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Higham House
48 Higham Hall Road
Higham
Lancashire

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

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Michael Dee, and Sanne Palstra

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Front Cover: Higham House in Lancashire. Photo Robert Howard

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SUMMARY
Dendrochronological analysis was undertaken on samples from seven oak timbers in the roof of this building. This analysis produced a single site master chronology, comprising four samples (HIHHSQ01), which is 107 rings long overall. Despite being compared to an extensive corpus of reference chronologies, no satisfactory consistent cross-matching could be identified. However the relative dating of the samples in the site master chronology indicates that the two principal rafters are coeval, as are the two purlins, but that these two pairs of timbers, although broadly coeval, are likely to have been derived from trees felled some years apart. A further single sample from the tiebeam was dated by ring-width dendrochronology individually with its extant final ring, the heartwood/sapwood boundary ring, dating to AD 1604.

The dating by ring-width dendrochronology of only a single timber led to the decision to obtain dating evidence for the site master chronology through radiocarbon dating. Radiocarbon measurements were obtained on six single-year samples from one of the four component cores, HIH-H04. Wiggle-matching of these results suggests that the final ring of HIHHSQ01 formed in *cal AD 1607–1631 (95% probability)*, probably in *cal AD 1613–1626 (68% probability)*.

Interpretation of the range of relative dates of the heartwood/sapwood transitions of all five dated timbers in the roof suggests at least two episodes of felling are represented, with construction probably occurring in the AD 1620s or AD 1630s (if all timbers are assumed to be associated with the primary construction of Higham House).

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INTRODUCTION

Higham House stands close to the centre of the village of Higham (Fig 1) and although the building is currently unlisted, it is believed that it is probably of late sixteenth-century date, this dating being at least in part based on the stylistic evidence of two plaster friezes in the house (Fig 2a–b). The dating of these features, however, is problematic.

While the lower body of the house does not retain any timbers, the roof comprises a single principal-rafter truss with tiebeam, set centrally between the two gable-end walls. The truss supports a single purlin to each pitch of the roof, these in turn supporting a ridge beam and a series of common rafters.

SAMPLING

The house was being considered for possible listing. However, because the late sixteenth-century date is based on some unusual plaster friezes, which are acknowledged to be very difficult to date stylistically, a dendrochronological survey was requested by Crispin Edwards, Historic England Listing Adviser. It was hoped that this would provide independent dating evidence to corroborate the date in order to inform assessment with respect to possible designation.

Thus, from of the modest number of timbers available, a total of seven samples was obtained by coring. Each sample was given the code HIH-H (for 'Higham House) and numbered 01–07 (Table 1). All sampled timbers were of oak (*Quercus* spp) and their locations are illustrated in Figures 3a–c.

TREE-RING ANALYSIS AND RESULTS

Each of the seven samples obtained from the roof timbers at Higham House was prepared by sanding and polishing. At this stage it was seen that the sample from the ridge beam had too few rings for ring-width analysis. The remaining six samples were measured, the ring-width data being given at the end of this report. The six measured series were compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of a single group comprising four cross-matching samples at a minimum *t*-value of 4.7.

The four cross-matching samples were combined at their indicated offset positions to form HIHHSQ01, this site chronology having an overall length of 107 rings (Fig 4). HIHHSQ01 was then compared to an extensive corpus of reference chronologies for oak, but there was no consistent, reliable, cross-matching at any position, and the four component samples must, therefore, remain undated by ring-width dendrochronology.

The two remaining ungrouped samples were then compared individually with the oak reference chronologies, this indicating consistent cross-dating for sample HIH-H01, the sample having a first ring date of AD 1514 and a last ring date of AD 1604 (Table 2). The other ungrouped sample remains undated.

RADIOCARBON DATING

Following the failure of the ring-width dendrochronology to provide secure calendar dating for site master chronology, HIHHSQ01, sample HIH-H04 was selected for radiocarbon dating and wiggle-matching as this had the least number of very narrow rings that would be impossible to dissect precisely for radiocarbon dating of the four samples in the master chronology (Table 1; Figs 4–6).

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).

Five radiocarbon measurements have been obtained from single annual tree-rings from timber HIH-H04 (Table 3). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was rechecked against the ring-width data. Then each annual growth ring was split from the rest of the core 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 Centre for Isotope Research, University of Groningen, the Netherlands in 2019. Each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee *et al* 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma *et al* 1996; Aerts-Bijma *et al* 1997). The graphite was then pressed into aluminium cathodes and dated by AMS (Synal *et al* 2007; Salehpour *et al* 2016). Data reduction was undertaken as described by Wacker *et al* (2010). The facility maintains a continual programme of quality assurance procedures (Aerts-Bijma *et al* forthcoming), 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). The quoted $\delta^{13}C$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

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, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 7.

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 7 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 7 (bottom) illustrates the chronological model for HIHHSQ01. This model incorporates the gaps between each radiocarbon dated annual ring known from tree-ring series (eg that the carbon in ring 3 of the tree-ring series for HIH-H04 (GrM-19897) was laid down 23 years before the carbon in ring 26 of the tree-ring series (GrM-19899; Fig 6)), along with the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020). The calibrated radiocarbon dates are shown in outline in this model, with the posterior distribution for each dated ring in black. From the offsets between the ring-width series in HIHHSQ01 (Fig 4), we can also estimate the dates of the heartwood/sapwood transitions in each of these samples (shown in blue), the last measured ring (where this is different, shown in yellow), and the felling date (where complete sapwood is retained, shown in red).

The model has good overall agreement (Acomb: 129.1, An: 31.6, n: 5), and all five radiocarbon dates have good individual agreement (A: > 60.0). It suggests that the final ring of HIHHSQ01 formed in *cal AD 1607–1631 (95% probability; HIH-03 felling*; Fig 7 (lower)), probably in *cal AD 1613–1626 (68% probability)*. The estimated dates for the heartwood/sapwood boundaries and, where this is different, for the formation of the last measured rings on these four samples are given in Table 4.

INTERPRETATION

Tree-ring analysis and radiocarbon dating in combination have dated five timbers the roof of Higham House. Ring series HIH-H01 has been dated by ring-width dendrochronology, with a date of AD 1604 for the last measured ring which marks the heartwood/sapwood boundary). The ring series from four samples (HIH-H02 - HIH-H05) were combined to form the site master chronology, HIHHSQ01, which has been dated by radiocarbon wiggle-matching (Fig 7 (bottom)). HIH-H02 retains the heartwood/sapwood boundary and 10 rings of (incomplete) sapwood, HIH-H03 retains complete sapwood, and HIH-H04 and HIH-H05 end at their heartwood/sapwood transitions (Table 1).

The felling date of all five of the dated timbers has been estimated independently by adding an empirical probability distribution of the expected number of sapwood rings in ancient oak timbers from England (Arnold *et al* 2019, fig 9) to the estimated dates of the last rings of the respective timbers. These distributions are shown in red in Figure 7 (middle), and their date ranges are given in Table 4. For HIH-H01, the expected number of sapwood rings (9–42 at 95% probability, or 12–28 at 68% probability) is simply added to the date of the heartwood/sapwood boundary ring provided by the ring-width dendrochronology (AD 1604). This date range is given in normal type in Table 4. For HIH-H04 and HIH-H05, we employ the same sapwood estimate, but account for the uncertainty in the estimated dates of the heartwood/sapwood boundaries of these timbers inherited from the radiocarbon wiggle-matching. These date ranges are consequently given in italics in Table 4. For HIH-H02, we apply the probability distribution for the expected number of sapwood rings truncated to allow for the surviving 10 sapwood rings (Bayliss and Tyers 2004, 960–1), to the estimated date for the heartwood/sapwood transition of this timber provided by the radiocarbon wiggle-matching. HIH-H03 requires no sapwood estimate as it retains complete sapwood, so the estimate date for the last measured ring of this timber produced by the radiocarbon wiggle-matching is the same as the estimated date of felling for this timber.

The variation in the position of the heartwood/sapwood boundaries on the five dated samples (Fig 4; Fig 7 (middle)), however, is not consistent with them having been produced from a single contemporaneous felling event. Sample HIH-H03 in site sequence HIHHSQ01, for example, retains complete sapwood (ie, it has the last ring produced by the tree it represents before it was felled) at relative year 107 of the site chronology HIHHSQ01. The relative position of the heartwood/sapwood boundary on sample HIH-H04 (relative year 102 of the site chronology HIHHSQ01) is such that, were it to have been felled at the same time, it would have had only five sapwood rings. This is highly unlikely as, of the 4960 historic oak timbers complete to bark edge that make up an empirical distribution of the number of sapwood rings present on English oak (Arnold *et al* 2019, fig 9), none has as few as five sapwood rings. The four timbers represented in the site master chronology, HIHHSQ01, therefore appear to have come from two episodes of felling: an earlier episode represented by the trees used for the principal rafters (HIH-H02 and HIH-H03), and a slightly later episode represented by the purlins (HIH-H04 and HIH-05). In comparison with the estimate dates of the heartwood/sapwood boundaries for the four timbers in the site master chronology (Table 4), the sample from the tiebeam (HIH-H01), which has a heartwood/sapwood transition dated by ring-width dendrochronology to AD 1604, is more likely to have been part of the later felling episode.

There is no obvious evidence that any of the timbers in the roof were reused or inserted – the joints all fit together snugly and there are no redundant peg holes or the like. This therefore suggests that, it is more likely than not that the trees used for the principal rafters were felled first, with those used for the purlins and tiebeam being felled a little later. The date of construction of the roof is probably best estimated by the later felling episode, with the principal rafters reflecting the use of stockpiled timber or deadwood.

The dates of the two postulated felling episodes are then estimated by combining first the estimated felling dates of those timbers thought to have been felled shortly before the construction of the roof (Fig 7 (upper); *construction)*, and second the estimated felling dates of those timbers thought to have been felled slightly earlier (Fig 7 (upper); *stockpiled)*. These distributions for the dates of the two felling episodes of the timbers used in the roof are shown in green. This analysis suggests that the roof is perhaps most likely to have been constructed in *cal AD 1620–1642 (95% probability; construction;* Fig 7 (upper)), probably in *cal AD 1624–1636 (68% probability)*, incorporating some timbers felled in *cal AD 1607–1628 (95% probability; stockpiled*; Fig. 7 (upper)), probably in *cal AD 1612–1623 (68% probability)*.

Comparison of the probability distributions of these dates, suggests that the timbers used as the principal rafters were felled *–2–28 years (95% probability; duration stockpiling*; Fig. 8), probably *5–21 years (68% probability)* before the timbers used for the purlins and tiebeam. The negative part of the range reflects the very small chance (*4% probability*) that the principal rafters were actually felled after the other dated timbers. Evidence of stockpiling of this duration is unusual as, with the exception of reused timbers, in most historical periods construction took place within a very few years of felling (Miles 2006).

DISCUSSION AND CONCLUSIONS

This analysis has indicated that the five dated roof timbers most likely represent two episodes of felling. The principal rafters appear to have been felled in *cal AD 1607–1628 (95% probability; stockpiled*; Fig 9), and subsequently stockpiled prior to their use in the construction of the roof some years later along with timbers felled in *cal AD 1620–1642 (95% probability; construction;* Fig 9). Thus based on the interpretation that the later timbers are primary to the construction of the roof, it appears that this roof was probably constructed in the AD 1620s or AD 1630s.

The ability to date only one timber by ring-width dendrochronology from the samples that could be obtained from Higham House is not surprising. One sample contained insufficient growth rings for measurement, and another only 60 rings. The five longest measured ring series all show the presence of abrupt growth changes (eg Fig 5). Such abrupt growth changes suggest non-climatic influences, possibly through woodland management practices such as pollarding or lopping, which result in an abrupt decrease in growth rate followed by a period of recovery. This has the effect of disturbing the general climatic signal within the ring series and hence hampering the cross-dating process. It also remains a possibility that the trees were sourced from some niche woodland location for which, as yet, there is insufficient local data to create a useable reference pattern, although this seems somewhat less likely. As further samples are obtained from the locality, it may be possible eventually to obtain a precise date for this site master chronology through ring-width dendrochronology and it is of note that the ring-width dated individual series, HIH-H01, shows the highest levels of similarity with reference chronologies from sites further south in the Midlands.

REFERENCES

Aerts-Bijma, ATh, Paul, D, Dee, MW, Palstra, SWL, and Meijer, HAJ, forthcoming An independent assessment of uncertainty for radiocarbon analysis with the new generation high-yield Accelerator Mass Spectrometers, *Radiocarbon*

Aerts-Bijma, A T, Meijer, H, and van der Plicht, J, 1997 AMS sample handling in Groningen, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **123**, 221–5 (https://doi.org/10.1016/S0168-583X(96)00672-6)

Arnold, A J, and Howard, R E, 2003 unpubl St Catherine's Church, Cossall Leicestershire; Tree-ring Analysis of Bell Frame Timbers – Nottingham Tree-ring Dating Laboratory unpubl computer file *NBFISQ02*

Arnold, A J, and Howard, R E 2007 List 184 no 13 – Nottingham Tree-ring Dating Laboratory, *Vernacular Architect,* **38**, 106–14

Arnold, A J, and Howard, R E, 2009 *Bentley Hall, Derby Lane, Hungry Bentley, Derbyshire: tree-ring analysis of timbers,* English Heritage Res Dept Rep Ser, **33/2009**

Arnold, A, and Howard, R E, 2018 unpubl Woodford Old Hall, Old Hall Lane, Woodford, Stockport, Manchester; Tree-ring Analysis of Timbers – Nottingham Tree-ring Dating Laboratory unpubl computer file *WDOHSQ02*

Arnold, A J, Howard, R E, and Litton, C D, 2008 List 197 nos 6, 7, 29 – Nottingham Tree-ring Dating Laboratory, *Vernacular Architect*, **39**, 119–28

Arnold, A J, Howard, R E, and Tyers, C, 2020 *Weston Hall, Main Street, Weston upon Trent, South Derbyshire, Tree-ring Analysis of Oak Timbers,* Historic England Res Rep Ser, **195/2020**

Arnold, A J, Howard, R E, Tyers, C, Tyers, I, Bayliss, A, Bollhalder, B, Hajdas, I, and Wacker, L, 2019 *Auckland Castle, Bishop Auckland, County Durham, Tree-ring Analysis and Radiocarbon Wiggle-matching of* ex situ *Timbers form the West Mural Tower,* Historic England Res Rep Ser, **77/2019**

Bayliss, A, and Tyers, I, 2004 Interpreting radiocarbon dates using evidence from tree rings, *Radiocarbon*, **46**, 957–64 (https://doi.org/10.1017/S0033822200036018)

Bronk Ramsey, C, 2009 Bayesian analysis of radiocarbon dates, *Radiocarbon*, **51**, 37–60 (https://doi.org/10.1017/S0033822200033865)

Bronk Ramsey, C, van der Plicht, J, and Weninger, B 2001 'Wiggle matching' radiocarbon dates, *Radiocarbon*, **43**, 381–9 (https://doi.org/10.1017/S0033822200038248)

Christen, J A, and Litton, C D, 1995 A Bayesian approach to wiggle-matching, *J Archaeol Sci*, **22**, 719–25 (https://doi.org/10.1016/0305-4403(95)90002-0)

Dee, M W, Palstra, S W L, Aerts-Bijma, A T, Bleeker, M O, de Bruin, S, Ghebru, F, Jansen, H G, Kuitems, M, Paul, D, Richie, R R, Spriensma, J J, Scifo, A, von Zonneveld, D, Verstappen-Dumoulin, B M A A, Wietzes-Land, P, and Meijer, H A J, 2020 Radiocarbon dating at Groningen: new and updated chemical pretreatment procedures, *Radiocarbon*, **62**, 63–74 (https://doi.org/10.1017/RDC.2019.101)

Galimberti, M, Bronk Ramsey, C, and Manning, S, 2004 Wiggle-match dating of tree-ring sequences, *Radiocarbon*, **46**, 917–24 (https://doi.org/10.1017/S0033822200035967)

Haddon-Reece, D, Miles, D, Tapper, M C, and Fletcher, J M, 1987 Tree-ring dates from the Ancient Monuments Laboratory: List 22, *Vernacular Architect*, **18**, 54–5

Howard, R E, Laxton, R R, and, C D, 1999 List 96 no 3 – Nottingham University Tree-Ring Dating Laboratory: results, *Vernacular Architect*, **30**, 90–1

Miles, D W H, 2006 Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales, *Vernacular Architecture*, **37**, 84–96

Reimer, P J, Austin, W E N, Bard, E, Bayliss, A, Blackwell, P, Bronk Ramsey, C, Butzin, M, Cheng, H, Edwards, R L, Friedrich, M, Grootes, P M, Guilderson, T P, Hajdas, I, Heaton, T J, Hogg, A G, Hughen, K A, Kromer, B, Manning, S W, Muscheler, R, Palmer, J G, Pearson, C, van der Plicht, J, Reimer, R W, Richards, D A, Scott, E M, Southon, J R, Turney, C S M, Wacker, L, Adolphi, F, Büntgen, U, Capano, M, Fahrni, S, Fogtmann-Schultz, A, Friedrich, R, Kudsk, S, Miyake, F, Olsen, J, Reinig, F, Sakamoto, M, Sookdeo, A, and Talamo, S, 2020 The IntCal20 Northern Hemispheric radiocarbon calibration curve (0–55 kcal BP), *Radiocarbon*, **62** (https://doi.org/10.1017/RDC.2020.41)

Salehpour, M, Håkansson, K, Possnert, G, Wacker, L, and Synal, H-A, 2016 Performance report for the low energy compact accelerator mass spectrometer at Uppsala University, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **371**, 360–4 (https://doi.org/10.1016/j.nimb.2015.10.034)

Scott, E M, Naysmith, P, and Cook, G T, 2017 Should archaeologists care about ^{14}C intercomparisons? Why? A summary report on SIRI, *Radiocarbon*, **59**, 1589–96 (https://doi.org/10.1017/RDC.2017.12)

Stuiver, M, and Polach, H A, 1977 Reporting of ^{14}C data, *Radiocarbon*, **19**, 355–63 (https://doi.org/10.1017/S0033822200003672)

Stuiver, M, and Reimer, P J, 1993 Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program, *Radiocarbon*, **35**, 215–30 (https://doi.org/10.1017/S0033822200013904)

Synal, H A, Stocker, M, and Suter, M, 2007 MICADAS: a new compact radiocarobn AMS system, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **259**, 7–13 (https://doi.org/10.1016/j.nimb.2007.01.138)

Tyers, I, 1999 *Dendrochronological analysis of timbers from Black Ladies, near Brewood, Staffordshire,* ARCUS Rep, **484**

Wacker, L, Christl, M, and Synal, H A, 2010 Bats: A new tool for AMS data reduction, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **268**, 976–9 (https://doi.org/10.1016/j.nimb.2009.10.078)

Wacker, L, Scott, E M, Bayliss, A, Brown, D, Bard, E, Bollhalder, S, Friedrich, M, Capano, M, Cherkinsky, A, Chivall, D, Culleton, B J, Dee, M W, Friedrich, R, Hodgins, G W L, Hogg, A, Kennett, D J, Knowles, T D J, Kuitems, M, Lange, T E, Miyake, F, Nadeau, M-J, Nakamura, T, Naysmith, J P, Olsen, J, Omori, T, Petchey, F, Philippsen, B, Ramsey, C B, Prasad, G V R, Seiler, M, Southon, J, Staff, R, Tuna, T, 2020 Findings from an in-depth annual tree-ring radiocarbon intercomparison, *Radiocarbon*, **62** (https://doi.org/10.1017/RDC.2020.49)

Wijma, S, Aerts, A T, van der Plicht, J, and Zondervan, A, 1996 The Groningen AMS facility, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **113**, 465–9 (https://doi.org/10.1016/0168-583X(95)01420-9)

TABLES

Table 1: Details of tree-ring samples from Higham House, Higham, Lancashire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
HIH-H01	Tiebeam, truss 1	91	h/s	AD 1514	AD 1604	AD 1604
HIH-H02	North principal rafter, truss 1	90	10	1 [SQ01]	80 [SQ01]	90 [SQ01]
HIH-H03	South principal rafter, truss 1	92	27C	16 [SQ01]	80 [SQ01]	107 [SQ01]
HIH-H04	North upper purlin	79	h/s	24 [SQ01]	102 [SQ01]	102 [SQ01]
HIH-H05	South upper purlin	83	h/s	18 [SQ01]	100 [SQ01]	100 [SQ01]
HIH-H06	Ridge beam	nm	---	------	------	------
HIH-H07	North common rafter 3 (from east), bay 2 (west bay)	60	2	------	------	------

h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample
NM = not measured
[SQ01] = relative date span within site master chronology HIHHSQ01

Table 2: Results of the cross-matching of sample HIH-H01 and relevant reference chronologies when the first-ring date is AD 1514 and the last-ring date is AD 1604

Reference chronology	Span of chronology	*t*-value	Reference
Woodford Old Hall, Stockport, Cheshire	AD 1458 – 1606	5.9	Arnold and Howard 2018 unpubl
Weston Hall, Weston on Trent, Derbyshire	AD 1480 – 1628	5.9	Arnold *et al* 2020
Old Hall Cottage, Twyford, Leicestershire	AD 1424 – 1654	5.8	Arnold *et al* 2008
Sinai House, Burton on Trent, Staffordshire (central range)	AD 1529 – 1616	5.3	Howard *et al* 1999
St Catherine's Church bell frame, Cossall, Leicestershire	AD 1461 – 1619	5.2	Arnold and Howard 2003 unpubl
Cheddleton Grange, Cheddleton, Staffordshire	AD 1551 – 1682	5.1	Arnold *et al* 2008
St Stephen's Church, Sneinton, Nottingham	AD 1484 – 1654	5.0	Arnold and Howard 2007
Newington House, Oxfordshire	AD 1540 – 1678	5.0	Haddon-Reece *et al* 1987
Black Ladies, nr Brewood, Staffordshire	AD 1372 – 1671	5.0	Tyers 1999
Bentley Hall, Hungry Bentley. Derbyshire	AD 1444 – 1675	5.0	Arnold and Howard 2009

Table 3: Radiocarbon measurements and associated $\delta^{13}C$ values from HIH-H04

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)
GrM-19897	HIH-H04, ring 3 (*Quercus* sp., heartwood)	293±16	−26.46±0.15
GrM-19899	HIH-H04, ring 26 (*Quercus* sp., heartwood)	312±18	−26.24±0.15
GrM-19900	HIH-H04, ring 60 (*Quercus* sp., heartwood)	355±16	−25.46±0.15
GrM-19901	HIH-H04, ring 68 (*Quercus* sp., heartwood)	378±18	−25.57±0.15
GrM-19926	HIH-H04, ring 77 (*Quercus* sp., heartwood)	371±20	−25.40±0.15

Table 4: Estimated dates for the heartwood/sapwood transitions, last measured rings, and felling of the five timbers from the roof (dates in italics derive from the chronological modelling (Fig 7, bottom); dates in normal type derive independently from ring-width dendrochronology)

Sample number	Sample location	Sapwood rings	Last heartwood ring date (probability)	Last measured ring date (probability)	Estimated felling date (probability)
HIH-H01	Tiebeam, truss 1	h/s	AD 1604	AD 1604	AD 1613–1646 (95%) AD 1616–1632 (68%)
HIH-H02	North principal rafter, truss 1	10	*cal AD 1580–1604 (95%)* *cal AD 1586–1599 (68%)*	*cal AD 1590–1614 (95%)* *cal AD 1596–1609 (68%)*	*cal AD 1596–1636 (95%)* *cal AD 1603–1623 (68%)*
HIH-H03	South principal rafter, truss 1	27C	*cal AD 1580–1604 (95%)* *cal AD 1586–1599 (68%)*	*cal AD 1607–1645 (95%)* *cal AD 1613–1625 (68%)*	*cal AD 1607–1645 (95%)* *cal AD 1613–1625 (68%)*
HIH-H04	North upper purlin	h/s	*cal AD 1602–1626 (95%)* *cal AD 1606–1619 (68%)*		*cal AD 1617–1659 (95%)* *cal AD 1625–1645 (68%)*
HIH-H05	South upper purlin	h/s	*cal AD 1600–1624 (95%)* *cal AD 1606–1619 (68%)*		*cal AD 1615–1657 (95%)* *cal AD 1623–1643 (68%)*

FIGURES

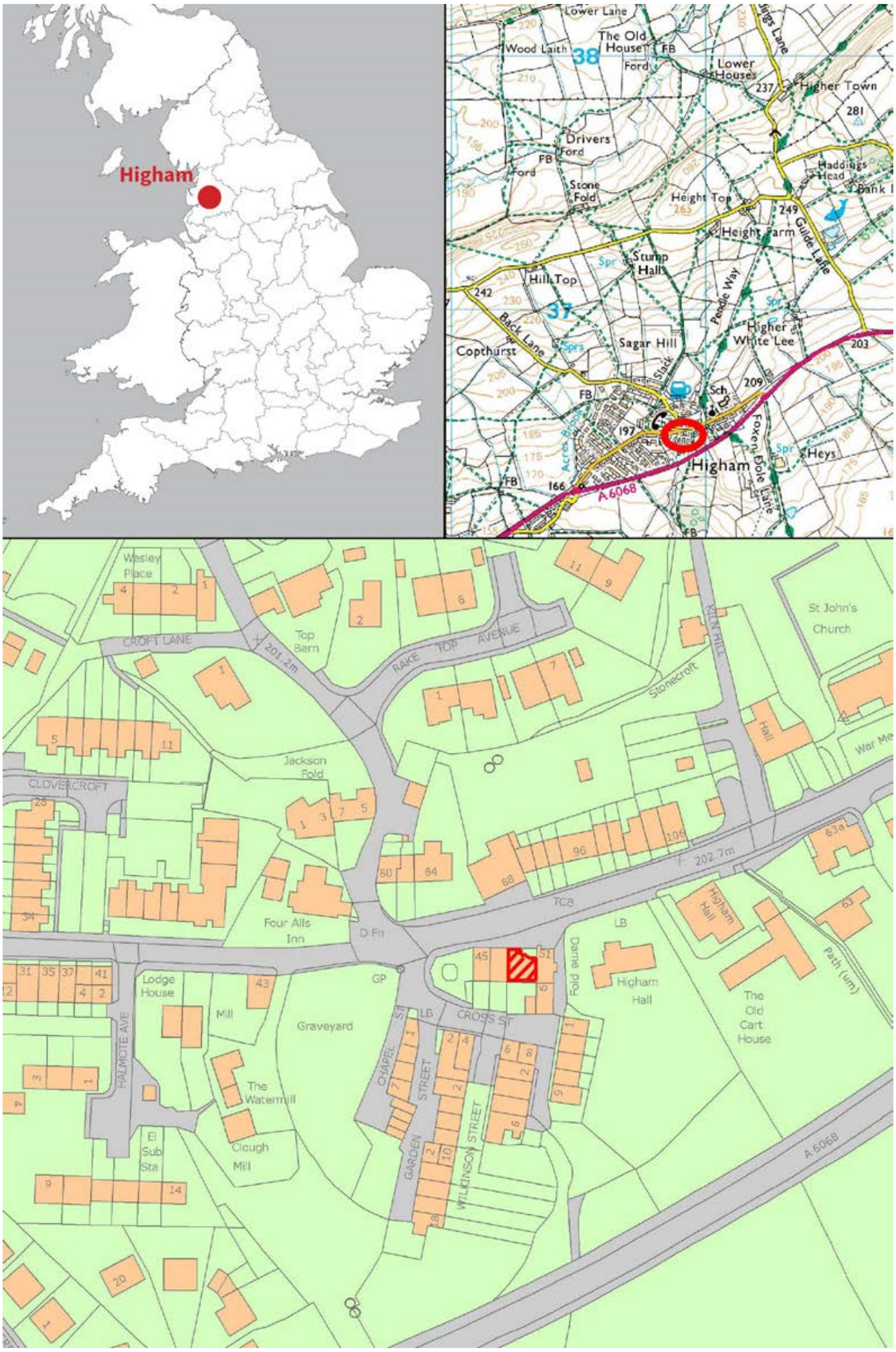


Figure 1: Maps to show the location of Higham House in Lancashire, marked in red. Scale: top right 1:20000; bottom 1:1500. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

Figure 2a/b: View of the frieze (photograph Robert Howard)

Figure 3a/b: Annotated photographs to help identify sampled timbers (photographs Robert Howard)

Figure 3c: Annotated photograph to help identify sampled timbers (photograph Robert Howard)

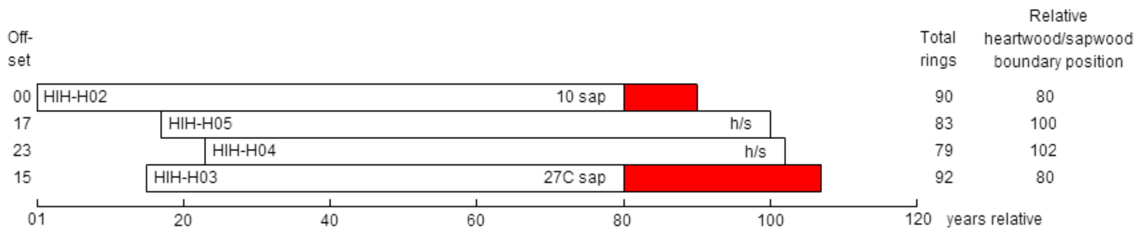


Figure 4: Bar diagram of the samples of site chronology HIHHSQ01

White bars = heartwood rings
Red bars = sapwood rings
h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample

Figure 5: The cores from the principal rafters, HIH-H02 (top) and HIH-H03 (bottom), showing the abrupt growth changes and the clear lack of recovery to previous growth levels throughout the latter years of growth of the tree from which HIH-H03 was derived (photograph Robert Howard)

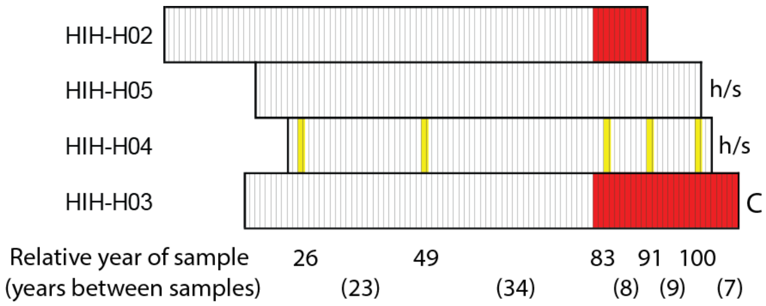


Figure 6: Schematic illustration of site sequence HIHHSQ01 to locate the single-ring sub-samples submitted for radiocarbon dating from timber HIH-H04

White bars = heartwood rings
Red bars = sapwood rings
Yellow bars = rings sampled for radiocarbon dating
h/s = heartwood/sapwood boundary
C = complete sapwood is retained on the sample

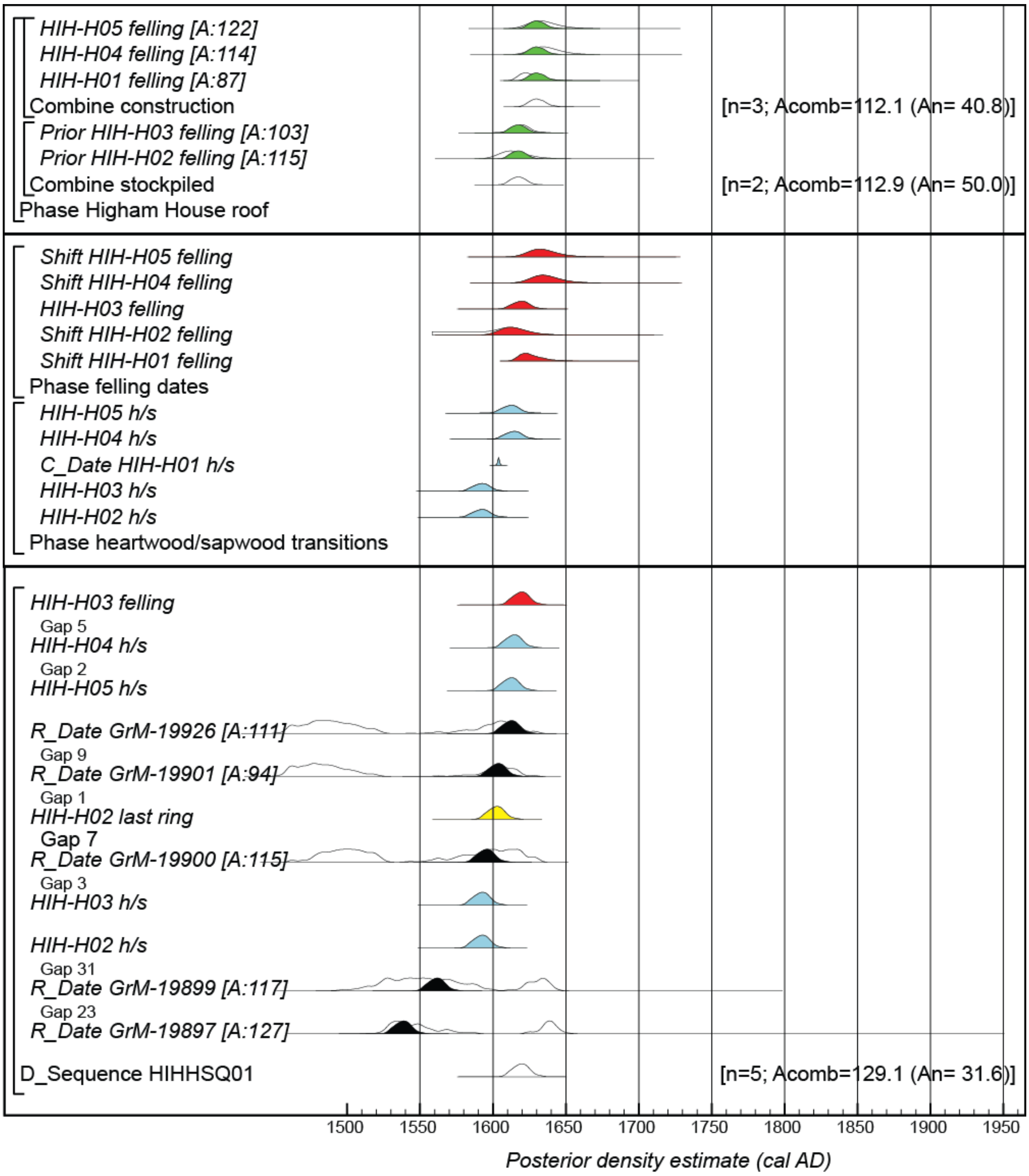


Figure 7: Probability distributions of dates from site master sequence HIHHSQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model (heartwood/sapwood transitions = blue; last surviving sapwood ring = yellow; felling date = red; combined felling estimates = green). The large square brackets down the left-hand side of the bottom graph along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

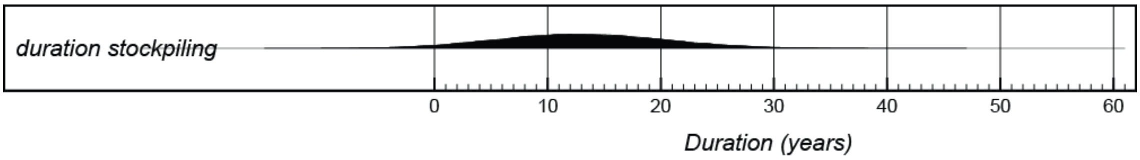


Figure 8: Probability distribution of the number of years between the date when the timbers used for the principal rafters were felled and the date when the timbers used for the purlins and tiebeam were felled

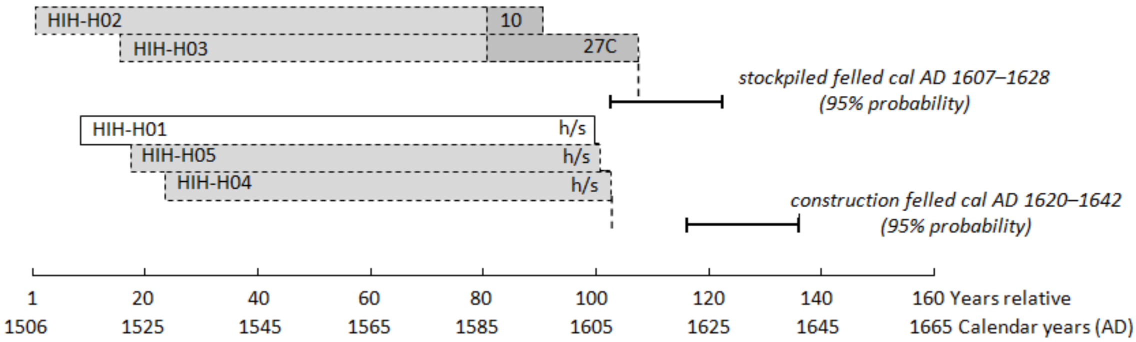


Figure 9: Summary diagram showing the dated timbers from the roof of Higham House (date ranges for felling episodes derive from the model defined in Figure 7)

C = complete sapwood is retained on the sample
h/s = heartwood/sapwood boundary
white = heartwood rings dated by ring-width dendrochronology
light grey = heartwood rings dated by radiocarbon wiggle-matching
dark grey = sapwood rings dated by radiocarbon wiggle-matching

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HIH-H01A 91
209 295 254 379 321 218 206 166 201 142 146 214 264 350 303 217 257 362 351 277
289 289 296 306 273 370 337 262 226 266 281 230 102 40 48 54 46 79 40 68
64 67 63 96 120 137 167 71 43 37 36 32 34 34 48 43 43 51 43 55
58 58 69 59 56 84 101 79 49 86 114 129 109 103 87 125 91 83 106 143
231 177 156 124 93 68 85 114 104 186 218

HIH-H01B 91
209 291 250 362 335 244 214 159 201 134 151 228 260 344 307 219 258 350 355 271
296 278 294 309 271 370 332 256 231 260 284 245 92 39 65 42 54 83 47 71
62 65 53 103 123 142 163 68 42 39 39 29 32 35 50 43 49 50 41 55
62 60 70 60 55 85 97 80 53 82 107 133 116 104 90 121 89 81 109 142
229 179 162 128 95 63 86 117 101 179 228

HIH-H02A 90
129 110 84 193 94 146 184 250 295 351 358 432 435 324 296 381 310 250 313 414
351 346 339 255 192 294 385 347 404 339 364 371 334 387 375 260 197 246 278 203
265 167 221 43 42 81 40 84 69 85 109 145 158 141 136 134 59 30 40 37
50 84 107 101 112 56 93 103 59 64 66 46 55 90 66 62 56 80 115 138
79 57 61 56 62 70 79 99 79 95

HIH-H02B 90
128 103 89 191 96 142 181 254 297 348 372 414 416 327 289 394 312 246 296 390
364 367 343 237 197 295 370 332 401 446 311 343 342 389 371 249 196 259 268 203
257 182 229 46 49 75 43 89 76 87 132 153 155 157 130 134 56 28 48 44
53 81 106 102 122 64 93 107 59 73 63 56 50 84 71 63 42 88 124 146
80 60 59 56 58 71 84 100 77 97

HIH-H03A 92
252 158 171 239 343 349 376 280 260 232 335 398 371 416 411 335 421 443 515 474
287 268 309 381 340 378 360 308 132 67 90 57 75 59 71 81 137 103 100 106
126 116 89 68 40 54 76 82 51 103 46 70 79 62 39 29 32 54 40 37
37 64 95 101 46 51 45 46 49 43 68 56 48 56 50 62 38 46 46 43
38 25 31 35 53 50 55 50 60 52 54 76

HIH-H03B 92
249 146 163 222 333 350 380 287 231 231 326 402 376 395 359 350 427 449 519 471
317 265 318 371 309 379 330 307 118 73 100 46 82 60 62 87 131 106 101 109
123 115 96 56 50 53 73 83 59 101 57 68 76 57 39 30 41 51 35 40
43 59 94 102 53 46 40 48 46 51 62 60 49 57 54 50 35 43 51 43
39 18 36 35 46 47 59 48 56 60 45 75

HIH-H04A 79
309 246 299 237 289 253 337 289 253 296 359 285 263 211 260 299 264 265 216 242
78 57 67 44 66 67 78 68 107 122 136 149 137 129 107 101 98 167 154 174
78 35 29 48 31 29 41 52 29 34 47 38 42 25 40 53 59 70 59 48
84 62 64 98 101 132 125 132 128 120 95 104 107 73 79 183 237 229 266

HIH-H04B 79
305 236 297 226 290 259 314 290 246 294 388 280 264 221 262 303 268 269 205 253
76 62 70 47 62 64 75 75 105 123 142 164 131 129 110 100 101 167 160 173
79 50 22 46 32 26 42 51 28 34 42 37 43 31 33 50 60 62 56 59

81 65 65 100 104 126 137 134 139 115 104 103 104 78 79 183 231 232 275

HIH-H05A 83
263 246 251 380 380 222 316 333 332 375 273 275 323 282 364 357 401 462 375 336
354 392 240 273 279 277 40 76 100 76 89 76 103 92 142 143 150 112 139 132
120 82 73 76 91 138 38 32 21 31 28 35 32 28 26 31 48 29 31 26
34 34 60 88 68 50 58 56 57 85 92 123 118 93 85 67 82 80 73 54
60 101 137

HIH-H05B 83
265 253 243 379 367 217 331 328 337 379 271 260 329 282 369 360 405 469 373 338
368 465 281 270 281 278 40 75 106 71 90 76 101 100 139 142 150 121 144 116
118 81 77 75 90 139 45 22 32 34 32 32 28 41 27 31 38 36 34 32
29 48 50 82 71 46 58 53 64 82 93 121 126 95 75 70 89 67 59 59
54 107 133

HIH-H07A 60
130 140 193 231 152 142 149 204 209 208 205 328 252 224 180 102 200 203 190 94
117 207 196 235 232 228 90 100 87 110 80 89 98 149 123 71 52 75 98 128
162 137 162 121 100 104 176 292 284 228 139 82 92 68 62 50 45 26 59 57

HIH-H07B 60
133 148 186 240 152 143 148 199 216 203 208 332 251 218 167 98 192 193 200 85
134 219 185 223 229 205 85 103 107 101 88 100 104 139 114 70 58 76 89 120
156 134 156 133 97 104 175 289 263 242 142 87 81 73 62 51 43 34 54 59

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 Buildings* (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 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.

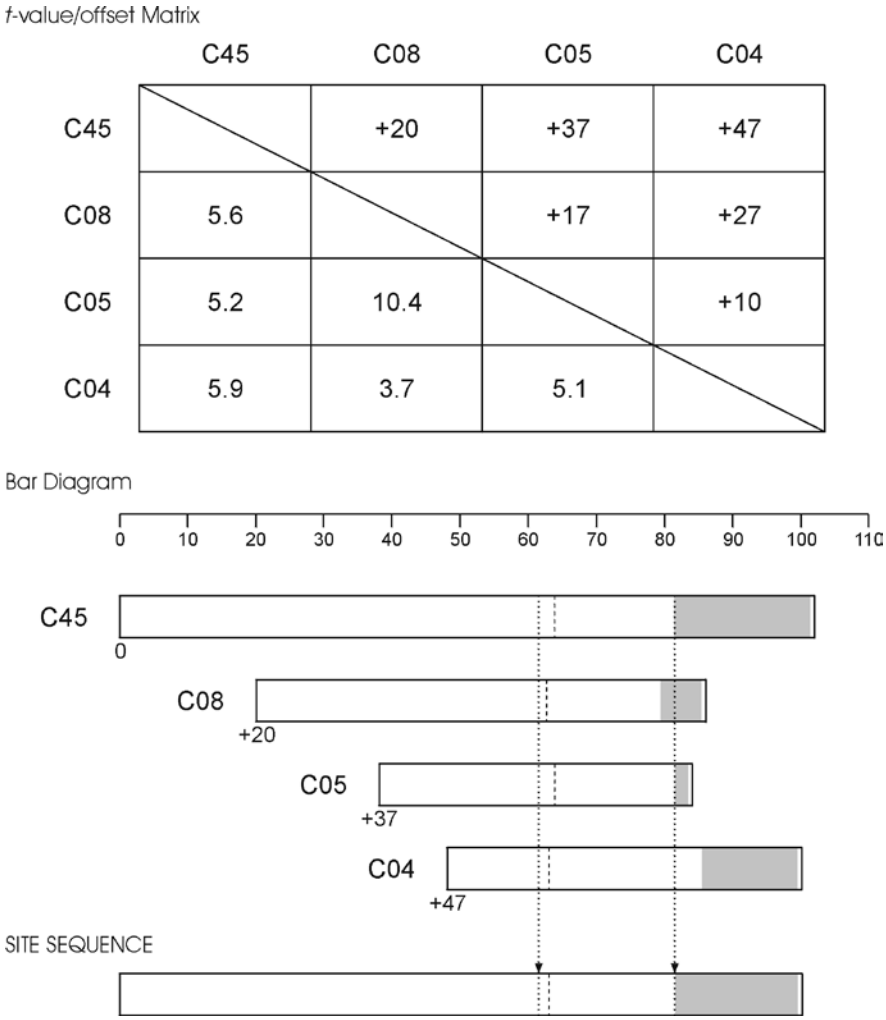


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

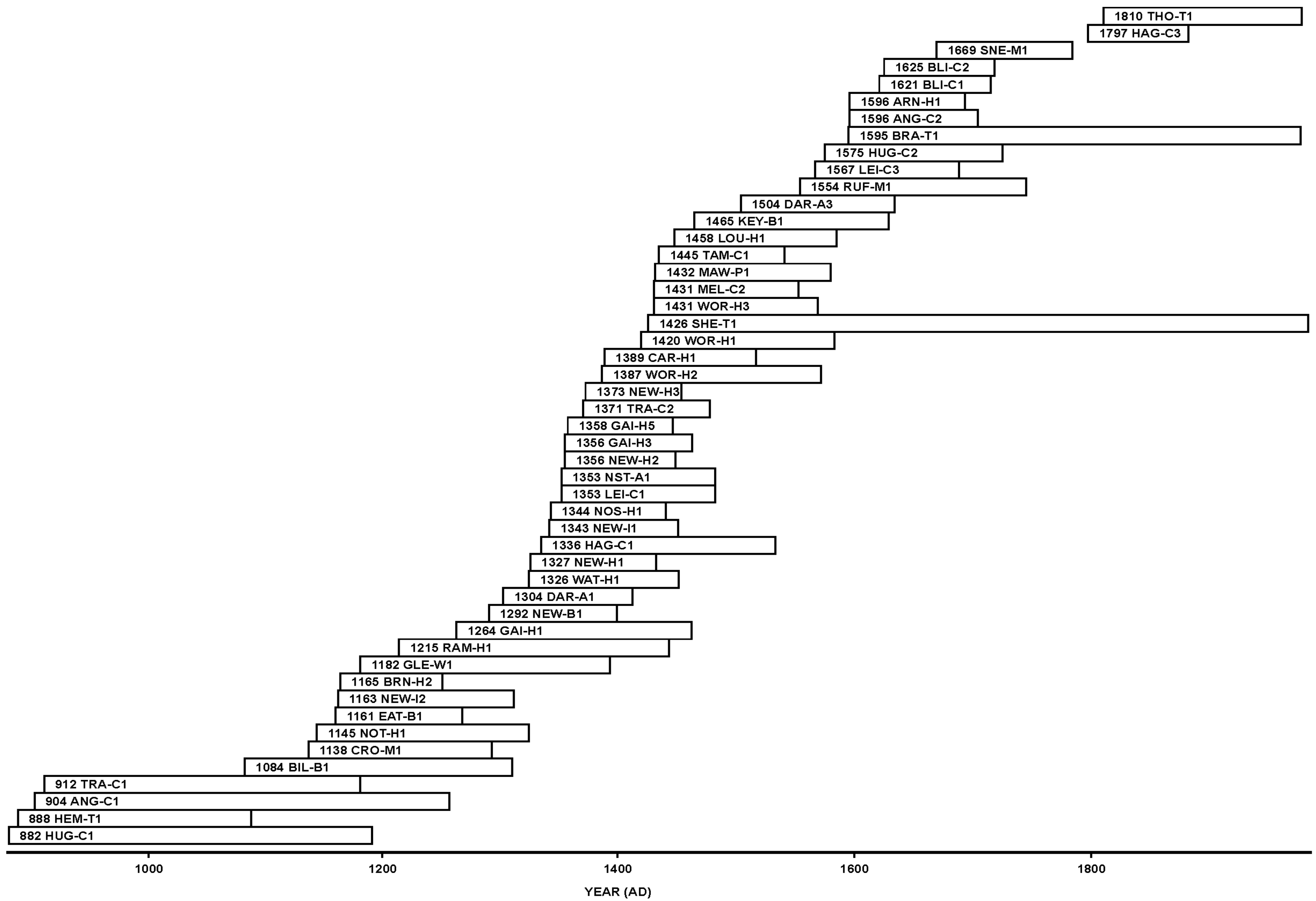
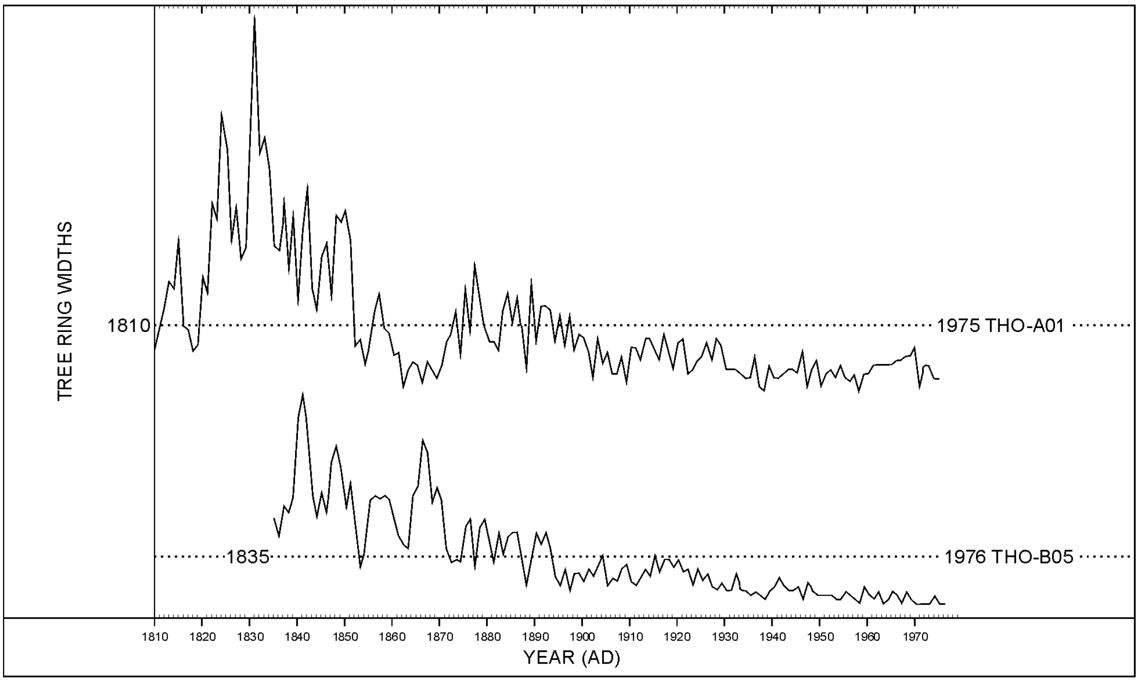


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

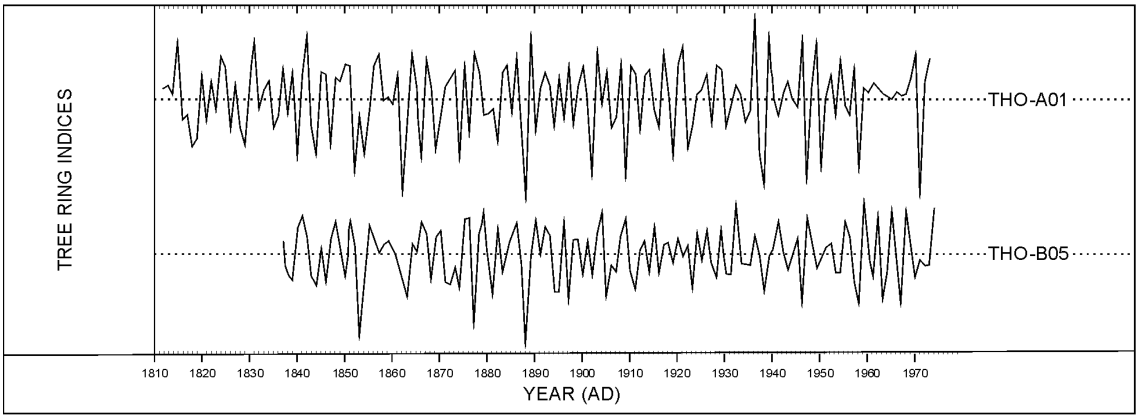


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

References

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

English Heritage, 1998 *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates,* London

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95 Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect,* 15–26

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, 23, 51–6.

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, 22, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series III

Laxton, R R, and Litton, C D, 1989 Construction of a Kent master dendrochronological sequence for oak, AD 1158 to 1540, *Medieval Archaeol*, 33, 90–8

Laxton, R R, Litton, C D, and Howard, R E, 2001 Timber: *Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, 7

Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸ 18, 29–40

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

Pearson, S, 1995 *The Medieval Houses of Kent, an Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London

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