Historic England

Scientific Dating

North Wing of the Kilve Chantry, Sea Lane, Kilve, Somerset
Tree-Ring and Radiocarbon Dating of Timbers

Alison Arnold, Robert Howard, Zoe Outram, Gordon Cook, and Christopher Bronk Ramsey

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 71-2015

NORTH WING OF THE CHANTRY
SEA LANE, KILVE
SOMERSET

TREE-RING AND RADIOCARBON DATING OF TIMBERS

Alison Arnold, Robert Howard, Zoe Outram,
Gordon Cook, and Christopher Bronk Ramsey

NGR: ST 1464 4401

ISSN 2059-4453 (Online)

SUMMARY

Dendrochronological analysis of eight oak samples from window lintels in the north wing of the Chantry at Kilve has produced a single dated site chronology (KLVASQ01) comprising two of the samples measured from lintels at the upper floor levels. This site chronology has an overall length of 120 rings, these dated as spanning the years AD 1425–1544. Interpretation of the sapwood indicates that at least one of these lintels was felled in the period AD 1559–84, while the second lintel was not felled before AD 1539 and may well be coeval with the sixteenth century felling date identified. A second site chronology (KLVASQ02) comprising two further samples, and the three ungrouped samples, remain undated. One sample was rejected as unsuitable prior to measurement.

Single ring subsamples from two of the undated timbers, KLV-A01 (part of KLVASQ02) and KLV-A04, were submitted for radiocarbon dating by Accelerator Mass Spectrometry (AMS). Analysis of these results by wiggle-matching suggests that both of the ground floor lintels in site sequence KLVASQ02 were felled in the late thirteenth century cal AD, along with the ungrouped timber KLV-A04.

CONTRIBUTORS

Alison Arnold, Robert Howard, Zoe Outram, Gordon Cook, and Christopher Bronk Ramsey

ACKNOWLEDGEMENTS

We would like to thank Barry Jones, Historic England (Assessment Team West) and both Peter Marshall and Cathy Tyers (Scientific Dating Team) for help in bringing such a challenging application to a successful conclusion.

ARCHIVE LOCATION

Somerset Historic Environment Record
Somerset Heritage Centre
Brunel Way
Norton Fitzwarren
Taunton, TA2 6BT

DATE OF RESEARCH

2012–2015

CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham, NG5 1FT
0115 960 3833
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Christopher Bronk Ramsey
Oxford Radiocarbon Accelerator Unit
Research Laboratory for Archaeology and the History of Art
Dyson Perrins Building
South Parks Road
Oxford, OX1 3QY
01865 285215
christopher.ramsey@rlaha.ox.ac.uk

Gordon Cook
Scottish Universities Environmental Research Centre
Scottish Enterprise Technology Park
Rankine Avenue
East Kilbride, G75 0QF
01355 270136
g.t.cook@suerc.gla.ac.uk

Zoe Outram
Historic England
24 Brooklands Avenue,
Cambridge, CB2 8BU
01223 582707
zoe.outram@HistoricEngland.org.uk

CONTENTS

INTRODUCTION

The Chantry site, that is ‘Chantry Cottage’, ‘Priory Cottage’ and the ‘Chantry’, are situated approximately one kilometre north of the village of Kilve (Figs 1 and 2). The medieval elements of the site, thought to date from the late-thirteenth or early-fourteenth century, comprised a hall range (probably aisled), a solar wing, two additional substantial wings (the north wing and the west wing), and extensive apartments, all contemporary. Other structures which at one time stood on the site included an in-line range of probable medieval date at the western end of the hall, and a chapel, which may be a slightly later addition. The extensive nature of the site indicates that the house was built by a wealthy owner, possibly of the Furneaux family, and it may have been the capital messuage of Kilve Manor. The extended medieval plan form sets the site apart from other contemporary houses.

In 1329 Simon de Furneaux, Knight, received a licence to found a college of priests at Kilve, the chantry foundation supporting five priests who were to recite prayers for the soul of the founder and give mass at Kilve Church. The foundation was dissolved in the late-fourteenth century.

The entire Chantry complex suffered from a catastrophic fire *c* 1849 which destroyed the medieval roofs and floors. Since this time parts of the Chantry have fallen into decay and the buildings (Fig 3) now comprise the remains of the hall range (forming the main block of the Chantry site) along with the ruined solar wing, chapel, the east wing, and the west and north wings. The site is now on the Heritage at Risk Register, and, along with Chantry Cottage and Priory Cottage, is listed grade II*, and is a scheduled ancient monument. The buildings have been the subject of a detailed English Heritage Historic Building report (Jones 2003).

Like the rest of the Chantry site, the north wing, the subject of this particular report, is constructed of blue lias random rubble being of two storeys beneath a slate roof (Fig 4). The north wing is orientated north–south, and comprises four-bays. All the original roof and first floor timbers are now gone, presumably lost in the fire, and there is no framing to the wall (Figs 5 and 6); the structure was re-roofed and given a new first floor in the twentieth century. The only older timbers remaining are the lintels to a series of ground and first floor window openings and a door to the first floor.

TREE-RING SAMPLING AND ANALSIS

Sampling and analysis by dendrochronology of the door and window lintels of the north wing were requested by Barry Jones (Historic England), this programme of analysis being undertaken to provide independent dating evidence for the lintels, and therefore potentially the construction of the north wing.

Assessment of the extant historic oak (*Quercus* sp) lintels identified eight as having dendrochronological potential and samples were subsequently obtained by coring. Although there were other timbers that were potentially available for sampling, these appeared to be derived from fast-grown trees and to thus have too few rings for reliable analysis (ie, less than 40). Such timbers were not sampled. Each sample was given the code KLV-A (for Kilve, site ‘A’) and numbered 01–08 (Table 1). The location of the sampled timbers was noted at the time of coring and marked on a set of simple plans (Fig 7) and photographed (Figs 8a–h).

Each of the eight samples obtained from this site was prepared by sanding and polishing. It was seen at this time that one of the samples, KLV-A07, had too few rings, ie, less than 40, for reliable analysis and it was rejected from this programme of analysis. The annual growth ring widths of the remaining seven samples were measured (see Appendix). The data of the seven measured samples were compared with the Litton/Zainodin grouping procedure (see Appendix), which identified two groups of two cross-matching samples (Figs 9a/b). The samples of each group were combined at their indicated offset positions to form site chronologies KLVASQ01 (120 rings) and KLVASQ02 (125 rings).

The two site chronologies were compared to an extensive corpus of oak reference material. This process indicated a consistent and repeated cross-match with independent reference chronologies for KLVASQ01 only; the date for the first ring of this sequence is AD 1425 and the last measured ring is AD 1544 (Table 2). Site chronology KLVASQ02 was undated by dendrochronology.

The two site chronologies, KLVASQ01 and KLVASQ02, were compared to the three ungrouped samples, but there was no further satisfactory cross-matching. The ungrouped samples also did not achieve satisfactory cross-matches with any of the reference data corpus.

RADIOCARBON DATING SAMPLING AND ANALYSIS

The dendrochronological analysis successfully dated two of the lintels to the sixteenth century but it had not been able to identify whether any of the other lintels were associated with the initial construction of the north wing of the Chantry, thought to date to the late-thirteenth or early-fourteenth century. Thus, in order to address this outstanding question, it was decided to undertake radiocarbon dating and wiggle-matching on some of the tree-ring samples that remained undated. The tree-ring samples were selected on the basis of being from the ground floor, considered more likely to have been associated with the initial construction, and having retained the heartwood/sapwood boundary which would allow a posterior density estimate for felling to be produced. The two tree-ring samples selected were KLV-A01 (part of the undated site sequence KLVASQ02) and KLV-A04. Six single-ring subsamples were taken from both KLV-A01 and KLV-A04, with three samples from each submitted to the Oxford Radiocarbon Accelerator Unit (ORAU) and the Scottish Universities Environmental Research Centre (SUERC) radiocarbon laboratories.

Subsequently, due to issues identified with the wiggle-matching of the radiocarbon dates from timbers KLV-A01 and -A04 (see below), 12 single-ring subsamples were also submitted for radiocarbon dating from the dendrochronologically dated KLV-A06, with six samples each measured at ORAU and SUERC.

Samples dated at ORAU were pretreated using the acid-base-acid protocol followed by bleaching (Brock *et al* 2010, table 1 (UW)). Samples were combusted and graphitized as described by Brock *et al* (2010, 110) and Dee and Bronk Ramsey (2000), and dated by Accelerator Mass Spectrometry (AMS) (Bronk Ramsey *et al* 2004).

The samples dated at SUERC were pretreated through a three-step Soxhlet extraction process using an organic solvent mixture of ethanol-chloroform (1:2 by volume). Following the Soxhlet extraction the sample is dried, washed with acid/alkali/acid and then bleached until the cellulose is white in colour. The sample is then washed with high purity water to remove all traces of the bleach, before the acid/alkali/acid washes are repeated, leaving alpha cellulose. The sample is then combusted using the approaches described in Vandeputte *et al* (1996) and Freeman *et al* (2010). Following combustion, the samples are graphitized using methods described in Slota *et al* (1987), and dated by AMS (Xu *et al* 2004; Freeman *et al* 2010).

Both laboratories maintain a continual programme of quality assurance procedures, in addition to participation in international inter-comparisons (Scott 2003; Scott *et al* 2010). These tests indicate no laboratory offsets and demonstrate the reproducibility and accuracy of these measurements. As part of internal laboratory quality assurance procedures at ORAU two samples were measured twice (KLV-A01, ring 65 and KLV-A06, ring 106). For both samples the two replicate measurements are statistically consistent (Table 3) and a weighted mean (Ward and Wilson 1978) was calculated as providing the best estimate for their age of formation.

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Table 3), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986).

RADIOCARBON DATING

Radiocarbon dating is based on the radioactive decay of carbon-14 and can be used to date organic materials, including wood. A small proportion of the carbon atoms in the atmosphere are of a radioactive form, carbon-14. Living plants and animals take up carbon from the environment, and therefore contain a constant proportion of carbon-14. Once a plant or animal dies, however, its carbon-14 decays at a known rate. This makes it possible to calculate the date of formerly living material from the concentration of carbon-14 atoms remaining. Radiocarbon measurements, like those in Table 3 are expressed in radiocarbon years BP.

CALIBRATION

Calibration is an essential step in using radiocarbon measurements to estimate the calendar date of samples. It is necessary because the production rate of radiocarbon in the atmosphere is not constant, but varies through time. This means that we need to convert the radiocarbon measurement of a sample to the calendar scale using a calibration curve made up of radiocarbon ages on samples of known calendar date.

That independent scale is the IntCal13 calibration curve (Reimer *et al* 2013) constructed from radiocarbon measurements on tree rings, plant macrofossils, speleothems, corals, and foraminifera. The calibrations which relate the radiocarbon measurements directly to the calendrical time scale have been calculated using IntCal13 and the computer program OxCal4.2 (https://c14.arch.ox. ac.uk/oxcal/; Bronk Ramsey 1995; 1998, 2001; 2009a). The calibrated date ranges quoted for each sample in Table 3, expressed 'cal AD', were calculated by the maximum intercept method (Stuiver and Reimer 1986; Fig 10) and are rounded outwards to the nearest ten years, or five for measurements with errors <25, as recommended by Mook (1986). The graphical distributions of the calibrated dates, shown in outline in Figures 11–12, 14–15, and 17–18 are derived from the probability method (Stuiver and Reimer 1993).

BAYESIAN WIGGLE MATCHING

Wiggle-matching uses information derived from tree-ring analysis, in combination with radiocarbon measurements to provide a revised understanding of the age of a timber; a review is presented by Galimberti *et al* (2004). In this technique, the shapes of multiple radiocarbon distributions can be "matched" to the shape of the radiocarbon calibration curve. The exact interval between radiocarbon results can be derived from tree-ring analysis.

Although the technique can be done visually, Bayesian statistical analyses (including functions in the OxCal computer program) are now routinely employed. A general introduction to the Bayesian approach to interpreting archaeological data is provided by Buck *et al* (1996). The approach to wiggle-matching adopted here is described by Christen and Litton (1995).

Details of the algorithms employed in this analysis — a form of numerical integration undertaken using OxCal — are available from the on-line manual or in Bronk Ramsey (1995; 1998; 2001; 2009a). Because it is possible to constrain a sequence of radiocarbon dates using this highly informative prior information (Bayliss *et al* 2007), model output will provide more precise posterior density estimates. These posterior density estimates are shown in black in Figures 11–12, 14–15, and 17–18, and quoted in italic in the text.

The A_{comb} statistic shows how closely the dates as a whole agree with other information in the model; an acceptable threshold is reached when it is equal to or greater than A_n, a value based on the number of dates in the model. The A statistic shows how closely an individual date agrees with the other information in the model; an acceptable threshold is reached when it is equal to or greater than 60.

Noisy data

The two main approaches for dealing with noisy date or 'outliers' in radiocarbon dating are either to eliminate them manually from the analysis or to use a more objective statistical approach (Bronk Ramsey 2009b; Christen 1994). The model averaging approach (Bronk Ramsey *et al* 2010) offers a more systematic approach than testing many different models individually by adding variable parameters to a model.

In order to deal with the potential problems of measurement offsets as a result of either a sample or the measurement being contaminated and the potential effects of short-lived offsets in the calibration curve which might only affect one of a series of samples we have used the OxCal model (*r*-type; Bronk Ramsey 2009b) for individual radiocarbon offsets. Each measurement is a given a prior probability of being an outlier (in this case 0.05) and the model then averages over cases where the shift is allowed and where it is not (Bronk Ramsey *et al* 2010). The model also provides a parameter defining whether the sample is an outlier (with an offset – see for example Fig 13).

KLV-A01

The chronological model for the dating of timber KLV-A01 is shown in Figure 10, and shows poor agreement between the radiocarbon dates and the model derived from the tree-ring sequence for the relative number of years between each sample (A_{comb} = 3.8%, An = 28.9%, n=6).

Implementing a model for the treatment of individual radiocarbon offsets (OxCal *r*-type, Bronk Ramsey 2009b – see Noisy data (above)) (Fig 12) identifies three samples (OxA-26565, OxA-26568, and SUERC-40198) that might have offsets (Fig 13). The model provides an estimate for the formation of the final ring of sample KLV-A01 of *cal AD 1230–1295* (*95% probability*; *Ring_109*; Fig 12) and probably *cal AD 1235–1280* (*68% probability*).

It is unlikely that contamination of the timber (eg through chemical treatment) accounts for the offsets identified as samples from both ends of the sequence were identified in Figure 13. As the calibration curve data (Reimer *et al* 2013) for the medieval period was obtained from decadal blocks it remains a distinct possibility that during this period atmospheric ^{14}C concentrations showed significantly more structure. This may explain the limits of the precision of the wiggle-match results given the samples were themselves obtained from single year rings.

KLV-A04

The chronological model for the dating of timber KLV-A04 is shown in Figure 13, and shows poor agreement between the radiocarbon dates and the relative age gaps between them (A_{comb} = 7.3%, An = 28.9%, n=6).

Implementing a model for the treatment of individual radiocarbon offsets (OxCal *r*-type, Bronk Ramsey 2009b – see Noisy data (above)) (Fig 15) identifies two samples (SUERC-40201 and SUERC-40202) that might have offsets (Fig 16). The model provides an estimate for the formation of the final ring of sample KLV-A04 of *cal AD 1190–1255* (*95% probability*; *Ring_52*; Fig 15) and probably *cal AD 1205–1225* (*68% probability*).

KLV-A06

The chronological model for the dating of timber KLV-A06 is shown in Figure 17, and shows poor agreement between the radiocarbon dates and the model (A_{comb} = 3.3%, An = 20.4%, n=6).

Implementing a model for the treatment of individual radiocarbon offsets (OxCal *r*-type, Bronk Ramsey 2009b – see Noisy data (above)) (Fig 18) identifies four samples (SUERC-48668–9, SUERC-48671 and OxA-28709) that might have offsets (Fig 19). The model provides an estimate for the formation of the final ring of sample KLV-A06 of *cal AD 1520–1540* (*95% probability*; *Ring_120*; Fig 18) and probably *cal AD 1525–1535* (*68% probability*). Notably the model only provides an estimate for the formation of the final ring of sample KLV-A06 that contains the dendrochronological date of AD 1544 at *99% probability* (*cal AD 1515–1545*; *Ring_120*; Fig 18).

As the calendar age of all the samples from this sequence have been determined by tree-ring dating, the radiocarbon ages obtained from single ring samples can be compared directly with the radiocarbon calibration curve derived from measurements on decadal blocks (Fig 20) until the single year data from AD 1510–1950 (Stuiver *et al* 1998). The offset between the Kilve Chantry data points and the calibration curve in the late AD 1400s and early AD1500s suggests that more structure may be apparent in the calibration curve than the current decadal sampling exhibits.

INTERPRETATION

Dendrochronological analysis has resulted in the dating of two samples, as part of site sequence KLVASQ01 (Table 1; Fig 9a). Neither of the two dated samples retains complete sapwood (the last ring produced by the trees from which the sampled timbers were derived before they were cut down) and thus it is not possible to determine a precise felling date for either. The two lintels represented are, however, clearly broadly coeval. Sample KLV-A06 has retained the heartwood/sapwood boundary so, using the 95% confidence limit of 15–40 sapwood rings standardly applied by the Nottingham Tree-ring Dating Laboratory to native oak, given that the heartwood/sapwood boundary is dated to AD 1544 an estimated felling date in the range AD 1559–84 is obtained. The second dated sample, KLV-A08, is without its heartwood/sapwood boundary. The last heartwood ring present dates to AD 1524, and thus a *terminus post quem* for felling of AD 1539 is obtained. It could therefore be coeval with the felling date range identified for KLV-A06, though this cannot be proven from the dendrochronological analysis.

In addition the dendrochronological analysis has shown that the two samples forming site sequence KLVASQ02 are also likely to be broadly coeval and hence potentially have been felled at the same or similar time. However, the dendrochronological analysis could not conclusively date this site sequence. Wiggle-matching of timber KLV-A01 allows estimated dates to be determined for site sequence KLVASQ02 with a first ring date of *cal AD 1105–70*(*95% probability*) and last ring date of *cal AD 1230–1295 (95% probability)*, Sample KLV-A01 has retained the heartwood/sapwood boundary ring and applying the standard NTRDL 15–40 sapwood rings given the the heartwood/sapwood boundary estimated of *cal AD 1230–95 (95% probability)* an estimated felling date in the range *AD 1255–1330 (95% probability)* is obtained. The second dated sample, KLV-A03, is without its heartwood/sapwood boundary. The last heartwood ring present is estimated to date to *cal AD 1215–80* (*95% probability)*, and thus a *terminus post quem* for felling of *cal AD 1230–95 (95% probability)* is obtained.

CONCLUSIONS

Radiocarbon dating and wiggle-match analysis, combined with the dendrochronological analysis, has identified that three of the window lintels from the ground floor are likely to have been felled in the latter part of the thirteenth century and are thus likely to represent the initial construction of the north wing (Fig 21). Dendrochronological analysis has also identified that the two of the upper floor lintels date to the sixteenth century and are thus likely to represent later alterations or repairs to the north wing. The principal focus of the post-medieval alterations is associated with the late sixteenth or seventeenth centuries heating of the building (Jones 2003, 27). Radiocarbon wiggle-matching of sample KLV-A06 that had been dated by dendrochronology was undertaken in attempt to understand the issues raised by the radiocarbon wiggle-matches of samples of unknown age (KLV-A01 and KLV-A04) that it was thought might have been contaminated. The results indicate that chemical contamination of the timbers is unlikely and that problems with accurate radiocarbon wiggle-matching in the medieval period, when using single-year samples, is probably a result of IntCal13 (Reimer *et al* 2013) being predominantly based on radiocarbon determinations of decadal dendrochronologically dated wood samples. Decadal samples together with methods used to construct IntCal13 (Niu *et al* 2013) removes high-frequency changes (<10 years) in atmospheric radiocarbon content and diminishes short-term changes in the measured raw data (Wacker *et al* 2014). The recently identified dramatic increases in atmospheric ^{14}C content between AD 774 and 775 (Miyake *et al* 2012) and AD 993 and 994 (Miyake *et al* 2013) were masked by the decadal sampling that underpins the IntCal calibration curves and suggests that significant more fine structure is apparent in the past radiocarbon content of the atmosphere.

Accurate wiggle-matching of timbers from medieval buildings, especially given the common-place use of single-ring samples is therefore going to require an extension of the single-year calibration data (Stuiver *et al* 1998) beyond AD 1510.

REFERENCES

Arnold, A J, Howard, R E, and Litton, C D, 2008 List 197 no. 26 – Nottingham Tree-Ring Dating Laboratory, *Vernacular Architect*, **39**, 119–28

Bayliss, A, Bronk Ramsey, C, van der Plicht, J, and Whittle, A, 2007 Bradshaw and Bayes: towards a timetable for the Neolithic, *Cambridge Archaeological Journal*, **17 (suppl 1)**, 1–28

Bridge, M C, 2002 *Tree-Ring Analysis of Timbers from Muchelney Abbey, Muchelney, Near Langport, Somerset*, EH, Centre for Archaeol Rep, **114/2002**

Brock, F, Higham, T, Ditchfield, P, and Bronk Ramsey, C, 2010 Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU), *Radiocarbon*, **52**, 103–112

Bronk Ramsey, C, 1995 Radiocarbon calibration and analysis of stratigraphy, *Radiocarbon*, **36**, 425–30

Bronk Ramsey, C, 1998 Probability and dating, *Radiocarbon*, **40**, 461–74

Bronk Ramsey, C, 2001 Development of the radiocarbon calibration program OxCal, *Radiocarbon*, **43**, 355–63

Bronk Ramsey, C, 2009a Bayesian analysis of radiocarbon dates, *Radiocarbon*, **51**, 337–60

Bronk Ramsey, C, 2009b Dealing with outliers and offsets in radiocarbon dating, *Radiocarbon*, **51**, 1023–45

Bronk Ramsey, C, Higham, T, and Leach, P, 2004 Towards high-precision AMS: progress and limitations, *Radiocarbon*, **46**, 17–24

Bronk Ramsey, C, Dee, M, Lee, S, Nakagawa, T, and Staff, R A, 2010 Developments in the calibration and modelling of radiocarbon dates, *Radiocarbon*, **52**, 953–61

Buck, C E, Cavanagh, W G, and Litton, C D, 1996 *Bayesian Approach to Interpreting Archaeological Data*: Chichester, John Wiley and Sons

Christen, J A, 1994 Summarising a set of radiocarbon determinations: a robust approach, *Applied Statistics* **43**, 489–512

Christen, J, and Litton, C, 1995 A Bayesian approach to wiggle-matching, *Journal of Archaeological Science*, **22**, 719–25

Dee, M, and Bronk Ramsey, C, 2000 Refinement of graphite target production at ORAU, *Nuclear Instruments and Methods Physics Research B*, **172**, 449–53

Galimberti, M, Bronk Ramsey, C, and Manning, S W, 2004 Wiggle-match dating of tree-ring sequences, *Radiocarbon*, **46**, 917–24

Hogg, A G, McCormac, F G, Higham, T F G, Reimer, P J, Baillie, M G, and Palmer, J G, 2002 High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850-950, *Radiocarbon*, **44**, 633-40

Howard, R E, Laxton, R R, and Litton, C D, 1996 *Tree-ring analysis of timbers from Mercer's Hall, Mercer's Lane, Gloucester*, Anc Mon Lab Rep, **13/1996**

Howard, R E, Laxton, R R, and Litton, C D, 1998 *Tree-ring analysis of timbers from 26 Westgate Street, Gloucester*, Anc Mon Lab Rep, **43/1998**

Howard, R, Litton, C D, Arnold, A, and Tyers C, 2006 *Tree-ring analysis of timbers from Warleigh House, Tamerton Foliot, Bickleigh, South Hams, near Plymouth, Devon*, EH Res Dept Rep Series, **38/2006**

Hurford, M, Arnold, A J, and Howard, R E, 2009 *Trerice, Kestle Mill, Cornwall, tree-ring analysis of timbers*, EH Res Dep Rep Ser, **38/2009**

Freeman, S P H T, Cook, G T, Dougans, A B, Naysmith, P, Wicken, K M, and Xu, S, 2010 Improved SSAMS performance, *Nuclear Instruments and Methods Physics Research B*, **268**, 715–17

Jones B V, 2003 *Chantry Cottage, Priory Cottage and Remains of Chatry, Kilve, Somerset*, EH Hist Build Areas Dept Rep Pap **B/005/2003**

Miyake, F, Nagaya, K. Masuda, K, and Nakamura, T, 2012 A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan, *Nature*, **486**, 240–42

Miyake, F, Masuda, K, and Nakamura, T, 2013 Another rapid event in the carbon-14 record of tree rings, *Naure Communications*, **4**, 1748

Mook, W G, 1986 Business meeting: recommendations/resolutions adopted by the Twelfth International Radiocarbon Conference, *Radiocarbon*, **28**, 799

Nayling, N, 1999 *Tree-ring analysis of timbers from the White House, Vowchurch, Herefordshire*, Anc Mon Lab Rep, **73/1999**

Niu, M, Heaton, T J, Blackwell, P G, and Buck, C E, 2013 The Bayesian approach to radiocarbon calibration curve estimation: the IntCal13, Marine13, and ShCal methodologies, *Radiocarbon*, **55**, 1905–22

Pearson, G W, Pilcher, J R, Baillie, M G L, Corbett, D M, and Qua, F, 1986 High-Precision C-14 Measurement of Irish Oaks to Show the Natural C-14 Variations from AD 1840 to 5210 BC, *Radiocarbon*, **28**, 911–34

Reimer, P J, Bard, E, Bayliss, A, Beck, J W, Blackwell, P G, Bronk Ramsey, C, Buck, C E, Cheng H, Edwards R L, Friedrich, M, Grootes, P M, Guilderson, T P, Haflidason, H, Hajdas, I, Hatté, C, Heaton, T J, Hoffmann, D L, Hogg, A G, Hughen, K A, Kaiser, K F, Kromer, B, Manning, S W, Niu, M, Reimer, R W, Richards, D A, Scott, E M, Southon, J R, Staff, R A, Turney, C S M, and van der Plicht, J, 2013 Intcal 13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP, *Radiocarbon*, **55**, 1869–87

Scott, E M 2003 The third international radiocarbon intercomparison (TIRI) and the fourth international radiocarbon intercomparison (FIRI) 1990–2002: results, analyses, and conclusions, *Radiocarbon*, **45**, 135–408

Scott, E M, Cook, G T, Naysmith, P, Bryant, C and O'Donnell, D 2007 A report on phase 1 of the 5th international radiocarbon intercomparison (VIRI), *Radiocarbon*, **49**, 409–26.

Scott, E M, Cook, G T and Naysmith, P 2010 A report on phase 2 of the fifth international radiocarbon intercomparison (VIRI), *Radiocarbon*, **52**, 846–858

Slota, Jr P J, Jull, A J T, Linick, T W, and Toolin, L J, 1987 Preparation of small samples for ^{14}C accelerator targets by catalytic reduction of CO, *Radiocarbon*, **29**, 303–6

Stuiver, M, and Polach, H A, 1977 Reporting of ^{14}C data, *Radiocarbon*, **19**, 355–63

Stuiver, M and Kra, R S 1986 Editorial comment, *Radiocarbon*, **28**

Stuiver, M, and Reimer, P J, 1986 A computer program for radiocarbon age calculation *Radiocarbon*, **28**, 1022–30

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

Stuiver, M, Reimer, P J, and Braziunas, T F, 1998 High-precision radiocarbon age calibration for terrestrial and marine samples, *Radiocarbon*, **40**, 1127–51

Tyers, C, Hurford, M, and Bridge, M, 2014 *Dauntsey House, Church Lane, Dauntsey, Wiltshire: Tree-Ring Analysis of Timbers*, Eng Her, Res Rep Ser **62-2014**

Vandeputte, K, Moens, L, and Dams, R, 1996, Improved sealed-tube combustion of organic samples to CO_2 for stable isotope analysis, radiocarbon dating and percent carbon determinations, *Analytical Letters*, **29**, 2761–73

Wacker, L, Güttler, D, Goll, J, Hurni, J P, Synall, H-A, and Walti, N, 2014 Radiocarbon dating to a single year by means of rapid atmospheric ^{14}C changes, *Radiocarbon*, **56**, 573–9

Xu, S, Anderson, R, Bryant, C, Cook, G T, Dougans, A, Freeman, S, Naysmith, P, Schnable, C, and Scott, A E M, 2004 Capabilities of the new SUERC 5MV AMS facility for ^{14}C dating, *Radiocarbon*, **46**, 59–64

Ward, G K and Wilson, S R, 1978 Procedures for comparing and combining radiocarbon age determinations: a critique, *Archaeometry*, **20**, 19–31

TABLES

Table 1: Details of tree-ring samples from the north wing, the Chantry, Kilve, Somerset

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
KLV-A01	Ground floor, east wall, north window, inner lintel	109	h/s	------	------	------
KLV-A02	Ground floor, west wall, north window, inner lintel	76	no h/s	------	------	------
KLV-A03	Ground floor, west wall, south window, outer lintel	110	no h/s	------	------	------
KLV-A04	Ground floor, south wall, window lintel	52	h/s	------	------	------
KLV-A05	First floor, east wall, north window lintel	126	19	------	------	------
KLV-A06	First floor, east wall, south window lintel	120	h/s	1425	1544	1544
KLV-A07	First floor, west wall, south window lintel	nm	---	------	------	------
KLV-A08	Second floor, north gable window lintel	60	no h/s	1465	------	1524

h/s the last ring on the sample is at the heartwood/sapwood boundary
nm = not measured

Table 2: Results of the cross-matching of site sequence KLVASQ01 and relevant reference chronologies when the first-ring date is AD 1425 and the last-ring date is AD 1544

Reference chronology	Span of chronology	*t*-value	Reference
Court House, Shelsley Walsh, Worcestershire	AD 1387–1575	7.7	Arnold *et al* 2008
26 Westgate Street, Gloucester	AD 1399–1622	7.6	Howard *et al* 1998
Muchelney Abbey, Somerset	AD 1148–1498	7.5	Bridge 2002
White House, Vowchurch, Herefordshire	AD 1364–1602	7.2	Nayling 1999
Mercer's Hall, Westgate Street, Gloucester	AD 1289–1541	6.9	Howard *et al* 1996
Dauntsey House, Dauntsey, Wiltshire	AD 1393–1580	6.9	Tyers *et al* 2014
Warleigh House, Tamerton Foliot, Devon	AD 1367–1539	6.7	Howard *et al* 2006
Trerice, Kestle Mill, Cornwall	AD 1394–1562	6.6	Hurford *et al* 2009

Table 3: Radiocarbon results from the north wing, Chantry, Kilve, Somerset

Laboratory Number	Sample details	Calendar Age (AD)	δ¹³C (‰)	Radiocarbon Age (BP)	Calibrated Date – cal AD (95% confidence)	*Posterior Density Estimate – cal AD (95% probability)*
KLV-A01						
SUERC-40198	*Quercus* sp, heartwood, ring 2		-25.1±0.2	790±30	1205–1280	*1125–1185*
OxA-26565	*Quercus* sp, heartwood, ring 23		-26.6±0.2	933±27	1020–1170	*1145–1210*
SUERC-40199	*Quercus* sp, heartwood, ring 44		-27.7±0.2	795±30	1190–1280	*1165–1230*
OxA-26566	*Quercus* sp, heartwood, ring 65		-26.6±0.2	811±26		
OxA-26567	*Quercus* sp, heartwood, ring 65		-26.9±0.2	825±27		
Ring 65	Weighted mean (T'=0.1; T'(5%)=3.8; ν=1)			818±19	1185–1265	*1185–1250*
SUERC-40200	*Quercus* sp, heartwood, ring 86		-26.0±0.2	780±30	1210–1280	*1210–1270*
OxA-26568	*Quercus* sp, heartwood, ring 107		-24.6±0.2	804±26	1185–1280	*1230–1290*
KLV-A04						
OxA-26569	*Quercus* sp, heartwood, ring 3		−23.6±0.2	901±26	1035–1220	*1135–1205*
SUERC-40201	*Quercus* sp, heartwood, ring 12		−26.3±0.2	765±30	1215–1290	*1145–1215*
OxA-26570	*Quercus* sp, heartwood, ring 21		−25.4±0.2	884±26	1040–1220	*1155–1225*
SUERC-40202	*Quercus* sp, heartwood, ring 29		−25.7±0.2	780±30	1210–1280	*1165–1230*
OxA-26571	*Quercus* sp, heartwood, ring 39		−25.3±0.2	892±26	1040–1220	*1175–1240*
SUERC-40203	*Quercus* sp, heartwood, ring 49		−24.8±0.2	830±30	1155–1270	*1185–1245*
KLV-A06						
OxA-28706	*Quercus* sp, heartwood, ring 2	1426	−24.5±0.2	535±23	1325–1435	*1405*–1420
SUERC-48663	*Quercus* sp, heartwood, ring 12	1436	−25.5±0.2	522±26	1330–1440	*1415–1430*
OxA-28707	*Quercus* sp, heartwood, ring 22	1446	−24.8±0.2	465±21	1420–1455	*1425–1440*
SUERC-48667	*Quercus* sp, heartwood, ring 33	1457	−25.1±0.2	442±21	1430–1460	*1435–1455*
OxA-28708	*Quercus* sp, heartwood, ring 43	1467	−25.1±0.2	407±22	1440–1615	*1445–1465*
SUERC-48668	*Quercus* sp, heartwood, ring 55	1479	−23.7±0.2	497±26	1400–1450	*1455–1475*
OxA-28709	*Quercus* sp, heartwood, ring 64	1488	−25.8±0.2	317±23	1485–1650	*1465–1485*
SUERC-48669	*Quercus* sp, heartwood, ring 74	1498	−25.0±0.2	422±23	1435–1485	*1475–1495*
OxA-28710	*Quercus* sp, heartwood, ring 84	1508	−25.6±0.2	332±22	1465–1645	*1485–1505*
SUERC-48670	*Quercus* sp, heartwood, ring 95	1519	−25.0±0.2	400±26	1440–1620	*1495–1515*

Laboratory Number	Sample details	Calendar Age (AD)	δ^{13}C (‰)	Radiocarbon Age (BP)	Calibrated Date – cal AD (95% confidence)	*Posterior Density Estimate – cal AD (95% probability)*
KLV-A06						
OxA-28711	*Quercus* sp, heartwood, ring 106	1530	−25.5±0.2	352±23		
OxA-28712	*Quercus* sp, heartwood, ring 106	1530	−25.5±0.2	297±23		
Ring 106	Weighted mean (T'=2.9; T'(5%)=3.8; ν=1)	1530		325±17	1485–1645	*1510–1525*
SUERC-48671	*Quercus* sp, heartwood, ring 117	1541	−25.1±0.2	367±26	1445–1640	*1520–1535*

FIGURES

Figure 1: Location of Kilve. © Crown Copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900

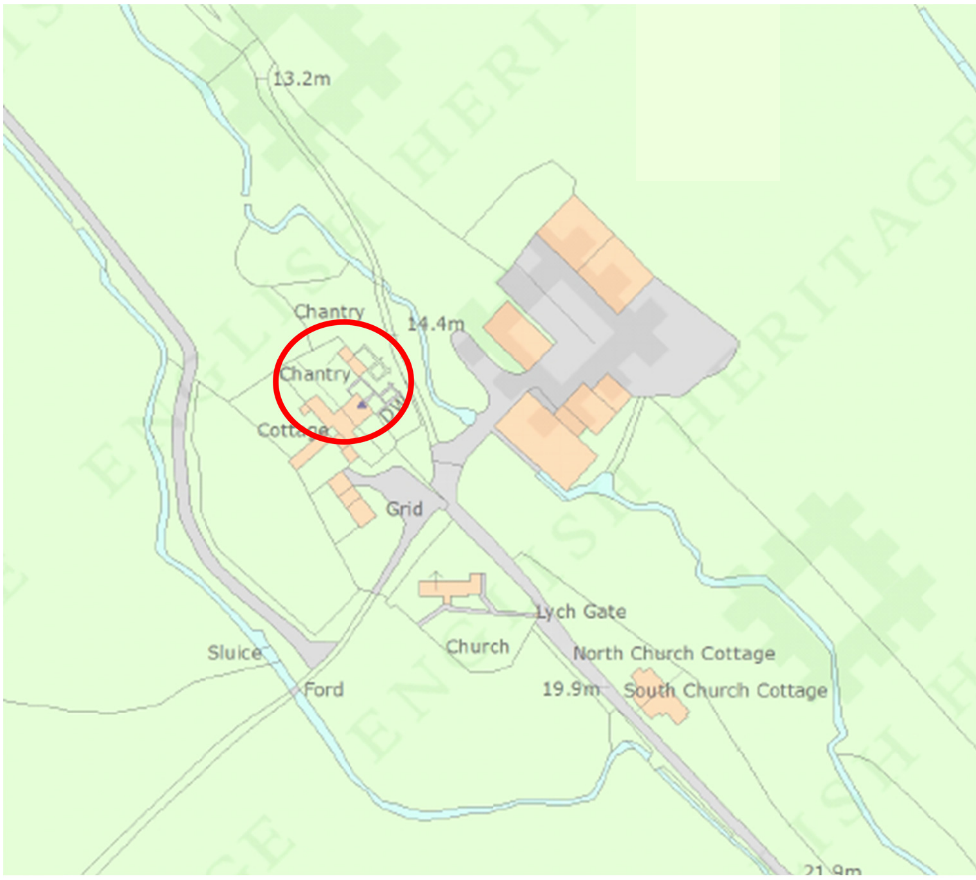


Figure 2: Map to show the location of the Chantry at Kilve (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

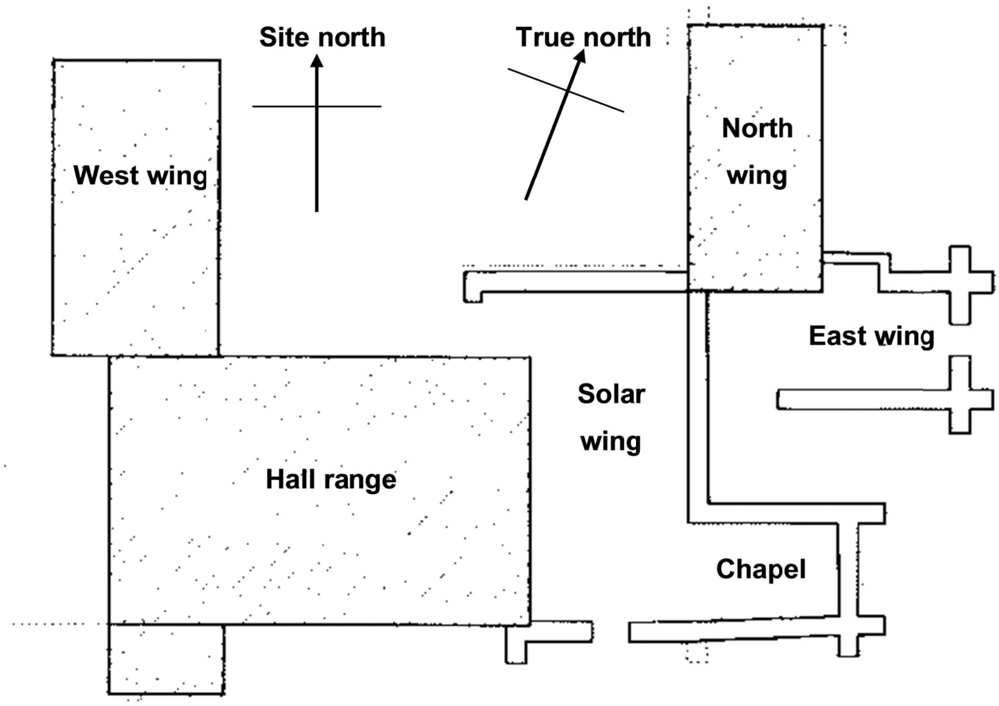


Figure 3: Plan to show arrangement and location of the Kilve Chantry buildings (afterJones 2003)

Figure 4: The north wing viewed from the west looking east (photograph Robert Howard)

Figure 5: The north wing: ground floor looking north (photograph Robert Howard)

Figure 6: The first floor looking south (photograph Robert Howard)

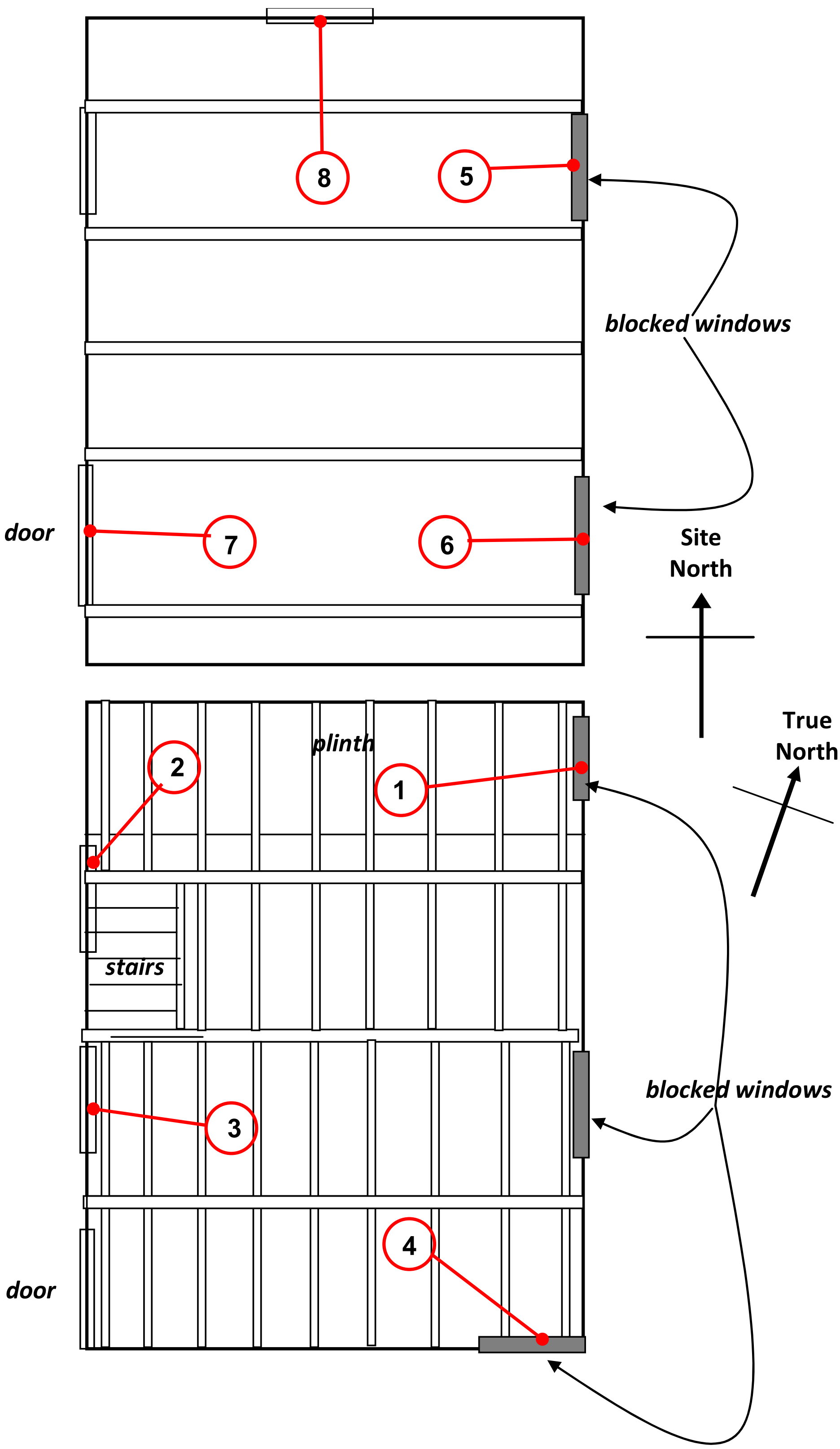


Figure 7: The north wing to show sampled lintels (first floor - top, ground floor - bottom)

Figure 8a: KLV-A01: ground floor, east wall, north window, inner lintel (photograph Robert Howard)

Figure 8b: KLV-A02: ground floor, west wall, north window, inner lintel (photograph Robert Howard)

Figure 8c: KLV-A03: ground floor, west wall, south window, outer lintel (photograph Robert Howard)

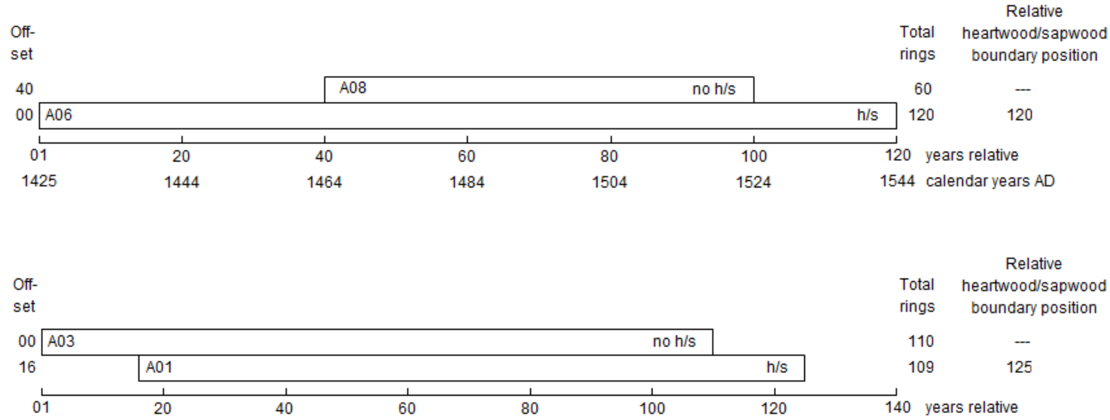
Figure 8d: KLV-A04: ground floor, south wall, window lintel (photograph Robert Howard)

Figure 8e: KLV-A05: first floor, east wall, north window lintel (photograph Robert Howard)

Figure 8f: KLV-A06: first floor, east wall, south window lintel (photograph Robert Howard)

Figure 8g: KLV-A07: first floor, west wall, south window lintel (photograph Robert Howard)

Figure 8h: KLV-A08: second floor, north gable window lintel (photograph Robert Howard)



white bars = heartwood rings
h/s = heartwood/sapwood boundary

Figure 9a/b: Bar diagrams of the samples in site chronologies KLVASQ01 (top) and KLVASQ02 (bottom

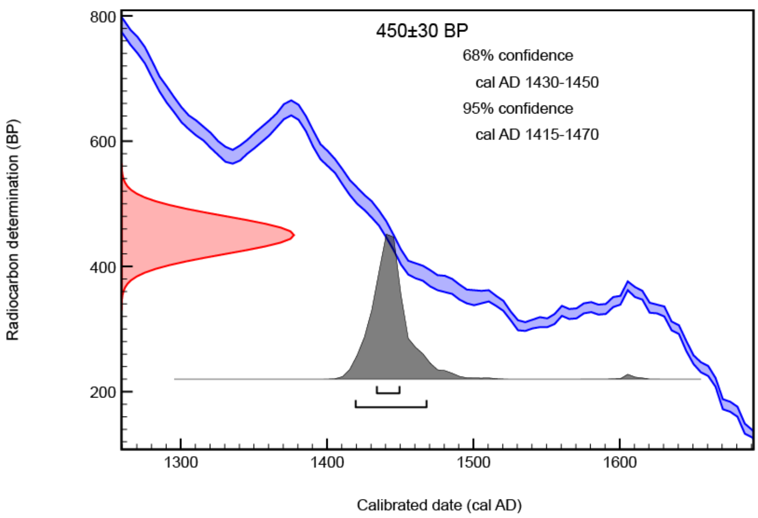


Figure 10: A radiocarbon measurement of 450±30 BP (in pink on the vertical axis) calibrated to AD 1430–1450 at 68% confidence and AD 1415–1470 at 95% confidence (in black on the horizontal axis). The blue band is the relevant part of the calibration curve

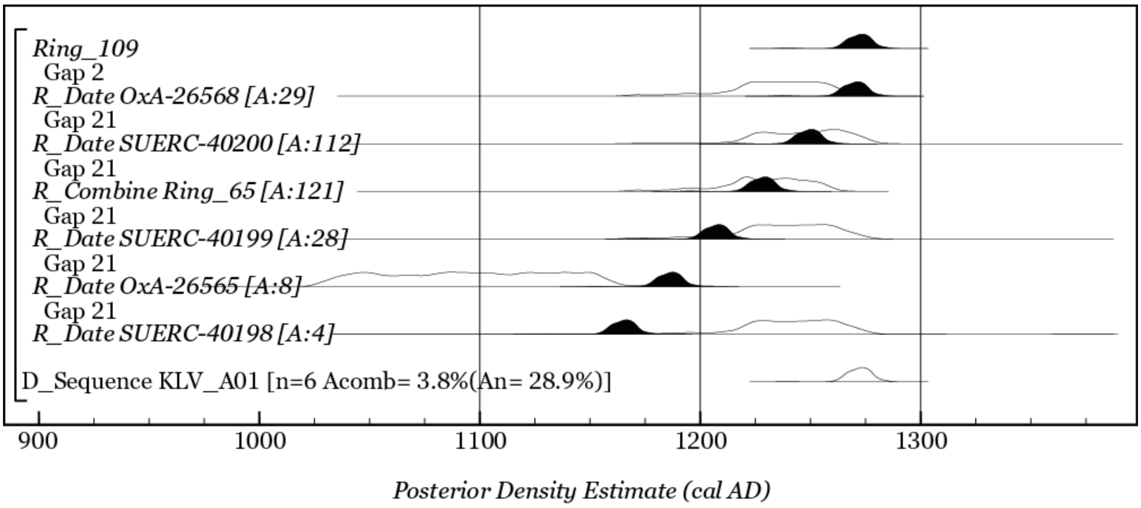


Figure 11: Probability distributions of dates from timber KLV-A01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, 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

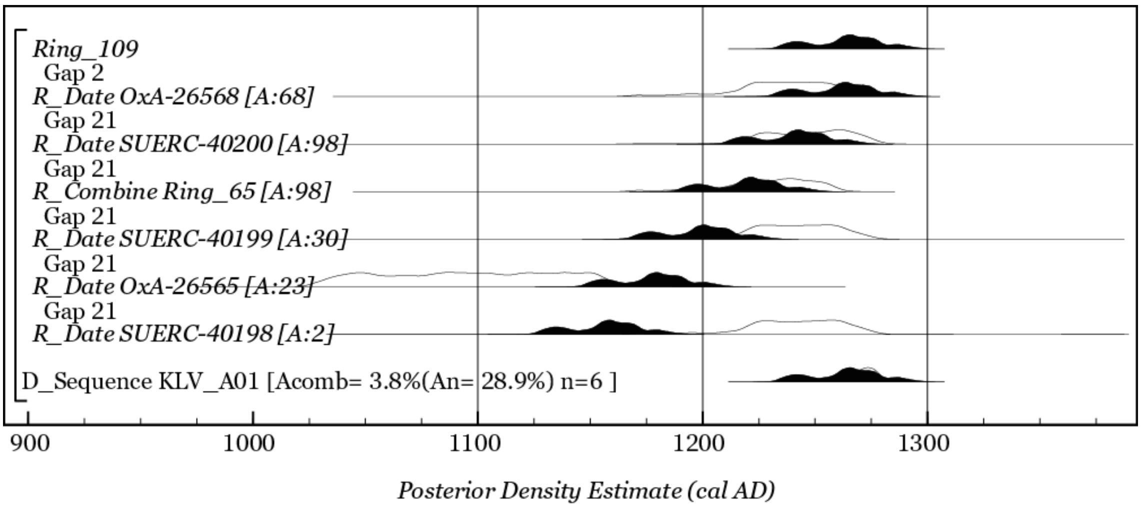


Figure 12: Probability distributions of dates from timber KLV-A01 – r-*type outlier model (Bronk Ramsey 2009b). The format is identical to Figure 10*

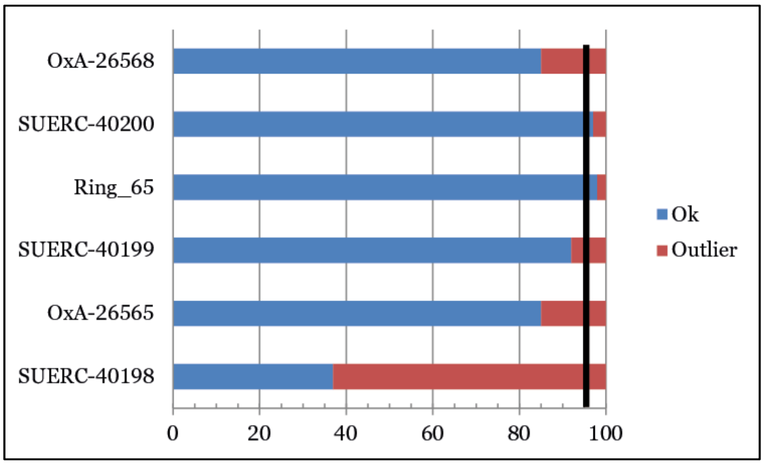


Figure 13: KLV-A01 - OxCal (r-type) outlier analysis (Bronk Ramsey 2009b), The prior probability of each date being an outlier was set at 5%

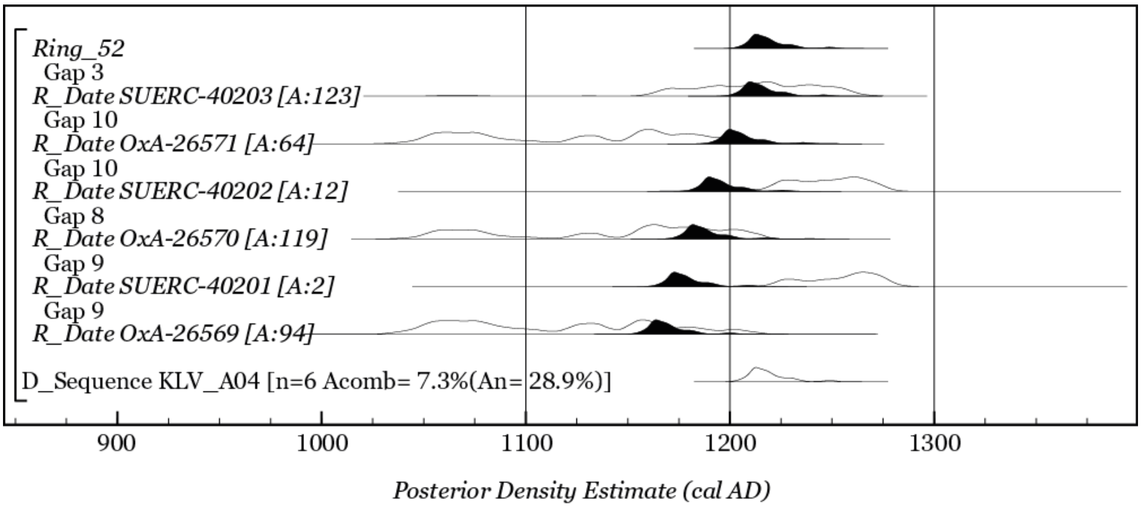


Figure 14: Probability distributions of dates from timber KLV-A04. The format is identical to Figure 10

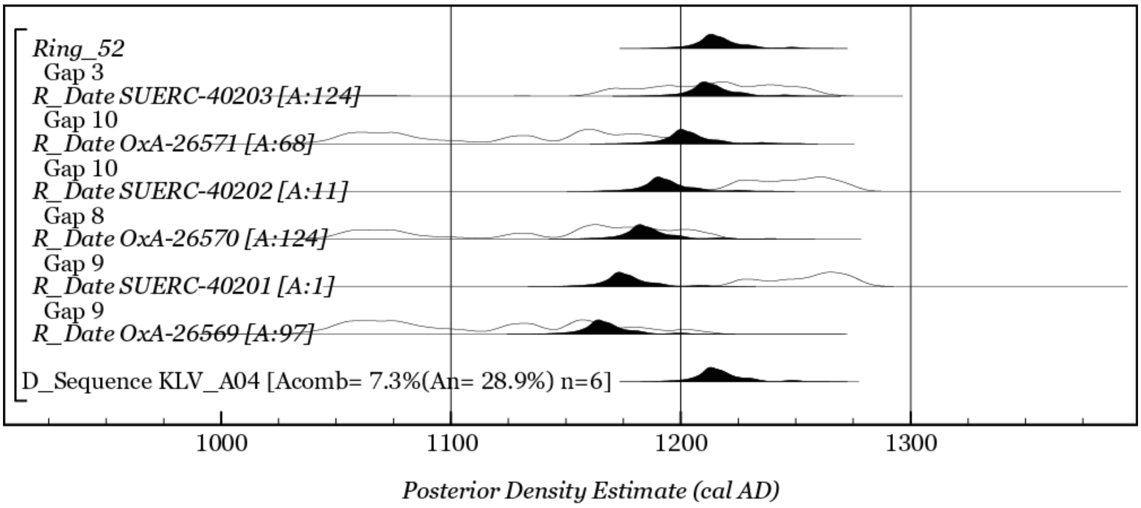


Figure 15: Probability distributions of dates from the timber KLV-A04 – r*-type outlier model (Bronk Ramsey 2009b). The format is identical to Figure 10*

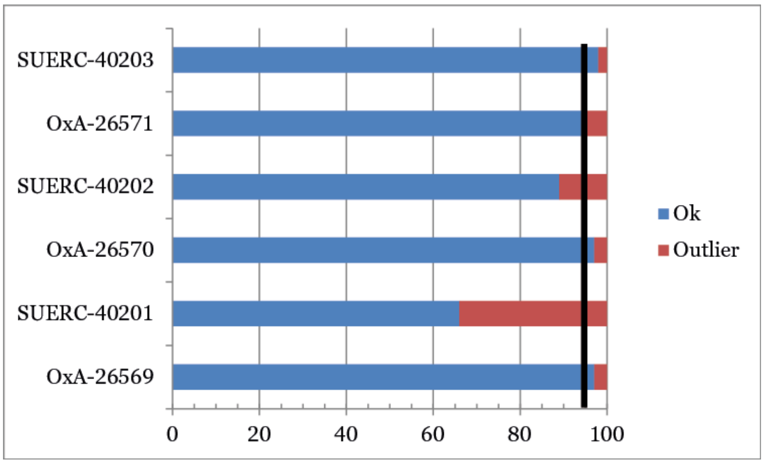


*Figure 16: KLV-A04- OxCal (*r*-type) outlier analysis (Bronk Ramsey 2009b). The prior probability of each date being an outlier was set at 5%*

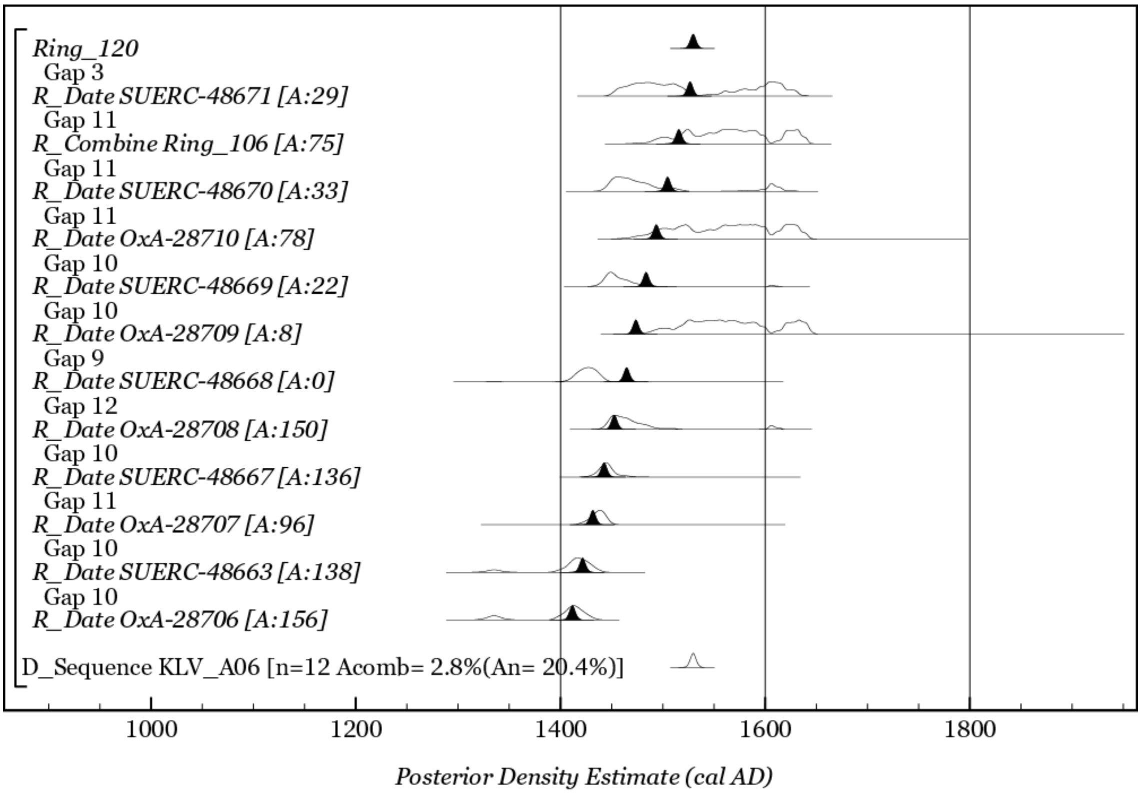


Figure 17: Probability distributions of dates from timber KLV-A06. The format is identical to Figure 10

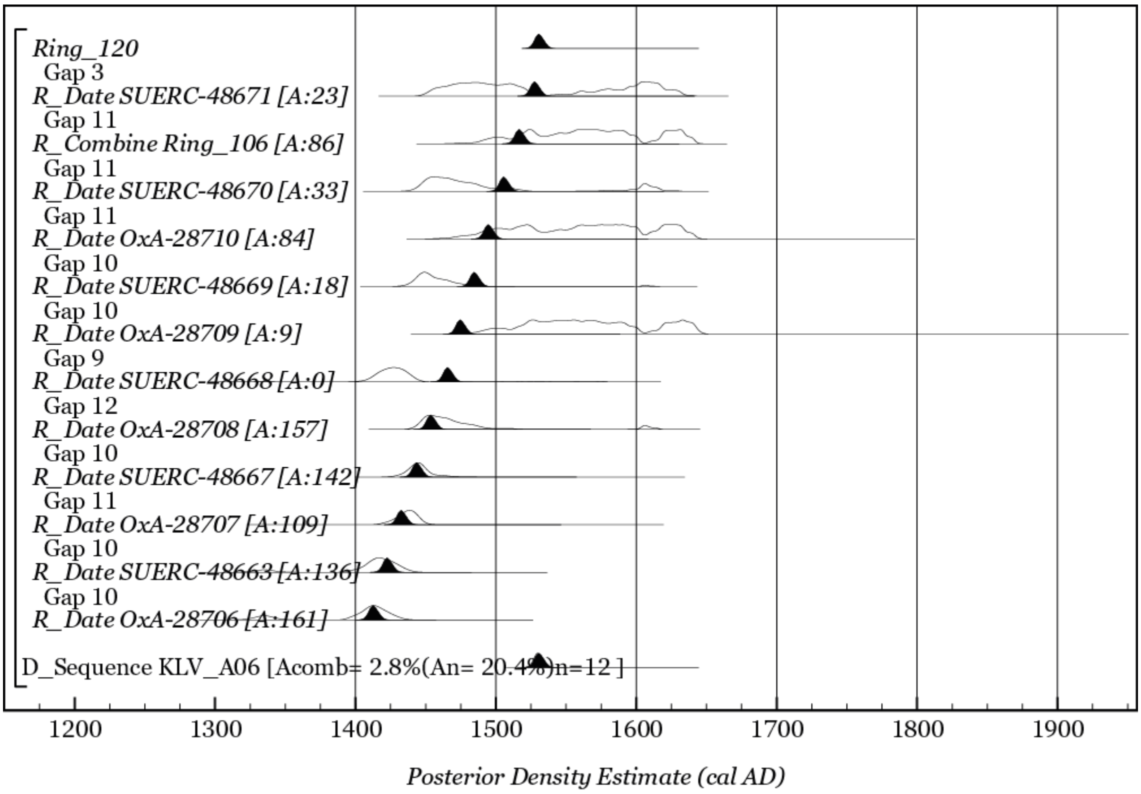


Figure 18: Probability distributions of dates from timber KLV-A06 – r*-type outlier model (Bronk Ramsey 2009b). The format is identical to Figure 10*

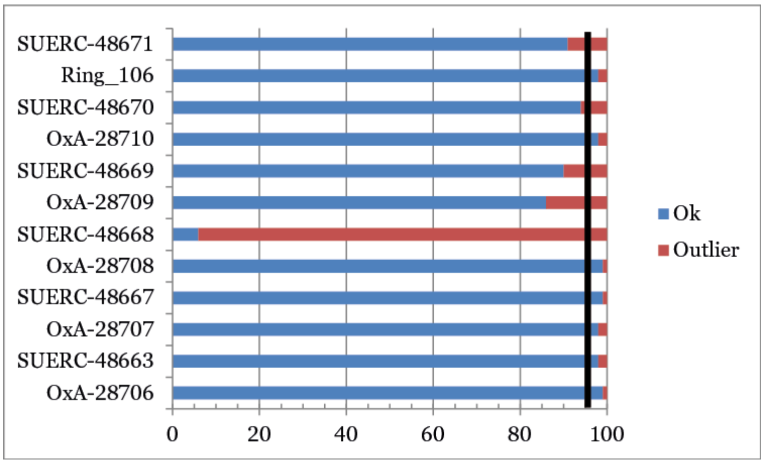


*Figure 19: KLV-A06- OxCal (*r*-type) outlier analysis (Bronk Ramsey 2009b). The prior probability of each date being an outlier was set at 5%*

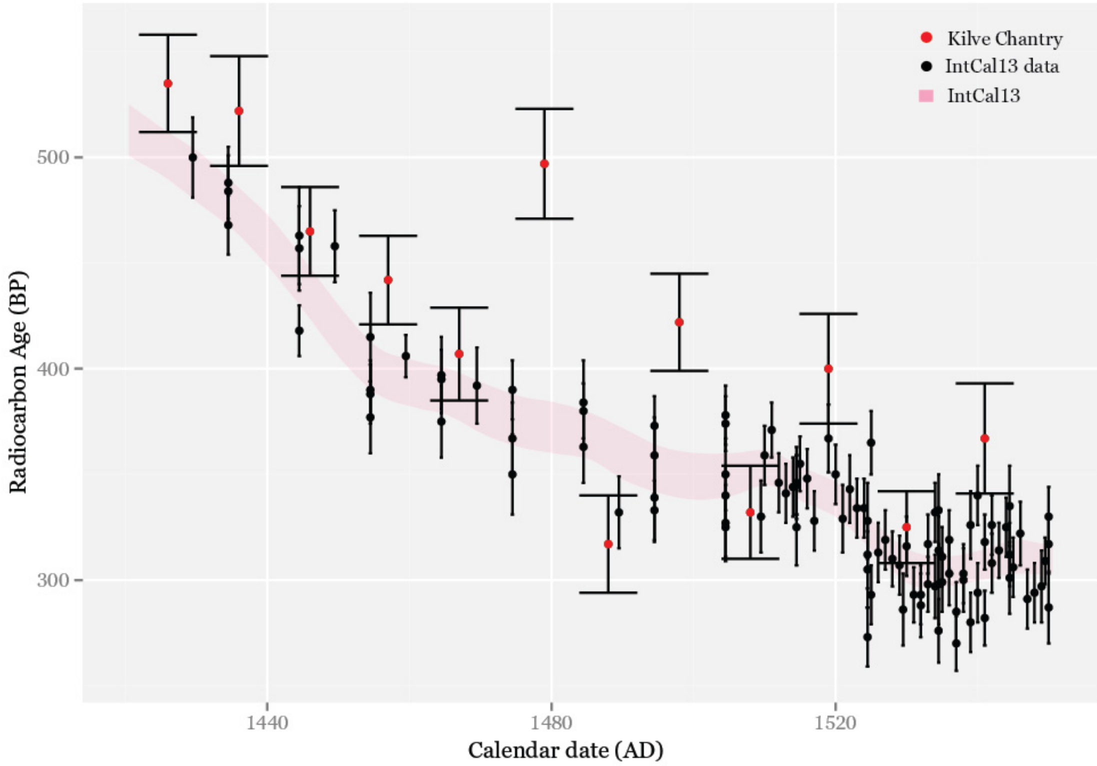


Figure 20: ^{14}C measurements of tree-ring samples from Kilve Chantry plotted on the IntCal13 calibration curve together with the IntCal13 data points; Hogg et al *(2002), Pearson* et al *(1986) and Stuiver* et al *(1998)*

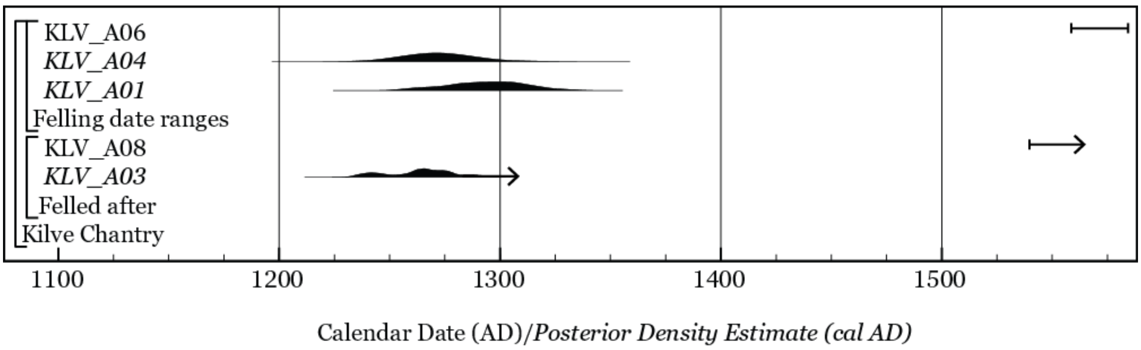


Figure 21: Summary of the scientific dating evidence from Kilve Chantry lintels

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

KLV-A01A 108
368 453 497 369 308 283 209 166 197 216 253 271 182 173 96 71 65 134 113 94
106 104 103 120 130 94 45 44 49 53 78 87 104 110 130 168 197 109 109 106
131 108 96 135 124 138 126 116 132 176 157 239 183 145 152 158 158 88 59 47
65 66 60 80 86 72 75 85 69 70 73 71 85 89 98 73 57 69 82 89
60 116 61 70 90 78 65 66 79 123 117 107 117 92 120 132 113 113 163 148
116 126 143 107 120 127 166 77

KLV-A01B 109
365 456 512 365 314 294 200 167 196 207 250 256 175 174 88 82 68 134 97 100
115 113 113 113 135 100 38 38 55 50 84 89 95 114 136 159 202 103 115 110
127 105 97 131 128 142 128 110 135 171 170 245 157 138 164 156 162 91 56 42
64 64 60 80 86 70 77 66 72 76 88 72 79 91 105 74 50 63 77 102
60 99 77 80 82 88 66 55 88 102 111 98 126 96 119 137 111 105 176 163
108 125 130 110 133 115 166 85 128

KLV-A02A 76
158 263 294 317 177 148 220 171 156 191 340 300 263 180 423 369 369 392 383 316
402 275 166 211 214 360 319 335 275 250 320 213 124 234 118 175 187 142 112 92
117 185 221 199 184 184 186 191 137 176 150 237 171 148 182 201 146 85 107 103
171 141 119 155 90 123 70 84 184 131 161 115 67 55 54 72

KLV-A02B 76
161 283 274 315 174 157 211 190 182 177 350 297 252 186 427 375 333 374 366 338
424 266 165 216 191 378 316 336 278 244 336 207 122 228 146 151 193 142 120 97
110 183 217 199 172 189 195 192 142 174 156 227 174 154 187 191 140 69 118 107
173 138 123 138 110 116 79 73 184 117 155 119 67 56 54 60

KLV-A03A 110
193 129 81 156 267 191 181 190 160 173 155 262 241 207 209 180 212 138 167 155
213 174 152 106 144 128 161 246 214 206 112 95 134 160 178 185 215 246 144 208
304 217 194 245 186 140 195 169 103 115 136 100 178 93 114 115 122 76 63 113
97 135 129 55 65 125 87 86 69 94 73 96 149 105 64 70 195 162 57 147
115 108 67 89 54 105 107 75 79 84 78 56 59 72 123 131 95 79 80 79
123 92 79 78 128 146 86 85 72 77

KLV-A03B 110
161 124 77 176 268 194 212 237 207 156 153 303 256 222 183 169 194 134 199 178
226 178 152 105 136 130 163 234 225 211 116 92 139 152 182 184 216 243 140 208
317 197 193 249 199 132 182 182 113 107 142 97 187 92 106 121 118 73 67 117
94 123 119 54 43 122 89 86 74 86 77 101 146 104 62 76 194 156 59 142
134 102 65 84 62 101 109 79 81 78 80 42 72 83 118 127 98 80 74 85
121 87 86 78 127 145 91 82 75 79

KLV-A04A 52
123 44 144 170 47 271 211 292 361 332 342 352 397 289 161 130 138 118 178 239
158 97 122 169 93 70 87 82 82 76 64 95 93 133 125 89 110 91 101 123

161 167 131 126 256 145 266 218 145 111 123 109

KLV-A04B 52
128 48 141 176 54 215 228 361 333 271 335 335 381 302 164 138 128 122 162 236
157 100 118 174 82 77 81 78 88 79 63 95 92 133 123 95 108 86 114 116
161 169 129 134 257 135 272 227 153 109 106 96

KLV-A05A 126
168 326 342 257 253 220 169 208 165 197 191 206 259 224 145 229 228 202 193 189
199 183 193 146 143 139 172 170 229 260 190 263 100 38 41 42 40 33 21 36
35 24 36 77 69 83 54 73 52 86 29 29 37 24 21 27 40 30 45 45
81 59 76 52 70 25 51 37 70 97 66 51 70 48 64 71 50 112 144 127
126 165 101 46 24 21 27 39 59 51 66 118 108 127 89 104 128 89 96 116
47 31 25 27 23 41 125 148 166 178 139 123 127 127 125 81 127 175 79 132
96 152 151 168 117 128

KLV-A05B 126
168 318 348 253 248 213 166 212 177 194 190 212 261 221 143 226 224 210 194 190
195 179 188 146 142 128 180 189 230 262 183 256 96 37 51 32 38 34 20 40
38 28 36 74 66 83 50 60 53 88 29 32 34 30 24 28 38 30 48 46
76 63 79 56 67 27 42 48 67 99 66 55 67 50 65 85 44 112 151 131
115 170 95 48 23 23 30 36 60 53 64 119 111 127 97 102 127 91 99 108
50 33 23 26 21 42 130 149 172 163 157 125 131 120 115 78 128 170 78 131
98 153 154 168 110 127

KLV-A06A 120
285 283 235 212 160 196 214 326 221 184 401 281 338 242 232 211 282 174 172 185
214 212 192 204 232 197 233 144 197 163 152 128 163 184 143 205 136 144 164 91
126 114 147 158 146 191 113 98 88 108 94 95 94 72 80 84 133 126 129 113
106 119 131 116 116 117 104 76 126 163 163 227 134 159 220 141 154 148 198 153
143 134 294 214 206 162 158 136 152 162 136 122 181 161 228 148 174 251 187 137
138 113 135 145 144 111 217 109 58 82 84 128 127 130 123 171 213 97 127 151

KLV-A06B 120
303 288 229 227 162 194 205 318 205 180 338 303 336 226 233 226 331 186 164 196
220 209 195 189 244 199 229 143 180 162 161 134 154 188 136 208 133 149 152 96
133 117 137 169 147 181 104 109 84 94 92 102 77 68 76 82 144 121 123 126
91 115 132 117 114 120 104 84 118 166 160 227 136 163 209 150 217 131 205 153
138 135 298 212 203 167 162 136 154 156 134 125 189 153 231 146 170 244 199 132
145 112 127 152 134 132 206 123 58 79 82 124 115 133 136 174 217 119 143 163

KLV-A08A 60
134 127 135 143 141 177 133 123 106 109 103 93 88 93 120 88 168 141 147 99
151 150 178 145 149 174 151 117 157 213 239 336 263 466 958 839 627 553 398 434
302 346 292 322 471 282 302 316 270 298 246 188 368 353 540 272 429 581 442 329

KLV-A08B 60
138 110 141 147 140 180 126 116 110 111 100 97 84 98 116 96 168 141 146 113
142 147 184 144 161 169 144 118 167 218 230 328 254 458 985 844 619 566 388 442
311 342 297 333 455 287 303 317 268 297 255 192 357 365 535 281 450 591 408 335

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can

sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form

they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

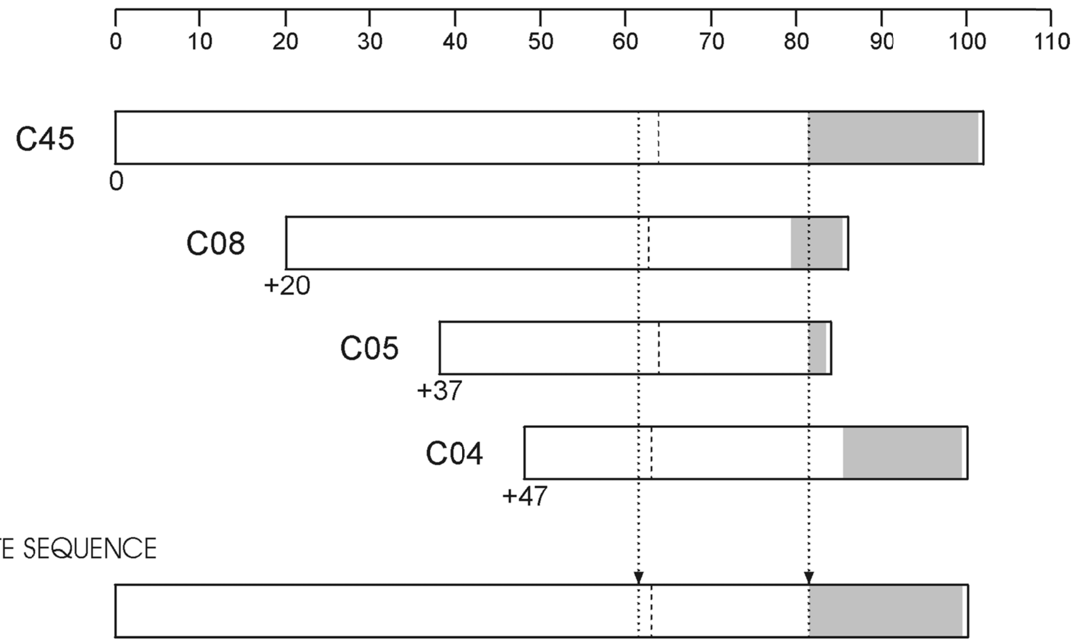


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

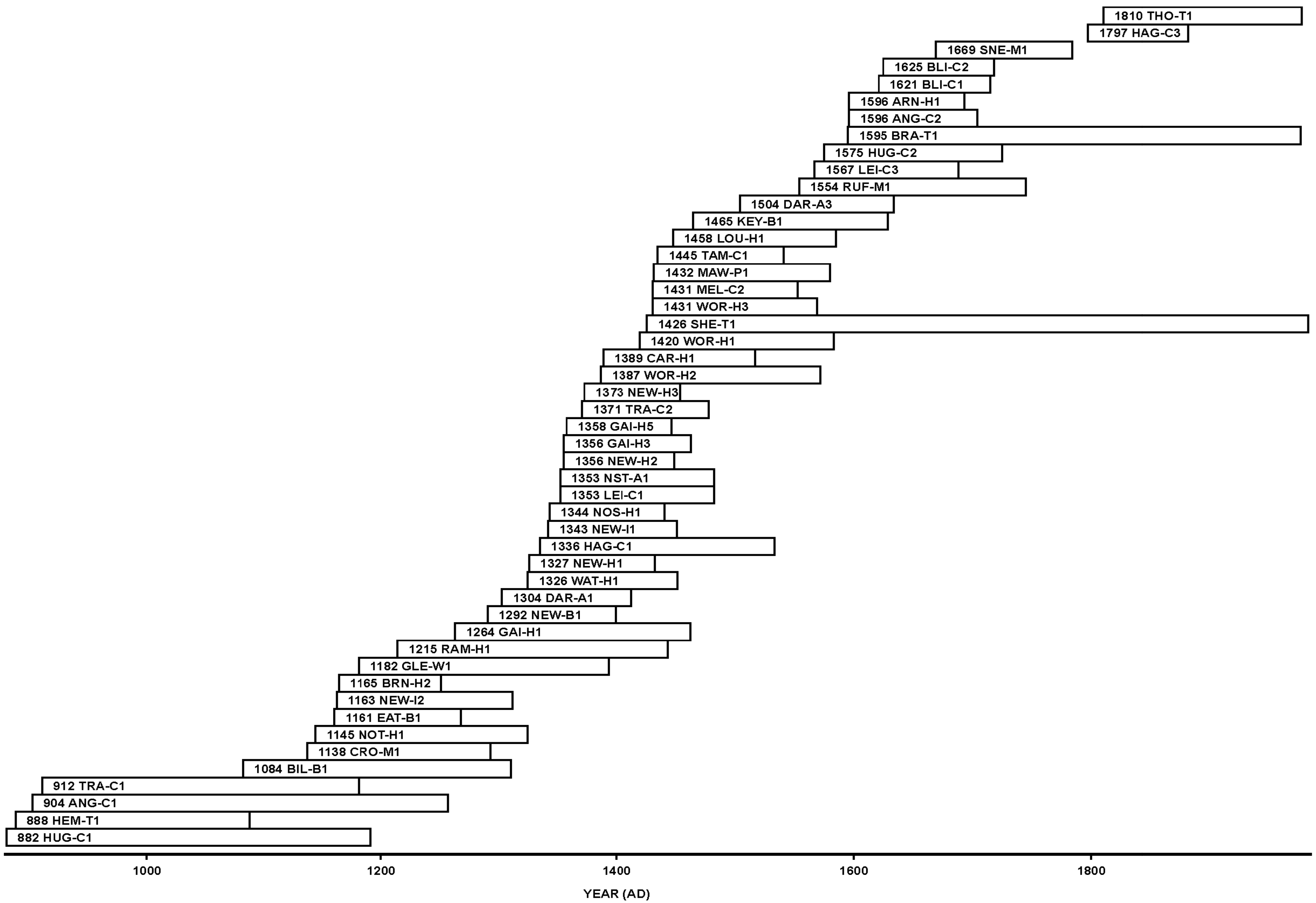
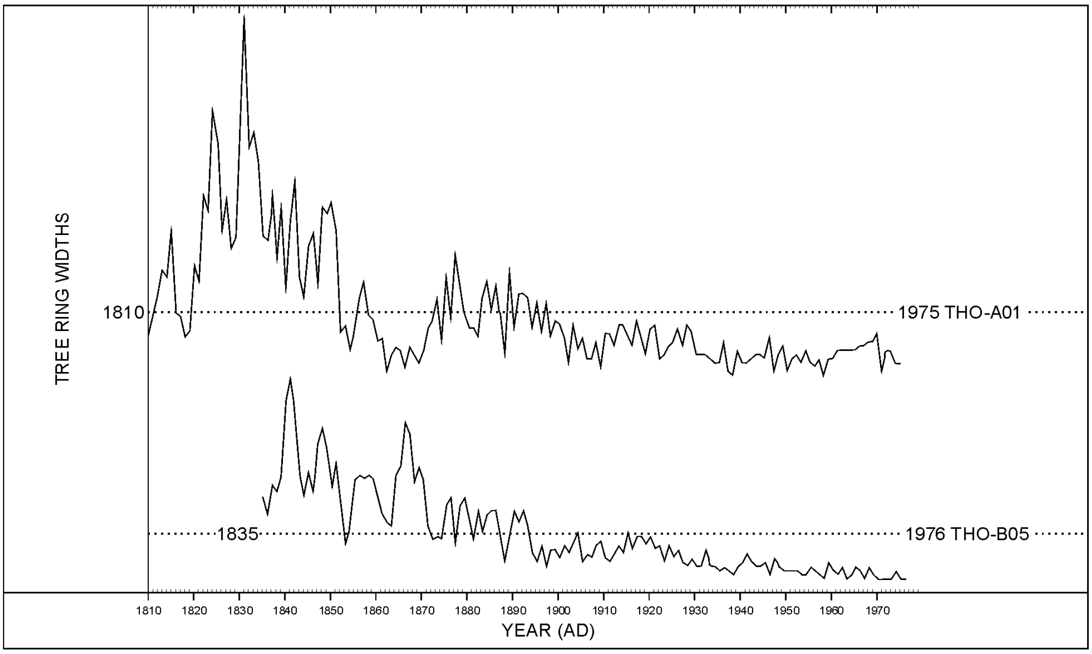


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

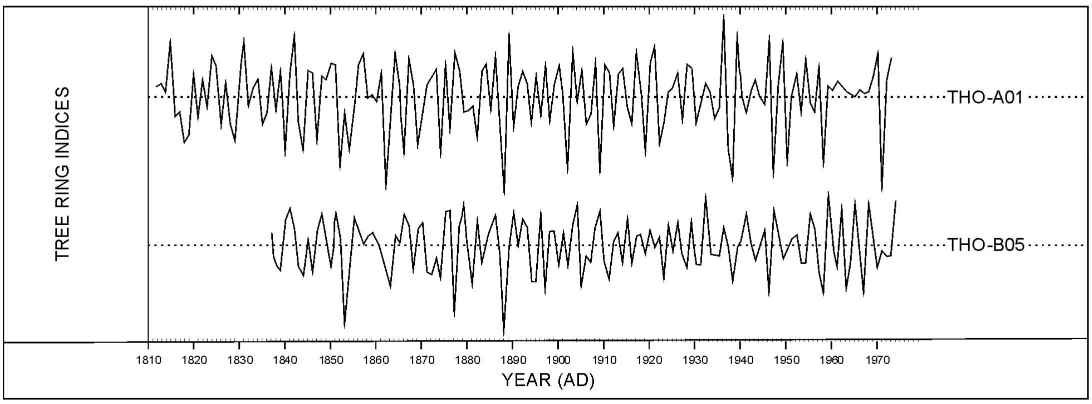


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known.

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

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

The growth trends have been removed completely

References

Baillie, M G L, and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-Ring Bulletin*, **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 Architecture*, **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 Architecture*, **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 A*n 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 Archaeology*, **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, *Journal of Archaeological Science*¸ **18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architecture*, **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

Historic England Research and the Historic Environment

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

Historic England works to improve care, understanding and public enjoyment of the historic environment. We undertake and sponsor authoritative research. We develop new approaches to interpreting and protecting heritage and provide high quality expert advice and training.

We make the results of our work available through the Historic England Research Report Series, and through journal publications and monographs. Our online magazine Historic England Research which appears twice a year, aims to keep our partners within and outside Historic England up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.HistoricEngland.org.uk/researchreports

Some of these reports are interim reports, making the results of specialist investigations available in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation.

Where no final project report is available, you should consult the author before citing these reports in any publication. Opinions expressed in these reports are those of the author(s) and are not necessarily those of Historic England.

The Research Reports' database replaces the former:

Ancient Monuments Laboratory (AML) Reports Series
The Centre for Archaeology (CfA) Reports Series
The Archaeological Investigation Report Series and
The Architectural Investigation Reports Series.

ISSN 2059-4453 (Online)