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CHURCH OF ST LAWRENCE, DIAL PLACE, WARKWORTH, NORTHUMBERLAND
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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SUMMARY

Analysis of 51 samples from St Lawrence's Church, Warkworth, has resulted in the production of two dated site chronologies comprising seven and 29 samples, of overall length 217 and 120 rings, spanning the years AD 1174–1390, and AD 1324–1443 respectively. Three further site chronologies, comprising two samples each, 141, 97, and 80 rings long overall, remain undated.

Interpretation of the sapwood on the dated samples indicates the earliest definite felling phase is represented by material from the bell frame, with two timbers felled in the mid-AD 1380s, with a third timber possibly coeval or slightly later. Two ceiling beams of the 'winding chamber' below the belfry have slightly later estimated felling dates in the range AD 1386–1411 and AD 1405–30 respectively. The next phase of felling is represented by the south aisle's upper and lower roofs, these likely to have been cut as part of a single programme of felling spread over a small number of years in the late AD 1420s and early AD 1430s. The timbers of the Parvise roof, the latest episode of felling detected in this programme of analysis, were also cut as part of a single programme of felling in AD 1443. Seven samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

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INTRODUCTION

The Grade-1 listed parish church of St Lawrence, Warkworth, containing some of the best Romanesque work in rural Northumberland, stands at the lower end of the long high street, on the south bank of the river Coquet (NU 24686 06184, Figs 1 and 2). According to Pevsner (1992), Ryder and Roberts (2009 unpubl), and the historic building listing entry, from which this introduction is summarised, the nave, which is unusually long and narrow, and the chancel date from the early twelfth century. A west tower was added *c* AD 1200. A belfry stage and spire were added atop this tower, probably in the fourteenth century, though possibly in the fifteenth century, although there is a possibility that an existing belfry was rebuilt at this time. A south aisle was then added, its date being variously ascribed to between the late-fourteenth and late-fifteenth century. As part of this work, a two-storey porch to the south aisle was also built. To the north side of the chancel, a vestry building has been added, probably in the thirteenth century.

THE TIMBERS

Of particular interest to this programme of analysis were the timbers from various elements within four different parts of the church: the south aisle, the porch or Parvise, the Tower, and the Vestry. It was hoped that tree-ring analysis would establish the date of these parts of the church with greater precision and reliability, and hence inform understanding of its sequential development.

South aisle

The roof of the south aisle is actually composed of two elements, an outer, or upper, roof, and an inner, or lower, roof, this latter only visible from within the south aisle.

The lower, or inner, roof (Fig 3) comprises 11 slightly cranked and cambered tiebeam trusses forming 10 bays. The trusses carry a ridge beam, with single purlins to either pitch, there being common rafters to each bay. The tiebeams, ridge, and purlins are moulded, the common rafters are left plain and square. At some time in the past, a number of these common rafters to the south pitch at the east end of the aisle, have been moved from their housing in the ridge and wall plates, and apparently reset (Fig 4), although there is the possibility that some of these common rafters may have been renewed.

The upper, or outer, roof (Fig 5) is formed of a single, continuous, run of common rafters, each common rafter rising from the south, or outer, wall of the south aisle, to a plate in the south clerestory wall. There are no principals to this element of the roof but for additional support, a single purlin is provided towards the upper ends of the rafters, this being supported at varying intervals by stub posts stood on the north purlin of the lower roof. As far as the limited access to the void between these two roofs allows, there appears to be no physical connection between them, the stub posts not being tenoned to the purlin of the lower roof.

Parvise

Attached to the south wall of the south aisle is the two-story porch or Parvise. There is some element of uncertainty as to the place of this porch in the sequential development, at least in part due to a slight difference between the stonework of the porch and that of the church, suggesting they are of two, if only slightly, different periods of work. The roof of the Parvise is composed of 10, close-set, cambered, joists.

Tower

The bell frame (Fig 6) comprises two parallel pits aligned north–south formed by three trusses, with sills (concealed by the modern floor), long heads, and posts with heavy arch braces from post to head (designated Pickford type 6N). At the foot of the east wall of the belfry is a bench-like feature supporting a timber plate from which two posts rise to a horizontal beam at the same level as the heads of the bell pits, thus forming a rectangular frame, truss 4 (Fig 7). This frame is sometimes thought of as a potential pre-tower 'bell-cote'.

Below the belfry may be found the 'winding chamber'. The ceiling, set below the concealed base of the bell frame, comprises five main north–south bridging beams, their ends set in the walls of the tower (Fig 8). These north–south bridging beams are now further supported by modern rolled steel joists. The floor of the 'winding chamber', accessible only from below, is formed of four north–south bridging beams of variable size (Fig 9), their ends again set in the tower walls.

Vestry

The Vestry has a low-pitched gabled roof of four principal rafter trusses with coupled common rafters to the bays between.

SAMPLING

Sampling and analysis by tree-ring dating of various timber elements within the Church of St Lawrence were requested by Martin Roberts, Historic Buildings Inspector based at English Heritage's Newcastle upon Tyne Regional Office, this work being undertaken to inform a programme of grant-aided repairs. Part of these works necessitated the erection of a scaffold platform to the south aisle and the lifting of certain roof boards, thus providing access to areas usually beyond ready reach.

Thus, from the timbers available, a total of 51 samples was obtained by coring. Each sample was given the code WKW-B (for Warkworth, site 'B') and numbered 01–51. Eighteen of these samples, WKW-B01–18, were obtained from the timbers of the lower roof of the south aisle, with a further 10 samples, WKW-B42–51, being obtained from the upper, or outer, covering of the. Eight samples, WKW-B19–26, were also taken from the roof of the porch or Parvise. From the bell frame proper, nine samples, were obtained, WKW-B27–35, with an additional three samples, WKW-B36–38, being taken from the small number of timbers in the east truss of the belfry. Finally, three samples, WKW-B39–41 were obtained from the three suitable beams of the 'winding chamber' ceiling.

Timbers from other areas of interest, notably the floor of the 'winding chamber' and the vestry roof were not sampled. In the first of these, it was seen that the beams were derived from fast grown trees and as such were unlikely to provide samples with the minimum number of rings, at least 54, required for reliable dating. In the case of the vestry roof it was seen on the close examination afforded at the time of the building works, that this roof is composed of modern oak timbers, there being no reuse of any older material at all.

Where possible the positions of these samples are marked at the time of sampling on drawings made and provided by Martin Roberts, or on annotated photographs. These are reproduced here as Figures 10a-e. Details of the samples are given in Table 1. In this table all the trusses and other timbers have been numbered from east to west and further identified on a north–south basis as appropriate.

ANALYSIS

Each of the 51 samples obtained in this programme of tree-ring dating was initially prepared by sanding and polishing. It was seen at this time that two samples, WKW-B16 and B46, had less than 54 rings, the minimum necessary for reliable dating. These samples were, therefore, rejected from this programme of analysis. The annual ring widths of the remaining 49 samples were, however, measured, the data of these measurements being given at the end of this report.

The data of these 49 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing five separate groups, accounting for 42 measured samples, to be formed at a minimum value of t=4.0. The samples of each group cross-match as shown in Figures 11–15. The cross-matching samples of each group were combined at their indicated offsets positions to form site chronologies WKWBSQ01–SQ05

Each of the five site chronologies was then compared to an extensive corpus of reference material for oak, including not only that held by the Nottingham Tree-ring Dating Laboratory but also that held, for example, at the Sheffield University Dendrochronology Laboratory, this process resulting in the satisfactory dating of two site chronologies.

Site chronology WKWBQ01, comprising seven samples with an overall length of 217 rings, was also found to match repeatedly and consistently with a series of reference chronologies, when the date of its first ring is AD 1174 and the date of its last measured ring is AD 1390. The evidence for this dating is given in Table 2.

Site chronology WKWBSQ02, comprising 29 samples with an overall length of 120 rings, was found to match repeatedly and consistently with a series of reference chronologies when the date of its first ring is AD 1324 and the date of its last measured ring is AD 1443. The evidence for this dating is given in Table 3.

All other site chronologies remain undated. The seven remaining measured but ungrouped single samples were also compared to the reference chronologies, but again there was no satisfactory cross-matching and these timbers, therefore, must also remain undated.

This analysis may be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
WKWBSQ01	7	217	1174–1390
WKWBSQ02	29	120	1324–1443
WKWBSQ03	2	80	undated
WKWBSQ04	2	97	undated
WKWBSQ05	2	141	undated

INTERPRETATION

Tower: bell frame

The bell frame is represented by samples WKW-B27–35. Of these nine samples, five are dated as part of site chronology WKWBSQ01 (Fig 11). Two of these samples, WKW-B32 and B35, retain complete sapwood, meaning that they have the last growth ring produced by the trees represented. In one case, sample WKW-B35, the last measured, complete, sapwood ring, and thus the felling of the tree, is dated to AD 1385, and in the second case, sample WKW-B32, the last complete sapwood ring, and thus the felling of the tree, is dated to AD 1386.

A further sample from the bell frame, WKW-B28, retains the heartwood/sapwood boundary and seven sapwood rings. The heartwood/sapwood boundary on this sample is at a similar date, AD 1373, as the two others from the bell frame discussed above. Such similarity is an indicator of a group of trees felled at a similar, if not identical, time. However, if the timber represented by sample WKW-B28 was also felled in AD 1385/86 it would have had only 12–13 sapwood rings, slightly less than the usual minimum 95% confidence limit of 15 sapwood rings. Lower sapwood ring numbers, though, while not common, are certainly not unknown, and it may be noted that other samples with complete sapwood from this site also have low numbers of sapwood rings. There is little reason to suspect, therefore, that this timber was not felled at a similar time

Two further samples from the bell frame, WKW-B33 and B34, do not retain the heartwood/sapwood boundary. It is thus not possible to indicate the felling of the timbers represented with reliability except to say that, with last heartwood rings dates of AD 1333 and AD 1334, and a 95% probability of a minimum of 15 sapwood rings, the timbers are unlikely to have been felled before AD 1348 and AD 1349 respectively. It is thus possible that these timbers are coeval with the other timbers in the bell frame, but this cannot be proven by tree-ring analysis, particularly bearing in mind the variable quality of the intra-site cross-matching.

Tower: 'winding chamber' ceiling

The 'winding chamber' ceiling is represented by samples WKW-B39–41, two of which are dated as part of site chronology WKWBSQ01. Neither of these samples retains complete sapwood and it is thus not possible to indicate a precise felling date for the timbers represented. The two samples do, however, retain the heartwood/sapwood transition.

On sample WKW-B41 this transition is dated to AD 1371. Using a 95% probability of 15–40 sapwood rings the trees might have had would give the timber represented an estimated felling date in the range AD 1386–1411. On sample WKW-B40 this transition is dated to AD 1390. Using a 95% probability of 15–40 sapwood rings the trees might have had would give the timber represented an estimated felling date in the range AD 1405–30. It would appear, therefore, that whilst they may represent a single felling phase, they could also have been felled at slightly different times in the late fourteenth century or early fifteenth century.

South aisle: upper roof

The upper roof of the south aisle is represented by samples WKW-B42–51. Of these 10 samples, eight are dated as part of site chronology WKWBSQ02. Two of these samples retain complete sapwood, meaning that they each have the last growth ring produced by the trees represented. In one case, sample WKW-B43, the last measured, complete, sapwood ring, and thus the felling of the tree, is dated to AD 1428. In the second case, sample WKW-B44, the last full sapwood ring is dated to AD 1429. Under the microscope, however, it is possible to see that the spring cell growth for the following year has just commenced and thus the tree represented cannot have been felled until the spring of AD 1430. It is likely that the majority of other timbers from the upper roof were felled at about this time as well.

Such an interpretation is based on the fact that three other samples from the upper roof, WKW-B45, B48, and B50, come from timbers which retain complete sapwood but from which, due to the soft and fragile nature of this part of the wood, portions of the sapwood have been lost in sampling. Notes and observations made at the time of sampling, and in the Laboratory, would indicate, given the dates of the last extant rings on these samples, that the lost sapwood, amounting in each case to no more than a few millimetres, would give each of the trees represented a felling date of in the late AD 1420s or early AD 1430s as well.

A further sample from the upper roof, WKW-B47, retains only the heartwood/sapwood boundary. This boundary, however, is at a very similar relative position and date, AD 1414, as those others from the upper roof discussed above. The overall range in heartwood-sapwood boundary dates is only 10 years and such similarity is a clear indicator of a group of trees felled at a similar, if not identical, time. Although using a 95% probability of 15–40 sapwood rings the tree might have had would give this timber an estimated felling date in the range AD 1429–54, this range encompasses the known, or likely, felling dates of other timbers, particularly, as intimated above, one takes into account the possible low numbers of sapwood rings seen on some samples from this site.

The probability of the timber represented by WKW-B47 being felled at the same time as all the others from the upper roof is enhanced by the fact that this sample cross-matches very well with a number of others from this roof suggesting that the tree represented had been growing in the same area as these other. This is a phenomenon less likely to be found had the timbers been felled at different times because of the possibility that they might be sourced from different woodlands.

The two remaining samples from the upper roof, WKW-B42 and B49, do not retain the heartwood/sapwood boundary. It is thus not possible to indicate the felling of the timbers represented with reliability except to say that, with last heartwood rings dates of AD 1303 and AD 1397, and a 95% probability of a minimum of 15 sapwood rings, the timbers are unlikely to have been felled before AD 1318 and AD 1412 respectively. It is thus possible that the timbers were also felled in the late AD 1420s or early AD 1430s, but this cannot be proven by tree-ring analysis.

South aisle: lower roof

The lower roof of the south aisle is represented by samples WKW-B01–18, 13 of which are dated as part of site chronology WKWBSQ02. One of these samples, WKW-B05, retains complete sapwood, with a last-ring date of AD 1431. This is thus the felling of the tree represented. One other sample from the lower roof, WK-B04, comes from a timber which retains complete sapwood but from which a portion of the sapwood was lost in sampling. Notes and observations would, given the date of the last extant ring on the sample, AD 1421, indicate that the tree represented is likely to have been felled in the late AD 1420s or early AD 1430s.

A further nine samples from the lower roof retain some sapwood or at least the heartwood/sapwood boundary, this boundary again being at a very similar relative position and date as the two discussed above. Overall the heartwood/sapwood boundary on these nine samples from the lower roof varies by only six years, from relative position 84, AD 1407, on samples WKW-B10 and B15, to relative position 90, AD 1413, on samples WKW-B11 and B12, such a consistency again being indicative of a single phase of felling. The average date of the boundary on these nine samples is AD 1410. Using a 95% confidence limit of 15 to 40 sapwood rings that the trees might have had would give the timbers represented an estimated felling date in the range AD 1425–50, a span again encompassing the known precise felling date.

The two remaining dated samples from the lower roof, WKW-B09 and B13, do not retain the heartwood/sapwood boundary and it is again not possible to indicate the felling of the timbers represented. However, given that they have last heartwood ring dates of AD 1404 and AD 1405, and using the same 95% probability of a minimum of 15 sapwood rings, the timbers are unlikely to have been felled before AD 1419 and AD 1420 respectively. It is thus possible that the timbers were also felled at the same time as the others from this roof.

The Parvise roof

The Parvise roof is represented by eight dated samples in site chronology WKWBSQ02, with five of these samples retaining complete sapwood. In each case the last, complete, sapwood ring, and thus the felling of the tree, is dated the same at AD 1443.

Three other samples from the Parvise roof retain some sapwood or at least the heartwood/sapwood boundary, this being at a very similar date to that on the timbers whose felling date is known. The overall range of heartwood-sapwood boundary dates is 14 years; such similarity is again indicative of a group of timbers that represent a single programme of felling and it is likely that these timbers were felled in AD 1443 as well. The average date of the boundary on these three samples is AD 1421. Using a 95% confidence limit of 15 to 40 sapwood rings that the trees might have had would give the timbers represented an estimated felling date in the range AD 1436–61. It will be seen that this estimate encompasses the known felling dates of other timbers from this roof.

CONCLUSION

Analysis by tree-ring dating has shown that the dated timbers represent a number of different felling phases. The earliest material with precise felling dates is associated with the main timbers of the bell frame, at least two of which were felled in AD 1385 and AD 1386. It is possible that a third timber from the bell frame was also felled at about this time, but with the possibility that it may have been felled slightly later. The felling date of two other timbers from the bell frame cannot be proven. They are clearly broadly coeval, but whilst it is possible that they were felled in the mid-AD 1380s, they too may have been felled at a slightly different date.

This is of particular note given that one of the timbers from the ceiling of the 'winding chamber', below the belfry, has an estimated felling date in the early fifteenth century, and another timber possibly so. As such it would mean that these timbers are later than at least two of those in the bell frame, and it may have been impossible to insert these timbers with the bell frame still in place.

The results from the bell frame in combination with those obtained from the only two dated timbers from the 'winding chamber' ceiling, the felling dates of which span the late fourteenth and early fifteenth century, appear to suggest that the structural elements from this ceiling post-dates the bell frame. It is possible, therefore, that while the bell frame itself contains some timber of late-fourteenth century date, which may represent a structure added to the tower at this time, the frame may have been reworked, perhaps with the insertion of later timbers, when the ceiling timbers were introduced into the tower. It is possible that this was undertaken as a first, or early, stage of the early-fifteenth century works which eventually saw the addition of the south aisles and the porch.

The three samples from the bell-cote, truss 4 of the bell tower, cannot be dated, despite two of them, B36 and B37, combining to form site chronology WKWBSQ03 of overall length 80 rings. However, although undated, it is likely that the two timbers represented in BSQ03 are broadly coeval with each other, though, because neither has the heartwood/sapwood boundary, their likely relative felling cannot be determined.

The roof to the south aisle, both the upper and lower, probably represent a single programme of felling, and hence construction, during the late AD 1420s and early AD 1430s. Whereas there was previously some debate as to whether one roof was earlier than the other, this now appears unlikely, though additional bark-edge dates would have potentially demonstrated whether the timbers used in the roofs differed by a year or two.

The Parvise roof is, perhaps not unexpectedly as it is attached to its south side, later than the south aisle. However, with the timbers used here being cut in AD 1443, they clearly post-date the south aisle roof, though the construction of the porch some 10–15 years later may represent part of a single overall planned programme of development spanning a couple of decades.

Judging by the cross-matching between samples, it is likely that some of the trees grew close to each other in the same area of woodland. Samples WKW-B44, B45, B47, and B48, for example, cross-match with each other with values ranging from t=7.5 to t=8.8, suggesting that the trees represented may be from the same copse or stand. Samples WKW-B22 and B24, cross-match with a value of t=9.3, suggesting the trees from which they are derived grew still closer together. Indeed, further pairs of samples, WKW-B27 and B30, or WKW-B29 and B31, which both cross-match with values of t=10.9, may be derived from the same tree.

The source woodland for the timbers dated here cannot be identified precisely by dendrochronology (eg Bridge 2000), but it seems probable that they are local to the region. As may be seen from Tables 2 and 3, which list short selections of the reference chronologies used to date the two site sequences, the best matches are with the reference chronologies made up of material from other sites in the north-east.

Of the 49 samples measured, seven remain ungrouped and undated. In most cases, this lack of cross-matching does not appear to be caused by any particular problem with the samples, such as narrow, distorted, or complacent rings. Sample WKW-B07 might be considered to have very slightly erratic growth and sample WKW-B18 might have some slight compression. Sample WKW-B51 is also, with 54 rings, towards the lower end of the acceptable minimum number of rings required. There is, however, nothing noticeably unusual about these, a small percentage of samples frequently remaining ungrouped and undated in any programme of tree-ring analysis, and those found here do not display any shared unusual features.

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TABLES

Table 1: Details of tree-ring samples from the Church of St Lawrence, Warkworth, Northumberland

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
South aisle, lower roof						
WKW-B01	Tiebeam, truss 5	77	h/s	1334	1410	1410
WKW-B02	South wall plate, bay 5	104	h/s	------	------	------
WKW-B03	Tiebeam, truss 7	72	h/s	1338	1409	1409
WKW-B04	Tiebeam, truss 8	77	13c	1345	1408	1421
WKW-B05	North purlin, bay 8	92	22C	1340	1409	1431
WKW-B06	South purlin, bay 8	75	2	1336	1408	1410
WKW-B07	Tiebeam, truss 9	94	5	------	------	------
WKW-B08	North purlin, bay 9	54	h/s	1358	1411	1411
WKW-B09	South purlin, bay 9	67	no h/s	1338	------	1404
WKW-B10	Tiebeam, truss 10	68	6	1346	1407	1413
WKW-B11	North purlin, bay 10	90	h/s	1324	1413	1413
WKW-B12	South purlin, bay 10	72	h/s	1342	1413	1413
WKW-B13	South common rafter 1, bay 1	54	no h/s	1352	------	1405
WKW-B14	South common rafter 4, bay 1	60	5	1356	1410	1415
WKW-B15	South common rafter 5, bay 2	56	h/s	1352	1407	1407
WKW-B16	South common rafter 2, bay 5	nm	---	------	------	------
WKW-B17	North common rafter 2, bay 8	63	no h/s	------	------	------
WKW-B18	North common rafter 3, bay 10	104	no h/s	------	------	------
Parvise roof						
WKW-B19	Roof beam 1	83	14	1352	1420	1434
WKW-B20	Roof beam 2	97	21C	1347	1422	1443
WKW-B21	Roof beam 3	88	23C	1356	1420	1443
WKW-B22	Roof beam 4	57	h/s	1367	1423	1423
WKW-B23	Roof beam 5	83	24C	1361	1419	1443
WKW-B24	Roof beam 6	85	18C	1359	1424	1443

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
Parvise roof continued						
WKW-B25	Roof beam 7	75	10C	1369	1433	1443
WKW-B26	Roof beam 8	80	6	1347	1420	1426
Bell frame						
WKW-B27	North post, truss 3 (east bell frame truss)	97	no h/s	------	------	------
WKW-B28	South post, truss 3	120	7	1261	1373	1380
WKW-B29	South archbrace, truss 3	86	no h/s	------	------	------
WKW-B30	North post, truss 2 (middle bell frame truss)	69	no h/s	------	------	------
WKW-B31	North archbrace, truss 2	141	no h/s	------	------	------
WKW-B32	South post, truss 2	162	16C	1255	1370	1386
WKW-B33	South archbrace, truss 2	160	no h/s	1174	------	1333
WKW-B34	North post, truss 1 (west bell frame truss)	130	no h/s	1205	------	1334
WKW-B35	Tiebeam, truss 1	78	18C	1308	1367	1385
Bell-cote (truss 4 to east belfry wall)						
WKW-B36	Top rail	80	h/s	------	------	------
WKW-B37	North post	65	h/s	------	------	------
WKW-B38	South post	127	h/s	------	------	------
'Winding chamber' ceiling						
WKW-B39	Joist 1	79	19C	------	------	------
WKW-B40	Joist 2	97	h/s	1294	1390	1390
WKW-B41	Joist 3	65	h/s	1307	1371	1371
South aisle, upper roof						
WKW-B42	Common rafter 2	61	no h/s	1343	------	1403
WKW-B43	Common rafter 4	66	21C	1363	1407	1428
WKW-B44	Common rafter 11	55(+1?)	12 (+1?)C	1375	1417	1429 (1430?)
WKW-B45	Common rafter 14	71	12c	1357	1415	1427
WKW-B46	Common rafter 20	nm	---	------	------	------
WKW-B47	Common rafter 21	55	h/s	1360	1414	1414

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
South aisle, upper roof continued						
WKW-B48	Common rafter 26	56	13c	1372	1414	1427
WKW-B49	Common rafter 27	65	no h/s	1333	------	1397
WKW-B50	Common rafter 31	64	17c	1362	1408	1425
WKW-B51	Post 2	54	1	------	------	------

* nm = sample not measured;

**h/s = the heartwood/sapwood ring is the last ring on the sample

c = complete sapwood retained on timber, but all or part lost from core in sampling

C = complete sapwood retained on sample, last measured ring date is the felling date of the timber represented

Table 2: Results of the cross-matching of site sequence WKWBSQ01 and relevant reference chronologies when first ring date is AD 1174 and last ring date is AD 1390

Reference chronology	Span of chronology	*t*-value	
Carlisle composite working mean (excl. The Lanes)	AD 900–1476	7.0	(Arnold and Howard 2009 unpubl)
North Transept roof, Newcastle Cathedral	AD 1187–1367	6.7	(Howard *et al* 2002a)
Moot Hall, Hexham, Northumberland	AD 1244–1378	6.6	(Arnold *et al* 2004a)
England Master Chronology	AD 401–1981	6.4	(Baillie and Pilcher 1982 unpubl)
Finchale Priory Farmhouse, Durham	AD 1174–1369	5.8	(Howard *et al* 2002b)
The Lanes buildings, Carlisle	AD 10621600	5.5	(Tyers pers comm)
Glasgow Cathedral	AD 9461360	5.2	(Baillie and Pilcher pers comm)
Durham Cathedral North Transept repairs	AD 1534–1728	5.0	(Howard *et a*l 1992)

Table 3: Results of the cross-matching of site sequence WKWBSQ02 and relevant reference chronologies when first ring date is AD 1324 and last ring date is AD 1443

Reference chronology	Span of chronology	*t*-value	
Old Durham Farm, Durham	AD 1390–1619	7.8	(Howard *et al* 1995)
35 The Close, Newcastle upon Tyne	AD 1365–1513	7.1	(Howard *et al* 1991)
Lanercost Priory, Brampton, Cumbria	AD 1350–1504	6.7	(Arnold *et al* 2004b)
Blanchland Abbey Gatehouse, Northumberland	AD 1326–1532	6.5	(Arnold *et al* 2009)
Witton Hall Farm, Witton Gilbert, Co Durham	AD 1342–1441	6.2	(Howard *et al* 1996)
Tunstall Hall Farm, Hartlepool	AD 1316–1484	5.7	(Howard *et al* 2002c)
Seaton Holme, Easington, Co Durham	AD 1375–1489	5.4	(Arnold *et al* 2008)
Prudhoe Castle Cates, Northumberland	AD 1318–1444	5.0	(Arnold *et al* 2002)

FIGURES

Figure 1: location of St Lawrence's Church Warkworth (circled)

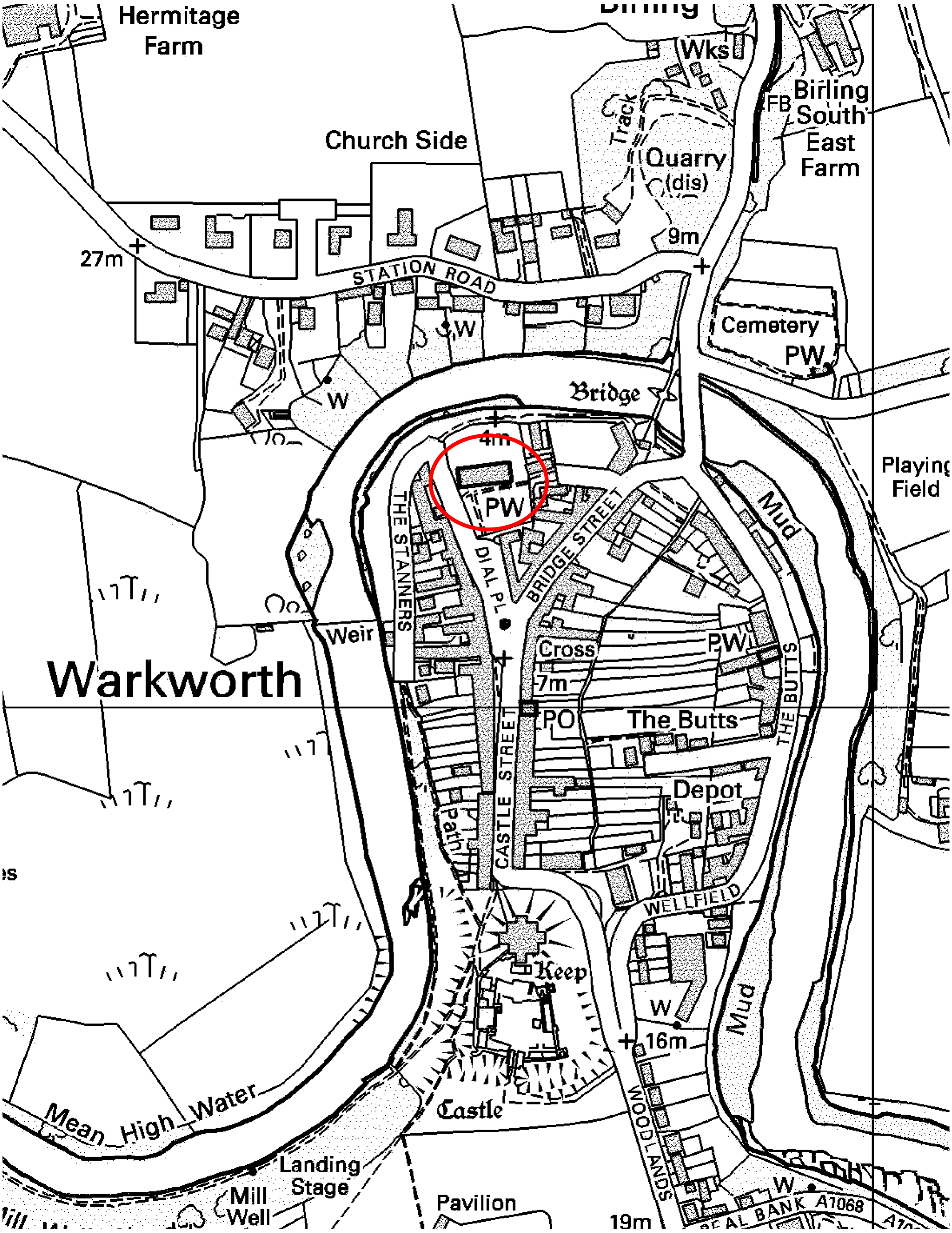


Figure 2: location of the Church of St Lawrence (circled)

Figure 3: View of the lower or inner roof to the south aisle

Figure 4: Empty mortices and reset common rafters to the south pitch of the lower roof

Figure 5: View of the upper or outer roof looking east to west

Figure 6: View of the bell frame

Figure 7: Truss 4, the 'bell-cote' in the bell chamber

Figure 8: The ceiling beams of the 'winding chamber'

Figure 9: The floor of the 'winding chamber'

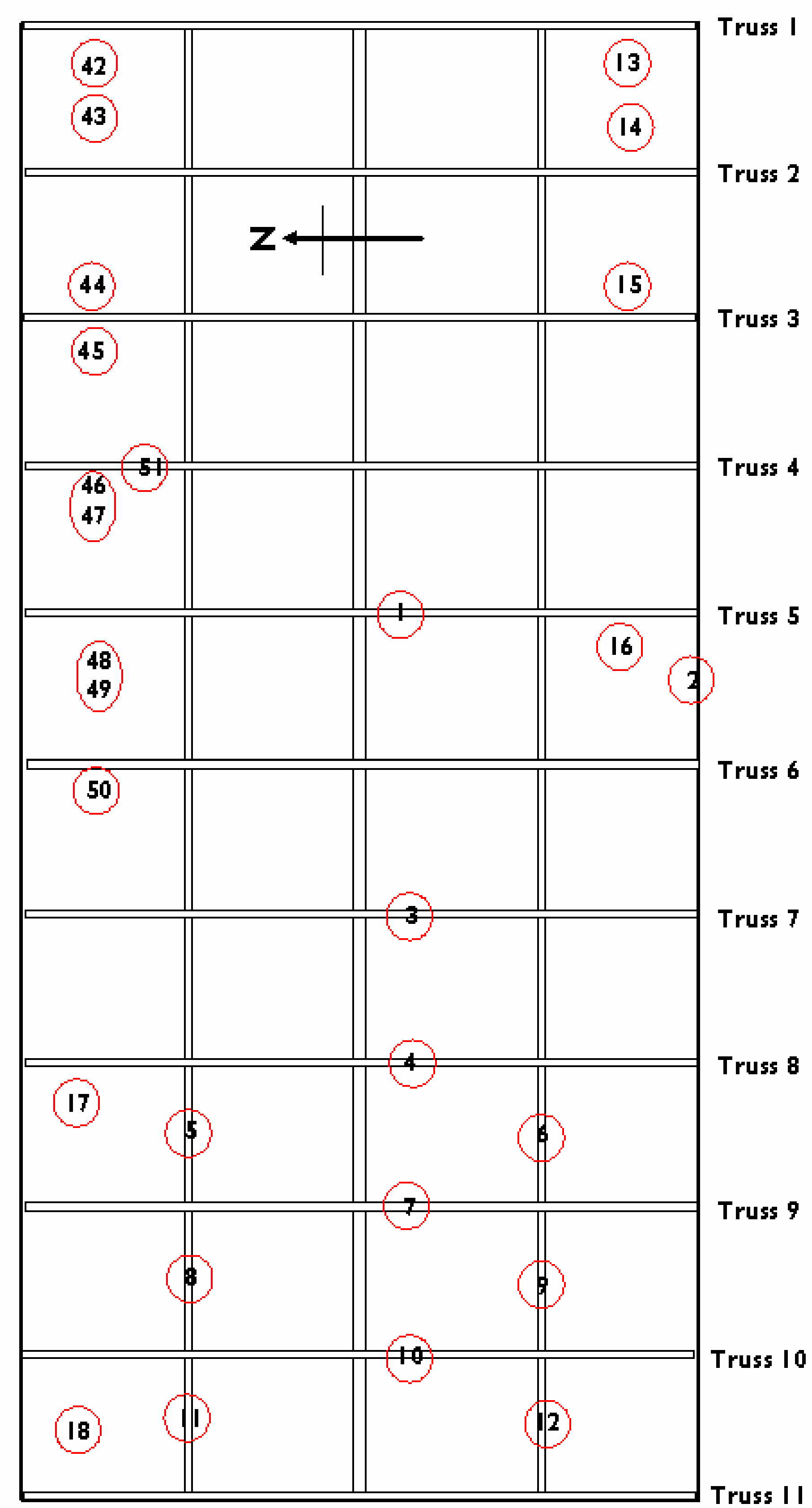


Figure 10a: Plan of the south aisle roof to show position of sampled timbers

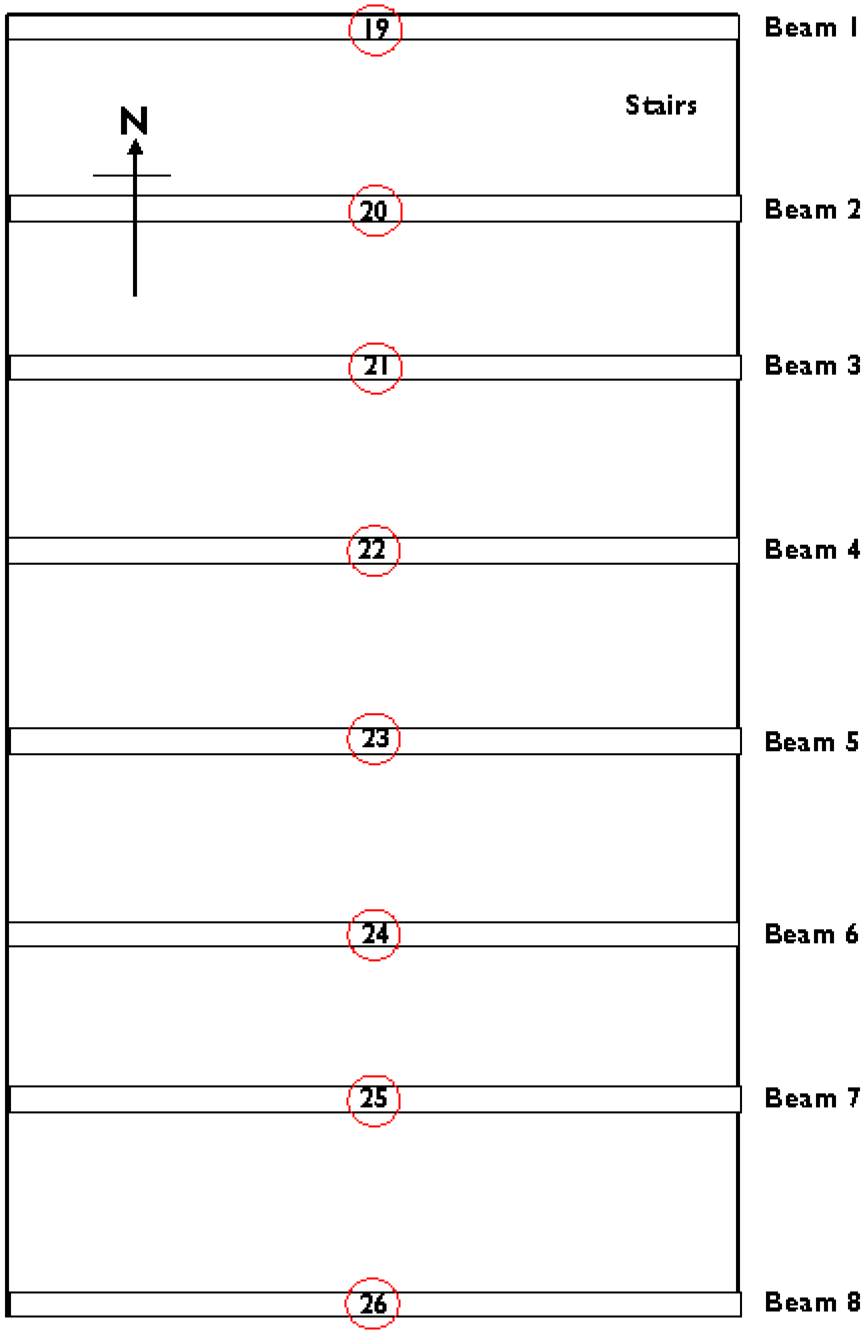


Figure 10b: Plan of the Parvise roof to show position of sampled timbers

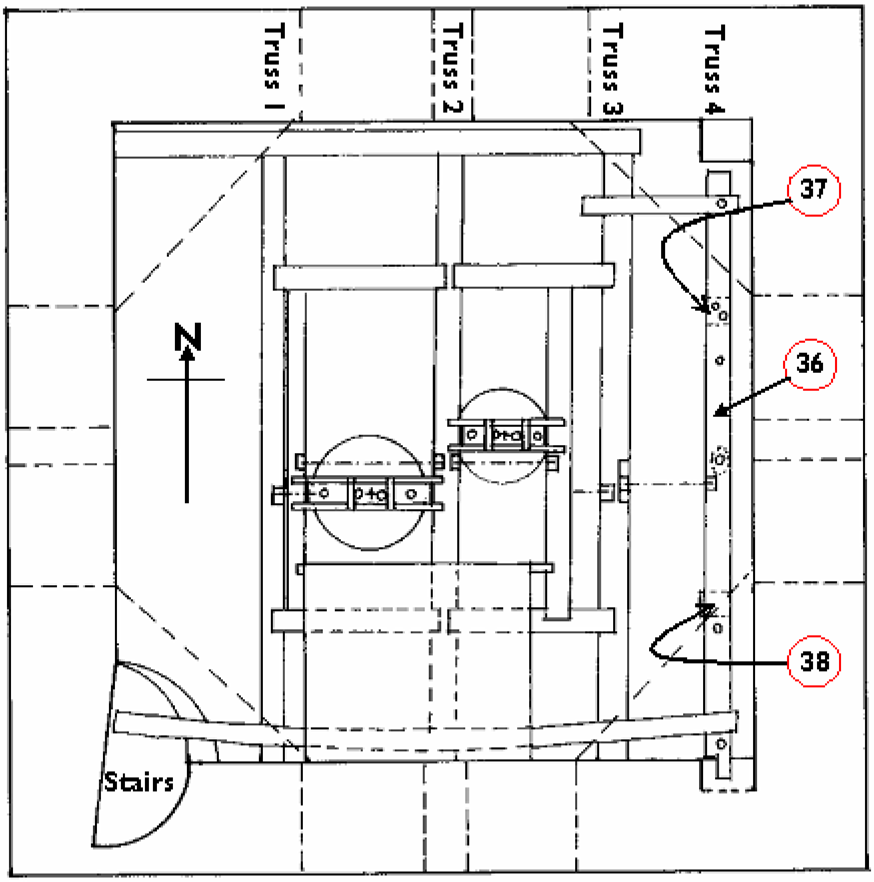


Figure 10c: Plan of the bell chamber to show position of trusses and of sampled timbers (after Martin Roberts)

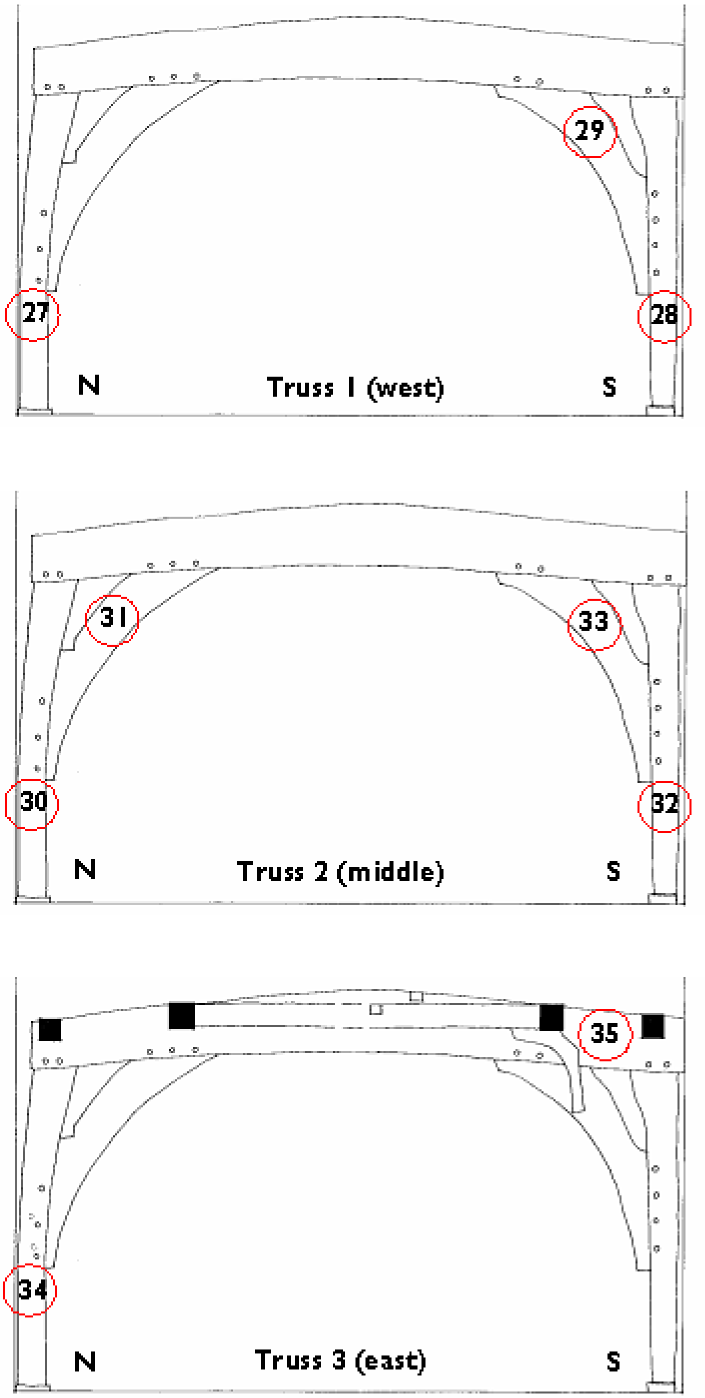
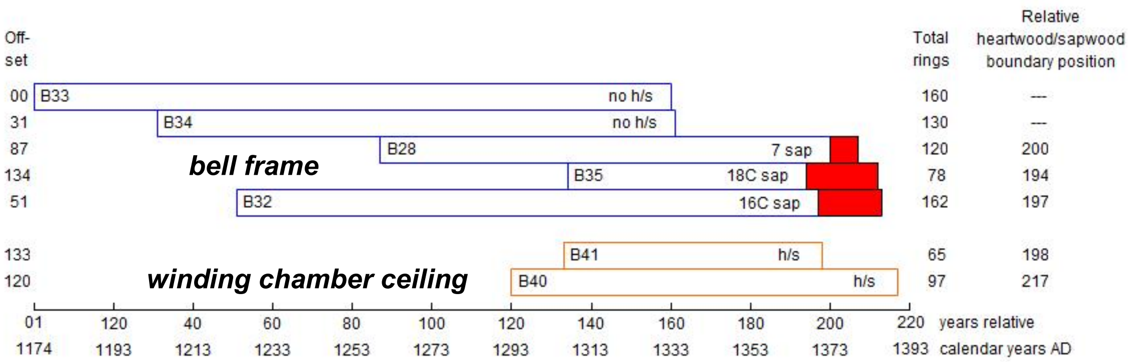


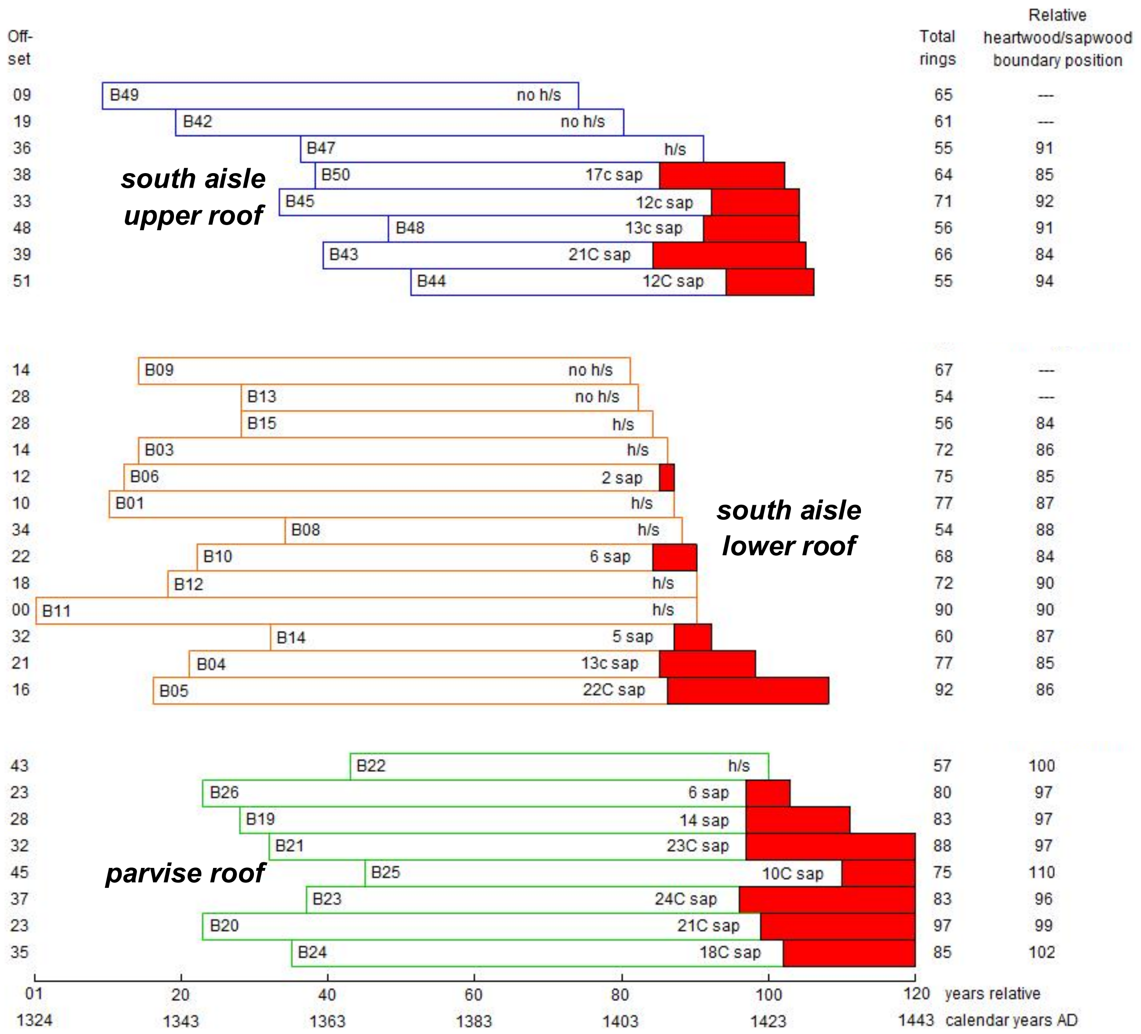
Figure 10d: Cross-section of the bell frame trusses to show sampled timbers (after Martin Roberts)

Figure 10e: View of the winding chamber ceiling to show sampled timbers



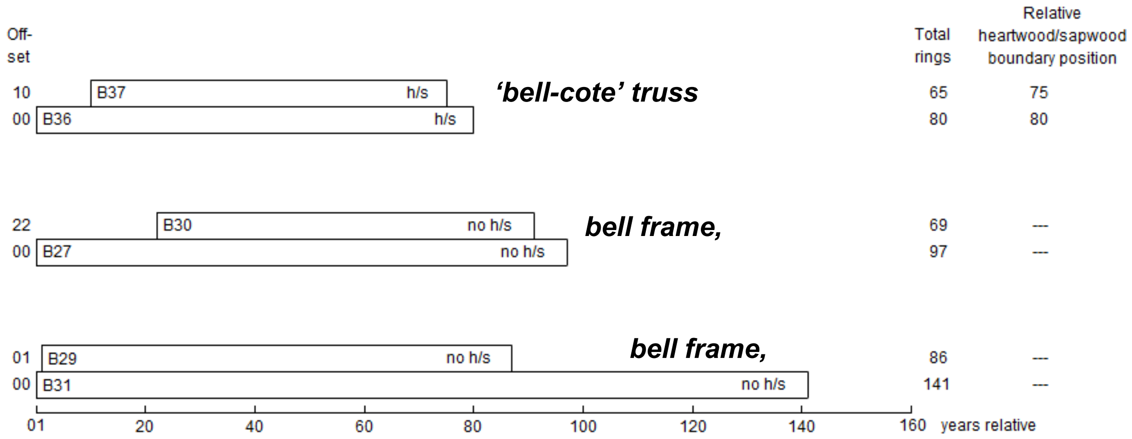
Blank bars = heartwood rings, shaded bars = sapwood rings
h/s = heartwood sapwood boundary
C = complete sapwood is retained on the sample; where dated the last measured ring is the felling date of the timber represented

Figure 11: Bar diagram of the samples in site chronology WKWBSQ01 sorted by sample location



Blank bars = heartwood rings, shaded bars = sapwood rings
h/s = heartwood sapwood boundary
c = complete sapwood exists on the timber but all or part has been lost from the sample during coring
C = complete sapwood is retained on the sample; where dated the last measured ring is the felling date of the timber represented

Figure 12: Bar diagram of the samples in site chronology WKWBSQ02 sorted by sample location



Blank bars = heartwood rings,
h/s = heartwood sapwood boundary

Figure 13-15: Bar diagrams of the samples in site chronologies WKWBSQ03 (top), BSQ04 (middle), and BSQ05 (bottom)

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WKW-B01A 77
112 99 167 127 149 178 105 143 145 177 169 213 145 191 222 300 246 361 329 392
358 304 330 365 273 261 297 324 270 291 325 352 333 297 302 304 181 168 210 280
358 298 258 260 226 251 271 288 200 174 250 254 260 357 306 227 178 199 250 335
247 245 322 255 272 341 372 284 223 287 247 215 201 206 260 238 221
WKW-B01B 77
110 100 160 131 155 172 102 146 143 168 165 182 143 203 205 289 260 313 311 401
365 305 294 330 237 268 306 307 283 286 320 354 297 310 285 302 184 170 204 277
358 291 268 267 232 251 282 299 214 161 238 240 266 343 280 209 203 185 261 335
265 261 287 268 277 319 365 294 272 301 235 223 190 206 243 251 242
WKW-B02A 104
68 44 73 55 65 171 236 296 333 247 305 215 221 178 179 133 108 92 34 28
29 36 36 72 89 94 117 124 148 165 226 234 153 87 81 106 140 104 43 52
78 60 74 72 61 72 116 146 111 138 154 129 98 146 145 216 148 137 131 151
184 139 82 96 107 120 160 164 161 142 138 132 127 142 152 119 96 103 100 112
97 137 114 84 86 116 98 173 166 153 145 150 213 218 252 197 116 163 204 207
161 137 206 200
WKW-B02B 104
69 44 71 51 70 169 237 299 316 225 299 230 216 184 153 128 92 59 38 28
25 31 44 65 92 94 148 124 159 205 207 234 159 82 79 108 146 91 50 66
62 61 82 65 58 80 110 145 112 137 153 131 102 155 143 214 154 141 132 148
173 153 78 87 107 106 142 173 170 123 142 134 135 147 156 120 125 83 118 108
81 132 111 83 84 122 112 167 160 163 138 154 201 223 247 201 124 160 221 198
167 139 181 229
WKW-B03A 72
342 358 320 303 288 311 346 273 254 260 413 464 280 389 484 524 449 478 462 541
438 374 388 395 271 408 401 369 333 328 348 315 305 249 320 355 299 284 269 259
271 273 321 288 232 240 338 256 269 262 263 230 180 262 206 252 239 232 256 191
211 236 265 240 228 250 192 183 178 200 196 237
WKW-B03B 72
362 376 305 307 271 321 331 269 268 263 409 464 296 383 471 504 463 443 477 514
424 374 375 379 280 378 387 371 364 348 344 314 295 275 333 333 314 270 281 245
287 283 330 301 251 227 342 263 266 270 242 240 198 250 211 251 240 225 251 177
209 255 259 254 218 255 203 183 177 195 180 223
WKW-B04A 77
109 83 102 132 153 192 147 232 291 297 341 319 309 272 364 378 394 314 294 399
477 438 425 405 377 160 261 352 470 433 416 493 412 456 393 446 376 356 511 353
283 309 326 324 213 198 216 158 254 198 201 257 209 339 297 355 230 202 241 337
253 205 119 114 104 123 113 103 144 154 152 122 135 146 128 165 203
WKW-B04B 77
104 132 108 126 160 179 180 290 316 280 335 337 250 301 364 423 383 304 306 379
479 459 422 399 379 169 272 352 454 442 413 490 419 424 402 426 378 354 481 409
301 304 326 312 230 201 211 159 225 193 192 259 227 329 307 359 223 200 253 314
249 204 125 105 99 131 107 106 129 161 145 132 123 148 139 193 196
WKW-B05A 92
192 204 227 239 269 291 283 293 253 319 240 361 343 481 421 375 427 404 345 335
362 414 240 221 288 284 259 277 276 294 266 308 278 269 284 307 279 237 248 240
246 201 213 233 301 270 313 315 263 213 184 229 202 308 198 179 232 191 147 180

183 166 131 151 151 123 128 109 139 152 149 141 133 188 158 161 117 71 105 112
133 113 182 158 174 149 98 103 132 145 116 175
WKW-B05B 92
192 210 225 240 271 277 275 301 247 326 238 377 349 491 428 355 391 396 337 345
357 410 241 235 273 269 266 301 279 286 266 308 271 279 286 295 290 228 235 244
226 215 189 229 302 277 304 320 255 220 189 234 205 289 217 187 225 194 131 203
179 160 143 153 146 115 136 104 148 148 143 149 131 171 174 166 121 81 107 95
123 138 175 195 140 151 121 62 108 157 122 191
WKW-B06A 75
291 247 303 242 229 233 255 235 294 319 279 281 258 288 213 292 330 427 389 345
384 326 297 297 381 306 283 339 294 259 257 266 334 366 299 281 362 305 360 334
239 185 220 211 252 232 171 318 284 204 265 267 232 203 215 185 195 276 293 179
239 168 192 180 195 146 161 175 209 118 125 141 188 173 310
WKW-B06B 75
317 252 316 260 208 225 239 233 296 308 262 281 266 270 214 282 349 402 371 320
405 335 296 290 357 323 275 349 291 267 228 279 305 360 297 277 350 301 326 340
245 224 226 209 263 229 175 290 295 205 259 240 261 209 226 181 203 282 267 182
254 178 179 171 194 146 174 172 212 107 128 145 191 166 204
WKW-B07A 94
212 243 237 265 169 110 133 123 155 145 167 120 80 72 120 121 167 168 182 184
280 136 103 115 80 69 84 139 154 199 176 178 123 92 83 101 165 83 153 162
131 102 88 78 111 109 44 63 73 118 87 82 73 82 109 100 124 112 118 120
78 80 113 141 117 70 81 93 94 86 62 93 93 108 101 79 80 86 127 110
83 64 89 105 142 167 157 211 313 146 189 205 217 229
WKW-B07B 94
204 241 216 276 148 111 125 153 157 142 177 128 69 71 118 121 174 178 186 178
262 147 121 106 67 69 84 143 173 204 182 200 104 91 84 93 128 81 123 146
131 97 90 79 112 102 51 72 60 114 101 82 70 81 107 99 130 101 118 113
76 81 97 159 111 64 95 86 72 95 53 87 107 107 93 96 78 98 122 95
100 65 88 112 141 163 168 200 299 166 183 196 190 229
WKW-B08A 54
296 307 387 506 252 316 382 350 358 420 457 377 230 289 382 431 538 454 385 354
381 380 507 509 350 535 501 400 445 454 428 351 328 400 383 675 443 430 457 285
321 342 520 477 249 470 464 243 186 177 155 143 228 258
WKW-B08B 54
350 305 394 495 235 333 388 377 363 433 472 379 237 271 357 413 522 465 385 365
391 427 474 515 362 510 536 388 461 467 434 346 332 381 383 632 438 425 468 296
336 340 507 469 274 469 408 255 177 173 154 135 228 214
WKW-B09A 67
157 137 145 136 139 155 202 212 207 228 166 202 164 171 206 239 259 283 264 235
176 210 256 296 175 214 235 248 251 274 241 211 256 267 318 272 262 234 198 207
206 237 229 269 210 268 303 232 326 311 217 226 211 240 192 303 233 229 264 230
180 225 246 249 219 290 264
WKW-B09B 67
94 127 150 151 144 134 186 189 208 229 183 207 144 165 196 243 266 278 262 239
184 207 235 283 167 205 243 248 241 267 247 204 271 257 323 270 251 234 180 221
222 232 208 243 204 266 288 232 295 272 231 222 229 228 233 340 241 219 256 233
189 225 219 243 215 302 262
WKW-B10A 68
353 238 317 564 318 451 297 507 359 271 310 245 177 186 235 293 138 188 239 254
255 256 257 318 238 277 311 416 467 370 234 299 337 325 404 401 339 420 370 375
344 355 396 300 329 292 242 391 322 342 454 327 284 371 528 372 333 464 316 245
265 267 281 240 307 259 336 311

WKW-B10B 68
260 243 313 539 302 454 301 458 350 267 295 250 182 165 251 306 140 183 229 247
295 249 247 312 241 286 319 409 478 349 243 297 362 318 411 402 364 400 365 366
327 369 389 323 339 272 238 405 337 340 459 315 279 355 541 381 312 457 328 265
237 265 290 254 293 213 330 295
WKW-B11A 90
74 66 60 134 113 134 132 108 122 111 138 172 187 224 256 204 156 205 256 229
226 242 251 264 213 249 215 362 232 323 354 285 296 304 272 325 491 456 179 306
499 376 362 348 330 361 302 342 394 321 353 308 277 247 270 282 320 279 264 389
304 216 289 216 234 194 217 202 204 231 226 201 248 218 170 186 193 174 189 216
184 174 164 163 175 163 212 230 192 253
WKW-B11B 90
92 55 71 131 107 134 125 121 115 121 136 164 213 203 263 202 166 203 261 222
225 233 265 251 215 254 210 340 259 334 349 288 289 312 271 331 497 434 176 312
508 393 340 365 340 361 302 330 379 343 343 320 262 272 249 293 315 280 267 385
299 214 280 217 222 183 228 216 218 217 231 207 251 205 182 174 220 186 198 214
175 175 147 163 165 157 214 211 204 263
WKW-B12A 72
342 270 317 360 349 307 301 335 170 215 308 429 383 389 356 369 297 391 434 377
265 387 472 377 331 357 350 432 378 379 357 378 385 319 198 266 252 226 209 279
247 294 262 203 234 180 207 223 210 218 193 234 178 200 220 167 161 174 198 143
160 175 134 133 128 183 124 134 173 150 177 180
WKW-B12B 72
347 268 295 317 351 321 281 318 189 209 299 436 384 376 344 379 332 367 440 390
278 351 508 362 351 377 337 400 377 369 377 334 378 314 227 255 263 223 205 289
272 274 259 206 231 190 219 202 217 219 195 211 197 198 225 180 162 174 180 157
146 185 129 146 123 180 143 122 132 190 158 206
WKW-B13A 54
189 201 170 228 285 226 179 204 275 299 267 279 239 176 157 183 178 227 218 212
311 425 417 240 295 287 360 359 286 222 271 248 292 163 203 283 247 217 185 237
192 264 188 202 224 135 182 279 236 202 164 163 278 224
WKW-B13B 54
154 192 163 230 298 226 185 203 271 282 266 295 240 175 146 204 160 244 227 208
285 424 394 250 289 285 361 355 282 215 280 239 292 165 201 300 253 209 185 231
189 258 200 206 199 137 182 269 242 191 166 160 275 231
WKW-B14A 60
428 245 186 233 310 310 247 229 219 266 323 220 200 240 256 295 317 285 412 215
202 198 210 193 268 237 217 245 217 210 210 229 211 162 204 127 183 229 177 177
161 145 152 177 211 134 172 178 176 120 126 93 118 96 92 93 109 97 116 80
WKW-B14B 60
401 260 185 215 290 326 247 233 222 262 312 224 211 272 262 301 324 296 398 216
183 187 227 207 269 244 214 262 210 212 219 236 221 173 197 146 177 207 198 170
185 154 152 170 222 122 200 142 170 120 133 100 115 102 85 83 98 93 66 64
WKW-B15A 56
211 270 257 234 281 197 170 211 387 298 184 152 194 233 202 251 210 265 253 319
291 322 335 224 206 209 218 211 258 226 219 275 254 284 292 279 235 196 198 176
236 230 172 177 201 177 192 207 250 186 185 226 186 137 114 143
WKW-B15B 56
186 270 239 251 279 260 181 208 346 330 188 154 195 242 202 247 203 260 259 300
293 331 306 238 212 200 240 212 250 231 210 262 279 255 299 271 211 174 213 164
206 224 201 152 214 185 172 209 232 177 182 232 183 137 106 142
WKW-B16A 48
432 316 278 188 173 129 138 150 244 204 182 177 206 196 234 215 227 227 184 275

290 241 152 159 224 269 289 227 191 152 150 146 149 137 197 208 249 141 150 172
182 147 156 208 128 144 187 231
WKW-B16B 48
375 296 273 195 158 128 142 158 251 212 188 191 209 181 232 221 211 233 192 268
283 229 165 147 222 258 300 221 179 150 141 139 154 129 198 223 227 144 159 145
179 153 179 163 118 158 169 225
WKW-B17A 63
221 137 146 149 99 99 122 118 108 94 122 139 139 145 150 160 154 184 170 187
197 174 138 155 135 144 166 138 110 126 107 122 127 119 81 95 90 88 81 101
84 132 143 125 127 114 120 110 167 130 161 137 58 97 61 153 138 133 141 161
184 160 177
WKW-B17B 63
199 139 150 149 104 101 127 128 106 111 119 142 136 139 150 159 146 187 170 179
197 181 157 137 133 126 150 151 123 132 116 142 120 128 87 92 105 88 91 104
90 121 117 137 111 103 123 108 178 125 162 131 68 82 84 130 135 123 141 159
188 161 170
WKW-B18A 104
242 207 269 250 183 260 212 214 208 190 182 138 100 147 166 198 283 229 189 218
235 165 148 219 84 161 128 149 152 107 108 95 89 117 103 103 74 125 105 104
100 96 88 111 107 98 108 100 88 66 70 74 90 60 48 61 70 112 90 88
96 77 81 75 94 122 101 112 133 141 134 104 73 71 52 75 79 83 84 112
115 67 51 55 47 62 63 57 62 55 81 50 44 57 45 46 65 61 90 68
67 68 59 96
WKW-B18B 104
296 213 251 209 198 286 209 200 212 177 158 145 113 169 180 192 248 206 213 201
229 189 166 190 75 160 130 141 157 94 121 85 92 124 97 101 72 135 116 102
113 92 87 111 108 94 120 84 85 72 69 84 82 66 38 64 74 115 83 89
77 89 97 64 103 106 108 124 132 125 137 101 77 60 59 71 84 89 90 112
124 71 52 52 60 59 61 46 61 69 73 49 45 41 45 52 57 70 89 70
65 68 56 94
WKW-B19A 83
222 360 277 273 311 222 224 186 232 277 233 200 244 223 194 171 146 164 177 183
187 201 239 193 143 151 154 167 153 171 167 177 209 164 150 159 145 144 144 162
152 159 122 126 106 122 119 140 152 135 124 137 113 104 89 83 108 88 95 77
86 102 83 84 62 51 75 60 86 87 94 105 136 95 88 68 103 112 103 157
169 154 165
WKW-B19B 83
291 356 291 260 304 216 225 203 211 296 209 214 244 225 178 173 144 167 185 205
178 215 219 198 140 154 148 163 147 167 154 183 205 165 160 158 140 134 140 160
147 163 129 131 117 108 130 130 150 141 120 142 120 103 91 79 118 82 95 83
72 107 84 83 63 55 73 64 91 84 94 101 144 90 97 63 102 100 105 161
168 146 168
WKW-B20A 97
80 192 182 181 220 245 346 296 277 281 215 215 223 356 361 316 263 293 291 256
266 236 231 207 277 304 321 327 315 231 221 209 249 211 254 224 262 231 226 250
195 173 163 172 186 156 246 177 188 208 158 204 191 215 207 190 188 127 155 178
133 159 142 138 113 119 145 91 102 70 82 78 83 74 102 80 113 132 152 131
105 131 149 155 139 163 140 167 148 125 147 151 117 122 102 104 133
WKW-B20B 97
86 179 175 155 206 241 349 294 291 287 223 216 224 362 346 330 256 267 279 256
272 237 248 212 274 304 321 334 315 232 226 199 247 227 257 209 236 260 225 246
197 164 172 188 192 177 261 175 185 192 167 197 189 216 209 184 179 142 159 167
149 160 145 133 116 116 142 101 81 81 68 73 81 82 97 76 114 133 135 122

114 132 142 153 141 156 116 164 157 132 135 147 128 107 113 110 120
WKW-B21A 88
386 215 177 221 342 391 333 320 280 351 321 318 301 312 314 282 361 387 352 218
218 245 266 317 256 255 247 243 253 231 234 262 195 222 162 204 169 239 153 174
185 151 166 210 309 222 171 187 186 177 198 150 198 152 171 158 188 154 136 152
145 154 182 120 147 165 158 132 134 166 143 113 175 181 151 171 144 119 121 111
125 126 99 84 74 110 96 102
WKW-B21B 88
408 223 172 228 341 388 345 310 291 355 324 331 295 329 323 282 350 409 342 198
238 240 272 323 249 260 246 232 264 230 233 256 192 225 162 209 168 232 162 165
180 157 167 219 279 214 182 208 196 164 210 153 194 154 175 158 179 164 130 151
148 155 175 124 147 152 160 140 124 183 150 124 176 190 156 148 146 119 113 111
130 122 88 99 82 101 90 110
WKW-B22A 57
387 444 535 433 396 440 411 495 312 259 263 233 362 332 313 243 299 314 178 198
283 243 225 182 247 223 428 250 275 309 236 324 434 390 293 217 311 244 245 355
235 287 255 216 232 200 211 162 124 157 223 207 121 174 163 178 221
WKW-B22B 57
409 435 550 442 392 468 439 460 285 299 261 250 395 328 305 282 305 312 169 203
283 248 217 186 226 219 420 269 270 308 235 322 427 366 316 215 303 239 250 359
235 282 263 210 238 203 209 165 116 167 219 202 131 166 166 159 209
WKW-B23A 83
287 357 345 334 380 354 316 272 373 361 304 406 427 353 245 249 266 307 355 332
327 301 363 298 183 206 217 195 146 133 161 140 255 181 167 158 126 123 141 155
176 127 142 136 128 150 145 162 131 103 126 118 98 131 156 107 145 133 102 152
138 165 161 137 142 131 108 117 106 144 131 119 109 124 116 143 117 106 89 63
94 87 118
WKW-B23B 83
285 371 344 335 356 391 306 289 385 390 298 407 431 336 239 246 270 287 362 332
324 302 369 288 180 198 217 188 152 125 163 143 265 172 160 158 141 113 143 152
159 140 141 141 125 148 148 153 113 123 110 110 100 123 156 105 136 142 110 136
140 160 159 147 125 138 111 118 116 134 130 118 104 122 121 137 118 105 84 65
102 90 109
WKW-B24A 85
474 474 284 337 341 292 218 252 287 224 287 251 161 226 234 286 134 134 114 113
139 102 92 153 174 171 94 152 170 149 139 154 164 118 186 133 171 200 179 267
417 328 280 158 290 212 185 226 187 235 201 191 176 178 183 169 138 150 229 214
116 240 169 161 280 216 278 257 199 238 251 318 219 315 201 292 320 177 234 149
132 261 215 185 237
WKW-B24B 85
474 467 330 322 359 278 211 252 263 211 310 227 187 214 232 278 144 134 110 101
140 105 105 153 157 166 92 172 160 157 134 157 163 117 177 132 164 190 189 274
389 312 293 159 300 209 173 224 179 233 228 185 174 166 189 169 126 150 231 237
127 219 163 159 276 214 250 233 208 240 253 305 232 287 228 287 308 180 242 138
153 254 194 210 237
WKW-B25A 75
402 423 346 369 537 446 298 309 335 392 407 362 345 302 427 418 298 374 403 291
221 231 298 270 338 257 294 363 332 323 398 383 250 227 237 184 126 151 169 216
163 191 176 204 184 116 152 151 234 212 163 230 245 287 237 221 161 164 130 166
250 173 154 232 192 241 170 199 191 187 141 133 170 137 178
WKW-B25B 75
455 413 349 371 535 466 260 299 343 407 425 420 371 322 395 416 321 363 404 325
228 229 282 277 343 267 287 401 298 346 392 394 255 245 218 182 134 168 161 225

182 190 171 190 187 97 167 148 238 213 159 222 234 302 253 201 172 183 148 163
244 168 151 223 208 239 169 202 186 192 155 142 146 149 187
WKW-B26A 80
208 277 265 233 208 234 316 199 193 276 236 256 243 323 371 331 278 265 295 286
263 246 236 221 255 222 281 254 261 172 149 165 219 157 161 173 195 193 156 147
159 142 129 120 134 124 172 126 135 139 96 114 128 180 148 142 149 128 113 112
102 113 122 98 86 86 90 58 74 62 42 68 65 68 73 77 102 120 81 101
WKW-B26B 80
303 279 260 243 229 227 328 200 188 272 237 268 236 330 377 325 254 267 299 270
275 246 236 218 221 230 272 261 261 163 163 166 214 152 166 175 186 172 162 140
157 144 127 119 120 127 179 105 136 133 103 104 128 181 154 141 150 121 109 133
112 124 114 104 88 83 82 61 75 53 50 63 63 78 65 70 102 117 67 105
WKW-B27A 97
307 188 164 130 146 168 169 195 188 258 192 175 246 221 160 134 162 212 239 192
113 167 181 176 161 175 158 168 177 183 178 188 171 225 211 186 153 158 175 238
191 213 178 189 141 128 166 122 168 134 96 112 165 150 132 105 96 55 111 173
164 205 165 219 125 93 187 203 180 161 128 104 118 132 131 145 148 201 147 140
121 156 192 99 131 151 175 164 164 176 146 125 147 166 156 195 183
WKW-B27B 97
246 196 217 108 125 168 173 194 194 229 199 184 246 231 159 125 174 184 234 210
187 164 166 166 154 181 167 166 169 171 175 179 190 210 191 188 136 183 176 233
189 208 171 190 138 135 170 101 162 122 87 120 151 145 139 111 90 74 93 177
180 201 147 217 123 135 153 220 169 162 136 113 111 135 132 146 149 187 162 141
102 157 183 114 134 148 172 160 188 172 172 110 149 171 176 198 189
WKW-B28A 120
319 384 318 302 202 229 288 338 294 295 421 307 278 175 157 218 250 227 200 150
60 71 84 105 136 128 93 186 258 187 172 239 193 175 157 228 373 253 195 247
345 175 177 173 273 305 307 182 207 248 202 149 109 81 67 73 115 121 128 101
172 201 162 141 153 103 84 72 94 99 96 116 133 102 84 61 81 43 99 147
129 185 112 74 83 79 69 100 134 68 77 112 134 134 155 164 207 133 120 117
114 138 175 229 264 278 204 164 188 132 119 124 124 208 227 206 185 174 199 201
WKW-B28B 120
246 410 325 302 190 256 258 346 285 329 421 293 259 179 157 230 278 238 204 148
67 61 91 122 138 124 99 197 246 191 167 229 207 182 145 229 376 271 178 242
333 183 188 157 284 282 325 164 209 227 210 140 94 88 60 79 103 121 130 108
160 205 160 144 150 106 86 82 88 90 93 126 125 96 90 61 75 46 100 135
133 175 114 77 87 78 67 87 138 78 78 112 126 129 162 166 217 114 129 111
111 147 172 221 264 284 208 164 173 134 115 118 116 197 221 196 191 168 176 203
WKW-B29A 86
399 320 343 271 291 276 265 440 437 534 548 250 105 156 235 299 443 417 308 253
220 207 251 212 200 200 194 231 252 210 234 303 245 212 194 345 310 252 278 254
289 236 269 280 242 236 244 226 275 302 232 289 261 283 282 242 214 222 206 242
216 370 218 204 238 246 158 197 158 238 188 235 272 173 215 246 285 281 287 178
203 97 105 181 177 256
WKW-B29B 86
367 324 361 247 273 277 271 420 435 525 539 241 113 183 219 296 426 409 304 249
193 214 249 209 168 213 186 247 254 198 232 310 272 204 173 338 319 230 266 278
278 235 270 270 246 243 233 218 282 302 237 293 243 289 277 248 193 206 197 243
230 384 209 188 226 252 160 200 174 202 193 214 316 176 196 244 288 275 292 180
224 86 99 187 165 223
WKW-B30A 69
234 282 280 316 296 291 390 332 270 254 286 278 255 260 243 272 237 298 272 242
203 202 182 165 205 152 242 209 179 156 245 263 217 171 111 88 155 238 258 270

205 236 120 85 182 199 156 142 174 131 148 188 195 176 197 267 206 101 90 107
161 104 112 125 169 178 166 160 243
WKW-B30B 69
228 269 287 303 302 299 371 333 263 241 213 229 253 266 251 270 242 297 277 253
196 201 189 165 204 153 239 226 189 161 238 253 219 168 110 78 146 242 264 260
226 208 116 78 169 167 187 160 165 121 149 174 168 176 199 232 219 87 89 122
147 109 101 133 178 163 175 177 189
WKW-B31A 141
169 169 162 168 122 139 180 159 199 179 234 204 95 66 61 87 85 112 138 109
146 123 108 159 138 144 108 113 130 107 112 144 163 128 96 105 140 110 87 118
110 132 122 163 141 121 133 96 106 110 158 137 147 123 220 223 168 110 86 75
96 69 132 73 67 104 123 107 181 161 161 147 188 198 122 157 214 165 147 140
95 91 36 39 57 67 108 76 66 76 51 68 75 79 88 62 64 55 35 33
47 68 62 58 78 59 61 66 51 37 29 72 80 93 81 69 74 98 43 124
125 205 190 189 229 174 197 160 161 160 171 154 145 132 103 183 128 84 98 131
163
WKW-B31B 141
159 171 168 162 126 152 177 155 198 185 216 203 106 49 69 106 96 133 122 101
139 129 115 149 145 140 123 105 128 100 109 137 151 107 99 108 154 121 96 112
113 142 132 154 138 114 136 111 115 103 141 143 143 125 255 217 164 105 94 64
104 53 132 67 75 100 126 110 185 161 161 141 187 199 117 159 177 197 129 123
97 92 38 40 56 73 99 65 80 72 51 64 86 73 79 56 61 63 37 28
60 60 59 65 59 52 60 64 46 32 32 63 76 92 75 71 75 87 54 120
109 226 179 190 228 179 182 156 170 163 173 173 151 126 112 163 117 85 111 132
100
WKW-B32A 162
158 165 156 182 160 215 184 171 194 269 244 179 250 192 198 224 270 192 171 236
259 283 409 332 330 169 214 252 220 238 249 251 267 204 242 275 251 218 167 131
110 104 144 179 147 186 222 246 271 145 146 206 206 151 137 102 69 52 70 64
148 114 108 95 76 121 176 141 116 135 135 134 153 168 157 229 177 162 153 142
172 122 131 107 139 173 161 114 96 70 61 68 81 117 130 156 135 162 143 122
124 111 94 104 78 75 93 106 167 117 160 103 89 96 120 140 119 204 81 87
87 80 74 90 128 113 129 108 104 103 89 122 147 110 74 73 52 57 78 98
132 172 241 203 159 88 147 209 180 303 178 137 150 161 184 200 194 243 277 186
228 260
WKW-B32B 162
167 158 161 200 150 166 179 179 181 239 251 183 248 206 202 229 251 206 163 237
275 286 378 337 304 174 229 259 225 233 250 250 289 195 272 255 224 172 185 136
100 119 136 174 147 192 229 376 388 190 158 212 214 170 194 113 100 64 76 65
113 111 94 119 111 123 134 147 169 157 148 134 163 144 150 200 217 187 138 135
143 117 254 278 225 153 143 85 97 82 75 82 141 197 147 186 136 187 153 141
156 120 95 126 159 196 194 150 209 139 210 129 92 120 125 181 173 248 101 75
119 77 105 113 163 176 151 191 149 140 164 180 238 168 158 123 137 144 205 258
283 266 226 195 191 75 136 156 145 277 189 150 162 172 163 176 208 211 214 194
225 269
WKW-B33A 160
130 155 107 135 157 289 192 158 149 194 130 127 112 103 98 87 106 66 68 99
147 100 108 55 54 65 75 77 70 94 65 67 89 49 86 108 93 117 91 86
78 36 42 46 58 64 55 78 65 76 74 84 48 48 61 114 134 116 113 105
121 179 137 148 154 152 140 111 108 85 93 85 56 91 83 57 57 84 58 49
70 77 75 65 62 80 81 91 89 52 76 95 89 112 168 152 142 131 135 142
91 124 127 173 130 135 116 82 53 69 92 93 105 74 92 84 71 81 65 79
80 83 97 88 93 83 76 83 70 74 82 88 77 98 77 70 79 72 51 36

47 46 66 79 63 79 60 69 67 60 60 56 63 45 54 70 49 57 69 64
WKW-B33B 160
143 139 111 142 168 299 184 163 157 180 126 119 105 123 79 88 100 84 65 103
141 94 105 52 56 57 80 74 70 95 66 76 77 56 90 96 106 109 93 103
65 45 44 43 59 62 52 85 70 72 79 87 37 38 70 100 130 112 108 116
119 197 133 162 151 145 137 124 107 76 88 86 61 86 82 58 72 76 50 39
78 70 64 63 75 87 67 85 72 63 70 97 126 129 185 135 137 119 129 148
105 128 125 172 134 130 119 84 55 70 74 98 121 83 85 73 78 77 72 72
82 83 94 95 91 90 65 85 73 76 78 94 81 92 68 71 77 77 40 45
43 43 69 77 73 76 58 67 66 61 56 54 57 58 65 62 61 51 65 56
WKW-B34A 130
92 116 63 86 98 87 143 115 125 135 91 82 89 149 128 159 144 148 137 141
150 93 64 80 98 192 104 121 120 147 223 149 195 174 164 159 173 129 66 113
110 78 126 108 95 105 159 155 130 128 172 146 147 112 131 151 156 117 99 90
108 98 125 144 92 99 92 72 75 50 58 70 113 81 90 76 60 39 41 58
96 117 117 132 97 102 129 187 191 148 144 185 185 217 146 173 171 160 169 170
145 146 142 104 110 117 98 60 41 41 45 52 84 94 79 68 58 62 55 56
52 55 67 47 50 38 50 73 82 75
WKW-B34B 130
108 122 72 82 108 102 132 105 138 138 92 82 107 150 122 150 146 153 149 133
168 112 64 88 118 211 134 152 140 150 272 163 199 199 156 162 174 120 67 108
108 79 109 126 101 104 150 163 135 135 165 168 145 105 131 147 147 114 83 98
119 95 108 139 103 93 94 82 73 51 42 78 120 62 93 67 61 40 36 63
96 117 109 132 110 95 120 187 171 158 127 191 182 225 152 180 167 151 172 164
171 144 145 94 112 126 95 54 35 39 51 55 77 110 58 64 74 59 51 46
58 64 55 49 57 44 52 72 83 78
WKW-B35A 78
256 290 360 263 139 131 123 107 149 285 334 242 177 192 238 207 151 306 288 250
206 243 173 184 292 389 228 268 229 139 77 158 224 208 369 160 93 114 99 124
191 280 235 263 394 291 248 150 181 208 332 247 253 231 223 260 271 242 319 319
214 178 130 111 236 181 354 279 228 231 271 214 222 183 154 271 229 235
WKW-B35B 78
251 293 363 273 134 126 129 111 145 272 302 244 184 193 238 198 156 297 306 237
222 221 184 193 297 397 226 279 215 157 85 151 210 228 371 164 104 113 98 122
188 272 233 262 396 312 215 160 188 200 341 255 264 223 240 241 274 269 344 318
234 185 127 120 229 196 349 289 223 259 271 218 235 172 161 277 230 270
WKW-B36A 80
229 287 209 130 197 101 122 95 172 170 179 137 219 209 190 224 231 255 335 325
207 188 155 77 148 278 321 272 348 290 234 251 226 212 206 132 185 227 146 89
112 122 159 169 172 151 109 155 114 108 95 80 90 94 81 61 109 104 75 87
108 80 66 61 71 50 56 70 90 79 81 65 82 84 80 76 92 73 91 66
WKW-B36B 80
235 276 201 140 201 103 120 93 175 176 160 139 186 198 205 206 242 242 313 323
193 184 152 94 147 285 308 264 340 289 253 249 200 201 188 140 182 228 153 77
117 120 157 173 171 145 113 148 114 104 90 85 84 93 107 88 98 89 92 88
95 93 67 63 65 59 63 66 87 85 69 78 94 69 87 75 93 71 90 68
WKW-B37A 65
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325 296 247 216 271 188 224 227 168 98 109 124 180 177 195 201 183 215 144 135
115 85 108 102 119 111 115 121 108 102 134 106 87 76 93 77 80 106 139 120
100 119 102 104 137
WKW-B37B 65
208 154 220 247 198 240 303 301 369 332 205 202 159 116 114 219 213 255 266 292

335 283 262 206 262 200 230 254 158 115 90 135 189 187 210 189 190 222 132 130
116 81 107 100 128 110 120 121 103 112 132 109 75 76 82 69 92 105 133 138
103 109 109 101 134
WKW-B38A 127
183 238 196 109 109 106 140 182 134 109 174 176 180 125 165 133 119 137 137 103
97 104 123 103 86 112 119 97 58 141 107 85 110 131 127 88 76 73 102 100
76 59 108 112 96 116 90 49 54 89 103 104 83 126 99 66 63 85 104 116
57 96 58 75 111 94 100 94 104 118 118 84 112 125 72 93 132 126 130 153
110 98 114 119 152 135 135 108 113 98 80 82 96 100 110 94 130 68 98 63
59 113 78 119 82 43 58 73 86 60 101 98 139 69 98 82 66 64 125 118
97 91 87 100 67 68 64
WKW-B38B 127
176 227 187 113 115 100 211 228 150 118 188 139 148 111 138 130 122 146 139 126
98 109 160 125 102 127 116 112 59 195 148 119 126 161 146 108 112 94 130 119
90 55 99 130 93 104 98 62 44 95 92 89 118 132 117 103 55 115 109 91
89 81 63 58 89 73 76 93 92 122 145 107 116 151 81 101 149 129 115 155
115 109 107 93 108 128 117 123 112 79 51 93 95 100 108 126 98 71 86 74
65 100 89 135 87 49 55 79 88 63 111 92 144 79 96 79 61 69 118 108
93 90 83 104 65 76 59
WKW-B39A 79
191 138 71 82 117 149 68 37 30 29 25 26 63 87 83 55 54 64 30 104
91 113 79 90 92 136 72 50 36 39 42 53 67 103 153 66 54 164 178 187
165 273 229 294 221 138 122 119 176 160 215 194 202 210 128 117 178 220 247 303
275 322 221 241 336 319 333 250 192 196 262 213 148 192 158 341 300 252 246
WKW-B39B 79
180 143 75 78 124 149 82 38 33 33 24 27 88 55 70 43 55 57 49 115
85 104 84 89 96 128 71 46 40 44 41 46 60 109 166 60 45 167 174 189
174 256 237 271 235 120 122 121 172 162 206 197 195 223 120 106 190 206 239 304
301 341 242 231 293 335 331 263 196 189 265 234 138 189 162 339 293 239 242
WKW-B40A 97
234 219 183 136 135 110 105 124 131 182 179 185 215 262 215 208 231 263 303 304
272 231 256 277 291 262 216 181 205 165 136 159 166 143 158 158 152 152 165 157
150 130 136 115 143 153 223 189 226 162 98 138 145 148 163 221 169 162 186 198
162 148 170 175 237 225 234 249 210 176 226 257 197 216 177 178 114 136 189 199
197 184 164 130 156 137 119 127 123 179 173 172 162 161 161 183 140
WKW-B40B 97
230 218 185 151 128 97 118 118 133 176 179 178 233 250 201 208 225 275 312 290
287 225 251 283 291 255 215 169 189 162 135 161 156 152 163 153 150 164 171 141
158 114 133 116 139 176 229 178 224 150 87 145 153 166 160 230 183 169 179 206
150 147 176 175 231 221 235 258 193 197 211 251 205 209 168 166 124 142 191 198
186 187 168 110 159 136 112 117 123 167 167 180 145 164 143 195 153
WKW-B41A 65
178 170 227 304 385 358 382 271 231 296 258 339 276 320 260 351 265 205 207 146
207 256 260 251 338 239 318 132 217 211 118 137 131 158 136 258 97 80 93 92
126 158 283 222 145 199 202 173 167 215 203 168 141 130 199 208 241 197 210 190
204 135 104 56 112
WKW-B41B 65
180 189 217 312 402 293 336 236 229 279 256 324 269 294 276 332 263 205 214 165
194 265 249 234 306 250 340 130 237 218 119 142 117 166 135 253 102 63 88 103
128 157 286 225 158 196 186 161 179 203 199 169 139 155 171 237 246 209 249 181
197 150 89 73 108
WKW-B42A 61
329 278 319 326 299 271 252 202 201 256 317 383 249 331 323 311 290 369 424 268

252 317 298 315 330 201 255 170 198 298 337 411 345 288 291 316 272 301 318 316
435 374 364 354 382 349 283 238 256 265 387 297 293 320 255 249 288 412 251 353
386
WKW-B42B 61
306 273 333 325 295 262 280 196 206 271 326 371 259 328 312 322 294 373 392 293
293 314 304 336 326 186 264 181 178 296 346 398 346 299 277 324 304 293 313 328
435 358 364 392 372 379 267 243 254 250 390 292 292 333 265 268 298 386 287 347
379
WKW-B43A 66
267 295 305 315 287 233 304 248 228 307 273 307 257 220 232 223 239 262 285 242
343 245 190 308 239 255 202 160 180 160 284 198 228 242 177 197 208 277 234 200
256 196 179 224 182 227 167 228 195 189 166 181 206 147 117 159 104 163 197 205
208 182 197 171 148 213
WKW-B43B 66
279 304 290 305 298 244 273 221 255 310 259 314 261 232 216 227 240 285 281 262
340 246 182 292 236 227 189 159 161 172 295 211 230 237 174 198 217 268 256 200
228 231 186 210 177 252 163 206 209 181 194 163 210 133 113 161 119 180 189 182
211 202 202 161 174 228
WKW-B44A 55
222 265 185 75 108 62 112 95 178 214 151 200 206 192 145 206 145 180 271 208
172 238 186 157 201 209 91 117 203 216 265 211 241 329 301 327 267 318 420 381
480 305 331 336 192 275 230 317 231 356 301 251 256 258 311
WKW-B44B 55
247 251 173 80 111 81 95 109 179 226 173 213 206 164 157 196 152 177 276 206
166 242 172 161 190 207 102 119 204 222 267 205 243 325 307 311 276 333 420 383
474 293 346 319 205 277 242 286 266 338 289 271 257 238 360
WKW-B45A 71
267 143 246 324 277 174 169 257 361 337 272 311 211 96 164 216 219 325 200 231
206 120 147 116 134 119 154 261 186 159 195 164 156 217 147 119 176 173 139 203
192 167 186 220 79 95 178 189 217 197 141 155 183 250 246 288 312 234 232 212
246 289 188 239 158 171 169 239 201 165 190
WKW-B45B 71
265 147 238 325 246 189 172 247 367 353 269 320 219 89 147 207 222 321 199 228
179 127 143 116 132 116 165 252 183 168 181 179 155 212 153 132 176 164 149 208
181 164 179 238 83 100 169 195 218 210 136 164 173 229 234 277 316 227 248 201
224 275 220 223 144 162 186 219 208 183 153
WKW-B46A 46
146 161 227 296 147 102 145 228 360 463 290 314 564 413 394 307 406 345 327 296
288 385 436 320 371 412 314 277 236 274 230 348 258 209 258 210 204 248 254 203
173 231 255 199 132 188
WKW-B46B 46
163 156 230 286 142 108 157 234 334 430 275 313 590 396 349 307 403 343 296 308
284 389 429 302 396 398 324 268 249 278 222 351 246 227 264 209 202 249 194 166
176 242 257 188 156 182
WKW-B47A 55
362 338 326 288 373 389 323 255 276 171 137 228 282 350 441 361 432 289 140 132
95 107 89 138 262 238 216 253 199 279 265 232 220 249 290 216 288 244 177 219
213 100 112 182 198 350 373 382 348 357 336 322 326 314 300
WKW-B47B 55
353 355 316 302 350 412 310 250 270 180 148 222 311 380 427 350 415 305 140 141
95 96 98 130 249 252 200 246 196 270 268 218 227 245 291 218 302 244 183 195
209 106 119 161 180 350 364 365 359 355 312 311 315 319 306
WKW-B48A 56

211 218 313 199 226 200 127 136 121 139 123 149 259 180 163 189 160 250 321 304
315 391 361 303 429 303 305 370 538 255 346 397 372 333 254 267 263 269 307 300
345 412 335 340 208 238 370 254 342 321 350 321 332 292 371 231
WKW-B48B 56
209 219 319 199 228 189 121 141 116 129 118 159 248 183 171 184 169 249 333 292
304 411 350 339 407 317 301 398 490 276 345 392 363 326 266 245 283 278 312 300
345 399 341 354 200 211 412 229 358 345 326 339 331 275 343 266
WKW-B49A 65
229 301 394 309 318 218 192 189 187 161 208 199 239 315 270 289 316 253 380 226
323 253 341 329 375 249 298 416 415 205 275 290 300 336 258 247 181 184 197 238
206 332 264 223 182 157 193 196 196 232 350 274 198 294 305 288 206 142 235 172
392 293 305 366 263
WKW-B49B 65
218 280 334 357 318 225 189 185 206 147 213 206 245 297 256 322 317 232 387 209
322 257 318 341 366 255 331 402 403 208 270 276 315 319 270 249 190 190 206 220
229 330 262 225 183 156 193 199 192 233 338 272 173 272 302 293 204 165 210 165
393 304 322 340 226
WKW-B50A 64
390 372 493 364 399 364 285 334 240 241 411 420 554 388 306 320 335 299 394 364
333 512 378 314 321 341 337 175 174 199 163 207 256 167 219 146 203 254 326 176
244 288 324 229 205 198 156 142 169 201 224 197 224 266 203 176 177 146 188 202
219 212 199 250
WKW-B50B 64
374 372 490 362 386 365 260 320 243 229 397 397 548 393 292 336 301 283 397 366
330 468 401 289 357 325 328 195 171 189 164 214 232 192 220 139 185 247 311 187
244 276 282 208 193 200 158 153 173 200 229 183 219 265 191 185 197 161 214 206
219 214 194 210
WKW-B51A 54
491 399 360 317 233 234 397 468 505 343 312 359 246 207 242 344 290 305 349 383
322 253 260 332 279 288 303 283 445 316 286 358 257 245 281 219 270 300 224 260
468 403 393 385 251 279 318 328 281 312 285 305 399 301
WKW-B51B 54
420 430 331 309 238 254 380 470 469 318 307 365 238 219 248 324 296 319 365 387
281 285 265 330 267 270 325 318 343 314 304 384 251 238 236 254 252 307 236 242
482 420 388 396 314 262 333 286 285 312 286 306 400 301

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

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

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

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

t-value/offset Matrix

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

Bar Diagram

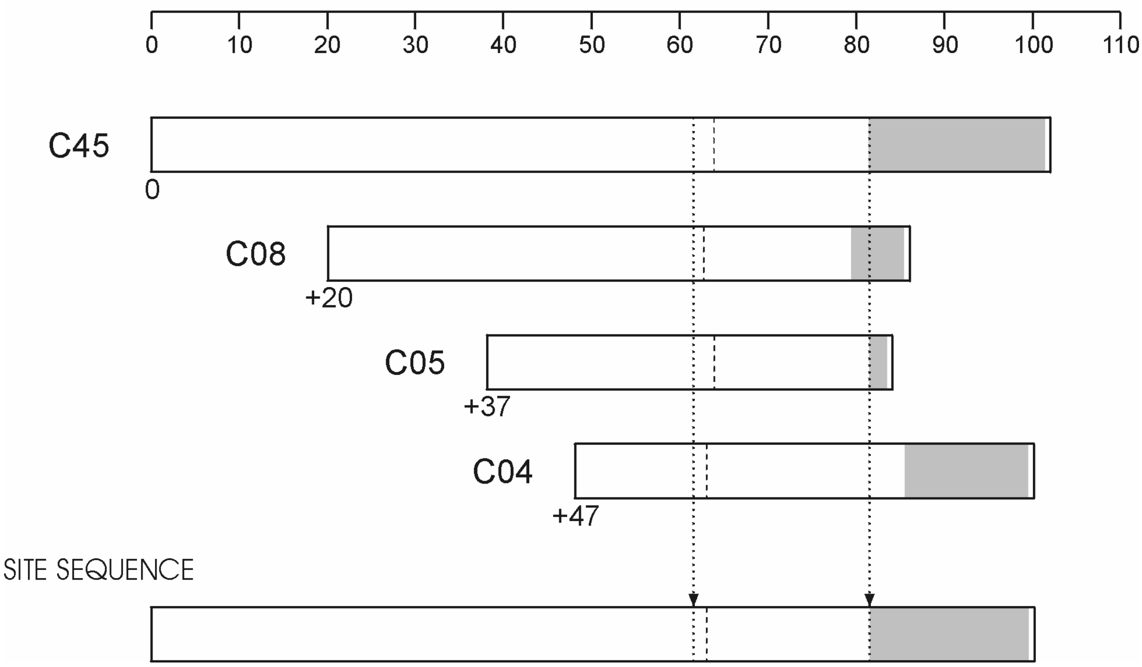


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

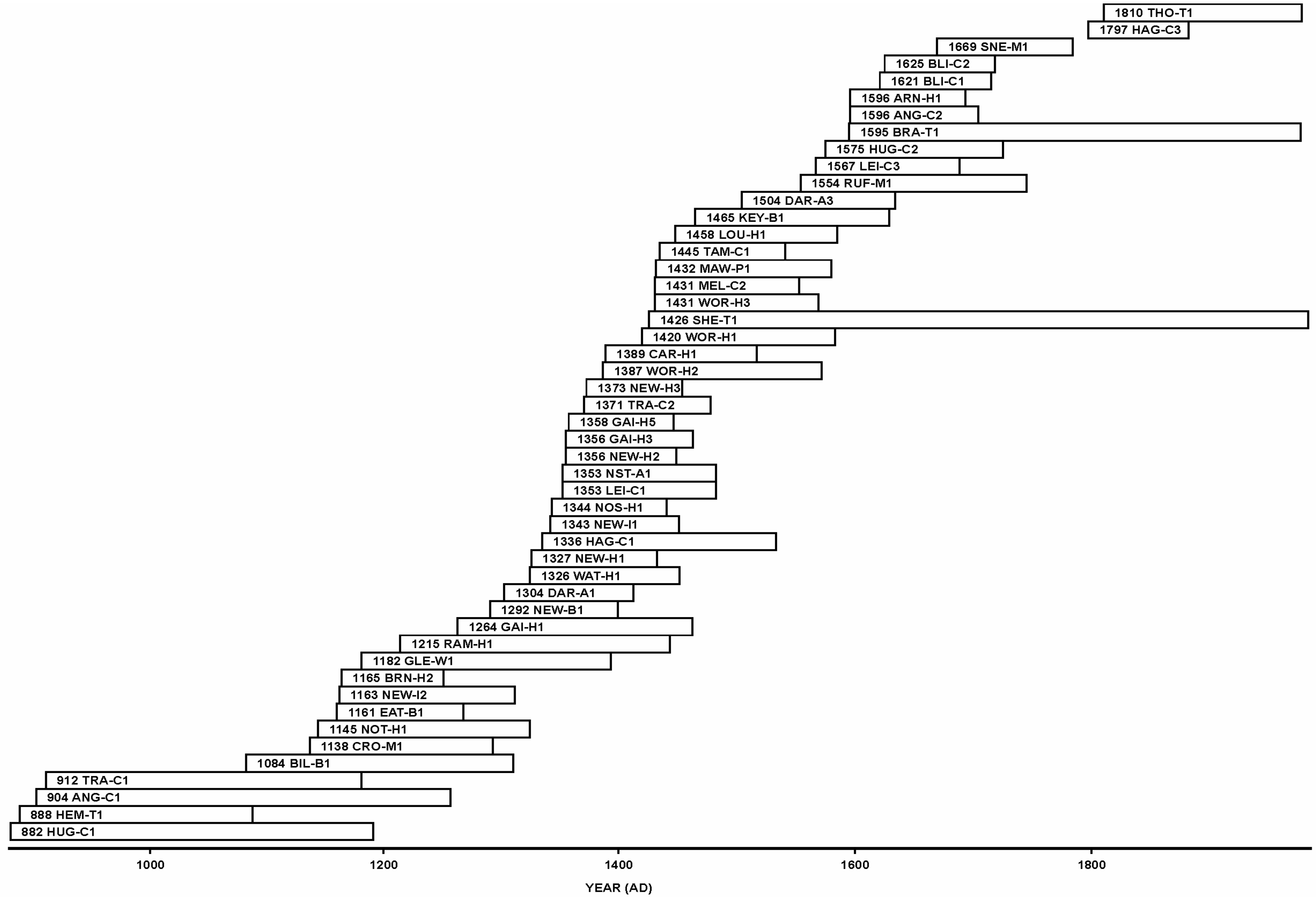
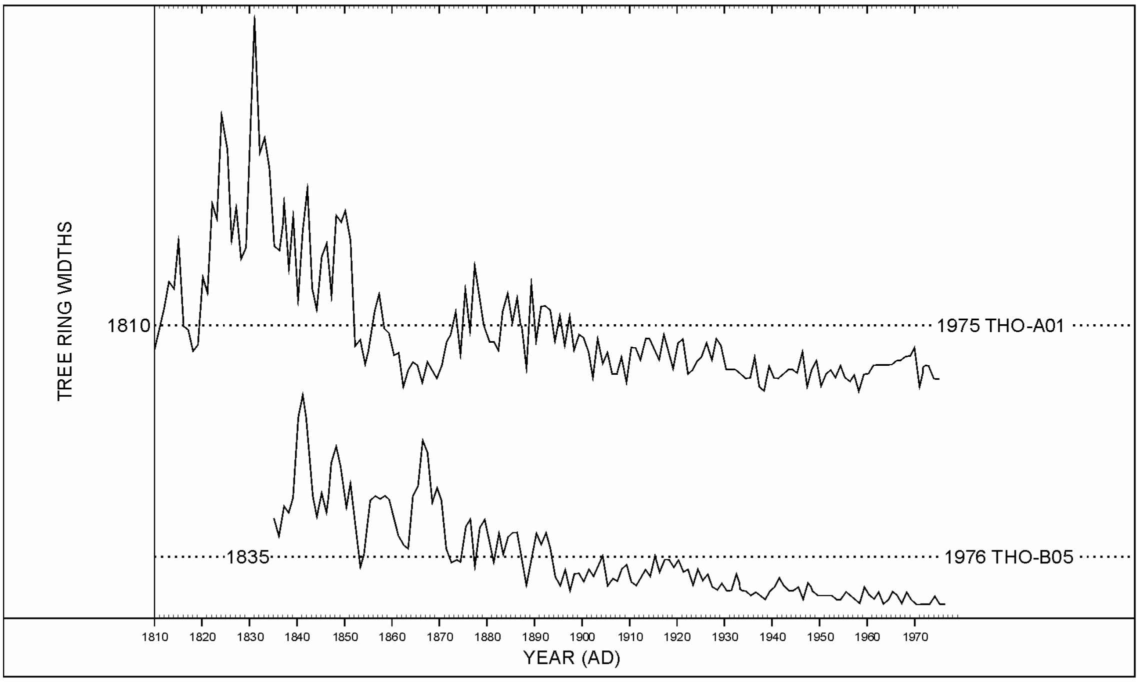


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

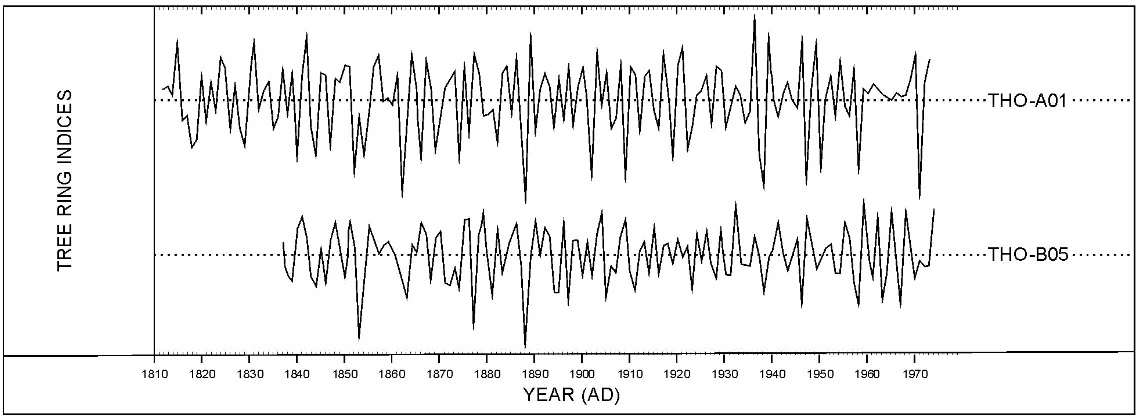


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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