bay 2	**59** to **68**	Five truncated scissors and five truncated collars
Nave Bay 1	**69** to **74**	Two truncated scissors and four truncated collars

Table 3 *t*-value matrix for the timbers forming the chronology PCRStructural., KEY: - = *t*-values under 3.0, \ = no overlap

a) correlation between the Nave samples

	17	18	19in	19out	20m	21	22	23	24	25	26	28m	29	30	31	32	33	34m	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60in	60out	61	63	64	65	66	67	68	69m	70	71	72m	73m	74
15	6.37	4.27	4.06	\	4.85	-	5.81	6.46	4.22	-	-	9.13	-	4.45	4.29	-	3.25	4.66	4.32	3.50	-	6.72	3.97	3.13	5.34	4.09	-	4.12	5.20	4.68	7.04	6.32	3.69	4.43	5.59	5.85	-	6.54	-	4.11	4.38	7.30	3.51	3.87	3.25	3.95	-	-	3.41	-	-	3.96	-	5.13	6.01	5.74	5.79	-
17		4.17	-	\	6.03	-	9.91	5.33	6.68	4.18	-	5.76	-	\	3.36	-	-	3.14	-	-	3.65	-	-	-	\	-	3.48	-	-	-	-	-	-	-	3.43	-	-	3.70	-	-	-	4.75	3.30	\	3.02	-	-	-	4.33	-	-	4.75	-	-	3.66	\	-	-
18			3.45	\	6.34	-	3.64	6.91	5.74	4.66	-	3.35	3.06	-	4.76	-	3.88	3.14	3.01	3.32	3.06	4.44	-	-	4.26	-	-	3.30	-	-	-	3.52	-	3.85	-	5.11	-	5.08	-	-	4.07	-	-	-	3.01	-	-	-	-	3.60	-	5.59	-	-	-	-	3.23	-
19in				\	4.74	-	4.90	3.81	3.82	-	-	-	-	-	3.31	-	3.26	3.89	-	3.91	-	5.08	5.38	4.01	3.32	-	-	-	-	-	4.23	-	-	-	3.42	3.91	3.66	3.56	-	3.52	3.15	-	-	-	-	-	-	-	3.72	3.35	3.05	-	-	-	3.60	-	3.16	4.00
19out					3.49	\	\	-	5.22	\	\	-	-	\	-	3.68	-	-	\	-	\	-	\	-	\	-	-	-	\	-	\	-	\	-	-	-	\	\	-	-	-	3.08	-	\	-	\	-	\	3.38	-	3.89	\	-	-	\	\	\	\
20m						4.43	3.80	6.54	5.96	6.25	3.74	7.17	3.68	-	6.22	4.91	4.40	4.55	-	5.54	-	-	-	4.20	4.19	4.22	3.01	-	3.61	3.70	3.65	3.48	3.54	4.76	3.02	3.97	3.32	4.22	3.14	-	4.45	3.14	3.34	-	-	3.36	-	-	3.47	3.19	3.15	5.29	3.57	-	3.76	-	-	-
21							-	-	4.19	6.02	5.04	-	-	\	-	4.67	-	3.06	-	3.08	-	-	-	-	\	-	-	3.46	-	-	-	-	-	3.76	-	-	-	3.61	-	-	-	-	-	\	-	-	3.71	-	-	4.05	4.40	-	-	-	3.75	\	-	3.39
22								4.29	6.73	-	-	4.09	-	-	3.57	-	-	3.17	-	-	-	-	3.96	-	3.46	-	-	-	3.42	3.85	4.59	3.77	-	-	3.19	3.61	3.97	3.73	3.14	-	-	5.32	4.63	-	3.46	-	-	-	3.90	-	-	-	-	-	4.04	-	-	-
23									4.75	4.09	-	8.73	-	3.74	6.61	-	-	4.07	6.20	6.37	-	6.41	3.39	3.74	4.90	6.20	-	3.17	-	3.20	4.22	5.05	5.55	6.34	6.17	7.32	-	6.19	-	3.12	3.72	4.57	3.06	4.12	3.89	3.54	3.80	4.33	-	4.07	3.41	8.81	-	3.82	5.12	5.69	6.40	-
24										5.95	5.56	4.04	3.23	-	-	6.43	-	3.03	3.70	-	3.01	5.54	3.51	-	3.03	3.35	3.34	5.45	4.36	3.35	3.27	3.87	3.00	3.41	-	4.74	3.32	4.94	3.43	-	3.19	5.43	4.24	-	-	3.98	3.27	3.14	3.63	5.78	4.29	-	3.67	-	4.16	-	-	4.00
25											7.63	3.69	-	\	3.63	11.32	3.24	-	-	-	-	-	-	3.37	-	-	3.32	3.06	-	-	-	-	3.17	4.44	-	-	-	5.28	-	3.05	-	3.28	-	\	-	-	4.25	3.52	-	-	3.34	3.34	3.46	-	-	\	-	-
26												3.51	3.24	\	-	8.61	3.28	-	-	-	-	-	-	-	\	-	3.61	-	-	-	-	-	-	-	-	-	-	-	3.27	-	-	3.36	-	\	-	-	7.07	3.96	3.56	3.51	3.94	-	-	-	-	\	-	-
28m													-	-	3.78	-	-	-	3.31	3.63	-	5.69	-	3.30	3.16	3.86	-	-	4.65	4.06	4.75	4.33	4.28	4.42	3.27	5.48	-	5.78	-	3.94	-	5.35	4.34	-	-	5.14	-	4.19	3.44	-	3.38	5.44	3.39	3.94	4.84	5.39	3.51	-
29														-	4.46	-	5.27	4.29	3.14	-	3.54	3.64	4.39	-	-	-	-	3.28	-	3.14	3.73	4.13	3.18	-	3.76	-	3.91	4.46	-	-	3.04	-	3.15	-	4.61	3.86	3.24	-	5.19	-	3.14	-	3.21	-	4.25	-	3.07	4.14
30															-	\	3.26	3.69	4.26	-	-	4.41	-	3.28	5.64	5.09	\	-	3.27	-	5.29	3.58	-	3.33	4.84	5.26	3.08	4.92	-	4.84	3.65	5.23	3.42	3.28	\	4.73	4.26	-	-	3.23	3.48	3.80	-	3.50	5.45	-	4.98	-
31																-	3.15	3.97	4.22	15.35	4.51	-	3.13	5.18	4.36	4.11	6.15	-	-	3.15	5.02	4.99	4.21	6.02	6.28	5.39	3.52	8.35	4.56	4.34	4.34	3.08	4.31	-	-	-	3.66	-	-	3.92	4.07	7.13	5.95	3.22	5.27	3.69	3.97	4.84
32																	-	-	\	-	-	-	-	-	\	-	4.44	3.12	-	-	-	3.13	-	-	-	-	-	3.88	3.53	-	-	3.76	-	\	-	-	4.61	5.30	3.94	3.26	3.22	-	3.24	-	-	\	-	-
33																		4.51	5.88	-	-	5.30	4.69	-	3.45	4.58	-	3.43	-	3.14	3.56	4.57	3.65	4.13	-	5.17	3.32	5.66	-	4.53	4.31	4.94	3.16	3.86	-	5.33	4.85	3.34	-	3.87	4.31	-	3.97	3.40	-	4.41	4.69	3.63
34m																			3.43	3.39	4.02	5.78	8.03	6.87	4.26	5.73	-	-	4.32	3.32	7.51	6.07	5.62	4.42	7.23	6.21	6.78	6.82	-	6.69	6.13	4.94	3.69	5.02	4.15	7.05	5.28	5.03	4.01	5.36	5.36	4.13	4.21	5.20	6.14	3.85	5.52	3.04
35																				3.53	4.92	5.47	4.29	-	3.82	5.05	-	3.92	3.43	-	3.70	3.86	3.77	3.09	3.35	5.49	4.08	5.24	-	-	3.09	5.19	-	3.67	\	-	5.83	3.58	4.27	5.63	3.58	3.03	-	3.47	3.66	3.27	5.64	3.73
36																					3.25	-	-	6.53	4.05	4.38	5.10	-	3.08	3.17	4.23	5.05	4.36	6.97	6.02	5.07	-	6.49	4.07	5.16	4.43	-	3.52	-	-	-	3.56	-	-	-	4.57	5.41	3.91	3.77	3.77	-	3.60	3.31
37																						-	4.85	-	-	4.30	-	3.72	3.10	-	-	4.38	-	-	-	4.70	-	5.11	4.63	-	-	3.14	-	4.15	-	-	4.45	-	3.86	4.39	-	-	3.56	-	4.29	-	-	6.70
38																							10.15	5.10	4.44	9.06	-	6.48	7.36	3.96	8.47	5.71	6.30	5.59	7.82	9.34	6.72	8.51	-	7.37	7.79	8.93	5.32	6.78	-	8.91	4.67	5.16	3.31	6.12	6.28	4.62	-	6.49	7.54	6.62	6.48	4.97
39																								3.07	-	5.39	-	4.66	5.67	3.65	6.12	6.05	3.27	3.85	5.64	5.54	6.22	6.67	4.31	7.27	4.12	6.02	-	5.10	-	5.73	5.73	3.50	3.48	5.21	5.20	-	3.17	4.16	5.24	4.68	4.18	5.20
40																									5.55	6.38	4.19	3.53	4.04	3.44	4.96	3.74	13.29	4.46	11.73	5.70	4.08	4.49	-	3.36	8.11	5.10	-	8.50	4.25	3.93	5.72	4.98	3.02	3.75	5.01	3.15	-	3.79	5.75	6.44	7.68	-
41																										5.94	\	-	5.35	-	9.01	4.01	4.61	3.36	8.65	7.19	5.19	6.37	-	6.16	6.13	8.04	3.76	6.02	\	4.10	4.16	3.17	-	4.34	4.50	4.19	-	4.55	5.39	5.55	6.31	-
42																											-	3.49	5.27	-	7.13	5.19	6.32	4.80	6.84	7.50	4.66	7.96	3.14	5.92	5.33	6.18	3.69	7.69	-	5.49	5.53	3.03	-	3.74	4.77	6.30	-	6.18	6.86	6.40	3.88	-
43																												-	3.63	-	3.49	4.76	-	3.97	5.42	3.12	3.76	5.58	6.22	-	-	4.79	3.26	\	3.13	-	5.13	3.28	5.65	4.85	-	4.26	5.85	-	4.20	\	-	5.61
44																													3.46	5.13	3.79	5.80	4.06	5.05	3.47	5.55	3.05	6.39	4.39	-	4.66	7.07	3.20	3.29	-	5.04	3.69	3.48	-	5.98	3.21	-	3.16	5.69	-	4.28	5.50	3.19
45																														-	9.69	4.80	3.40	-	5.28	5.09	7.80	5.82	4.69	5.76	4.58	8.81	4.78	5.86	-	7.20	3.87	-	-	3.70	5.39	-	5.27	4.48	8.95	4.54	3.45	5.12
46																															3.14	4.07	-	3.79	-	4.16	-	5.06	3.68	-	5.53	4.85	4.57	3.82	-	3.47	-	3.25	-	4.37	-	-	4.19	3.08	3.31	4.17	-	-
47																																6.06	4.38	3.18	8.90	7.65	9.44	7.33	-	7.39	6.64	9.69	6.16	6.14	-	11.28	4.85	4.60	3.19	6.26	5.90	4.22	3.83	7.58	7.39	5.42	5.54	-
48																																	-	8.05	6.39	5.29	4.88	8.29	5.99	5.73	5.68	6.84	7.45	4.21	3.25	5.04	6.10	3.96	3.40	3.80	4.86	5.09	7.15	6.43	6.87	6.29	5.06	3.10
49																																		4.90	8.75	7.94	3.82	6.47	-	4.28	7.10	4.68	-	8.26	3.47	5.33	4.11	5.05	-	4.20	4.21	4.88	-	5.55	4.72	4.88	7.86	-
50																																			6.32	5.87	3.45	8.27	-	5.35	6.22	5.48	4.66	3.71	-	4.30	5.41	4.57	-	4.98	5.90	6.18	3.28	5.00	3.83	4.69	4.62	-
51																																				7.20	6.25	7.59	4.21	6.43	7.94	6.98	3.97	12.78	-	6.53	6.26	4.62	3.08	4.80	5.36	6.18	3.82	6.94	6.49	6.27	9.93	-
52																																					5.09	7.36	-	6.78	6.26	6.37	5.39	6.36	-	7.25	5.16	5.07	3.15	7.35	5.19	5.45	-	6.36	8.55	9.13	6.83	3.88
53																																						6.90	4.79	8.87	5.02	8.70	5.95	4.54	3.23	8.35	5.94	3.52	4.28	6.17	6.49	4.33	4.77	3.33	6.20	-	5.38	4.52
54																																							5.66	9.10	4.51	8.76	6.55	7.04	3.08	6.30	6.00	5.11	3.93	6.50	6.43	6.37	7.18	5.85	5.87	6.10	5.27	3.53
55																																								3.95	-	4.23	3.01	-	-	-	-	-	3.16	-	-	-	9.99	-	3.30	-	-	4.89
56																																									4.71	7.40	4.81	3.58	-	7.04	4.33	6.55	-	4.42	5.49	4.21	3.44	4.89	5.44	4.54	3.67	-
57																																										5.12	4.69	4.99	-	6.13	3.08	3.82	-	4.39	3.39	5.15	-	5.70	5.55	5.17	8.84	-
58																																											11.57	5.66	-	9.13	8.01	4.32	4.59	5.69	5.27	-	6.14	5.71	6.82	5.19	5.71	4.07
59																																												-	-	4.88	5.76	-	3.15	3.79	4.13	4.93	5.86	4.61	4.50	5.03	3.15	-
60in																																													\	5.96	4.37	-	-	4.32	4.05	3.34	-	4.12	6.24	5.62	6.86	-
60out																																														-	-	-	4.47	-	-	3.04	3.39	-	3.37	\	-	-
61																																															5.95	4.79	3.42	5.73	5.09	3.73	3.72	6.35	5.76	5.45	5.92	3.77
63																																																4.36	6.16	5.81	6.21	3.28	4.08	3.16	5.37	4.23	5.71	3.94
64																																																	-	6.36	7.37	3.81	-	4.38	3.33	3.61	3.45	-
65																																																		4.13	-	-	3.07	-	3.47	-	-	5.01
66																																																			7.05	5.01	3.58	5.59	4.89	3.35	4.01	-
67																																																				4.76	3.21	3.41	5.84	3.81	-	-
68																																																					-	3.42	5.01	4.18	4.73	-
69m																																																						-	4.11	-	-	3.50
70																																																							3.45	5.64	5.06	-
71																																																								5.56	4.50	3.99
72m																																																									5.86	-
73m																																																										-

b) correlation between the Nave and the NW portico samples

	1	2	3	4	7	8	9	10	11	12	13	14
15	7.22	-	9.40	3.84	3.73	3.07	4.33	5.36	3.01	3.05	9.06	9.48
17	9.39	-	3.90	8.33	-	9.38	-	7.19	-	3.29	-	7.20
18	4.62	3.53	3.32	3.84	7.97	3.16	5.42	-	3.40	5.64	-	5.31
19in	3.52	-	5.63	-	4.24	-	5.44	4.30	4.59	-	3.98	4.66
19out	3.96	3.30	\	3.01	5.24	4.69	6.00	-	\	\	\	3.07
20M	5.34	4.03	7.56	5.84	7.84	5.94	5.79	4.37	3.69	6.19	5.52	6.36
21	-	9.11	-	-	-	-	4.54	-	-	-	\	-
22	4.72	-	6.01	4.23	4.66	7.45	3.90	5.65	5.36	3.70	5.70	6.36
23	5.19	-	7.27	4.88	4.34	-	4.62	-	4.43	3.10	5.52	6.79
24	6.10	4.60	6.14	5.68	8.23	6.26	6.69	4.78	4.54	6.87	5.07	5.91
25	3.94	5.25	3.71	4.24	3.09	-	4.23	4.64	-	3.95	-	3.72
26	-	5.05	-	-	3.09	-	4.83	3.23	-	3.08	\	-
28M	4.69	-	7.26	4.89	3.81	3.90	3.28	4.09	-	4.09	5.24	7.02
29	-	-	-	-	3.46	-	5.04	-	-	4.16	3.50	3.90
30	\	\	4.31	\	-	\	-	-	-	-	4.46	-
31	-	3.39	3.35	4.69	3.16	-	4.81	4.44	-	3.94	3.70	5.29
32	5.66	4.67	\	5.86	4.96	4.96	3.54	3.53	\	-	\	3.77
33	-	-	3.21	-	3.14	-	4.11	-	-	3.56	-	-
34M	3.70	-	3.68	-	3.08	-	5.16	-	-	-	4.44	3.67
35	-	\	3.99	-	3.30	\	3.88	-	3.58	-	-	-
36	-	4.25	-	3.66	3.53	-	4.29	-	-	-	-	4.07
37	-	-	-	3.55	-	-	5.94	-	-	4.26	-	-
38	-	-	4.72	-	-	-	4.68	-	3.06	-	6.25	4.61
39	-	-	3.16	-	-	-	5.75	3.04	4.40	-	4.05	3.97
40	-	3.31	4.16	-	3.92	-	3.93	-	-	-	3.68	3.21
41	\	\	6.55	\	3.72	\	-	-	-	-	5.51	-
42	-	-	3.72	-	-	-	3.92	-	-	3.28	5.37	-
43	4.09	3.29	-	3.45	-	-	-	4.70	-	-	-	3.23
44	-	4.58	3.16	-	4.71	-	4.77	-	-	-	3.43	3.26
45	-	-	5.03	-	-	-	-	-	-	-	6.25	4.06
46	3.05	-	3.87	-	-	-	4.33	-	3.30	-	3.82	4.57
47	-	-	5.87	-	3.13	-	3.62	-	-	-	6.98	5.27
48	3.61	3.76	4.58	-	4.53	-	3.94	3.69	3.12	-	4.18	5.75
49	3.57	3.04	3.82	-	-	-	3.22	-	-	-	3.69	-
50	-	3.98	-	-	4.04	-	4.36	4.51	3.73	3.76	-	5.21
51	3.10	-	5.03	-	-	3.11	4.02	-	-	-	4.77	4.78
52	-	-	6.45	-	-	-	3.84	-	4.25	-	5.40	3.92
53	-	-	-	-	-	-	3.21	-	-	3.58	3.88	3.62
54	3.49	3.64	4.43	4.33	-	-	5.57	4.18	3.58	5.11	5.39	5.42
55	-	4.06	-	-	-	3.43	3.46	-	-	4.37	3.24	3.25
56	-	-	3.95	-	-	3.79	-	-	-	-	4.37	3.45
57	-	-	3.18	-	4.54	-	3.48	3.31	-	-	3.11	4.19
58	-	4.83	6.59	3.29	-	4.70	3.59	-	3.26	-	6.81	4.41
59	-	3.10	-	4.12	-	3.06	3.23	-	-	3.15	4.08	4.43
60in	\	\	3.59	\	-	\	3.30	-	3.54	\	4.36	-
60out	4.74	-	\	3.88	-	3.49	-	-	\	-	\	3.59
61	-	-	4.51	-	-	-	-	-	-	-	4.81	4.24
63	-	5.03	3.35	-	-	-	4.20	-	-	-	-	3.27
64	-	-	3.76	-	3.69	-	-	-	3.27	-	3.52	3.43
65	5.29	-	-	3.59	3.56	4.20	3.69	3.67	-	3.08	-	3.24
66	-	3.58	-	-	3.83	-	4.25	-	-	-	-	-
67	-	3.97	3.38	-	3.33	-	5.00	-	4.60	-	3.95	-
68	4.67	-	-	4.53	-	-	-	3.34	-	-	3.50	4.09
69M	-	3.05	-	-	-	4.51	3.36	-	-	3.80	3.88	3.71
70	-	-	3.54	-	-	-	-	-	-	-	3.15	-
71	-	-	6.53	-	-	-	3.71	-	4.04	-	7.70	4.72
72M	\	\	5.78	\	-	\	-	-	-	\	3.51	5.00
73M	3.64	-	4.93	-	-	-	-	-	-	-	-	3.97
74	-	-	-	-	-	-	6.03	-	-	-	-	-

c) correlation between the NW portico samples

	2	3	4	7	8	9	10	11	12	13	14
1	-	3.09	8.81	4.90	7.72	3.87	5.49	-	-	-	5.71
2		\	-	5.58	4.05	6.35	-	\	3.35	\	-
3			-	5.49	5.77	4.04	3.50	5.42	3.34	12.79	10.08
4				3.29	8.99	-	5.29	-	-	-	6.32
7					5.43	8.52	-	4.96	6.35	3.71	5.71
8						3.86	-	3.51	-	\	7.02
9							3.26	4.54	4.77	4.77	4.87
10								-	3.68	3.31	7.24
11									5.36	4.99	3.68
12										3.68	4.76
13											7.34

Table 4

Ring-width data from site master 'PCRStructural', dated AD 887-1225 inclusive

Date	Ring widths (0.01mm)										No of samples									
AD 887							108	146	128	194							1	1	1	1
	95	82	73	169	200	137	114	116	157	142	1	1	1	2	3	3	3	3	3	3
AD 901	163	145	143	160	133	108	91	140	139	136	3	3	3	3	3	3	3	3	3	3
	151	225	153	150	121	143	131	133	131	127	3	4	5	6	6	7	7	8	8	9
	130	126	150	160	95	92	159	132	180	138	9	9	10	10	10	10	11	11	11	12
	139	150	95	146	110	153	153	154	149	129	15	16	17	17	17	18	19	20	21	22
	146	118	83	112	126	152	152	162	131	137	24	24	25	27	27	28	28	29	29	29
AD 951	101	88	74	93	129	87	97	120	112	95	31	32	32	32	33	33	33	34	34	34
	99	91	123	113	94	114	115	122	107	102	34	34	35	36	36	37	38	39	39	40
	96	88	60	75	97	87	101	75	98	107	40	40	40	40	40	40	40	41	41	43
	77	95	104	88	107	103	100	89	74	61	43	43	44	45	45	45	46	46	47	49
	78	80	95	93	94	89	94	89	106	96	49	50	50	50	50	50	50	50	51	51
AD 1001	101	99	111	100	93	88	81	100	92	86	51	52	52	52	52	53	53	53	53	54
	93	109	105	78	102	92	88	77	80	73	55	55	55	56	56	56	56	56	56	57
	82	82	94	82	71	79	81	88	85	94	58	58	58	58	58	58	58	58	58	58
	91	87	91	70	75	76	107	99	82	85	58	58	58	58	59	60	60	60	60	59
	79	81	63	68	77	78	87	89	90	77	59	59	59	59	59	59	59	59	59	58
AD 1051	79	78	72	60	81	82	85	98	95	112	58	59	60	60	60	60	60	60	60	60
	93	83	82	81	71	98	108	102	88	98	60	60	60	61	62	62	62	62	62	62
	85	80	72	75	82	94	98	97	86	96	62	63	63	62	62	63	64	64	64	63
	76	89	90	82	104	91	75	79	82	75	63	63	63	64	64	64	63	63	63	62
	86	69	76	75	93	79	79	82	76	75	62	62	62	62	62	62	62	62	62	62
AD 1101	62	67	85	70	76	75	74	85	75	66	61	61	61	61	61	61	61	61	60	59
	73	59	71	73	82	90	78	77	61	69	58	58	58	58	57	57	57	57	57	57
	77	86	103	96	85	76	78	82	68	73	57	57	56	56	56	56	56	56	56	56
	80	83	82	82	92	71	68	86	75	98	56	56	57	55	52	52	52	51	51	50
	104	95	80	77	80	86	83	89	94	88	48	48	47	46	45	43	41	41	41	41
AD 1151	81	80	101	88	87	86	85	86	92	107	38	38	38	36	35	35	32	30	28	26
	96	99	102	104	98	84	86	103	121	104	23	23	23	22	18	18	17	16	15	15
	115	104	116	103	107	117	78	86	102	92	13	13	13	13	12	11	10	10	10	10
	88	113	119	77	105	102	119	81	92	106	10	10	10	10	10	10	10	10	10	10
	95	82	108	97	110	110	114	110	109	95	10	10	10	10	10	10	8	8	8	8
AD 1201	102	78	86	74	91	113	94	105	107	107	8	8	8	7	7	5	4	4	3	3
	104	85	54	59	58	69	77	73	91	68	2	2	1	1	1	1	1	1	1	1
	80	76	80	65	62						1	1	1	1	1					

Table 5

Dating the mean sequence PCRStructural, AD 887-1225 inclusive. *t*-values with independent reference chronologies

Area	Reference chronology	*t*-values
Avon	Bristol Bridge (Hillam 1984)	8.18
Avon	Bristol, Dundas Wharf (Nicholson and Hillam 1987)	9.46
Cheshire	Nantwich, Willaston (Groves 1990)	11.13
Cumbria	Carlisle, Lanes (Groves unpubl)	9.15
East Midlands	East Midlands master (Laxton and Litton 1988)	18.21
Germany	North-west German master (Hollstein 1980)	7.00
Gloucestershire	Gloucester Blackfriars (Hillam and Groves 1993)	9.97
Herefordshire	Bordesley Abbey (Brown 1993)	12.01
Herefordshire	Hereford City (Tyers 1996a)	9.39
Herefordshire	Mamble Church (Tyers 1996b)	8.65
Herefordshire	Pembridge bell tower (Tyers forthcoming)	11.28
Ireland	Dublin master (Baillie 1977)	8.45
Lincolnshire	Barton coffin (Hillam pers comm)	11.32
London	Vintry House (author unpubl)	8.75
Staffordshire	Stafford, St Mary and Eastgate (Groves pers comm)	12.01
Wales	Magor Pill Wreck (Nayling 1998)	8.74
Yorkshire	Beverley, Dyer Lane (Groves and Hillam 1985)	9.95
Yorkshire	Beverley, Eastgate (Groves 1992)	11.68
Yorkshire	York Coppergate (Hillam pers comm)	9.16
Yorkshire	Doncaster boat (Groves pers comm)	8.21