Historic England

Scientific Dating

4 Walseker Lane Harthill with Woodall Rotherham South Yorkshire

Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, and Lukas Wacker

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Front Cover: 4 Walseker Lane, Rotherham. Photograph by courtesy of Oulsnam Design Limited

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HARTHILL WITH WOODALL
ROTHERHAM
SOUTH YORKSHIRE

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SUMMARY

Dendrochronological analysis was undertaken on cores from 15 of the 16 timbers sampled in the roof of number 4 Walseker Lane, near Rotherham in South Yorkshire, the sample from one timber having too few rings for dating. This analysis produced a single site chronology, which included ten ring-width series that could be securely cross-matched statistically. In order to guide the programme of radiocarbon dating, three further series were identified as tentatively linked by statistical cross-matching, as well as two series being identified as tentatively linked by visual matching. Although this site chronology, with an overall length of 57 rings, could not be dated conclusively by ring-width dendrochronology, it is highly likely that the timbers are coeval.

Radiocarbon dating was undertaken on eleven single-ring samples from five timbers in the site master chronology. Wiggle-matching of these results suggests that the final ring of this site master chronology formed in *cal AD 1428–1436 (95% probability)* or *cal AD 1430–1434 (68% probability)*.

This is compatible with one of the tentative dates for the site master chronology suggested by ring-width dendrochronology, when it spans AD 1376–1432. The tentative tree-ring date can only be accepted because it is supported independently by the radiocarbon wiggle-matching, but together they suggest that the fifteen timbers represented in site master chronology were felled in the winter of AD 1432/3$_{DR}$.

CONTRIBUTORS

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INTRODUCTION

The grade II* listed number 4 Walseker Lane, at Harthill with Woodall, some 12km south of Rotherham (Fig 1), is believed to be one of the earliest domestic buildings so far identified in South Yorkshire. It is a four-bay house (Fig 2), probably of the later fourteenth century, and retains a notable crown-post roof (Fig 3a). The property has been the subject of a programme of recording and survey from which the following description is taken (Ryder 1987).

Number 4 is unusual in being set well back from the surrounding roads, Walseker Lane to the west, and Killamarsh Lane to the south. The house consists of a rectangular block with a steeply pitched roof, hipped at the east end (Fig 3b), but gabled to the west, and incorporating a post-and-truss structure of four unequal bays. The two western bays of the framed building, together with a short extension westwards, are now used as a dwelling house, whilst the two eastern bays serve as outhouses with a storage loft over.

The medieval house apparently consisted of a central two-bay hall flanked by end bays which may or may not have been storeyed. The shorter eastern bay of the hall perhaps housed the dais, with the bay beyond containing the solar, its status suggested by the collar purlin and braces over the bay being neatly chamfered. At the west end of the hall a substantial stone wall may represent an original reredos for the hearth, whilst slight evidence in the roof above – notching on the rafters for a (removed) collar set at a lower level than its fellows – may also point to a louvre or fire hood position here.

If the house possessed a conventional medieval cross-passage entry behind the stack, this would have been within the western bay where a doorway on the south may perpetuate an earlier entrance. A cross-passage in this position, though, would leave little room within the bay for service apartments. The stone-built western extension (the fabric of which appears coeval with the possibly seventeenth-century cladding of the timber house), however, may replace an original end-aisle or outshot. A section of studded partition wall of uncertain date survives between the western bay of the framed structure and the extension. Alternatively, the reredos wall and firehood might be a later modification to a hall originally heated by a central open hearth, which would have allowed its western bay to accommodate a screens passage.

The impressive crown-post roof survives virtually intact. The open truss which spanned the hall is an impressive piece of carpentry, indicating the status of the original house. The slightly cambered tiebeam has a double chamfered soffit (the outer chamfer continued down the principal post, the inner down the long arched braces) and a crown post flanked by pairs of arcuate braces rising to the collar and dropping to the tie, the curve of each pair being continuous so as to produce what is visually a mouchette form between braces, tie, and rafter.

Trusses 2 and 4, at either end of the hall, have been closed, the infill being carried by strutting of various forms. The tiebeam of truss 4 shows a series of pegged mortices for studding. The lack of braces may perhaps indicate a bressumer at mid-height which might have carried the timbers of a floor in the solar bay beyond. Unfortunately both principal posts have been removed, so this arrangement must be largely a matter of surmise. The hip end of the roof is marked by a rafter pair provided with two collars, the upper carrying the hip rafters and the lower carrying the end of the collar purlin, which is only scarfed once over its 15.6m length.

The stone cladding of the house appears to have been carried out in a piecemeal manner in the seventeenth or eighteenth century. The hollow chamfer stops on the ceiling beams in the ground-floor room occupying the west bay of the framed house look like seventeenth-century work, but otherwise there is an almost total lack of dateable features. Partition into house and barn probably occurred at this time. The structural evidence underlines the decline in the status of the house suggested by the (lack) of historical evidence, a decline in status probably responsible for the preservation of such an important early building.

TREE-RING SAMPLING

Sampling and analysis by dendrochronology of the timbers in 4 Walseker Lane were requested by Emma Sharpe, Inspector of Historic Buildings and Areas for Historic England. Potentially being one of the earliest surviving buildings of this type in the Rotherham district, if not the whole of South Yorkshire, it was hoped that tree-ring analysis would provide independent dating evidence for the primary construction and subsequent phases of development of the property, the results to inform listed building consent for its renovation and alteration.

Surviving timbers from the primary construction of the hall roof and frame, and from subsequent alterations, were assessed for their potential for ring-width dendrochronology. All timbers were from very fast-grown trees and were of clearly marginal suitability for tree-ring analysis. It was decided to proceed with sampling, however, as a pilot study to investigate the potential for using oxygen isotope analysis and radiocarbon wiggle-matching in combination with ring-width dendrochronology for dating historic timberwork.

A total of sixteen timbers have been sampled by coring as part of this study, each being given the tree-ring code WLS-K (for "Walseker"), and numbered 01–16 (Table 1). All samples are from timbers associated with the primary construction of the hall roof, timbers from the framing and subsequent phases of alteration having too few rings for reliable ring-width dendrochronology. The location of each core was noted at the time of sampling and is recorded both on drawings taken from Ryder (1987) and on annotated photographs, these shown as Figures 4a–d and 5a–j. The trusses and bays of the house are numbered from east to west following the schema of the survey report (Fig 2).

The samples were obtained in two separate episodes of coring. Eight timbers from bays 1 and 2 were sampled in April 2019. Initial tree-ring analysis failed to produce grouping between any of the ring-width series from these samples, and so four single-ring samples from different timbers were submitted for radiocarbon dating to confirm the extent of surviving early fabric in the hall roof.

A further eight core samples were obtained in July 2019, when it was possible to access the western bays. At this time a second core was obtained from the crown-post in truss 1 (WLS-K02) so that it would be possible to obtain both radiocarbon and oxygen isotope measurements on this timber if deemed appropriate. In the event, the additional sampling enabled the grouping of timbers, and tentative dating, by ring-width dendrochronology presented below. Further samples were therefore submitted for radiocarbon dating to confirm the tentative dating suggested by the ring-width dendrochronology, and to test the potential for radiocarbon wiggle-matching to support tentative statistical and visual cross-matching between ring-width series specifically identified with the radiocarbon wiggle-matching in mind. No samples were submitted for oxygen isotope dendrochronology.

RING-WIDTH DENDROCHRONOLOGY

Each of the core samples obtained from the various timbers in the hall roof was prepared by sanding and polishing and, although it was seen that many of the samples had fewer than the 40 rings deemed necessary for reliable dating by ring-width dendrochronology, the annual growth ring-widths of all but one sample (WLS-K05) were measured. In one case, WLS-K02, duplicate cores had been taken, and the number of rings in each of the two core samples is thus slightly different. They do, however, cross-match with a value of t=9.9, and the mean of the two ring-width series was used in subsequent analysis. The data of all measurements are given at the end of this report.

Allowing for the short lengths of the sample series, these measured data were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process resulted in the production of a single cross-matching group of samples.

This single cross-matching group, which formed at a minimum t-value of 3.7, comprises the ring-width series from 10 samples. These 10 series were combined at the offset positions, as shown in Figure 6a, to form site chronology WLSKSQ01A with an overall length of 57 rings. Site chronology WLSKSQ01A was then compared to the full corpus of reference chronologies for oak from both the British Isles and from elsewhere in Europe (Table 2a–b). This process indicated that site chronology WLSKSQ01A cross-matched with the reference material at two different possible positions with similar t-value levels, although neither of these was wholly conclusive (Table 2a–b). At both possible positions the evidence was too tentative, and thus this site chronology remains undated by ring-width dendrochronology.

Site chronology WLSKSQ01A was then compared with the five remaining measured but ungrouped samples. This indicated possible cross-matching with a further three samples, this 13-sample group forming at a minimum t-value of 3.1. These 13 ring-width series were also combined at the offset positions, as shown in Figure 6b, to form site chronology WLSKSQ01B, again with an overall length of 57 rings. Site chronology WLSKSQ01B was similarly compared to the full corpus of reference chronologies for oak (Table 2a–b), but again there was no conclusive cross-matching and this site chronology also remains undated by ring-width dendrochronology.

The two measured samples that remain ungrouped both have less than 30 rings, which is insufficient for even tentative statistical cross-matching. An attempt was made, however, to visually cross-match the ring-width series from these two samples with the 10 ring-with series that have been cross-matched securely by statistical methods, and the additional three ring-width series that have been crossed-matched tentatively using statistics. Tentative visual matches for these series were produced when WLS-K06 spans relative years 24–51, and WLS-K08 spans relative years 31–55 (Fig 7). These two ring-width series were then combined with the 13 ring-width series included in WLSKSQ01B at the offset positions shown in Figure 6c, to form site chronology WLSKSQ01C, again with an overall length of 57 rings. Site chronology WLSKSQ01C was similarly compared to the full corpus of reference chronologies for oak (Table 2a–b), but again there was no conclusive cross-matching and this site chronology also remains undated by ring-width dendrochronology.

This analysis may be summarised thus:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
WLSKSQ01A	10	57	Undated
WLSKSQ01B	13	57	Undated
WLSKSQ01C	15	57	Undated
Unmeasured	1	---	---

RADIOCARBON DATING

Following the failure of the ring-width dendrochronology to provide conclusive calendar dating for the hall roof, samples were submitted for radiocarbon wiggle-matching. In June 2019, a series of four single-ring samples were submitted from four timbers, the tiebeams and crown-posts of trusses 1 and 2, in an attempt to confirm the extent of surviving timberwork from the primary construction of the hall. In January 2020, seven further single-ring samples were submitted from the four cores already radiocarbon dated and from one additional core, WLS-K04 (Table 3; Fig 8). These samples were submitted to confirm the inconclusive dating suggested by ring-width dendrochronology for site master sequence WLSKSQ01A, and to validate the tentative cross-matching of additional samples suggested both by weak statistical correlation (WLSKSQ01B) and by visual matching (WLSKSQ01C). Finally, samples were selected to test protocols for employing short wiggle-match series to enhance the precision of modelled chronologies for historic timbers (Nakao *et al* 2014).

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 3, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Eleven radiocarbon measurements have been obtained from single annual tree-rings from core samples WLS-K01, WLS-K02A, WLS-K04, WLS-K06, and WLS-K08 (Table 3; Fig 8). Dissection was undertaken by Alison Arnold and Robert

Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Laboratory of Ion Beam Physics, ETH Zürich, Switzerland in 2019–20. Cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (Synal *et al* 2007; Wacker *et al* 2010b). Data reduction was undertaken as described by Wacker *et al* (2010c). The facility maintains a continual programme of quality assurance procedures (Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table 3).

WIGGLE-MATCHING

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al* 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from the hall roof, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 9–13.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al* (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.3 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figure 9–13 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 9 illustrates the chronological model for site chronology WLSKSQ01A, which contains only ring-width series that have been cross-matched conclusively by statistics. The model incorporates the gaps between each dated annual ring known from the tree-ring sequence (eg that the carbon in ring 1 of WLS-K02A (ETH-104563) was laid down eleven years before the carbon in ring 12 of WLS-K01 (ETH-104562); Fig 8), along with the radiocarbon measurements from the two cores that are included in WLSKSQ01A (Table 3). The radiocarbon measurements have been calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 108.3, An: 31.6, n: 5; Fig 9), and all the radiocarbon dates have good individual agreement (A > 60). It suggests that the final ring of WLSKSQ01A formed in *cal AD 1426–1438 (95% probability; WLSKSQ01A felling*; Fig 9), probably in *cal AD 1429–1435 (68% probability)*.

Figure 10 illustrates the chronological model for site chronology WLSKSQ01B, which contains both the 10 ring-width series that have been cross-matched securely by statistics and three ring-series that have been tentatively linked to this by statistics. The model incorporates the gaps between each dated annual ring known from the tree-ring sequence (Fig 8), along with the radiocarbon measurements from the three cores that are included in WLSKSQ01B (Table 3). Two of these are securely linked to this sequence by statistics (WLS-K01 and WLS-K02A) and one is tentatively linked to it (WLS-K04). The radiocarbon measurements have again been calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 112.3, An: 26.7, n: 7 Fig 10), and all the radiocarbon dates have good individual agreement (A > 60). It suggests that the final ring of WLSKSQ01B formed in *cal AD 1428–1438 (95% probability; WLSKSQ01B felling*; Fig 10), probably in *cal AD 1430–1436 (68% probability)*.

Figure 11 illustrates the chronological model for site chronology WLSKSQ01C, which contains 10 ring-width series that have been cross-matched securely by statistics, three ring-series that have been tentatively linked to this by statistics, and a further two ring-series that have been tentatively linked by visual cross-matching (Fig 7). The model incorporates the gaps between each dated annual ring known from the tree-ring sequence (Fig 8), along with the radiocarbon measurements from the five cores that are included in WLSKSQ01C (Table 3). Two of these are securely linked to this sequence by statistics (WLS-K01 and WLS-K02A), one is tentatively linked to it by statistics (WLS-K04), and two are tentatively linked by visual matching (WLS-K06 and WLS-K08). The radiocarbon measurements have again been calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

This model also has good overall agreement (Acomb: 145.5, An: 21.3, n: 11; Fig 11), and all the radiocarbon dates again have good individual agreement (A > 60). It suggests that the final ring of WLSKSQ01C formed in *cal AD 1428–1436 (95% probability; WLSKSQ01C felling;* Fig 11), probably in *cal AD 1430–1434 (68% probability).*

DISCUSSION

Ring-width dendrochronology

Analysis by ring-width dendrochronology of the timbers from 4 Walseker Lane has produced a single site chronology of 57-rings. This site chronology contains the ring-series from 10 samples which cross-match securely by statistical methods (Fig 6a), although three further samples can be tentatively linked to this chronology using statistics (Fig 6b), and two more (very short ring series) tentatively linked by visual matching (Fig 6c; Fig 7). Without additional supporting evidence of these tentative matches cannot be accepted.

Comparison of the site master chronology with the extensive corpus of reference chronologies for oak failed to identify a conclusive cross-dating position, and so the timbers contained in this site master sequence remain undated by ring-width dendrochronology. However, some low but consistent correlations were noted against a number of reference chronologies when the site master chronology spans AD 1376–1432 (Table 2a) and, alternatively, when it spans AD 1407–1463 (Table 2b).

Although undated by dendrochronology, the site chronology does demonstrate that these timbers are coeval, as the samples have heartwood/sapwood boundaries at very similar relative positions and a number of them have complete sapwood rings at an identical last measured ring position (Figs 6a–c). These sapwood rings appear to have complete summer growth, but no sign of the spring growth of the following year, suggesting that the trees were felled at some point after the late summer of relative year 57 and before the spring of relative year 58.

The lack of secure dating by ring-width dendrochronology at this site is almost certainly due to the short ring sequences of the individual samples, virtually all of them having fewer than the usual minimum of 40 rings required for reliable dating. Being so short, it is likely that the growth rings contain insufficient climatic patterns to provide a firm cross-match with the available reference chronologies.

It is also possible that the trees used at Walseker Lane, each timber appearing to be an individual whole tree, were growing in a particular niche location or place for which, as yet, there are relatively few truly locally representative reference chronologies available. It is possible that in time, as the collection of local samples increases, the site chronology created for 4 Walseker Lane may be cross-matched more securely with local data and be reliably dated by ring-width dendrochronology.

This lack of dating by ring-width dendrochronology, the similarity in the number of rings the timbers have, and the fact that many of them appear to be single whole trees, would suggest that the trees used here were originally all growing under the same management regime. As such, it is possible that they were all growing in the same woodland, although the location of this woodland cannot be determined.

Radiocarbon-supported dendrochronology

The radiocarbon wiggle-matching supports both the tentative cross-matching of additional timbers suggested by weak statistical evidence and visual pattern matching (Figs 6b–c), and the tentative cross-dating of the site master sequence suggested by ring-width dendrochronology of AD 1376–1432 (Table 2a).

The two radiocarbon dates from WLS-K04, which is only tentatively linked to site master chronology WLSKSQ01B on statistical grounds, have good individual agreement in both the model for this chronology (*ETH-104565*, A: 89 and *ETH-104566*, A:128; Fig 10), and the model for chronology WLSKSQ01C ((*ETH-104565*, A: 76 and *ETH-104566*, A:132; Fig 11). This suggests that the offset positions tentatively suggested by the statistical analysis of the ring-width data are valid.

The four radiocarbon dates from WLS-K06 and WLS-K08, both of which are only tentatively linked by visual matching to site master chronology WLSKSQ01C, have good individual agreement in the model for this sequence (*ETH-104567*, A: 154, *ETH-99778*, A: 133, *ETH-104568*, A: 93, and *ETH-99779*, A: 133; Fig 11). This suggests that the relative positions of these samples in the master chronology suggested by the visual matching are correct.

The radiocarbon wiggle-matches for all three variants of the site master chronology produced by ring-width dendrochronology have good overall agreement (Acomb > An; Figs 9–11), and all three models produce posterior density estimates for the final ring of the sequence that are compatible with the last measured ring being formed in AD 1432 (Table 2a). Futhermore, when the last ring of the wiggle-match is constrained to be AD 1432, all three models have good overall agreement (WLSKSQ01A, Acomb: 117.6, An: 28.9, n: 6; WLSKSQ01B, Acomb: 120.7, An: 25.0, n: 8; WLSKSQ01C, Acomb: 153.3, An: 20.4, n: 12), and all the radiocarbon dates have good individual agreement (A > 60).

This allows one of the two tentative matches provided by the ring-width dendrochronology to be considered as a radiocarbon-supported dendrochronological date, that spanning AD 1376–1432 (Table 2a), with the trees represented felled in the winter of AD 1432/33$_{\mathrm{DR}}$ (Table 4). The superscript $_{\mathrm{DR}}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, WLSKSQ01A–C, should not be utilised as a ring-width master sequence for dating other sites.

The alternative tentative cross-dating for this sequence suggested by the ring-width dendrochronology, as spanning AD 1407–1463 (Table 2b) is clearly spurious as it is incompatible with the radiocarbon wiggle-matching.

Dating the roof of 4 Walseker Lane

The fifteen sampled timbers that have been included in the dated site master chronology, WLSKSQ01C, include the crown posts of trusses 1–3, the tiebeams of trusses 1 and 2, and a range of other timber elements from all four bays of the roof of the timber-framed house. Evidence suggests that, with the exception of reused timbers, in most historical periods construction took place within a very few years of felling (Miles 2006). The dates thus suggest that the construction of the building occurred in the winter of AD 1432/33$_{DR}$, or within a year or two after this date.

This dating is at least a generation, perhaps two, later than the later fourteenth--century date previously attributed to this building on typological grounds (Ryder 1987). It is clear, however, that the original roof remains largely intact.

A thought experiment

In circumstances when ring-width dendrochronology produces a site master chronology, radiocarbon wiggle-matching is clearly able to produce independent dating evidence for the assemblage of timbers included in the site master sequence. This means that, by dating a series of rings from one or two core samples, the whole site master can be dated either, as in this case, to provide supporting evidence for tentative ring-width dendrochronology that is not strong enough to stand alone, or by providing an independent date estimate for the final ring of the chronology (*felling WLSKSQ01C*; Fig 11).

We now consider the situation, however, where ring-width dendrochronology has produced no cross-matching between the ring-width series. This was the position we faced at 4 Walseker Lane after the first set of sampling. What if it had not been possible to obtain further samples or if no further samples were available? In this case, the single tree-ring series and the radiocarbon dates would have to stand alone.

First, it was necessary to obtain samples from a number of timbers that were unlikely to have been replaced. We therefore chose to sample the tiebeams and crownposts from trusses 1 and 2 (WLS-K01, WLS-K06, WLS-K02A, and WLS-K08). From each core, we dated one single ring that was a small distance from the edge of the timber (to avoid any potential surface contamination). All of these timbers retained at least some sapwood, and two retained bark edge.

We were therefore able to construct a model which estimates the date of the last measured ring of each core, by offsetting the radiocarbon date by the number of additional rings to the end of the ring series (Fig 12 (bottom)). Where bark edge was not present, we then offset the date of the final ring by the probability distribution of the number of sapwood rings expected in English oak (Arnold *et al* 2020, fig 9), truncated to allow for the surviving sapwood rings on each timber (Bayliss and Tyers 2004, 960–1). These distributions, which are estimates of the date of felling of each individual timber, are shown in Figure 12 (middle). Finally, we combine these individual felling date estimates to derive an estimated date for when they were felled as a group (and thus the roof constructed), which is in *cal AD 1425–1445 (95% probability; WLS-K construction (4 sample)*; Fig 12 (upper)), probably in *cal AD 1428–1439 (68% probability).*

This final step in the analysis is based on the assumption that the four timbers were felled at the same time, which we do not know without the relative dating provided by a ring-width site master chronology. If this assumption were untrue, however, then the Acomb statistic of the model would be less than the An statistic. In this case, the assumption appears to be valid (Fig 12 (upper)), and the posterior density estimate for the felling of these four timbers is compatible with the radiocarbon-supported dendrochronological date of winter AD 1432/33$_{DR}$.

Another thought experiment

In a situation where no cross-matching is available between the ring-width series of the sampled timbers, is it possible to produce a more precise estimate for felling but obtaining further radiocarbon dates?

In this example, we follow the protocol suggested by Nakao *et al* (2014), who obtained two or three single-ring samples from a number of timbers rather than a larger number from a single timber. This ensures that a representative sample of timbers in the building are selected for analysis, but also aims to achieve enhanced precision by using the spacing known by ring-counting between the dated samples in wiggle-matching (Fig 8).

This model incorporates the gaps between each dated annual ring known from counting the rings of each individual core sample, and then the gap to the last measured ring of each series (Fig 13 (bottom)). Again, where bark edge was not present, we then offset the date of the final ring by the probability distribution of the number of sapwood rings expected in English oak (Arnold *et al* 2020, fig 9), truncated to allow for the surviving sapwood rings on each timber (Bayliss and Tyers 2004, 960–1). These distributions, which are estimates of the date of felling of each individual timber, are shown in Figure 13 (middle). Finally, we combine these individual felling date estimates to derive an estimated date for when they were felled as a group, which is in *cal AD 1428–1444 (95% probability; WLS-K construction (11 sample)*; Fig 13 (upper)), probably in *cal AD 1431–1440 (68% probability)*.

The Acomb statistic of this model is greater than the An statistic (Fig 13 (upper)), and so the assumption that the five timbers were felled at the same time is plausible. Again, the posterior density estimate for the felling of these timbers is compatible with the radiocarbon-supported dendrochronological date of winter AD 1432/33$_{DR}$.

In this application very little additional precision has been produced by the short wiggle-match sequences for each sampled timber, with the range of the posterior distribution for felling reduced by only five years (at 95% probability) and two years (at 68% probability). This is in contrast to the experience of Nakao *et al* (2014), and probably arises from the fact that the roof at 4 Walseker Lane dates to a time when the radiocarbon calibration curve is steeply sloping and so single calibrated radiocarbon dates are comparatively precise (Fig 14).

CONCLUSIONS

Tree-ring analysis was undertaken on cores from 15 of the 16 timbers sampled in the roof of number 4 Walseker Lane, near Rotherham in South Yorkshire, one sample having too few rings for dating. The ring-width analysis produced a single site chronology, which included ten ring-width series that could be securely linked by statistical cross-matching, with three further series tentatively linked by statistical cross-matching, and two tentatively linked by visual matching. Although this site chronology, with an overall length of 57 rings, could not be dated conclusively by ring-width dendrochronology, it is highly likely that the timbers are coeval (Fig 6c).

Radiocarbon dating was undertaken on eleven single-ring samples from five timbers in the site master chronology. Wiggle-matching of these results suggests that the final ring of this site master chronology formed in *cal AD 1428–1436 (95% probability; felling WLSKSQ01C*; Fig 11*)* or *cal AD 1430–1434 (68% probability)*, and confirms the validity of the tentative cross-matching identified.

The results from the radiocarbon wiggle-matching are clearly compatible with the tentative dating for the site master chronology suggested by ring-width dendrochronology, when it spans AD 1376–1432 (Table 2a); and is clearly incompatible with the other option for tentative dating of the site master chronology suggested by the ring-width dendrochronology, when it spans AD 1406–1463 (Table 2b). The radiocarbon wiggle-matching, thus allows the tentative tree-ring dating of this sequence as spanning AD 1376–1432 to be accepted. In combination, the two techniques together suggest that the fifteen timbers represented in site master chronology were felled in the winter of AD 1432/33$_{DR}$.

As in most historical periods construction took place within a very few years of felling (Miles 2006), the dates thus suggest that the construction of the building occurred in the winter of AD 1432/33$_{DR}$, or within a year or two after this date. This dating is at least a generation, perhaps two, later than the later fourteenth-century date previously attributed to this building on typological grounds (Ryder 1987). It is clear, however, that the original roof remains largely intact and is an important survival.

Further analysis suggests that, even if secure relative dating of the timbers from the roof by ring-width dendrochronology had not been possible, radiocarbon wiggle-matching would have been able to produce accurate date estimates for the construction of the building to within a precision of less than two decades (Figs 12 and 13). This study, however, may be atypical because it falls on a particularly steep part of the radiocarbon calibration curve (Fig 14).

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TABLES

Table 1: Details of tree-ring samples from 4 Walseker Lane, Harthill with Woodall, Rotherham, South Yorkshire. Tree-ring cores sub-sampled for radiocarbon dating are shown in red

Sample number	Sample location	Total rings	Sapwood rings	Relative date of first measured ring	Relative date of last heartwood ring	Relative date of last measured ring
WLS-K01	Tiebeam, truss 1	49	8	4 SQ01A	44 SQ01A	52 SQ01A
WLS-K02	Crown post, truss 1	57	15C	1 SQ01A	42 SQ01A	57 SQ01A
WLS-K02A	ditto	54	15C	4 SQ01A	42 SQ01A	57 SQ01A
WLS-K02B	ditto	57	15C	1 SQ01A	42 SQ01A	57 SQ01A
WLS-K03	South principal rafter, truss 1	35	2	13 SQ01A	45 SQ01A	47 SQ01A
WLS-K04	South common rafter 9 (from east), bay 1	40	21C	18 SQ01B	36 SQ01B	57 SQ01B
WLS-K05	North wall plate, truss 1 – 2	10nm	---	---	---	---
WLS-K06	Tiebeam, truss 2	25	9	31 SQ01C	46 SQ01C	55 SQ01C
WLS-K07	Brace, south wall post to tiebeam, truss 2	32	h/s	15 SQ01A	46 SQ01A	46 SQ01A
WLS-K08	Crown post, truss 2	28	7	24 SQ01C	44 SQ01C	51 SQ01C
WLS-K09	East hip, common rafter 5 (from north)	50	18c	6 SQ01A	37 SQ01A	55 SQ01A
WLS-K10	South common rafter 5, bay 1	38	14C	20 SQ01B	43 SQ01B	57 SQ01B
WLS-K11	South common rafter 10, bay 1	37	16C	21 SQ01A	41 SQ01A	57 SQ01A
WLS-K12	South common rafter 2, bay 3	43	13C	15 SQ01A	44 SQ01A	57 SQ01A
WLS-K13	Collar frame 7, bay 3	37	11C	21 SQ01B	46 SQ01B	57 SQ01B
WLS-K14	Crown post, truss 3	34	13C/	24 SQ01A	44 SQ01A	57 SQ01A
WLS-K15	North outer strut, truss 3	38	10	19 SQ01A	46 SQ01A	56 SQ01A
WLS-K16	North common rafter 1, bay 4	45	18C	13 SQ01A	39 SQ01A	57 SQ01A

C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented
c = complete sapwood is found on the timber, but a portion of this has been lost from the sample in coring
h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured
SQ01A = relative date span within site master chronology WLSKSQ01A (secure statistical cross-matching for ten samples)
SQ01B = relative date span within site master chronology WLSKSQ01B (tentative statistical cross-matching for an extra three samples)
SQ01C = relative date span within site master chronology WLSKSQ01C (tentative visual cross-matching for an extra two samples)

Table 2a: Results of the ring-width cross-matching of site chronologies WLSKSQ01A, WLSKSQ01B, and WLSKSQ01C when the first-ring date is AD 1376 and the last-ring date is AD 1432 (--- = t-*value < 3.0)*

Reference chronology	Span of chronology	WLSKSQ01A	WLSKSQ01B	WLSKSQ01C	Reference
		t-value	*t*-value	*t*-value	
110/112 Uppergate Road, Sheffield, South Yorkshire	AD 1370–1507	5.7	5.4	5.6	Hillam and Ryder 1980
Pedagogue's House, Stratford upon Avon, Warwickshire	AD 1377–1502	5.4	5.6	---	Arnold and Howard 2006
Stank Hall Barn, Leeds, West Yorkshire	AD 1384–1444	5.2	6.0	5.3	Hillam and Groves1991
Stockbridge Farm, Arksey, South Yorkshire	AD 1387–1564	5.1	5.1	4.7	Morgan 1980
Headlands Hall, Liversedge, West Yorkshire	AD 1388–1487	5.1	5.4	5.2	Tyers 2001
Peel Hall, Manchester, Greater Manchester	AD 1378–1481	4.9	4.9	4.7	Leggett 1980
Old Rectory, Cossington, Leicestershire	AD 1375–1526	4.5	4.1	3.5	Howard *et al* 1992
41-47 High Street, Exeter, Devon	AD 1342–1636	4.5	4.2	3.3	Arnold *et al* 2020
Horbury Hall, Wakefield, West Yorkshire	AD 1368–1473	4.4	4.5	3.5	Howard *et al* 1992
23 Church Street, Eckington, Derbyshire	AD 1381–1474	4.3	4.5	5.1	Esling *et al* 1989

Table 2b: Results of the ring-with cross-matching of site chronologies WLSKSQ01A, WLSKSQ01B, and WLSKSQ01C when the first-ring date is AD 1407 and the last-ring date is AD 1463

Reference chronology	Span of chronology	WLSKSQ01A	WLSKSQ01B	WLSKSQ01C	Reference
		t-value	*t*-value	*t*-value	
St Nicholas' Church, Stanford, Northamptonshire	AD 1349–1482	5.5	5.6	5.4	Howard *et al* 1996
Dauntsey House, Dauntsey, Wiltshire	AD 1393–1580	5.4	5.2	4.7	Bridge *et al* 2014
St John the Baptist Church, Myndtown, Shropshire	AD 1420–1568	5.3	5.3	5.7	Arnold *et al* forthcoming
Brampton Bierlow Hall, Rotherham, South Yorkshire	AD 1423–1536	5.1	5.0	5.0	Hillam 1984
The Old House, Norwell, Nottinghamshire	AD 1340–1494	4.9	4.8	4.7	Hurford *et al* 2010
Flores House, Oakham, Rutland	AD 1408–1591	4.9	4.9	5.0	Hurford *et al* 2008
Gorcott Hall, Redditch, Warwickshire	AD 1385–1531	4.8	4.9	4.8	Nayling 2006
Hanson Hall barn, Normanton, West Yorkshire	AD 1359–1455	4.6	4.5	3.9	Tyers 2008
Bucknell Barn, Shropshire	AD 1414–1595	4.5	3.9	4.5	Leggett 1980
All Saints Church, Knipton, Leicestershire	AD 1414–1490	4.4	4.8	4.3	Arnold *et al* 2005

Table 3: Radiocarbon measurements and associated $\delta^{13}C$ values from oak samples WLS-K01, WLS-K02A, WLS-K04, WLS-K06, and WLS-K08

Laboratory Number	Sample	Relative year	Radiocarbon Age (BP)	$\delta^{13}C_{AMS}$ (‰)
ETH-104562	WLS-K01, ring 9 (*Quercus* sp. heartwood)	12[SQ01A]	618±14	−25.9
ETH-99776	WLS-K01, ring 34 (*Quercus* sp. heartwood)	37[SQ01A]	539±13	−23.9
ETH-104563	WLS-K02A, ring 1 (*Quercus* sp. heartwood)	1[SQ01A]	637±14	−25.2
ETH-104564	WLS-K02A, ring 21 (*Quercus* sp. heartwood)	21[SQ01A]	568±14	−25.1
ETH-99777	WLS-K02A, ring 43 (*Quercus* sp. sapwood)	43[SQ01A]	542±13	−22.7
ETH-104565	WLS-K04, ring 1 (*Quercus* sp. heartwood)	18[SQ01B]	575±14	−25.5
ETH-104566	WLS-K04, ring 35 (*Quercus* sp. heartwood)	52[SQ01B]	499±14	−24.5
ETH-104567	WLS-K06, ring 1 (*Quercus* sp. heartwood)	31[SQ01C]	560±14	−24.4
ETH-99778	WLS-K06, ring 14 (*Quercus* sp. heartwood)	44[SQ01C]	517±13	−23.4
ETH-104568	WLS-K08, ring 5 (*Quercus* sp. heartwood)	28[SQ01C]	580±14	−25.6
ETH-99779	WLS-K08, ring 19 (*Quercus* sp. heartwood)	42[SQ01C]	529±13	−24.0

[SQ01A] = relative date within site master chronology WLSKSQ01A (secure statistical cross-matching)
[SQ01B] = relative date within site master chronology WLSKSQ01B (tentative statistical cross-matching)
[SQ01C] = relative span within site master chronology WLSKSQ01C (tentative visual cross-matching)

Table 4: Radiocarbon-supported tree-ring dating for samples from 4 Walseker Lane, Harthill with Woodall, Rotherham, South Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	Date of first measured ring (AD$_{DR}$)	Date of last heartwood ring (AD$_{DR}$)	Date of last measured ring (AD$_{DR}$)
WLS-K01	Tiebeam, truss 1	49	8	1379$_{DR}$	1419$_{DR}$	1427$_{DR}$
WLS-K02	Crown post, truss 1	57	15C	1376$_{DR}$	1417$_{DR}$	1432$_{DR}$
WLS-K02A	ditto	54	15C	1379$_{DR}$	1417$_{DR}$	1432$_{DR}$
WLS-K02B	ditto	57	15C	1376$_{DR}$	1417$_{DR}$	1432$_{DR}$
WLS-K03	South principal rafter, truss 1	35	2	1388$_{DR}$	1420$_{DR}$	1422$_{DR}$
WLS-K04	South common rafter 9 (from east), bay 1	40	21C	1393$_{DR}$	1411$_{DR}$	1432$_{DR}$
WLS-K05	North wall plate, truss 1 – 2	10nm	---			
WLS-K06	Tiebeam, truss 2	25	9	1406$_{DR}$	1421$_{DR}$	1430$_{DR}$
WLS-K07	Brace, south wall post to tiebeam, truss 2	32	h/s	1390$_{DR}$	1421$_{DR}$	1421$_{DR}$
WLS-K08	Crown post, truss 2	28	7	1399$_{DR}$	1419$_{DR}$	1426$_{DR}$
WLS-K09	East hip, common rafter 5 (from north)	50	18c	1381$_{DR}$	1412$_{DR}$	1430$_{DR}$
WLS-K10	South common rafter 5, bay 1	38	14C	1395$_{DR}$	1418$_{DR}$	1432$_{DR}$
WLS-K11	South common rafter 10, bay 1	37	16C	1396$_{DR}$	1416$_{DR}$	1432$_{DR}$
WLS-K12	South common rafter 2, bay 3	43	13C	1390$_{DR}$	1419$_{DR}$	1432$_{DR}$
WLS-K13	Collar frame 7, bay 3	37	11C	1396$_{DR}$	1421$_{DR}$	1432$_{DR}$
WLS-K14	Crown post, truss 3	34	13C	1399$_{DR}$	1419$_{DR}$	1432$_{DR}$
WLS-K15	North outer strut, truss 3	38	10	1294$_{DR}$	1421$_{DR}$	1431$_{DR}$
WLS-K16	North common rafter 1, bay 4	45	18C	1388$_{DR}$	1412$_{DR}$	1432$_{DR}$

C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented
c = complete sapwood is found on the timber, but a portion of this has been lost from the sample in coring
h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured

FIGURES

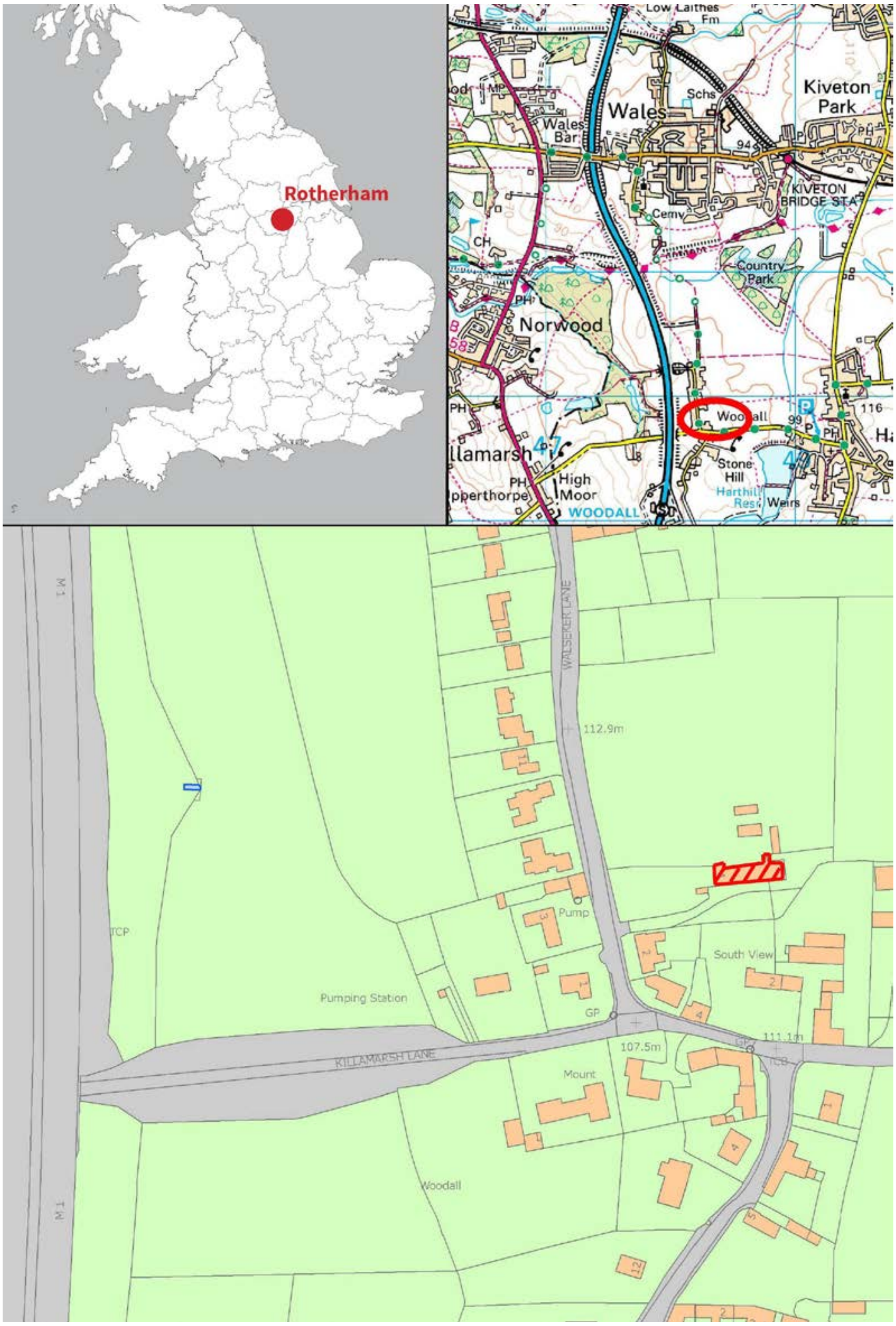


Figure 1: Maps to show the location of 4 Walseker Lane, Rotherham, South Yorshire, marked in red. Scale: top right 1:40000; bottom 1:2000. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

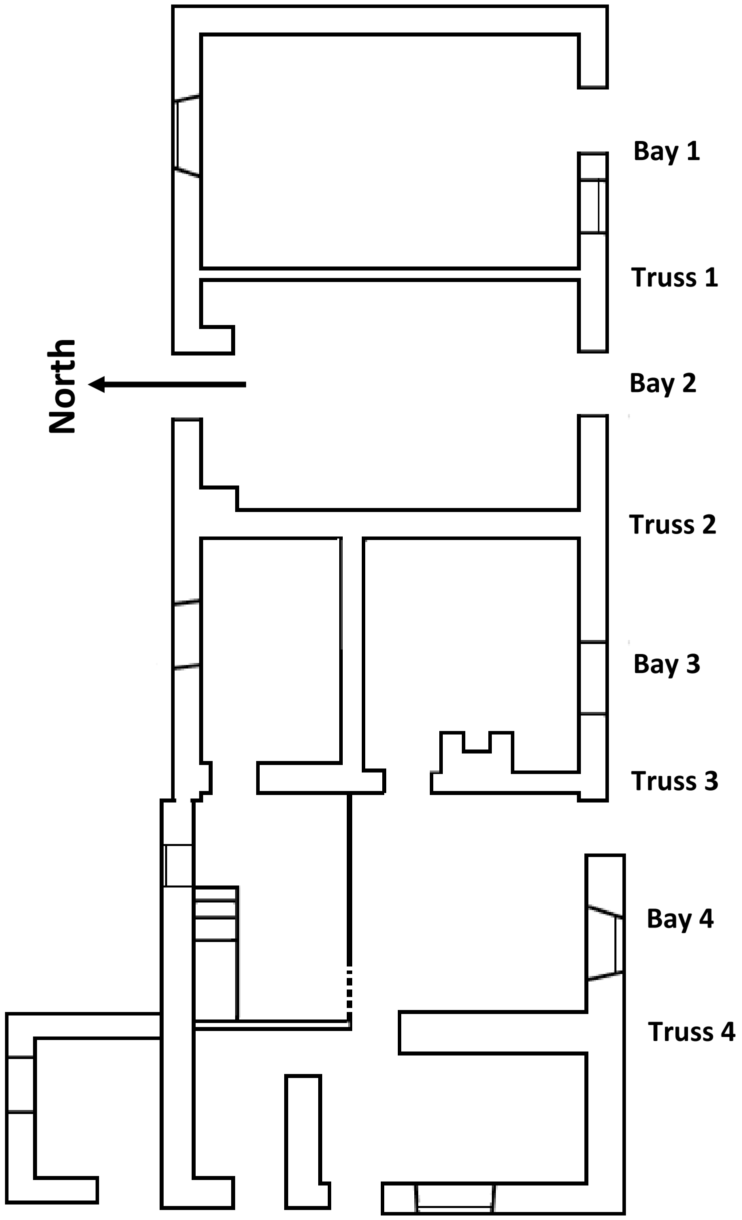


Figure 2: Outline of the ground-floor plan of 4 Walseker Lane to show the arrangement of the trusses and bays (after Peter Ryder)

Figure 3a/b: View of the roof looking east-west (top) showing truss 1 in the foreground with truss 2 beyond, and view of the south pitch looking eastwards (bottom) towards the hipped end (photographs Robert Howard)

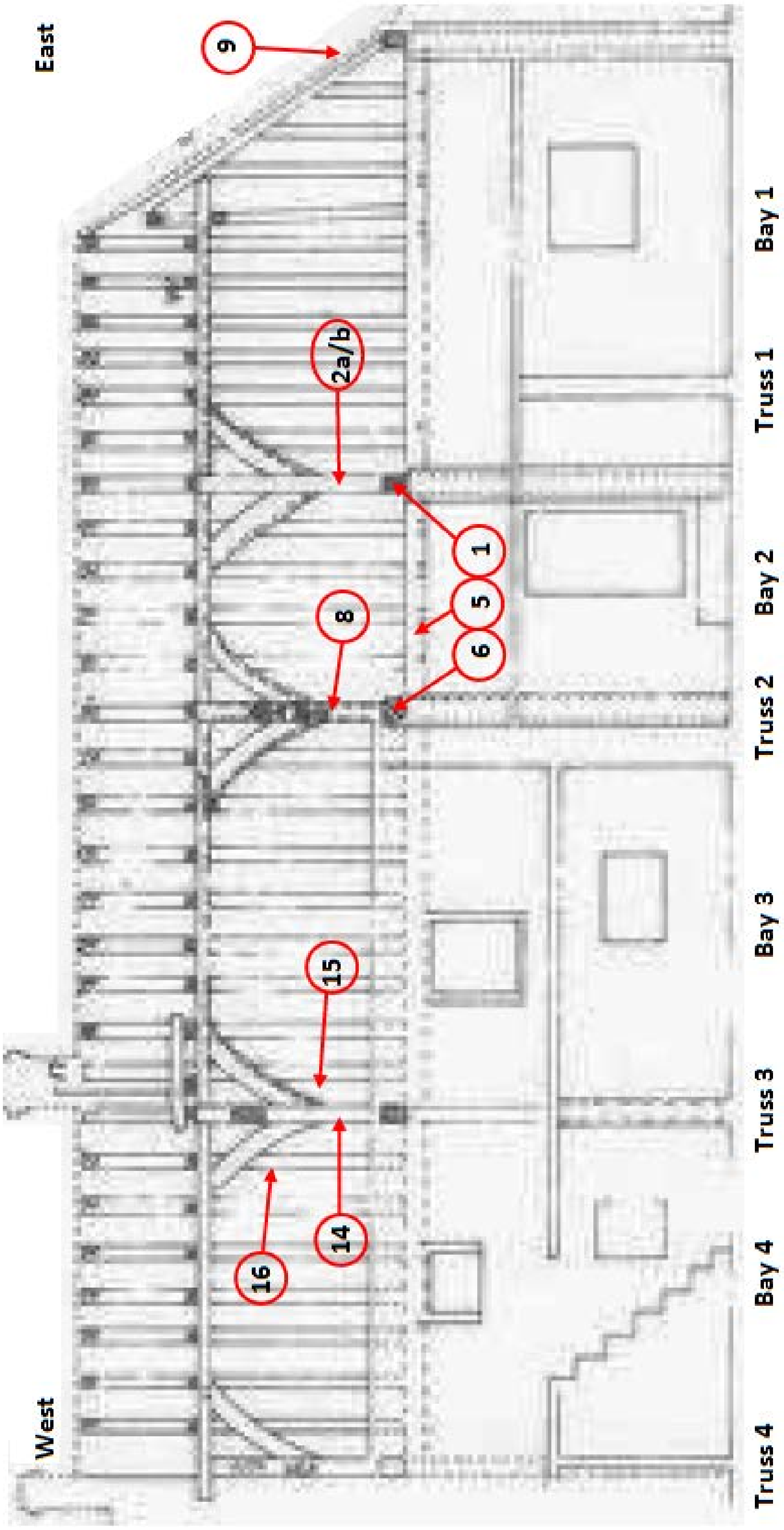


Figure 4a: Long-section looking north to help locate sampled timbers (after Peter Ryder)

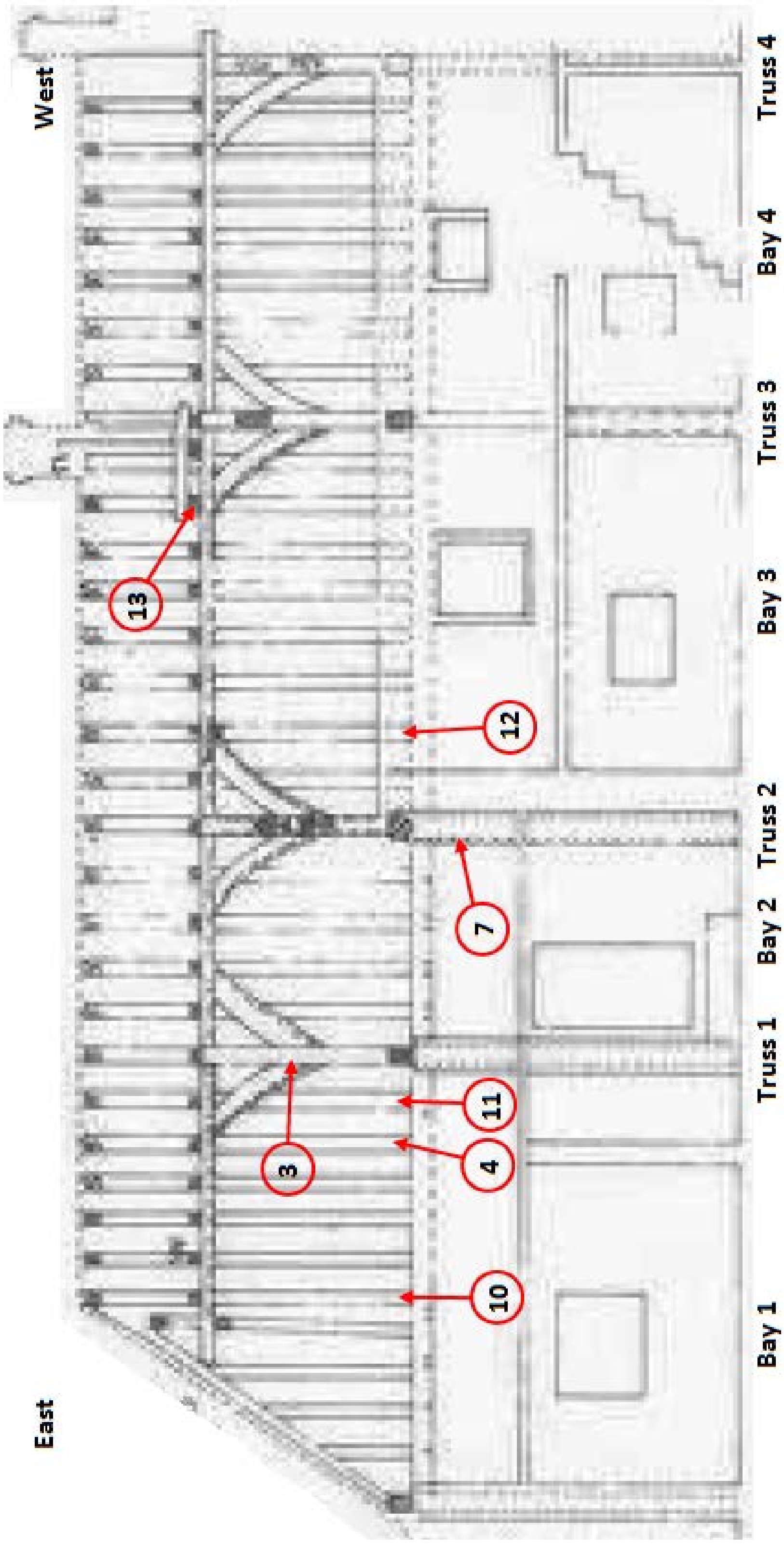
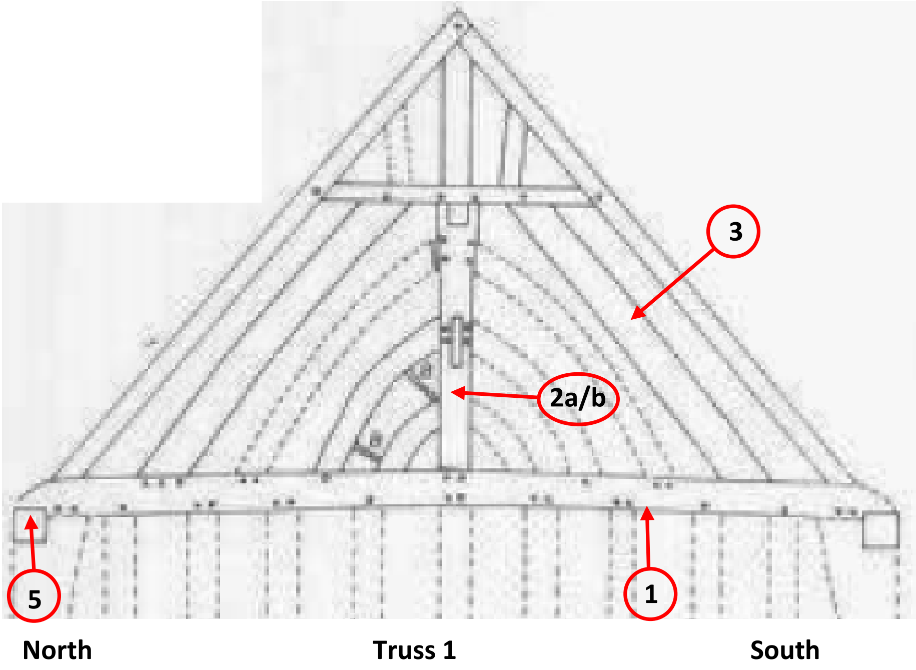


Figure 4b: Long-section looking south to help locate sampled timbers (after Peter Ryder)



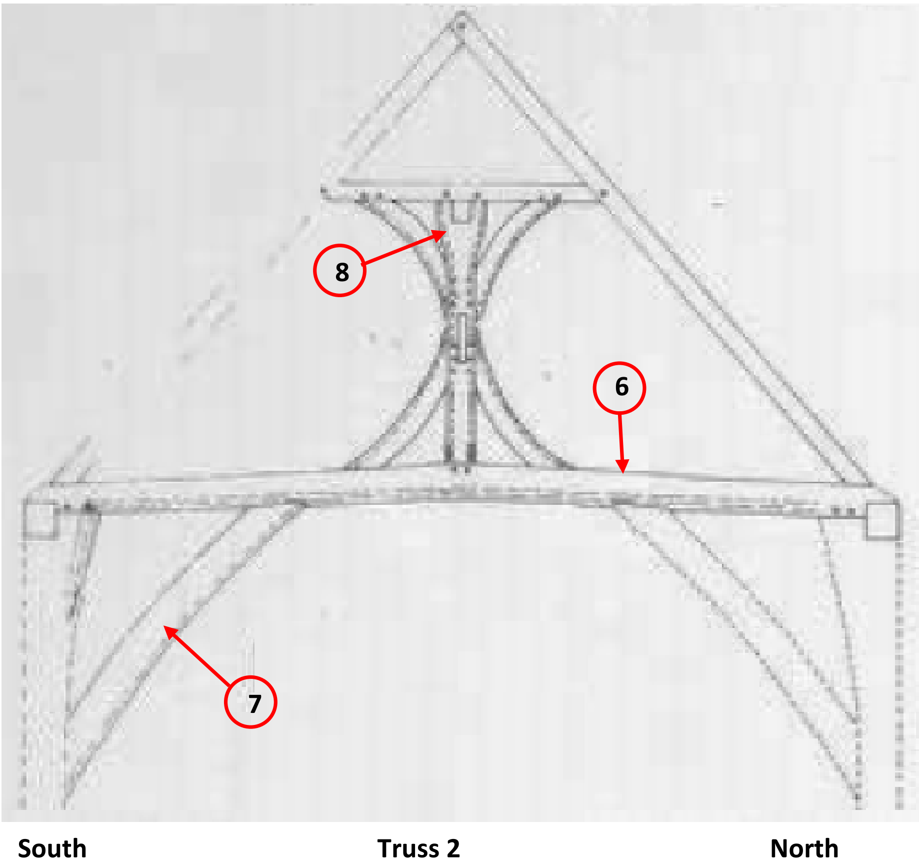


Figure 4c/d: Cross-section through truss 1 looking west to east (top) and truss 2 looking east to west (bottom) to help locate sampled timbers (after Peter Ryder)

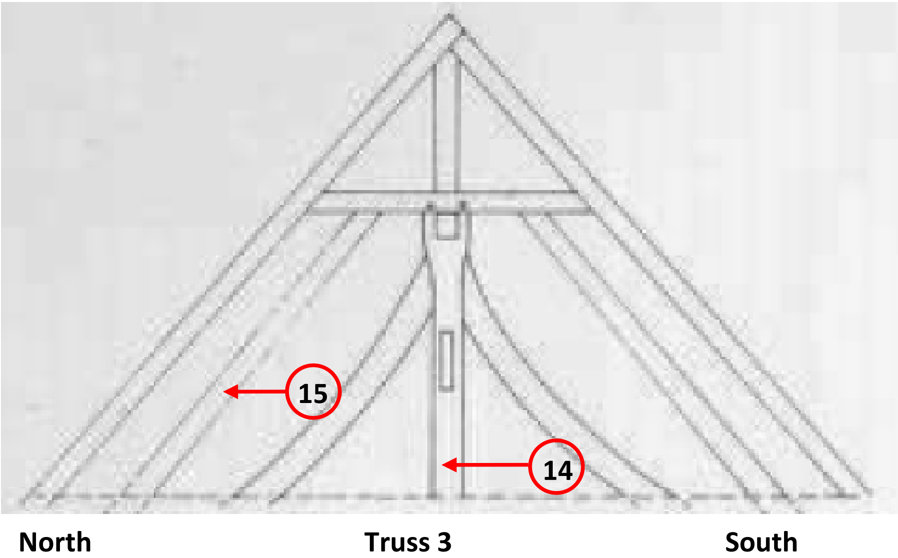


Figure 4e: Cross-sections through truss 3 looking west to east to help locate sampled timbers (after Peter Ryder)

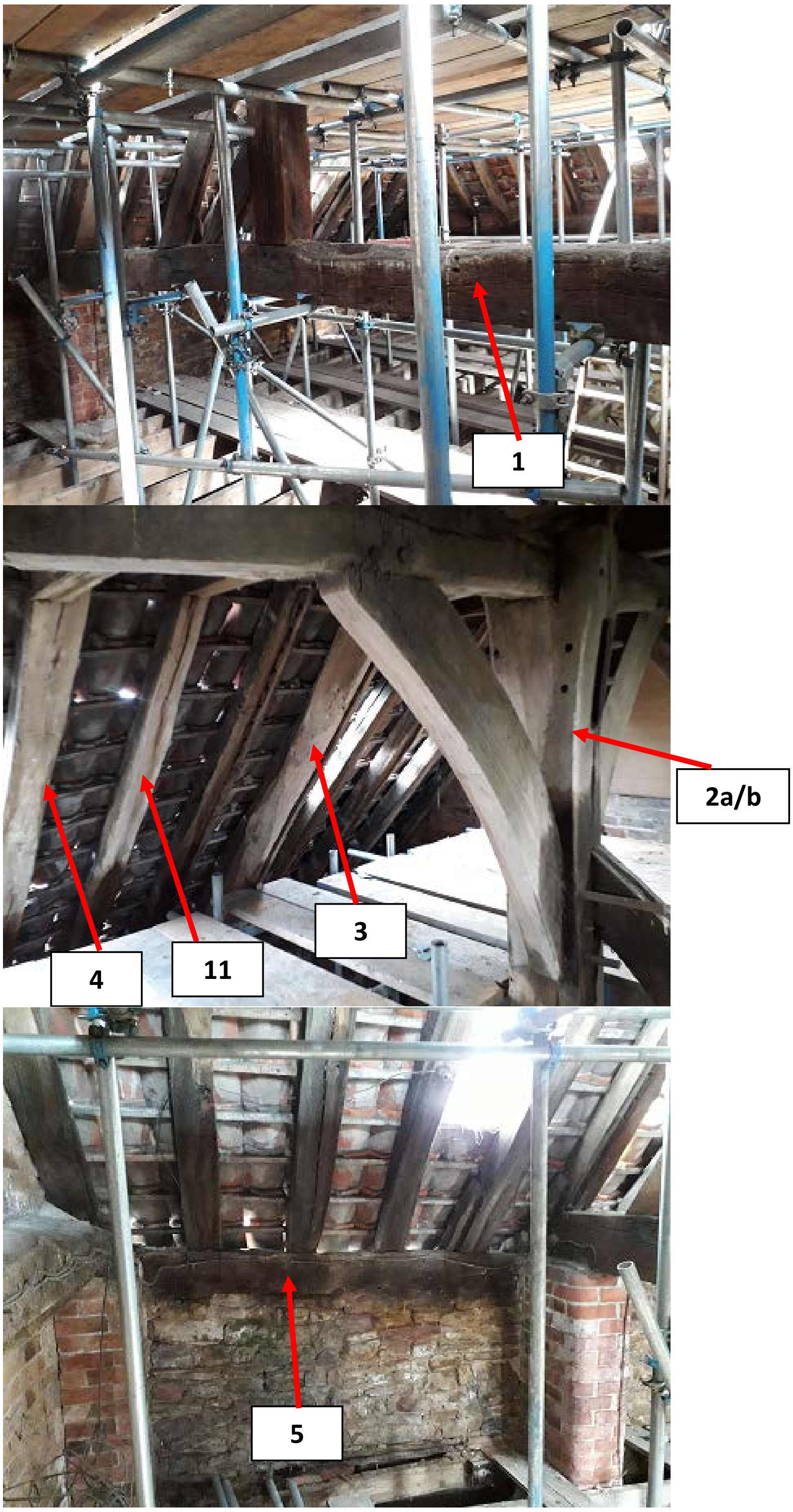


Figure 5a–c: Annotated photographs (a looking north-east, b looking south-west, c looking north) to help identify sampled timbers (photographs Robert Howard)

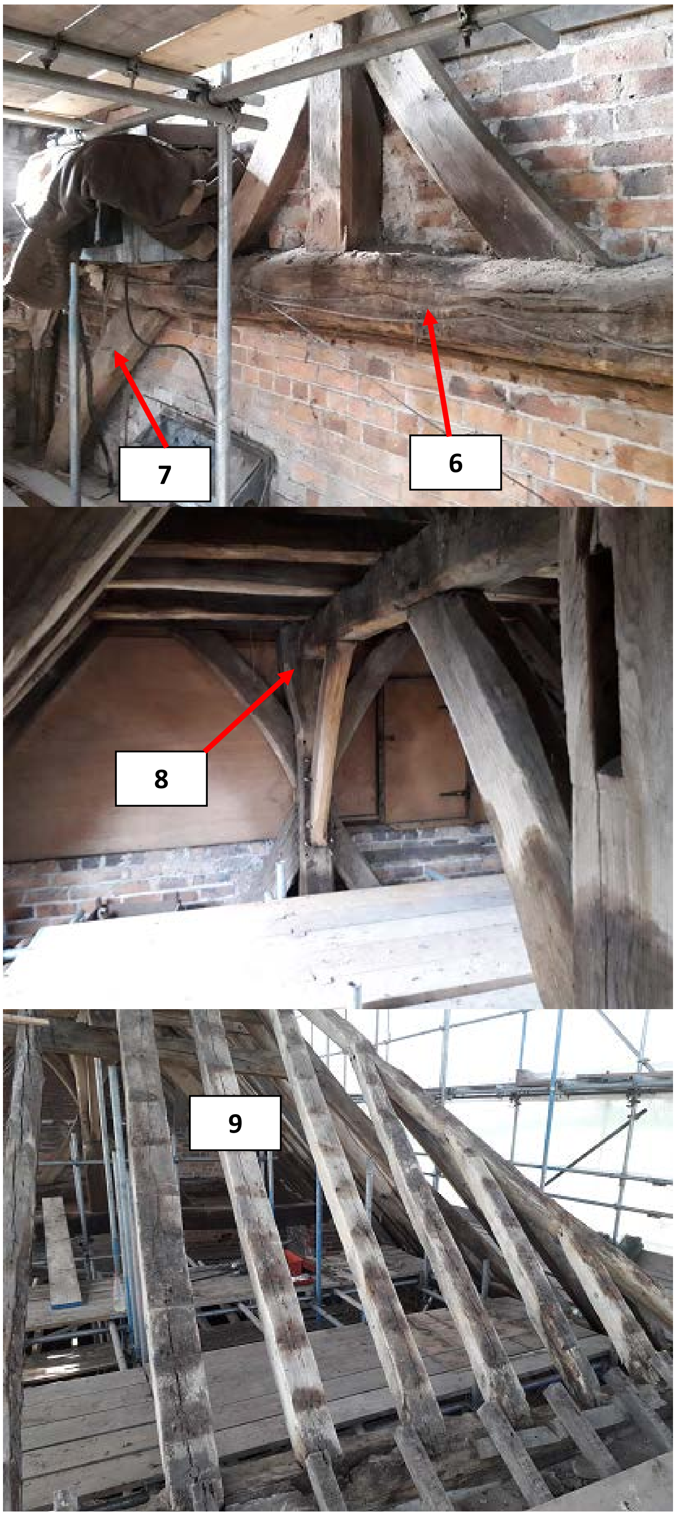
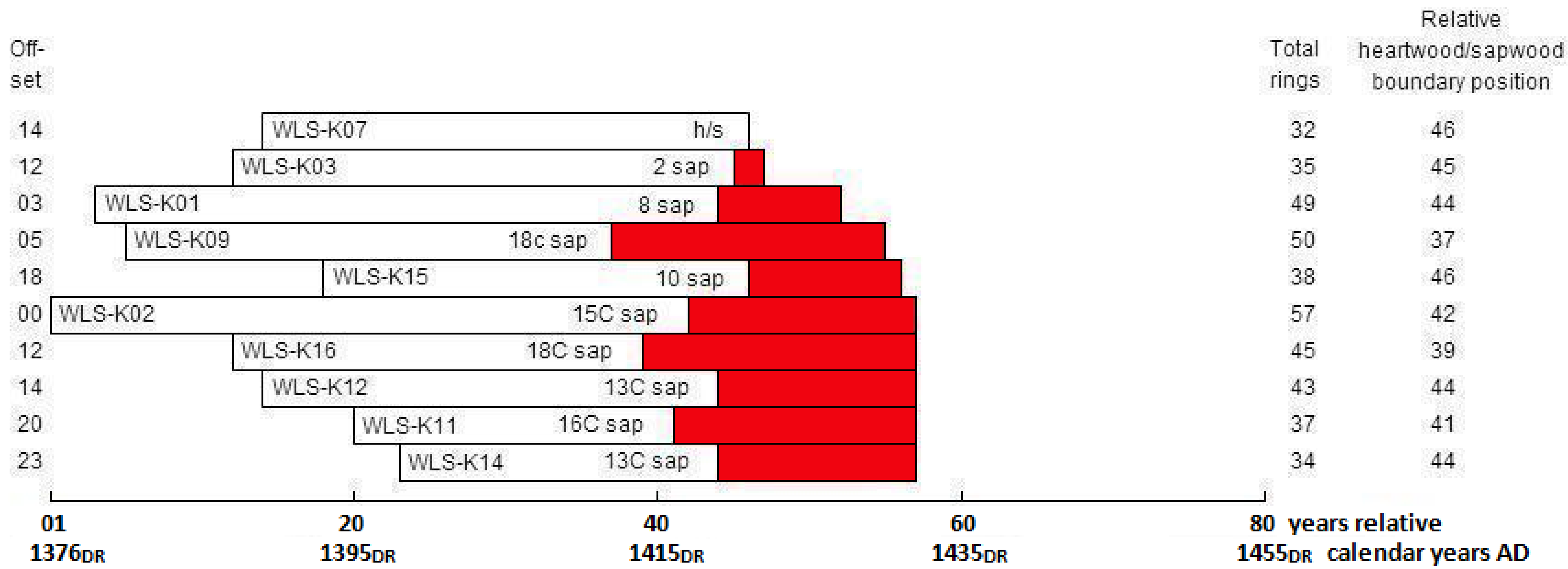


Figure 5d–f: Annotated photographs (d looking south-west, e looking west, f looking north) to help identify sampled timbers (photographs Robert Howard)

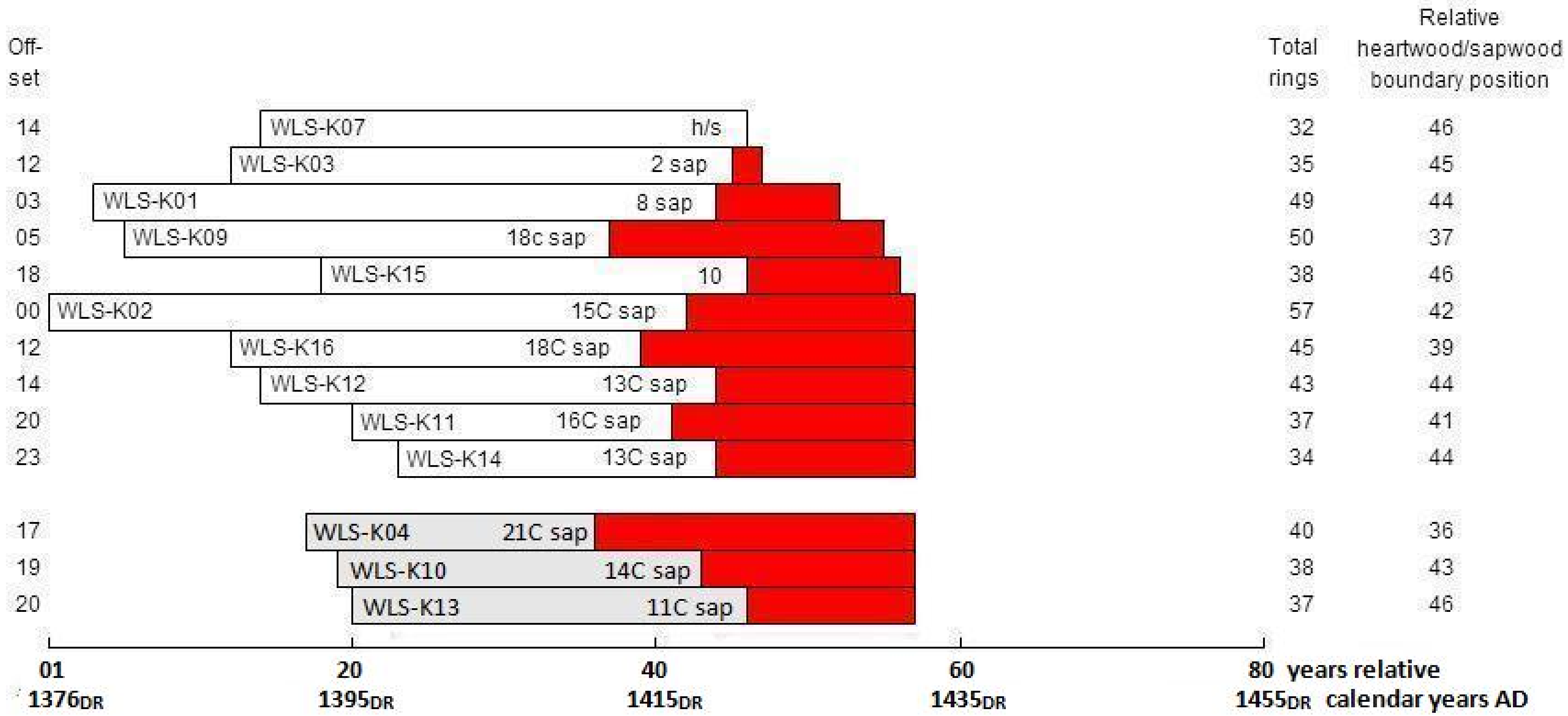
Figure 5g–i: Annotated photographs (g looking north-east, h looking east, i looking west) to help identify sampled timbers (photographs Robert Howard)

Figure 5j: Annotated photograph (looking east) to help identify sampled timbers (photograph Robert Howard)



h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample
c = near-complete sapwood is retained on the sample

Figure 6a: Bar diagram of the samples in site chronology WLSKSQ01A: white bars, heartwood (secure statistical cross-matching); red bars, sapwood



h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample
c = near-complete sapwood is retained on the sample

Figure 6b: Bar diagram of the samples in site chronology WLSKSQ01B: white bars, heartwood (secure statistical cross-matching); light grey bars, heartwood (tentative statistical cross-matching); red bars, sapwood

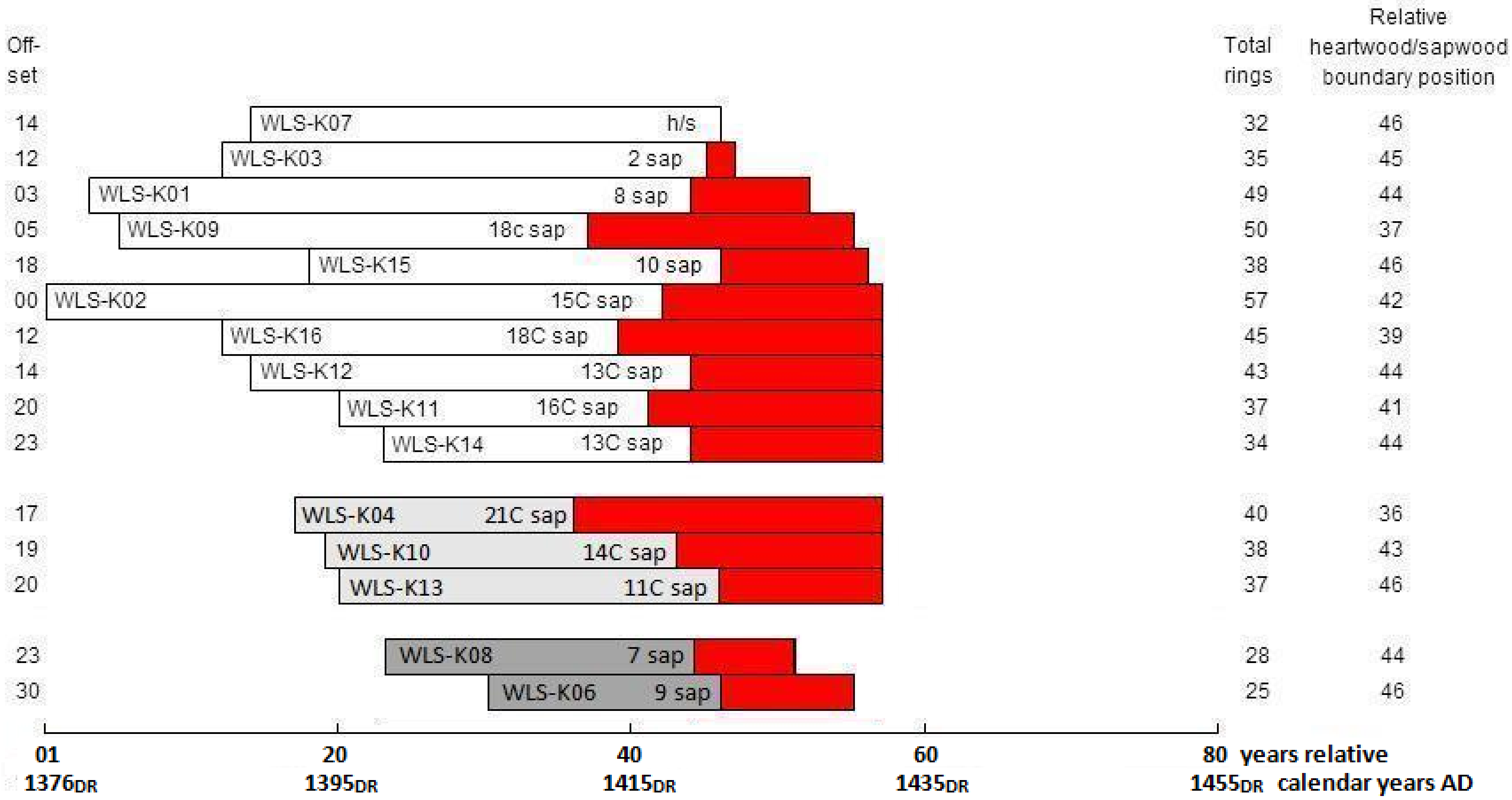


Figure 6c: Bar diagram of the samples in site chronology WLSKSQ01C: white bars, heartwood (secure statistical cross-matching); light grey bars, heartwood (tentative statistical cross-matching); dark grey bars, heartwood (tentative visual cross-matching); red bars, sapwood

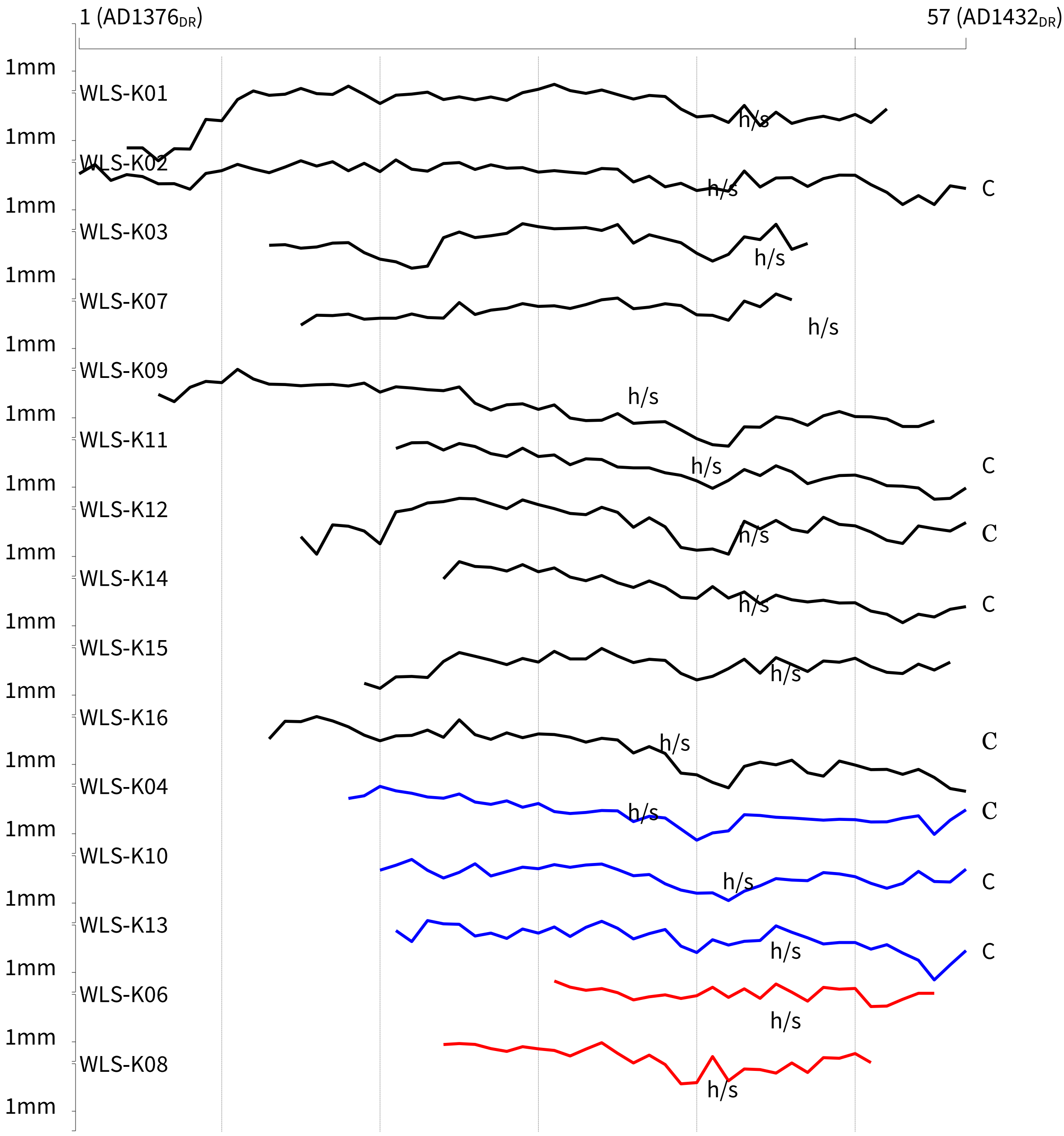


Figure 7: plots of ring-widths (in mm on a logarithmic scale) of the 15 measured ring-width series from the hall roof: black (secure statistical cross-matching); blue (tentative statistical cross-matching); red (tentative visual cross-matching). C = complete sapwood, the last measured ring date is the felling date of the timber represented; h/s = indicates the location of the heartwood/sapwood boundary

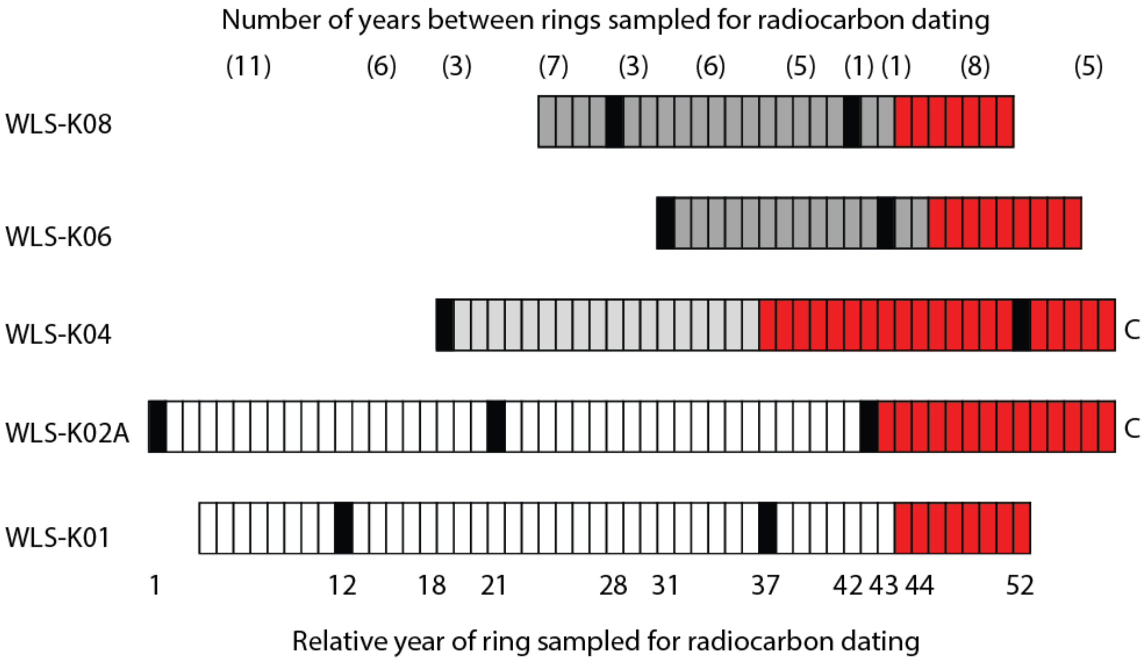


Figure 8: Schematic illustration of samples WLS-K01, WLS-K02A, WLS-K04, WLS-K06, and WLS-K08 to locate the single-ring sub-samples submitted for radiocarbon dating (C = complete sapwood; white bars, heartwood (secure statistical cross-matching); light grey bars, heartwood (tentative statistical cross-matching); dark grey bars, heartwood (tentative visual cross-matching); red bars, sapwood)

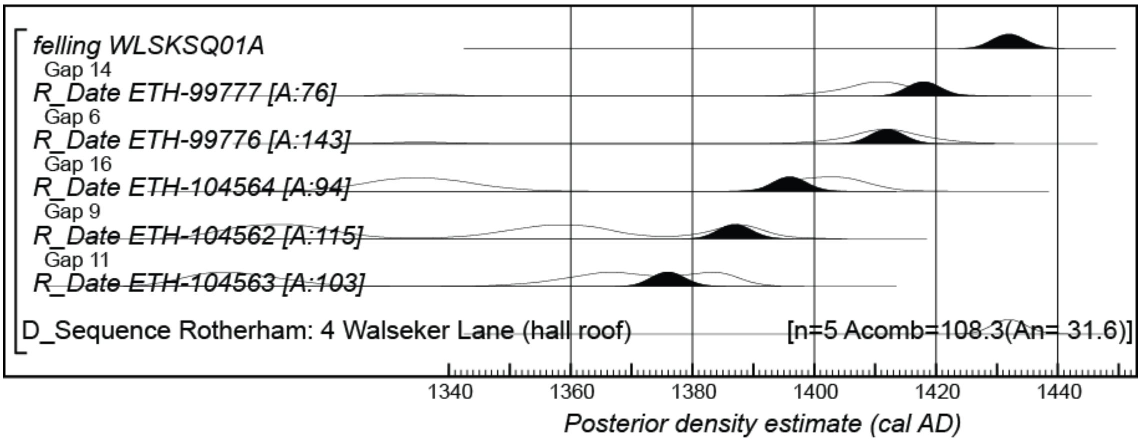


Figure 9: Probability distributions of dates from WLSKSQ01A. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

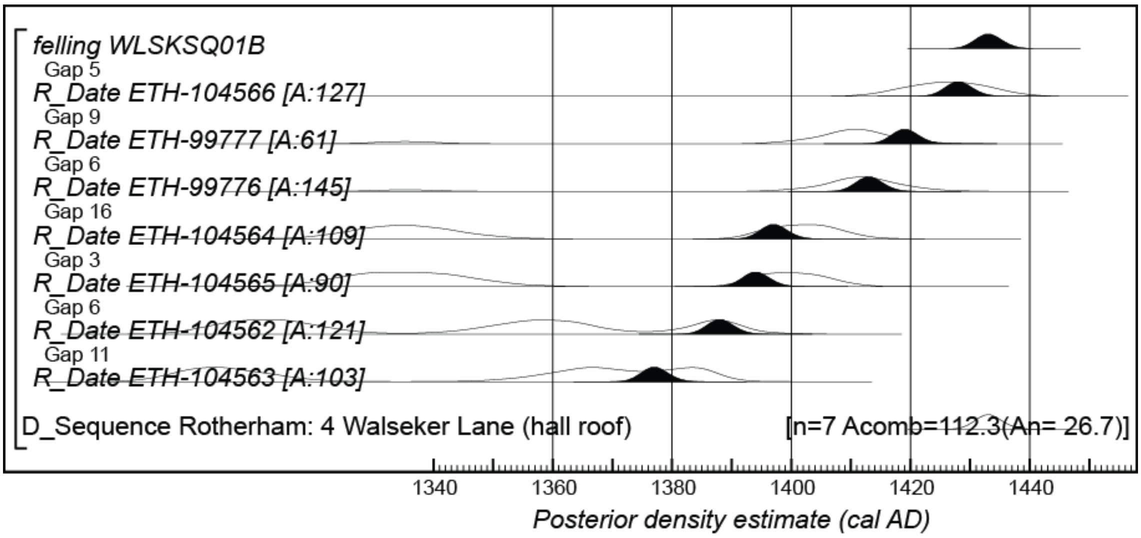


Figure 10: Probability distributions of dates from WLSKSQ01B. The format is identical to that of Figure 9. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

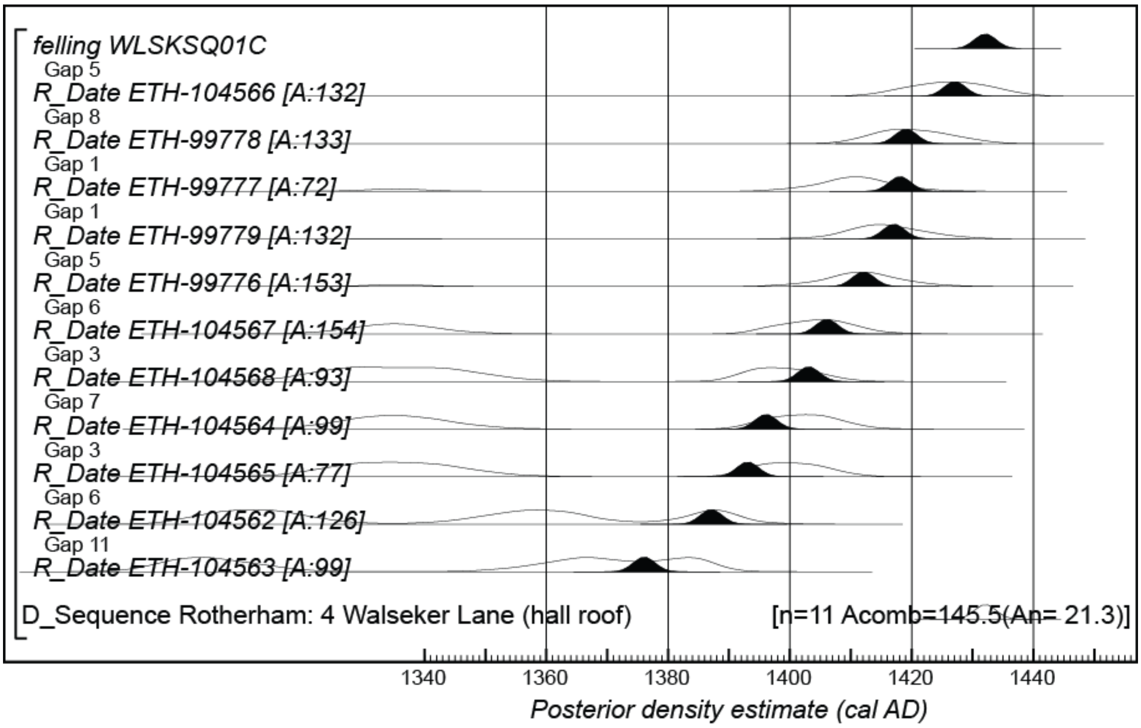


Figure 11: Probability distributions of dates from WLSKSQ01C. The format is identical to that of Figure 9. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

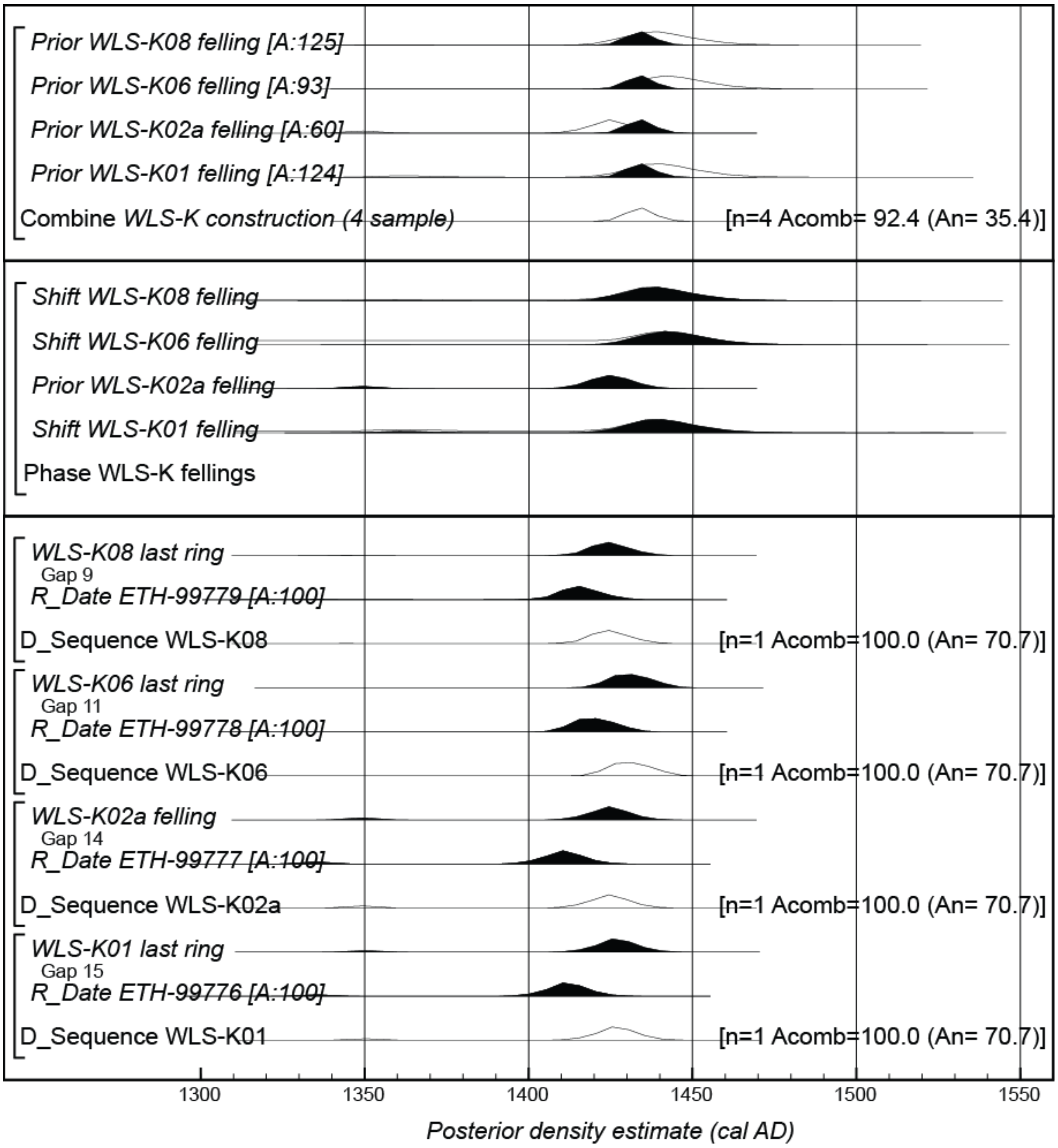


Figure 12: Probability distributions of the initial series of radiocarbon dates from timbers WLS-K01, WLS-K02A, WLS-K06, and WLS-K08. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'WLS-K construction' is the estimated date when the timbers used in the roof of 4 Walseker Lane were felled. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

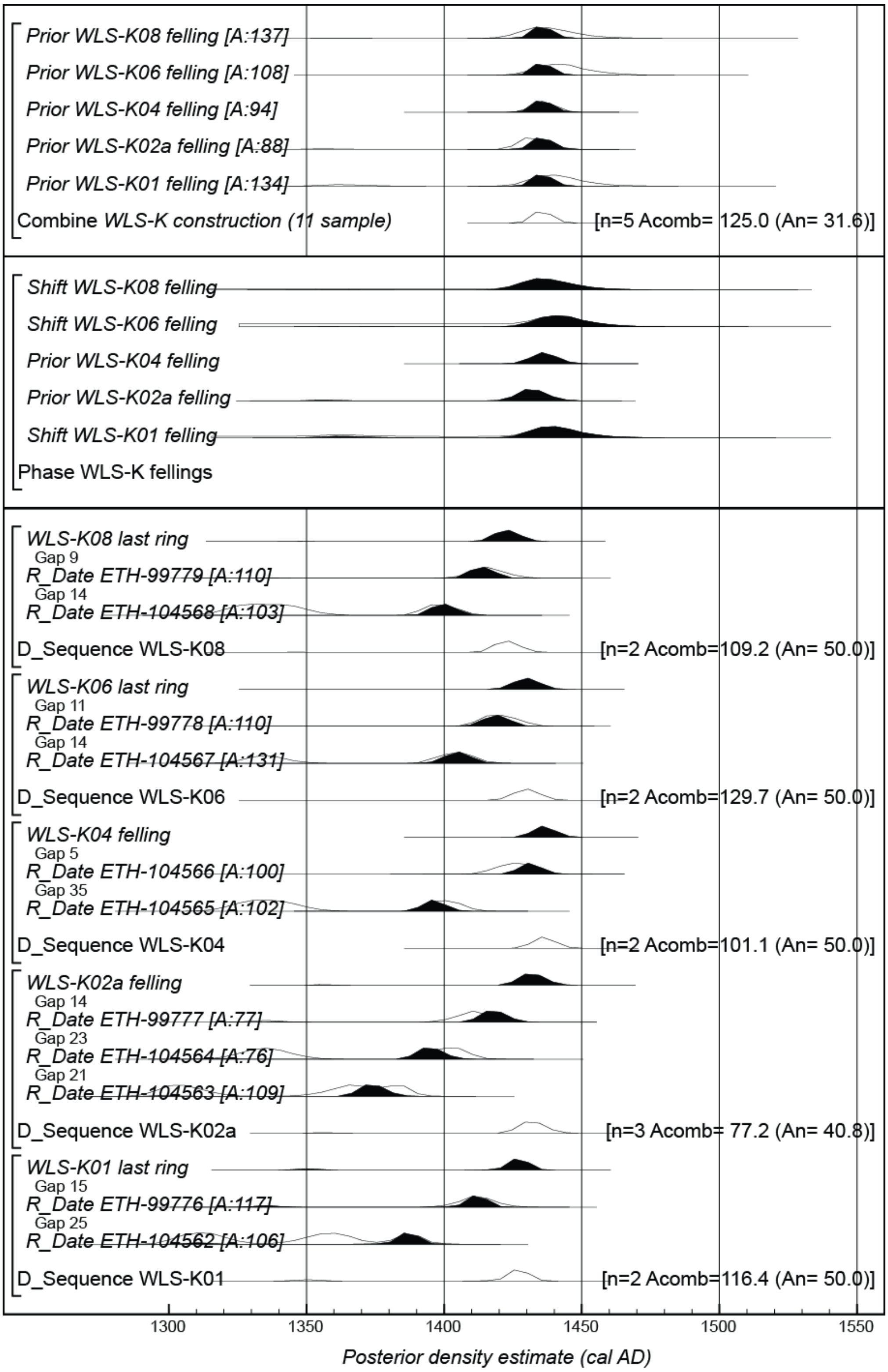


Figure 13: Probability distributions of dates from timbers WLS-K01, WLS-K02A, WLS-K04, WLS-K06, and WLS-K08. The format is identical to that of Figure 12. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

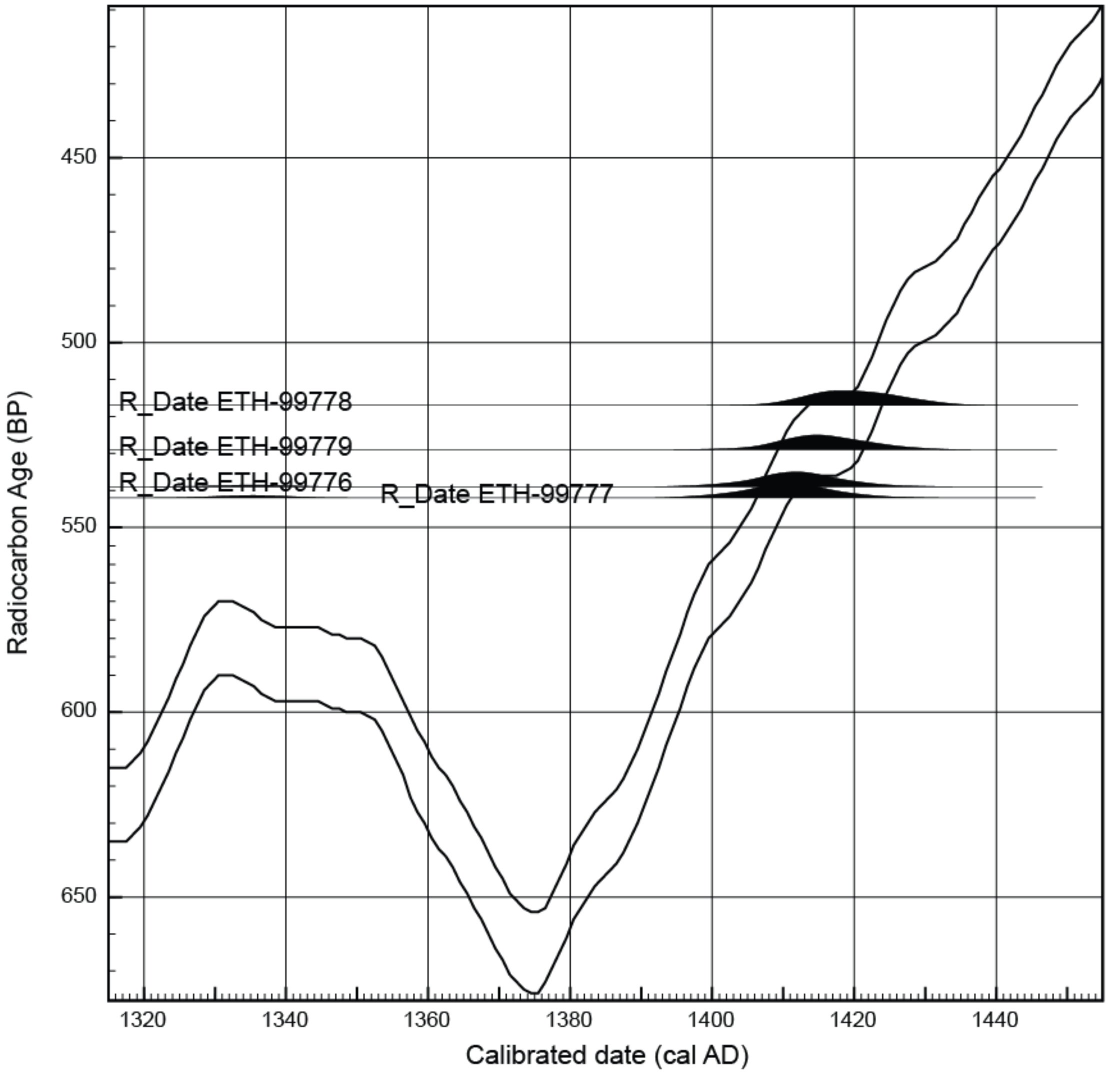


Figure 14: The initial series of radiocarbon dates from timbers WLS-K01, WLS-K02A, WLS-K06, calibrated using the probability method (Stuiver and Reimer 1993), and plotted on the IntCal20 calibration curve (Reimer et al *2020)*

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

WLS-K01A 49
77 76 51 78 75 204 208 385 512 452 462 561 485 503 585 486 337 442 470 499
383 416 375 437 378 490 534 640 529 465 523 462 389 446 498 265 231 233 181 306
165 256 168 210 221 205 237 165 287

WLS-K01B 49
80 81 52 75 75 199 176 394 522 444 466 566 461 418 630 435 346 457 464 494
395 434 395 409 378 489 558 651 517 490 545 456 403 446 365 302 207 223 184 334
162 257 184 198 225 191 237 197 283

WLS-K02Ai 54
342 313 296 296 236 334 384 484 432 361 408 478 410 475 395 450 365 510 368 381
452 483 368 420 381 400 357 370 343 352 400 365 242 319 181 248 206 256 189 373
244 275 278 234 274 275 289 220 171 121 156 120 231 210

WLS-K02Aii 54
339 320 301 283 234 338 394 498 409 364 412 476 388 497 396 463 369 510 371 364
450 496 357 409 392 404 360 365 345 328 397 347 261 297 194 233 198 234 184 378
225 281 290 228 267 276 300 207 174 121 154 126 228 199

WLS-K02Bi 57
333 456 279 328 306 167 184 160 335 338 416 343 328 425 547 453 502 332 482 345
534 401 342 488 473 407 470 396 415 349 364 343 342 389 412 250 307 245 238 184
147 186 359 192 292 302 203 290 351 356 236 188 117 168 112 212 200

WLS-K02Bii 57
329 444 251 275 268 187 192 165 330 350 411 371 321 407 541 455 500 339 478 343
539 400 357 473 467 398 478 423 404 332 368 361 314 391 414 255 300 239 245 170
190 181 338 194 300 297 205 294 362 318 259 181 118 164 120 215 203

WLS-K03A 35
309 318 280 298 329 286 236 194 164 130 142 394 476 400 421 460 634 576 530 540
559 500 611 328 435 385 328 227 189 223 412 375 630 270 328

WLS-K03B 35
305 311 278 285 331 387 247 195 192 159 166 396 479 397 424 454 625 565 535 543
551 507 614 335 436 377 340 245 175 234 403 367 607 267 325

WLS-K04A 40
325 350 477 406 385 333 334 369 285 264 297 234 282 210 189 200 224 210 144 178
171 114 82 103 105 189 183 175 161 162 156 157 160 146 159 170 173 100 153 220

WLS-K04B 40
322 356 490 429 386 348 319 382 289 268 302 250 265 208 204 206 211 218 157 181
167 121 81 103 116 187 186 172 177 164 159 168 160 150 139 167 192 96 162 224

WLS-K06A 25
749 623 533 610 503 423 449 478 426 466 617 436 574 417 662 526 385 579 575 581
324 331 407 492 506

WLS-K06B 25
760 606 573 560 521 381 443 472 418 459 610 439 586 429 702 514 387 640 573 593
323 326 415 511 498

WLS-K07A 32
214 310 297 315 262 268 269 310 275 280 475 303 362 382 438 410 425 372 430 508
521 389 396 447 414 304 284 259 481 401 609 507

WLS-K07B 32
220 293 300 311 267 279 278 318 284 268 444 315 352 377 448 399 400 382 428 501
545 359 395 435 417 307 317 252 482 398 614 501

WLS-K08A 28
916 944 911 801 731 856 792 766 622 771 981 676 490 651 478 240 260 609 265 407
392 356 500 368 596 587 676 503

WLS-K08B 28
915 940 921 791 725 842 792 737 629 798 957 686 501 634 465 256 256 618 283 403
404 353 490 353 587 571 681 502

WLS-K09A 50
219 172 272 334 325 502 362 308 305 289 298 302 285 311 229 288 271 256 242 282
164 130 152 161 129 158 104 84 92 117 84 84 90 62 51 39 42 76 75 112
90 78 104 128 103 103 100 78 77 89

WLS-K09B 50
216 171 279 336 318 498 364 303 298 291 301 304 289 323 239 271 268 253 250 275
160 128 157 157 135 148 95 98 93 114 82 88 87 73 49 43 37 73 72 95
100 79 110 118 106 104 92 73 73 92

WLS-K10A 38
308 357 391 321 249 297 376 248 282 341 318 357 309 362 366 309 251 257 189 156
139 136 117 151 173 232 215 223 273 284 257 180 168 184 285 207 203 300

WLS-K10B 38
288 348 463 273 212 259 362 244 289 319 311 361 350 348 368 301 245 262 192 153
140 146 102 147 184 220 216 200 279 245 226 207 160 200 289 203 201 316

WLS-K11A 37
355 434 437 343 428 384 303 273 363 278 282 210 253 243 198 188 189 164 150 121
100 117 185 152 192 165 104 134 155 146 126 106 96 104 59 71 94

WLS-K11B 37
367 439 441 343 424 388 305 278 365 275 300 210 260 257 192 192 192 159 146 126
93 134 174 142 214 168 120 128 139 153 135 104 111 90 76 68 100

WLS-K12A 43
186 109 288 271 235 152 438 476 594 621 689 669 578 492 646 553 489 410 410 510
429 259 370 264 127 126 131 103 323 240 331 242 226 351 281 270 230 166 158 272
259 233 309

WLS-K12B 43
200 108 282 275 232 153 441 485 589 618 692 687 577 485 661 565 492 426 393 515

438 268 353 273 144 121 125 114 321 260 331 250 221 384 300 283 221 176 150 278
243 233 308

WLS-K13A 37
400 266 561 519 484 381 370 306 431 366 449 335 443 553 433 314 365 426 243 192
296 250 279 293 473 373 315 254 262 263 228 255 185 150 74 137 206

WLS-K13B 37
405 293 558 488 507 291 368 314 417 375 457 325 452 539 435 296 364 406 238 196
296 248 284 287 468 387 317 262 279 277 207 247 197 150 82 122 208

WLS-K14A 34
475 830 721 697 615 761 604 686 508 458 535 415 364 450 363 256 243 360 245 307
209 284 236 230 226 218 218 160 148 101 148 137 168 187

WLS-K14B 34
473 852 712 699 619 759 600 680 503 436 528 421 350 439 360 259 254 374 258 310
207 273 239 213 242 209 212 167 146 121 146 132 178 192

WLS-K15A 38
147 128 184 187 179 309 426 368 321 285 356 293 412 342 328 475 369 284 340 313
206 160 178 242 335 194 370 265 236 308 304 335 256 214 210 268 231 296

WLS-K15B 38
149 123 183 185 180 304 398 358 318 268 321 307 445 323 339 465 364 306 318 321
206 172 197 240 325 220 327 289 203 315 292 345 260 212 201 293 229 303

WLS-K16A 45
237 424 424 491 419 351 265 216 258 260 316 245 442 271 232 290 242 274 266 252
213 237 231 140 181 145 78 73 50 48 89 110 98 113 72 73 107 101 92 82
67 90 67 45 41

WLS-K16B 45
232 417 406 491 430 347 266 223 258 267 310 248 438 268 228 282 245 278 275 243
207 239 221 152 181 143 73 70 60 45 100 106 101 117 80 63 117 95 76 89
78 81 64 46 41

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 Nottingham Tree-ring Dating 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 1998). 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 Figure 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

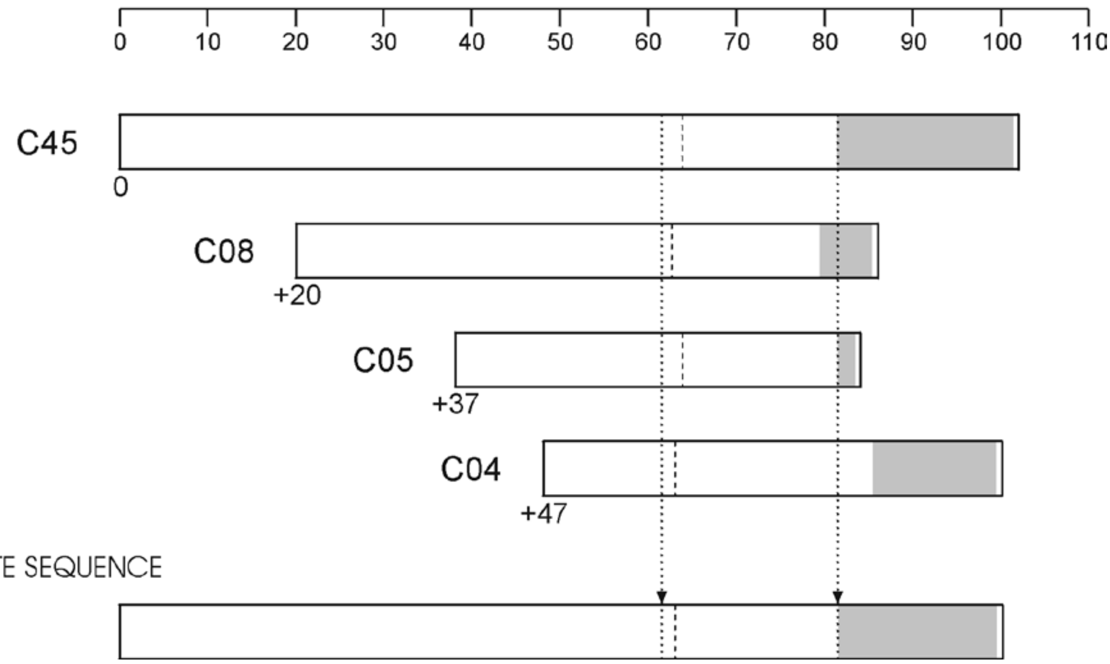


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

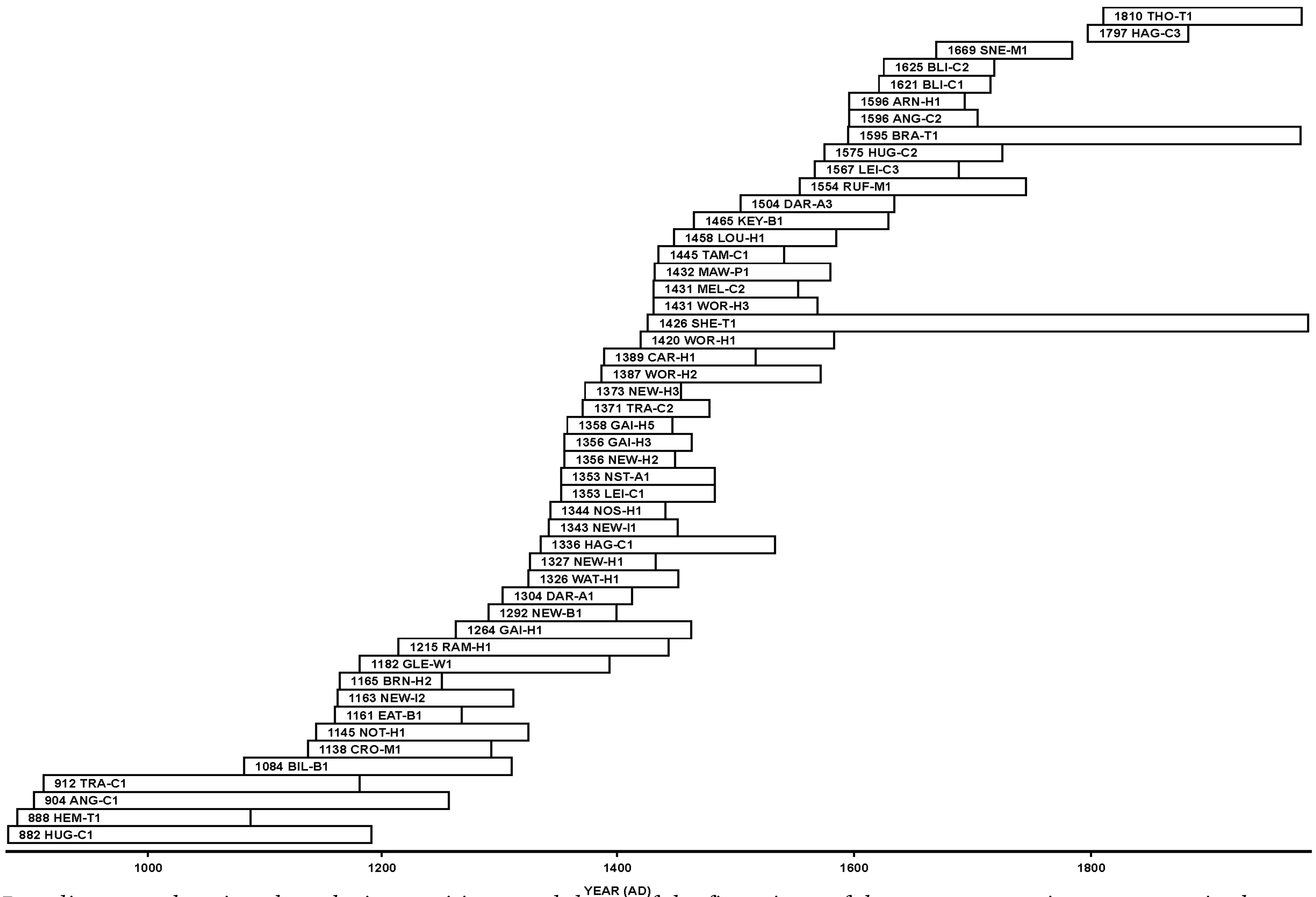
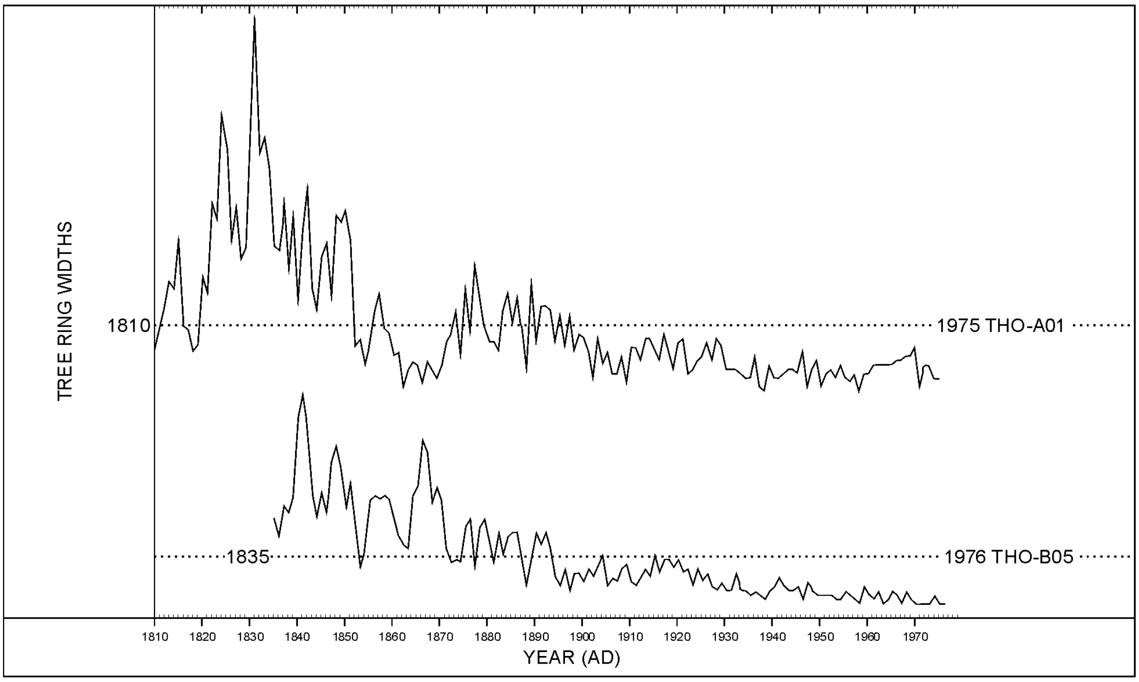


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

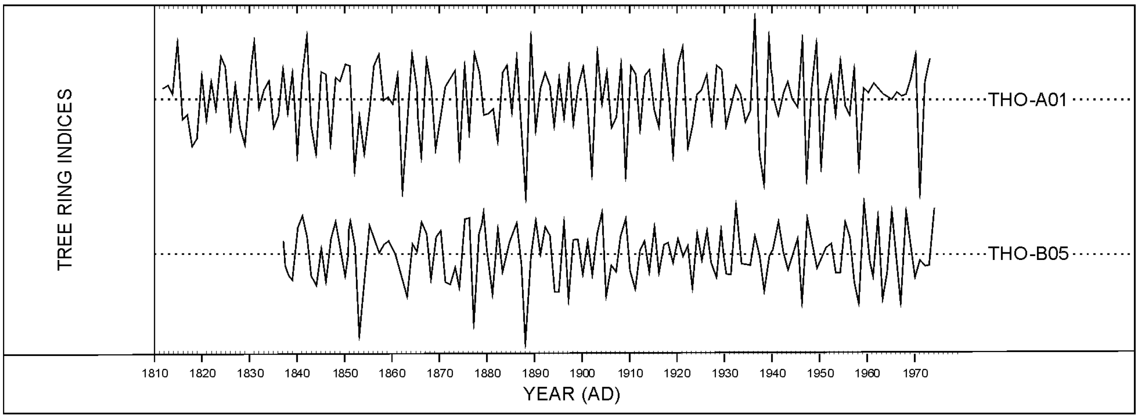


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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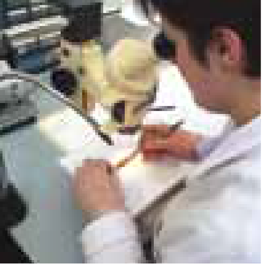
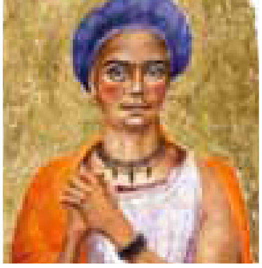


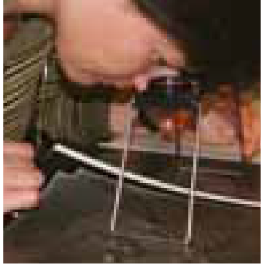


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