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Cropple How, Muncaster, Ravenglass, Cumbria

Tree-Ring Analysis and Radiocarbon Wiggle-Matching of Oak Timbers

Alison Arnold, Robert Howard, Shahina Farid,
Christopher Bronk Ramsey, Gordon Cook, and Paula Reimer

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SUMMARY
Dendrochronological analysis was undertaken on 39 of the 54 oak timber samples taken from different locations within the extensive complex of buildings at Cropple How. This resulted in the production of six site chronologies, each comprising between two and five samples, of lengths between 60 and104 rings. These six site chronologies account for 15 measured samples.

Only one site chronology, comprising two samples from principal rafters of the Garage barn, could be dated by dendrochronology, these giving an estimated felling date in the range of AD 1517–42. Thus, cores from three of the five undated sequences were selected for radiocarbon dating and wiggle-matching. This method suggested the likelihood that small assemblages of timbers were felled concurrently and episodically as required, ranging from the early mid-sixteenth to the mid-eighteenth centuries.

CONTRIBUTORS
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INTRODUCTION

The complex of structures at Cropple How (Figs 1–3) comprises a Former Farmhouse, now used as a barn incorporating a byre and outshot, the present farmhouse with an attached barn now used as a garage, and two further barns, High Leys and Back barn, closely adjacent (Fig 4). Although an interpretative description of the buildings is beyond the scope of this report a brief description of these is given here, condensed from on-site discussions with Adam Menuge.

Former Farmhouse

The Former Farmhouse (Fig 5a–b), facing northwards towards the lane at the west edge of the site, is believed, on the basis of limited structural detail, to be of approximately mid-to-late sixteenth century date. It was originally a cruck-built longhouse of hearth-passage plan, of one storey and an attic. It is now used for general storage.

An unusual feature associated with the primary construction phase of the former farmhouse is a fully intact timber, wattle, and daub smokehood complete with reredos and heck, unique in possibly being Cumbria's only known example of this date. It is believed that in the early eighteenth century what was once the external wall of the building, east of the smokehood, was reduced to its footings and rebuilt to two full storeys, the building also being extended eastwards.

Although the present roof, formed by four principal rafter trusses with collars and double purlins (Fig 5c), is later, possibly of eighteenth-century date, it is thought to contain several timbers reused from the primary cruck phase, eg principal rafters identified as former cruck blades and a tiebeam thought to have been a purlin. There are also two redundant purlins in a wall thought to be from this earlier roof.

A first-floor frame is present, that to the west end also believed to be primary, being formed of a large bressummer and a small number of chamfered joists (Fig 5d). The floor frame towards the middle and east end of this building is believed to be later, possibly being coeval with the re-roofing.

Another unusual feature found in this building is a possibly early oak-plank door of fully pegged construction hung on oak hinges. The door is formed by three planks and hung within an oak frame of two jambs and a lintel (Fig 5e)

Present Farmhouse

The present farmhouse is thought to have mid eighteenth-century origins. It is of two-storeys and divided into three bays and has chimneys at either end (Fig 6a). The roof (Fig 6b) consists of two trusses with principal rafter, collars, two sets of purlins, and a ridge; at least one purlin may be reused. There are also some ceiling beams on the first floor that may be associated with the primary construction phase (Fig 6c).

Garage barn

Attached to the east side of the present farmhouse is the so-called 'Garage' barn' (Fig 7a). The roof here (Fig 7b) comprises three trusses, two with principal rafters and tiebeams, the third also having queen struts. There are double purlins to each pitch, and a ridge. At least one timber here appears to be reused, possibly from a cruck structure. Half of the building is floored with three main beams and common joists.

High Leys barn

East of the Garage barn, also facing north on to the lane, stands High Leys barn (Fig 8a). The roof here is of two trusses (Fig 8b) with principal rafters, tiebeams, collars, two sets of purlins, and ridge. One truss contains reused timber, again possibly from a cruck structure, though less certainly so.

Back barn

To the rear of the site stands the 'Back' barn (Fig 9a). The roof is also of two trusses of principal rafters and tiebeams with two sets of purlins to each pitch and a ridge to the apex (Fig 9b). Again some timbers are thought to be reused from a cruck structure.

TREE-RING SAMPLING

Sampling and analysis by dendrochronology of the timbers of all suitable parts of the Cropple How site were requested by Adam Menuge as part of Heritage Protection Research into the building. In particular, it was hoped that analysis would provide a precise date for the construction of the various buildings and give some indication of the date and sequence of their subsequent development and alteration.

An assessment of the potential for tree-ring analysis of all the buildings was made prior to sampling. This showed that, although there were some timbers which, being apparently derived from fast-grown trees, would not provide samples with the minimum of 50 rings deemed necessary for reliable analysis at this site, there were sufficient other timbers in each building to merit sampling and analysis.

Amongst particular timbers which were not sampled were those of the smokehood in the former farmhouse. Most of these were derived from fast-grown trees with low ring numbers, and the two which might have had 50+ could not be cored from the optimum angle to maximise ring numbers. In addition, this structure was slightly fragile and there was some concern over the effect of coring vibration. The door, requiring sampling by *in* *situ* readings, provided only one timber that was accessible, had sufficient rings for reliable analysis, and could be prepared for measuring without causing undue damage. Some buildings, High Leys barn, for example, provided only a few worthwhile timbers.

Thus, from the timbers which were both suitable and accessible a total of 53 oak samples was obtained by coring, with the data for sample 54 being obtained by direct *in situ* measurement of the prepared edge of one oak plank from the door. Each sample was given the code CPH-A (for Cropple How, site 'A') and numbered 01–54. The location of the sampled timbers was noted at the time of coring and marked either on annotated photographs, schematic drawings, long-sections based on a drawing held by the owners, or on a drawing by Allan Adams, former English Heritage illustrator. These are reproduced in this report as Figures 10a–h. Further details relating to the samples can be found in Table 1.

TREE-RING ANALYSIS

Each of the 53 core samples obtained was prepared by sanding and polishing. It was seen at this time that 15 of these had less than the minimum of 50 rings here deemed necessary for reliable dating, and so these were rejected from this programme of analysis. The annual growth-ring widths of the remaining 38 core samples were, however, measured, the data of these measurements, along with that obtained from the *in situ* measurement of the door plank, being given at the end of this report.

The 39 data sets thus obtained were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing six satisfactory groups, accounting for 15 cross-matching samples, to be formed at a high minimum value of t=6.5. The cross-matching samples of each group, as shown in Figures 11a–f, were combined at their indicated offset positions to form site chronologies CPHASQ01–CPHASQ06. Other potential matches were identified but due to the extreme variability seen in the measured ring series these are cannot be confirmed.

Each of the six site chronologies were then compared with an extensive series of reference chronologies for oak, both those held by the Nottingham Tree-ring Dating Laboratory, and by other laboratories. This indicated a satisfactory cross-match and date for only one site chronology, CPHASQ01, its 104 rings dated as spanning the years AD1400–1503 (Table 2).

Each of the six site chronologies was compared with the other five site chronologies, and with the remaining 24 measured but ungrouped samples. There was, however, no further reliable cross-matching. Each of the remaining 24 measured but ungrouped samples was also compared individually with the full corpus of reference data, but again, there was no conclusive cross-matching. These individual samples must, therefore, also remain undated.

This analysis can be summarised as follows:

Sequence	Samples	Rings	Location	Date span
CPHASQ01	48, 49	104	Garage barn	AD 1400–1503
CPHASQ02	42, 43	60	Garage barn	undated
CPHASQ03	32, 33, 34, 39, 40	98	Present farmhouse	undated
CPHASQ04	36, 37	84	Present farmhouse	undated
CPHASQ05	03, 18	86	Former farmhouse	undated
CPHASQ06	26, 27	101	Back barn	undated
Ungrouped	24 samples	----------	----------	undated
Unmeasured	15 samples	----------	----------	----------

TREE-RING INTERPRETATION

Analysis of 39 ring sequences from timbers in the buildings of Cropple How has resulted in the production of six site chronologies, only one of which, CPHASQ01, can be conclusively dated, its 104 rings spanning the years AD 1400–1503. All other ungrouped individual samples also remain undated, including the door plank series.

The dated site chronology comprises two samples, both of them from the principal rafters of truss 3 of the Garage barn. Neither of these samples retains complete sapwood (the last ring produced by the tree represented before it was cut down), and it is thus not possible to provide a precise felling date for the timbers represented. Both samples, which appear likely to be coeval, do retain the heartwood/sapwood boundary, the average date of this being AD 1502. Using the standard 95% probability of 10–46 sapwood rings (Bayliss and Tyers 2004, table 1), gives the timbers represented an estimated felling date in the range AD 1512–48.

Although the other grouped timbers are undated by dendrochronology, it should be noted (Table 1, Figs 11b–f) that they do appear to be in groups related to their sample location, the timbers within each group probably representing timbers felled at the same time as each other. For example, the samples, CPH-A32, CPH-A33, CPH-A34, CPH-A39, and CPH-A40, in site chronology CPHASQ03 (Fig 11c), are all from the roof (three principal rafters and two purlins) of the Present Farmhouse. The relative position of the heartwood/sapwood boundary on the four samples which retain it is virtually identical, indicative of timbers of a single phase of felling. Indeed, such is the degree of cross-matching between these samples, with values in excess of t=20.0, that it is very likely that the timbers are all derived from a single tree, an interpretation made more plausible given that the timbers all appear to be quartered trees.

Likewise, the two samples CPH-A36 and CPH-A37, in site chronology CPHASQ04 (Fig 11d), are again both from the present farmhouse roof (purlins). In this case both samples retain complete sapwood, meaning they have the last ring produced by the tree represented before it was cut down. This last, complete growth ring is at an identical position on each sample. Once again, the degree of cross-matching (t=15.4) between the two samples makes it likely that the timbers are both derived from a single tree and in this instance it is thought that the timbers are half-trees.

The timbers represented by samples CPH-A42 and CPH-A43 from the principal rafters of truss 1 in the Garage barn (site chronology CPHASQ02, Fig 11b), again with very similar relative heartwood/sapwood boundary positions, are likely to have been felled at the same time as each other, as are the two timbers represented by samples, CPH-A03 and CPH-A18 from a principal rafter and a purlin in the Former Farmhouse, in site chronology CPHASQ05 (Fig 11e).

The only pair of cross-matching samples with noticeably different relative heartwood/sapwood boundary positions are CPH-A26 and CPH-A27, from the Former Farmhouse, in site chronology CPHASQ06 (Fig 11f), the variation here being 20 years. However, while it is possible that the two timbers represented (the principal rafters from truss 3) were felled at different times, given that they cross-match with each other with a value of t=10.5, there is a significant chance that they were cut at the same time. Such a high t-value is at least indicative of trees that were growing close to each other, and it would seem a little unlikely that two such trees, though felled at different times, would end up in the same truss of the same building. It is also possible that the two timbers were again derived from a single tree.

RADIOCARBON DATING, SAMPLING, AND ANALYSIS

The disappointing tree-ring analysis frustrated attempts to understand the development of this property, specifically in relation to the construction of the smokehood, which would be unique to Cumbria if dating to the mid-to-late sixteenth century as conjectured. Further dating by radiocarbon dating and wiggle-matching was, therefore, considered appropriate. The aim was to provide dating evidence for key elements of this complex of buildings and hence enhance understanding of the chronological relationship between these elements. Thus, samples with sapwood, or at least the heartwood/sapwood boundary present, that were grouped but undated by dendrochronology were selected from the roof of the Former Farmhouse, the roof of the Back barn, and the roof of the Present Farmhouse. This resulted in the selection of three cores for radiocarbon dating and wiggle-matching.

Core CPH-A18 is a purlin from the Former Farmhouse and was thought to be associated with the second-phase roof (Table 1). It is 83 rings long and includes 21 sapwood rings, but not bark edge. It cross-matches CPH-A03 from the south principal rafter of truss 3, thought to be a primary-phase roof timber, and together these form site chronology CPHASQ05 of 86 rings (Fig 11e).

Core CPH-A27 is the southern principal rafter from truss 3 from the Back barn, which has 81 rings and retains the heartwood/sapwood boundary (Table 1). It cross-matches with CPH-A26, the north principal rafter from truss 3 and together they form a 101-ring site chronology CPHASQ06 (Fig 11f).

Core CPH-A34 is the north principal oak rafter from truss 2 from the Present Farmhouse with 97 rings, including 26 sapwood rings. The timber had retained complete sapwood to bark edge but a small number of sapwood rings were lost during coring due to the friable nature of the outermost rings. It cross-matches with CPH-A32, CPH-A33, CPH-A39, and CPH-A40 to form site chronology CPHASQ03 of 98 rings (Fig 11c).

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 (before present, 'present' being a constant, conventional date of AD 1950).

Calibration

Radiocarbon ages are not the same as calendar ages because the concentration of carbon-14 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 IntCal13 calibration curve (Reimer *et al* 2013). This is constructed from radiocarbon measurements on samples dated absolutely by other, independent means: tree rings, plant macrofossils, speleothems, corals, and foraminifera. In this report the calibrations which relate the radiocarbon measurements directly to the calendrical time scale have been calculated using IntCal13 and the computer program OxCal v4.2 (https://c14.arch.ox. ac.uk/oxcal/; Bronk Ramsey 1995; 2001; 2009a). The graphical distributions of the calibrated dates, shown in outline in Figures 14, 16, and 18 are derived from the probability method (Stuiver and Reimer 1993). Figure 12 shows the effect of calibration on a radiocarbon determination.

Following a series of simulations relating to the radiocarbon dating and wiggle-matching the decision was made to take six single-year growth rings from each of the three core samples at relatively regular intervals including the earliest extant growth ring on the sample, and the last extant growth ring on the sample (Fig 13). Six tree-ring samples were carefully sliced from the cores using a sharp blade under a microscope. These were dated at three laboratories, each receiving two samples from each core: the Scottish Environmental Research Centre (SUERC) conducted measurements in November 2013; the Oxford Radiocarbon Accelerator Unit (ORAU) also conducted measurements in

November 2013, and ^{14}CHRONO, Queen's University Belfast (QUB) conducted measurements in August 2013. The samples dated by the Oxford Radiocarbon Accelerator Unit underwent an acid-base-acid pretreatment followed by bleaching (Brock *et al* 2010, Table 1 (UW)). They were then combusted and graphitized as described by Brock *et al* (2010, 110) and Dee and Bronk Ramsey (2000), and dated by Accelerator Mass Spectrometry (AMS) as described by Bronk Ramsey *et al* (2004). Those dated at SUERC underwent alpha cellulose treatment following the procedure set out in Hoper *et al* (1998), before being combusted as described by Vandeputte *et al* (1996). Following combustion, the samples were graphitized using methods described by Slota *et al* (1987), and dated by AMS as described by Xu *et al* (2004) and Freeman *et al* (2010).

The samples dated at The Queen's University Belfast were processed and measured as described in Reimer *et al* (2015). All three laboratories maintain a continual programme of quality assurance procedures, in addition to participation in international inter-comparisons (Scott *et al* 2017). These tests indicate no laboratory offsets and demonstrate the reproducibility and accuracy of these measurements.

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).

BAYESIAN WIGGLE-MATCHING

Wiggle-matching uses information derived from tree-ring analysis in combination with radiocarbon dates 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 dates can be derived from tree-ring analysis, since one ring is laid down each year.

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 the Figures 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.

North lower purlin between trusses 3–4 in the Former Farmhouse (core CPH-A18)

The chronological model for this core includes the radiocarbon dates for the six single-year tree ring samples, and includes the information that there are known ring intervals between each of the samples (Figure 13- top). The sampled core included 21 sapwood rings (Fig 11e). This analysis suggests that the last ring of this timber dates to *cal AD1525–1605 (89% probability)* or *1620–1635 (6% probability; RING_83*; Fig. 14*),* and probably to *cal AD 1530–1545 (16% probability)* or *1550–1585 (52% probability).* This model has good overall agreement (A_{comb}= 64.5, A_n= 28.9, n=6). As the last dated ring (Ring _83; Fig 14) is the last surviving sapwood ring of 21, the felling date needs to be estimated.

Calculating the felling date in dendrochronology is relatively straightforward if the sample has sapwood complete to the underside of, or including bark (ie the last ring produced by the tree before it was cut down). In this case the last measured ring is the felling of the timber. If the sapwood is partially missing, or if only a heartwood/sapwood transition boundary survives, then an estimated felling date range can be given for each sample. The number of sapwood rings can be estimated by using an empirically derived distribution of the number of sapwood rings on historic timbers (Bayliss and Tyers 2004, table 1). This distribution, truncated to allow for the 21 surviving sapwood rings on core CPH-A18, has been added to the estimated date for the final measured ring of the tree-ring sequence to produce an estimate for the felling date of the timber.

This analysis suggests that this timber was felled in *cal AD 1525–1615 (88% probability; CPHA18 felling*, Fig 15*)*, or *1620–1645 (7% probability),* and probably to *cal AD 1535–1590 (68% probability).*

Southern principal rafter from truss 3 from the Back barn (core CPH-A27)

The chronological model for this core includes the radiocarbon dates for the six single-year tree ring samples, and includes the information that there are known ring intervals between each of the samples (Fig 13- middle). This sampled core retains the heartwood/sapwood boundary (Fig 11f). The analysis suggests that the last ring of this timber is dated to *cal AD 1515–1550 (95% probability; RING_81;* Fig 16*)*, and probably to *cal AD 1520–1540 (68% probability).* This model has good overall agreement (A_{comb}= 75.8, A_n= 28.9, n=6). As the last dated ring (RING_81; Fig 16) is the heartwood/sapwood boundary, the complete distribution of the number of sapwood rings (ibid) has been added to the estimated date for the final measured ring of the tree-ring sequence to produce an estimate for the felling date of the timber.

This analysis suggests that this timber was felled in *cal AD 1525–1585 (95% probability; CPH27 felling;* Fig 17), probably to *cal AD 1535–1565 (68% probability)*.

North principal rafter from truss 2 from the Present Farmhouse (core CPH-A34)

The chronological model for this core includes the radiocarbon dates for the six single-year tree ring samples, and includes the information that there were known ring intervals between each of the samples (Fig. 13- bottom). The sampled timber retained complete sapwood but the very outermost sapwood rings failed to survive coring and hence only 26 survived intact on the core as shown in Figure 11c. If all six radiocarbon dates are included in the model, it falls into a poor overall agreement (A_{comb}= 11.0, A_n= 28.9, n=6), with three samples having low individual indices agreement, *OxA-28731* (A=27), *SUERC-49082* (A=7), and *UBA-23612* (A=16). Any of these dates could be outliers, incompatible with the known ring intervals between the dated samples.

The two main approaches for dealing with 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 approach employed here uses outlier analysis only for the identification of outliers and not model averaging (Bronk Ramsey *et al* 2010) with those date(s) identified as outliers excluded from further analysis.

The OxCal '*s-type'* model (Bronk Ramsey 2009b) tests the effect for each sample of increasing the uncertainty in the measurement (typically by just over 2) (Bronk Ramsey *et al* 2010) and if the agreement with the other samples is much better with such a change, it is more likely that the date is an outlier. Each sample is a given a prior probability of being an outlier (in this case 0.05) and the model identifies those samples that would agree better with the other dates if its error term were larger and so it can be identified as an outlier.

The systematic application of outlier analysis (OxCal '*s-type'* model) on the sequence of dates from CPH-A34 identified SUERC-49082 (O: 22), UBA-23612 (O: 21), and OxA-28731 (O: 12) as outliers. When SUERC-49082 is excluded as an outlier the overall agreement of the model still fails (A_{comb}= 30.1, A_n= 31.6, n=5), when UBA-23612 is excluded as an outlier, however, the overall agreement of the model passes (A_{comb}= 32.9, An 31.6, n=5; Fig 18), but when OxA-28731 is excluded it again fails (A_{comb}= 23.8, A_n= 31.6 n=5). This analysis therefore suggests, when excluding UBA-23612, that the last ring of this timber dates to *cal AD 1735–1760 (75% probability)* or *1760–1785 (20% probability; RING_96;* Fig. 19*)*, and probably to *cal AD 1735–1755 (68% probability)*.

As the last dated ring (RING_96; Fig 18) is the last surviving sapwood ring of 26, the distribution of the number of sapwood rings (Bayliss and Tyers 2004, table 1), truncated to allow for the surviving sapwood rings, has been applied to the estimated date for the final measured ring of the tree-ring sequence in order to produce an estimate for the felling date of the timber. The model was constrained by the calendar date of sampling AD 2011. This suggests that this timber was felled in *cal AD 1735–1790 (95% probability*) probably in *cal AD 1735–1765 (68% probability*).

RADIOCARBON DATING INTERPRETATION

The radiocarbon and wiggle-matching dating on a principal rafter from truss 2 of the Present Farmhouse (CPH-A34) suggests that this timber was felled in *cal AD 1735–1790 (95% probability; CPH34 felling*, Fig 19) or *cal AD 1735–1765 (68% probability*). The tree-ring analysis indicates that all five timbers (three principal rafters and two purlins) included in site chronology CPHASQ03 are coeval and hence represent a mid eighteenth-century episode of felling.

A principal rafter from truss 3 in the Back barn, CPH-A27, was probably felled in *cal AD 1525–1585 (95% probability*, *CPH27 felling;* Fig 17), or *cal AD 1535–1565 (68% probability*). The tree-ring analysis indicates that both of the timbers in site chronology CPHASQ06 are coeval and hence that the two principal rafters from truss 3 the Back barn were felled in the mid-sixteenth century.

Core, CPH-A18, from a purlin running between trusses 3 and 4 in the Former Farmhouse produces an estimated felling date of *cal AD 1525–1615 (88% probability; CPHA18 felling*, Fig 15*)* and *cal AD 1620–1645 (7% probability),* or *cal AD 1535–1590 (68% probability)*. The tree-ring analysis indicates that both of the timbers in site chronology CPHASQ05 are likely to be coeval. This indicates that this purlin and the principal rafter from truss 3 probably represent a mid/late sixteenth-century felling episode.

DISCUSSION AND CONCLUSION

The tree-ring and radiocarbon analysis indicates several discreet episodes of constructional activity at Cropple How dating to the first half of the sixteenth century (principal rafters from truss 3 of the Garage barn), the mid-sixteenth century (principal rafters from truss 3 in the Back barn), the mid/late sixteenth century (a purlin from trusses 3-4 and principal rafter from truss 3 of the roof of the Former farmhouse) which could be coeval with the dated timbers from the Back barn, and finally to the mid-eighteenth century (three principal rafters and two purlins from the roof of the Present Farmhouse). It is unfortunate that no dating evidence could be provided for either the smokehood or the door in the Former Farmhouse, nor the High Leys barn.

All but the latest of these felling episodes identified is represented by only two timbers thus the implications for the historic development of this complex have to bear this in mind and need to take into account detailed architectural and other evidence. The analysis does however clearly identify the presence of sixteenth-century timbers which would support the complex having origins in the mid/late sixteenth century as has been suggested. The two tree-ring dated timbers from the roof of the Garage barn appear slightly earlier than those four dated through radiocarbon wiggle-matching from the roofs of the Back barn and Former Farmhouse but the potential for reuse of timbers within this complex means that it is difficult to draw any conclusion as to the chronological relationship of these three structures. This issue is emphasised by the fact that of the two dated timbers from the roof of the Former Farmhouse, both shown to have been felled in the mid/late sixteenth century, one was thought to represent the original roof and the other the later replacement, possibly eighteenth-century, roof which it clearly isn't. The mid eighteenth-century felling episode identified, and represented by five timbers, indicates that this is the date of the roof of the Present Farmhouse, which supports the mid eighteenth-century date suggested for this building on architectural evidence.

The tree-ring dating of only two series, and the low numbers of series being grouped through tree-ring analysis, is notable, although such as issue has previously been noted in some Cumbrian sites (eg Eskdale Mill, Tyers 2014). A peculiarity of a number of samples obtained from the timbers is the presence of recurring bands of narrow, compressed, or distorted rings. This may indicate some particularly local environmental effects, perhaps late frosts and poor summers with short growing seasons or some aspect of woodland management such as coppicing or shredding, or could reflect the varied topographical nature of the woodland sources. Whatever the cause, the impact upon the growth pattern of the rings is to interfere with the wider overall climatic signal as represented in the currently available reference chronologies with which these tree-ring samples have been compared. This very poor success rate with respect to the dendrochronological analysis therefore cannot be taken to imply that the undated individual series and the remaining undated groups of timbers were felled at different times.

It is not possible, through dendrochronology, to identify the precise woodland source of the two timbers successfully dated by tree-ring analysis at Cropple How (eg Bridge 2000). The reference chronologies that CPHASQ01 shows the highest levels of similarity range from Cumbria down to Cornwall (Table 2). It has previously been noted that there is a level of similarity seen between reference chronologies down the west coast of England so this is not a particular surprise and, bearing in mind the location of Cropple How in the Fells, it is suggested that the woodland source for these two timbers is most likely relatively local (Table 2).

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TABLES

Table 1: Details of tree-ring samples from the Cropple How, Muncaster, Ravenglass, Cumbria

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Former Farmhouse – phase 1						
CPH-A01	North upper purlin, partition wall – truss 2	132	32C	------	------	------
CPH-A02	North principal rafter, truss 3	104	13	------	------	------
CPH-A03	South principal rafter, truss 3	69	no h/s	------	------	------
CPH-A04	Tiebeam, truss 3	126	37	------	------	------
CPH-A05	North lower purlin truss 3 to party wall	nm	---	------	------	------
CPH-A06	South lower purlin truss 3 to party wall	nm	---	------	------	------
CPH-A07	Door lintel	nm	---	------	------	------
CPH-A08	Bressummer beam ground-floor ceiling, room 2	nm	---	------	------	------
CPH-A09	Joist 2/8 (from north), ceiling to room 2	nm	---	------	------	------
CPH-A10	Joist 3/8 (from north), ceiling to room 2	nm	---	------	------	------
Former Farmhouse – phase 2						
CPH-A11	North principal rafter, truss 1	56	3 (+25-30nm)	------	------	------
CPH-A12	South principal rafter, truss 1	75	26	------	------	------
CPH-A13	North lower purlin, truss 1 to party wall	nm	---	------	------	------
CPH-A14	South lower purlin, truss 1 to party wall	80	26	------	------	------
CPH-A15	South lower, truss 4 to west gable	94	h/s	------	------	------
CPH-A16	South upper purlin, partition wall – truss 2	62	15	------	------	------
CPH-A17	North principal rafter, truss 2	71	19	------	------	------
CPH-A18	North lower purlin, truss 3 – 4	83	21	------	------	------
CPH-A19	East main beam, ground-floor ceiling, East room	93	27	------	------	------
CPH-A20	West main beam, ground-floor ceiling, East room	142	h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Back barn						
CPH-A21	North principal rafter, truss 1	78	h/s	------	------	------
CPH-A22	South principal rafter, truss 1	nm	---	------	------	------
CPH-A23	Tiebeam, truss 1	nm	---	------	------	------
CPH-A24	North principal rafter, truss 2	98	h/s	------	------	------
CPH-A25	South principal rafter, truss 2	76	h/s	------	------	------
CPH-A26	North principal rafter, truss 3	94	h/s	------	------	------
CPH-A27	South principal rafter, truss 3	81	h/s	------	------	------
CPH-A28	North lower purlin, party wall – truss 3	97	h/s	------	------	------
CPH-A29	South lower purlin, party wall – truss 3	108	h/s	------	------	------
CPH-A30	North upper purlin, truss 3 – west gable	62	h/s	------	------	------
CPH-A31	South upper purlin, truss 3 – west gable	58	h/s	------	------	------
Present farmhouse						
CPH-A32	North principal rafter, truss 1	88	24C	------	------	------
CPH-A33	South principal rafter, truss 1	90	23c	------	------	------
CPH-A34	North principal rafter, truss 2	97	26c	------	------	------
CPH-A35	South principal rafter, truss 2	nm	---	------	------	------
CPH-A36	South upper purlin, truss 1 - 2	84	28C	------	------	------
CPH-A37	South lower purlin, truss 1 - 2	84	28C	------	------	------
CPH-A38	North upper purlin, truss 1 - 2	nm	---	------	------	------
CPH-A39	North lower purlin, truss 1 – east gable	58	no h/s	------	------	------
CPH-A40	North upper purlin, truss 1 – east gable	79	19c	------	------	------
CPH-A41	North upper purlin, truss 2 – west gable	nm	---	------	------	------

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Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Garage barn						
CPH-A42	North principal rafter, truss 1	52	3	------	------	------
CPH-A43	South principal rafter, truss 1	60	14	------	------	------
CPH-A44	North lower purlin, truss 1 - 2	58	h/s	------	------	------
CPH-A45	North principal rafter, truss 2	62	13	------	------	------
CPH-A46	South principal rafter, truss 2	nm	---	------	------	------
CPH-A47	North lower purlin, truss 2 - 3	nm	---	------	------	------
CPH-A48	North principal rafter, truss 3	92	h/s	1412	1503	1503
CPH-A49	South principal rafter, truss 3	101	h/s	1400	1500	1500
CPH-A50	Tiebeam, truss 3	84+10nm	(h/s)	------	------	------
High Leys barn						
CPH-A51	North principal rafter, truss 2	70	h/s	------	------	------
CPH-A52	South principal rafter, truss 2	nm	---	------	------	------
CPH-A53	North upper purlin, truss 1 – 2	72	h/s	------	------	------
Former Farmhouse - door						
CPH-A54	Door panel 1	103	no h/s	------	------	------

nm = sample not measured

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

c = complete sapwood is found on the timber, but all or part has been lost from the sample in coring

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

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Table 2: Results of the cross-matching of site sequence CPHASQ01 and relevant reference chronologies when the first-ring date is AD 1400 and the last-ring date is AD 1503

Reference chronology	Span of chronology	*t*-value	Reference
Dacre Hall, Lanercost Priory, Brampton, Cumbria	AD 1350–1504	7.6	(Arnold *et al* 2004)
Whalley Abbey, Lancashire	AD 1362–1559	7.6	(Arnold and Howard 2015)
1–3 North Gate, Newark, Nottinghamshire	AD 1339–1523	7.5	(Arnold and Howard 2009 unpubl)
St Ildierna, Lansallos, Cornwall	AD 1355–1514	7.4	(Arnold and Howard 2006)
2-3 Church Street, Eardisley, Herefordshire	AD 1415–1512	7.3	(Tyers 2005)
Hardwick Old Hall, Hardwick, Derbyshire	AD 1375–1590	7.1	(Howard *et al* 2002)
Trerice, Kestle Mill, Cornwall	AD 1394–1562	7.1	(Hurford *et al* 2009)
Nether Levens Hall, Kendal, Cumbria	AD 1395–1541	7.0	(Howard *et al* 1991)

Table 3: Radiocarbon results from Cropple How

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C$ (‰)	*Highest posterior density interval – cal AD (95% probability)*
CPH-A18				
OxA-28726	Oak heartwood, ring 1 from core CPH-A18	366±23	–27.2±0.2	*1440–1520 (89%), 1535–1555 (6%)*
SUERC-49074	Oak heartwood, ring 17 from core CPH-A18	368±34	–25.4±0.2	*1455–1540 (89%), 1550–1570 (6%)*
UBA-23608	Oak heartwood, ring 33 from core CPH-A18	363±28	–26.9±0.56	*1475–1555 (89%), 1570–1585 (6%)*
OxA-28727	Oak heartwood, ring 49 from core CPH-A18	324±23	–26.8±0.2	*1490–1570 (89%), 1585–1600 (6%)*
SUERC-49075	Oak sapwood, ring 66 from core CPH-A18	384±34	–25.9±0.2	*1505–1585 (89%), 1600–1620 (6%)*
UBA-23609	Oak sapwood, ring 81 from core CPH-A18	342±29	–26.8±0.56	*1520–1600 (89%), 1615AD 1635 (6%)*

The highest posterior density intervals are derived from the models shown in Figures 14, 16 and 18.

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Table 3: continued

Laboratory Number	Sample	Radiocarbon Age (BP)	δ^{13}C (‰)	*Highest posterior density interval – cal AD (95% probability)*
CPH-A27				
UBA-23610	Oak heartwood, ring 2 from core CPH-A27	386±22	–25.8±0.56	1435–1470 (95%)
OxA-28728	Oak heartwood, ring 17 from core CPH-A27	382±23	–25.1±0.2	1450–1485 (95%)
SUERC-49076	Oak heartwood, ring 33 from core CPH-A27	399±34	–25.5±0.2	1465–1500 (95%)
UBA-23611	Oak heartwood, ring 49 from core CPH-A27	351±26	–26.2±0.56	1480–1515 (95%)
OxA-28729	Oak heartwood, ring 65 from core CPH-A27	371±22	–26.2±0.2	1500–1531 (95%)
SUERC-49080	Oak heart/sap, ring 81 from core CPH-A27	366±34	–24.9±0.2	1516–1547(95%)
CPH-A34				
SUERC-49081	Oak heartwood, ring 1 from core CPH-A34	260±34	–24.2±0.2	1640–1665 (75%), 1665–1690 (20%)
UBA-23612	Oak heartwood, ring 20 from core CPH-A34	288±30	–24.8±0.56	1490–1605 (63%), 1615–1665 (32%)
OxA-28730	Oak heartwood, ring 40 from core CPH-A34	122±23	–24.7±0.2	1675–1700 (75%), 1705–1730 (20%)
SUERC-49082	Oak heartwood, ring 60 from core CPH-A34	190±34	–23.1±0.2	1695–1720 (75%), 1725–1750 (20%)
UBA-23613	Oak sapwood, ring 79 from core CPH-A34	115±23	–26.1±0.56	1715–1740 (75%), 1745–1765 (20%)
OxA-28731	Oak sapwood, ring 96 from core CPH-A34	210±23	–24.8±0.2	1735–1760 (75%), 1760–1785 (20%)

FIGURES

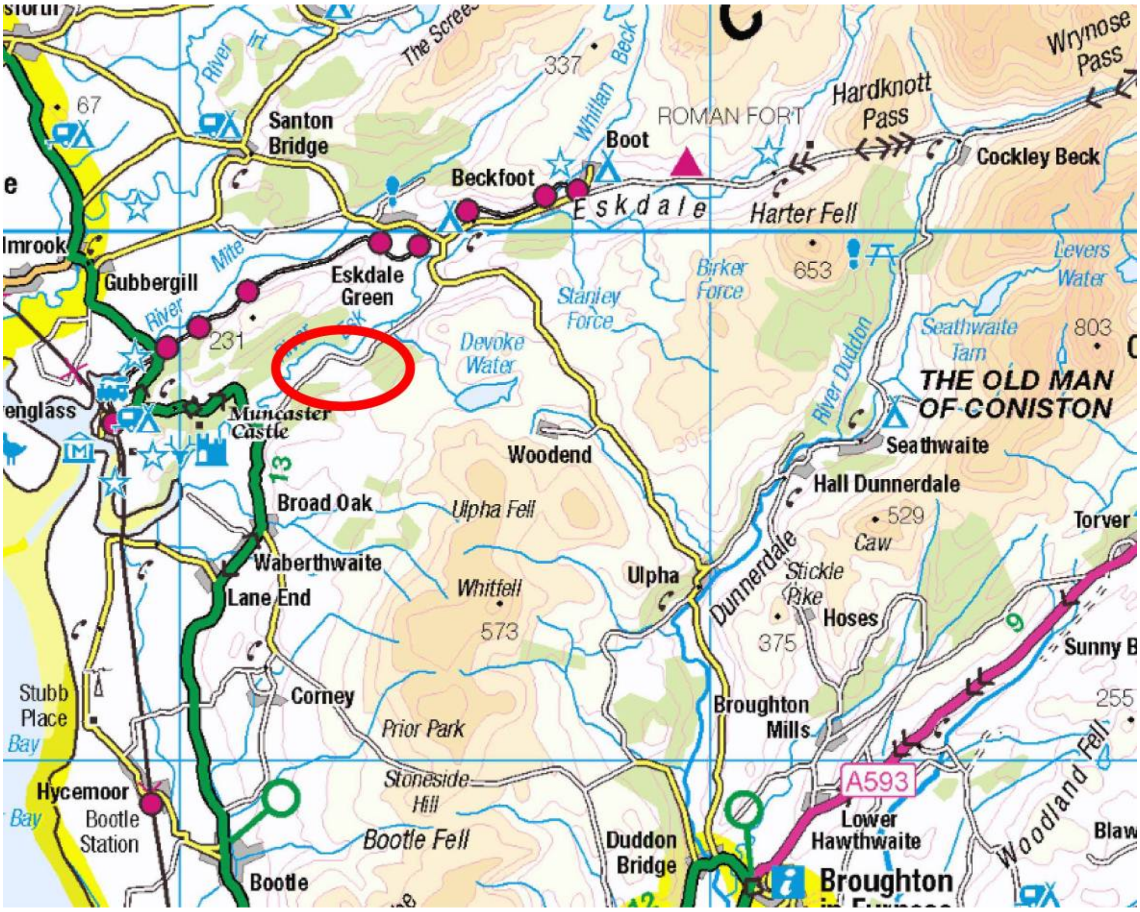

Figure 1: Map to show the general location of Cropple How (red ellipse). © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

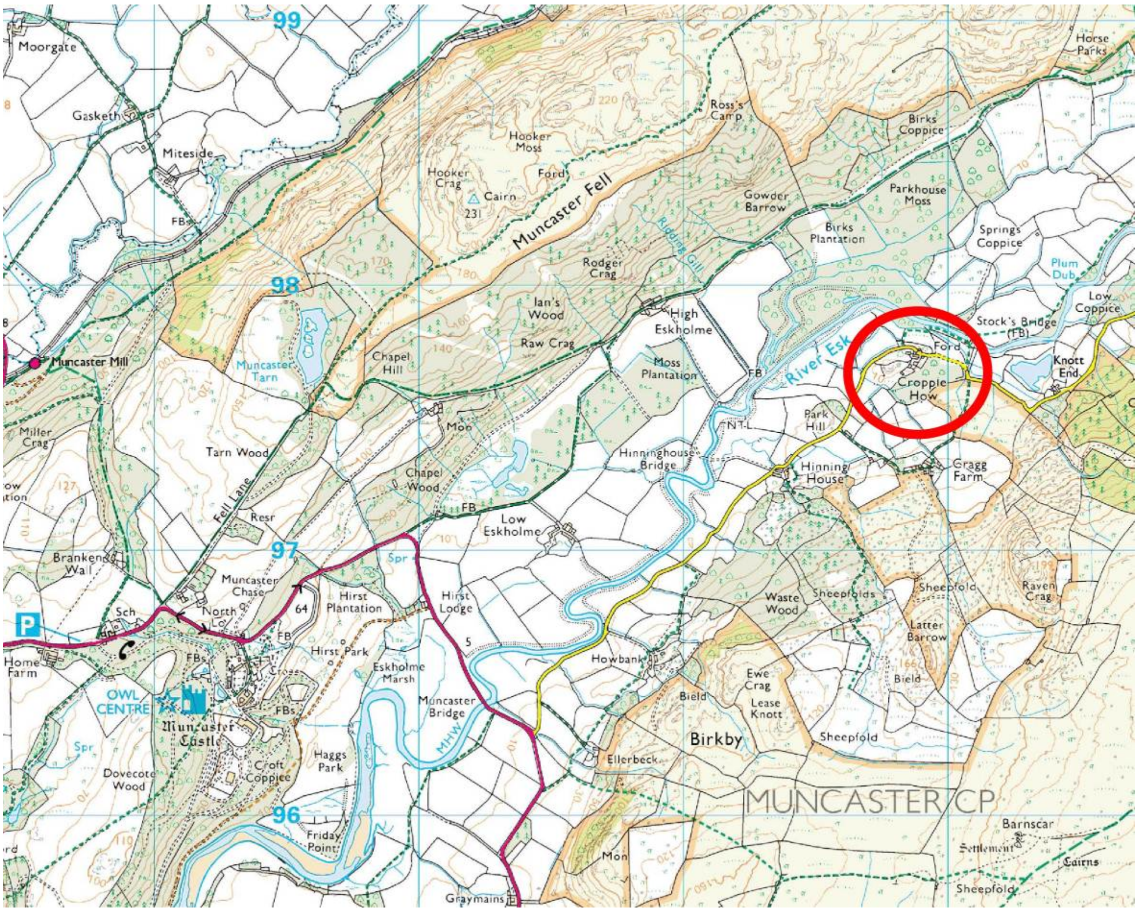

Figure 2: Map to show the location of Cropple How (red ellipse). © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

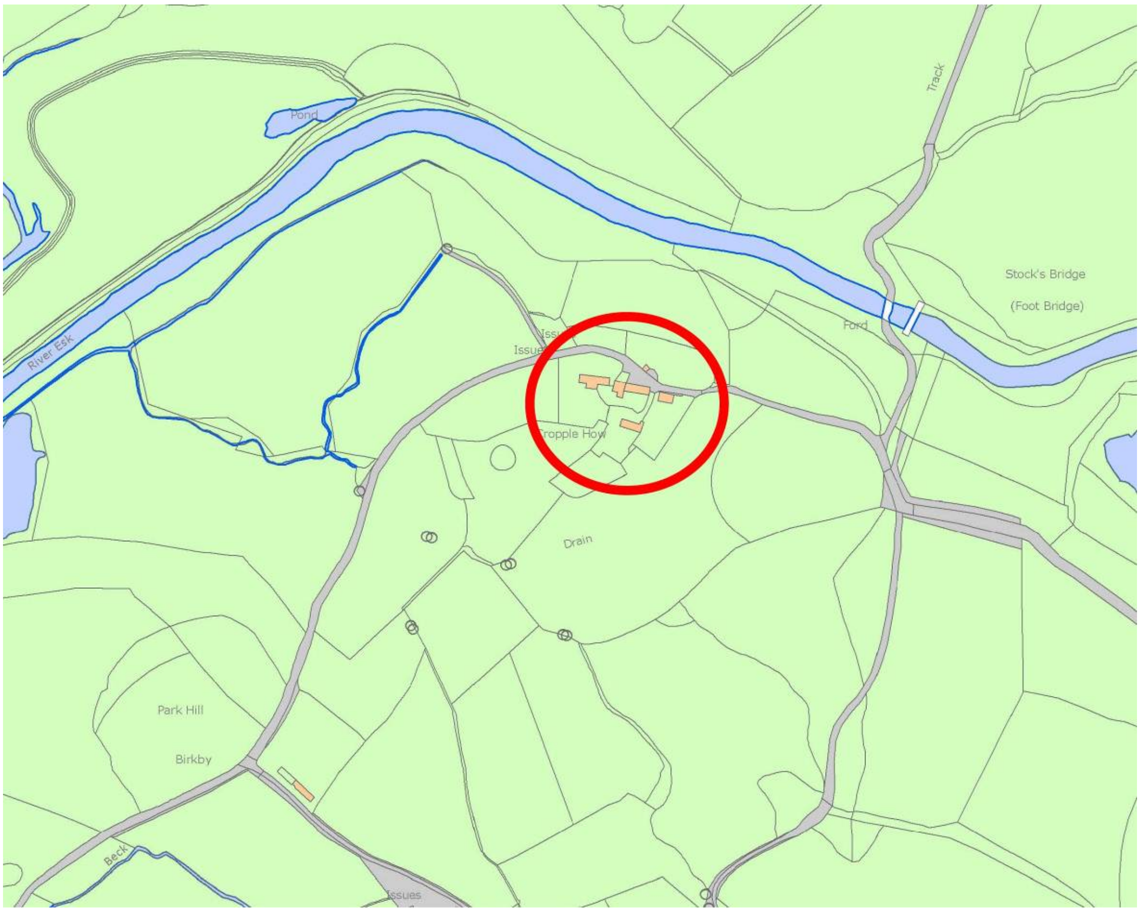

Figure 3: Map to show the detailed location of Cropple How (red ellipse). © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

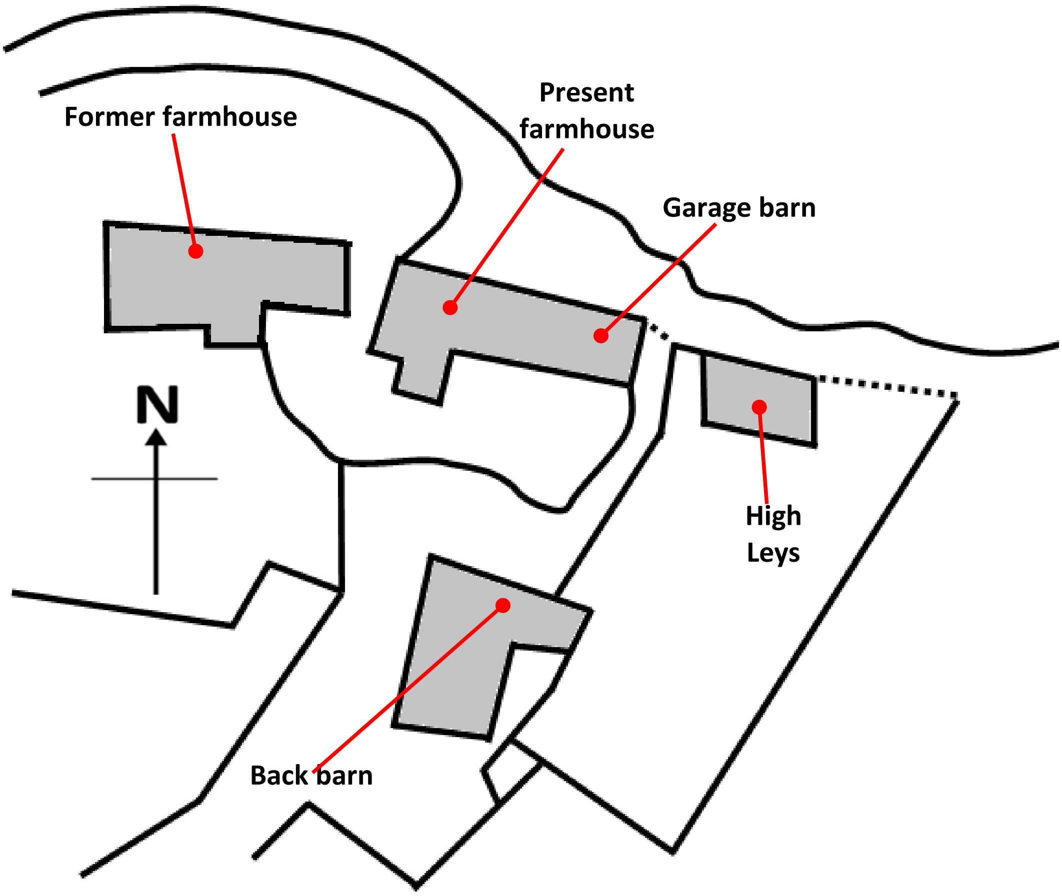

Figure 4: Simple site plan of the Cropple How complex, based on Fig.3

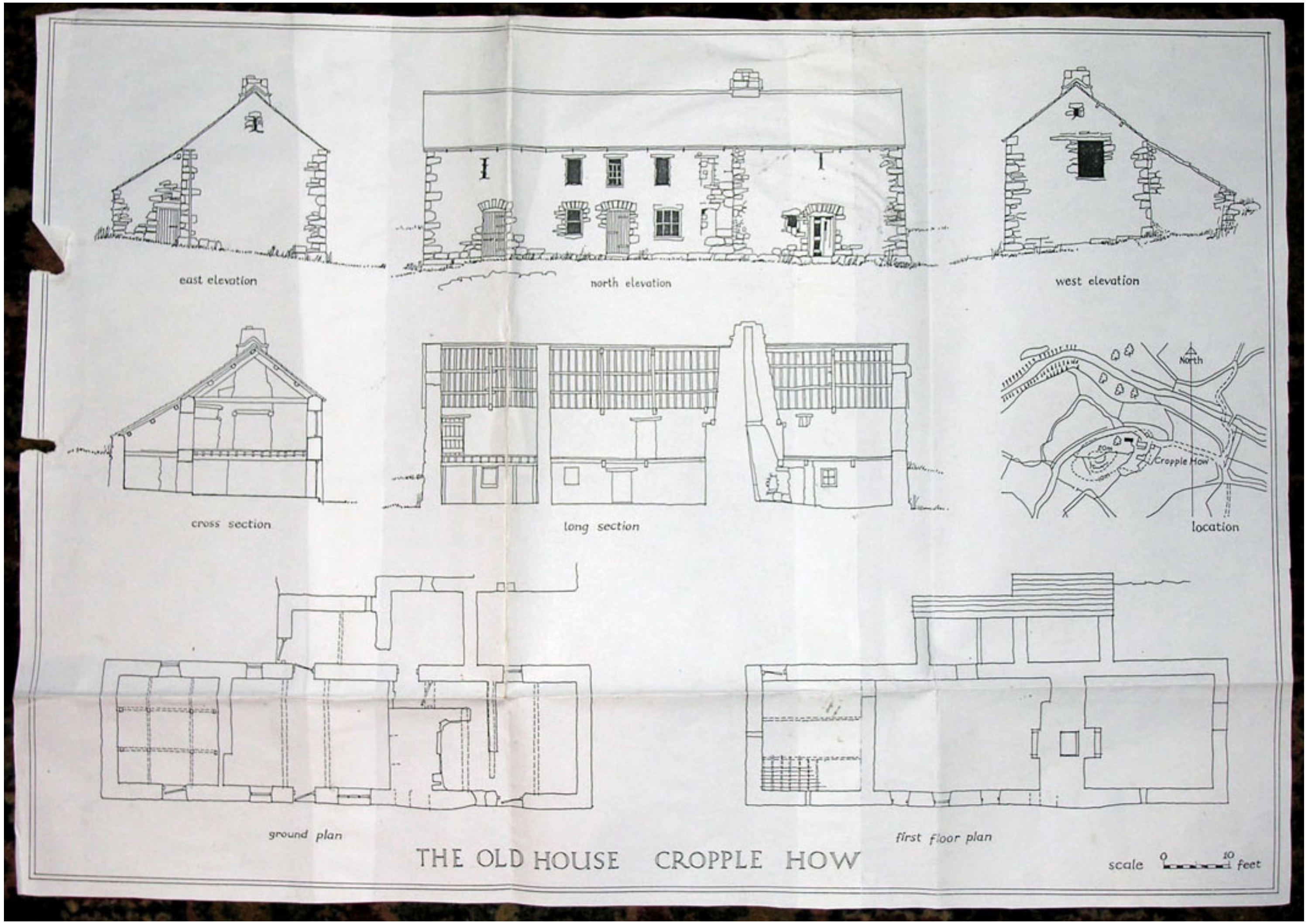

Figure 5a: Plan of the Former Farmhouse -The Old House (plan in possession of the owner of unknown source)

Figure 5b: View of the Former Farmhouse from the north east (photograph Robert Howard)

Figure 5c: View of the roof to the former farmhouse (photograph Robert Howard)

Figure 5d: View of bressummer and common joists to floor of room 2 (photograph Robert Howard)

Figure 5e: View of the plank door (photograph Robert Howard)

Figure 6a: View of the Present Farmhouse from the north (photograph Robert Howard)

Figure 6b: The roof of the Present Farmhouse (photograph Robert Howard)

Figure 6c: First floor ceiling beams to Present Farmhouse (photograph Robert Howard)

Figure 7a: View of the Garage barn (photograph Robert Howard)

Figure 7b: The roof of the Garage barn (photograph Robert Howard)

Figure 8a: High Leys barn (photograph Robert Howard)

Figure 8b: The roof of High Leys barn (photograph Robert Howard)

Figure 9a: The Back barn from the north (photograph Robert Howard)

Figure 9b: The roof of the Back barn (photograph Robert Howard)

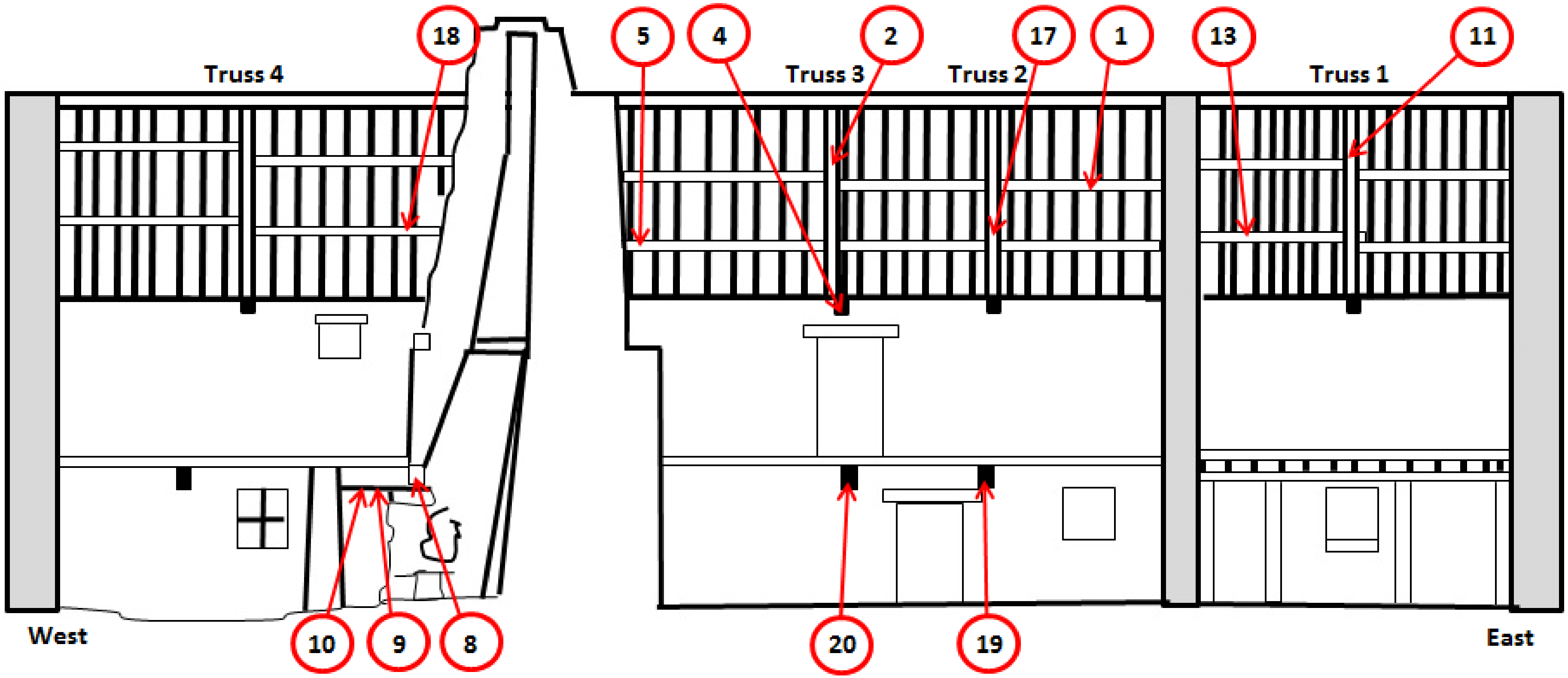

Figure 10a: Long-section of the Former Farmhouse, viewed looking north, to locate sampled timbers (based on drawing in possession of the owners of unknown source)

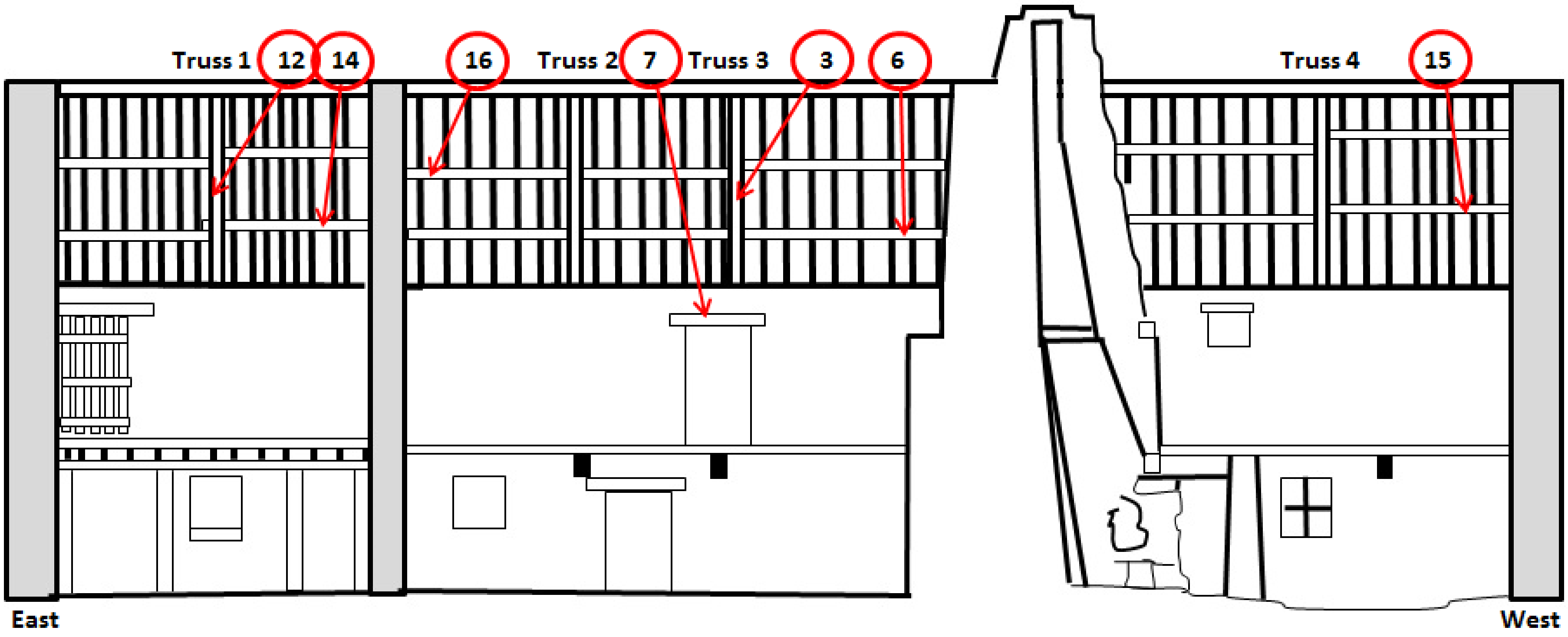

Figure 10b: Long-section of the Former Farmhouse, viewed looking south, to locate sampled timbers (based on drawing in possession of the owners of unknown source)

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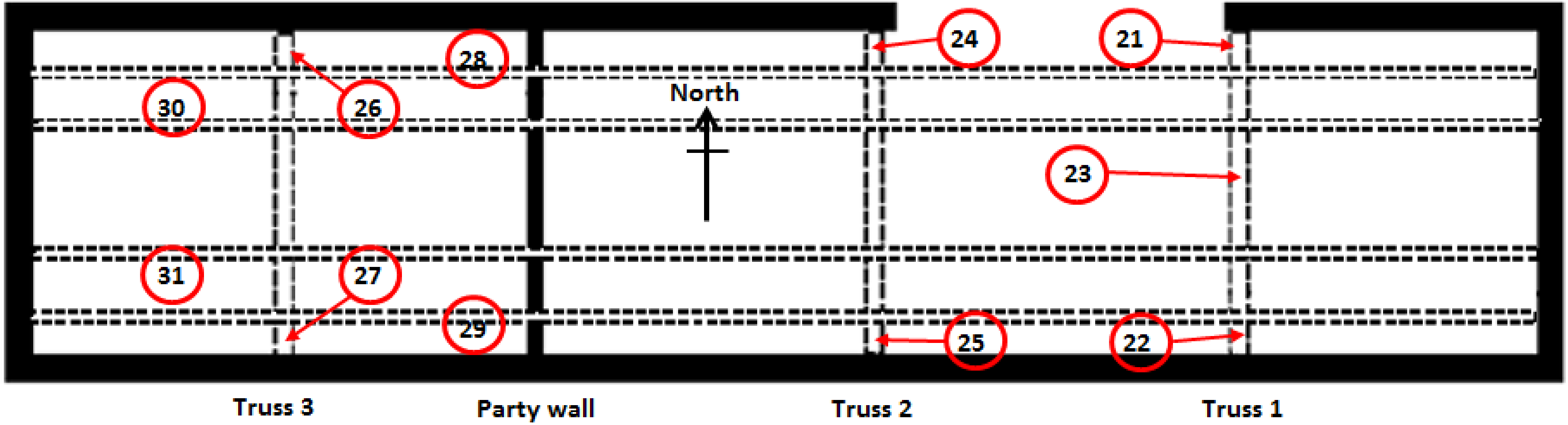

Figure 10c: Schematic plan of the Back barn to locate sampled timbers (plan Robert Howard)

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Figure 10d: Annotated photograph of the present farmhouse to locate sampled timbers (photograph Robert Howard)

Figure 10e: Annotated photograph of the Garage barn to locate sampled timbers (photograph Robert Howard)

Figure 10f: Annotated photograph of the Garage barn to locate sampled timbers (photograph Robert Howard)

Figure 10g: Annotated photograph of High Leys to locate sampled timbers (photograph Robert Howard)

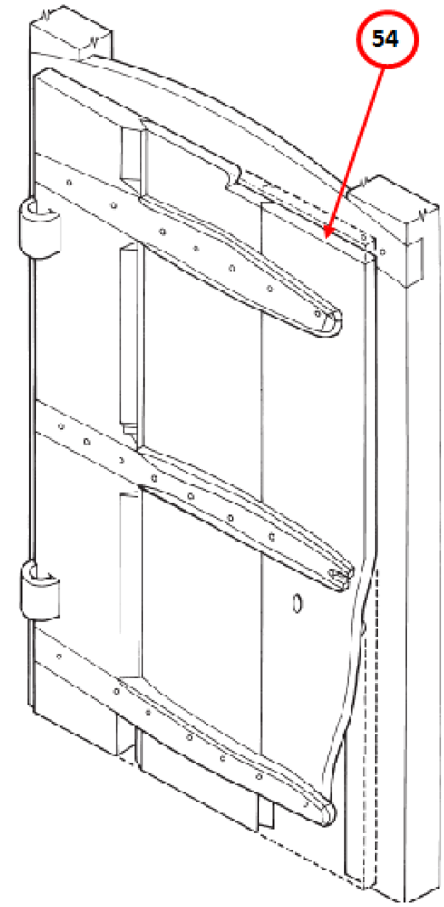

Figure 10h: Drawing of the panel door to the Former Farmhouse to identify sampled timbers (after A T Adams)

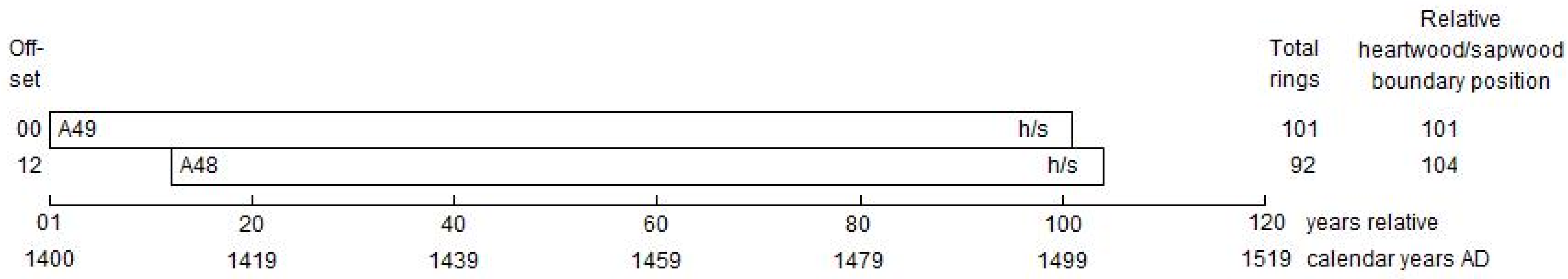

Figure 11a: Bar diagram of the samples in site chronology CPHASQ01

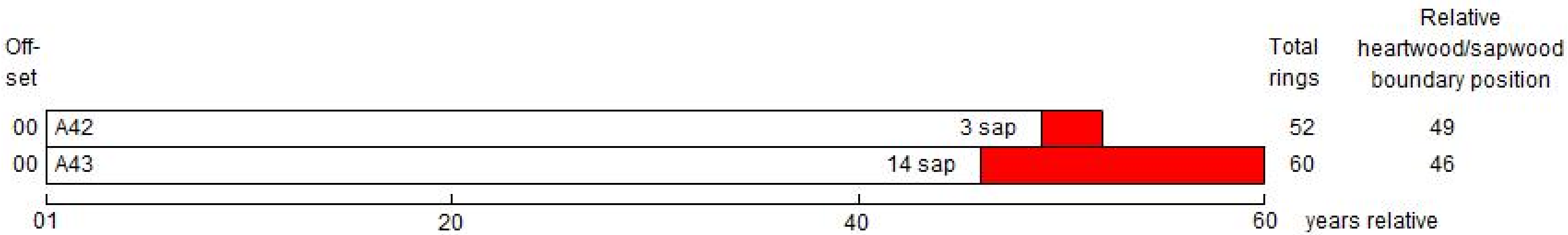

Figure 11b: Bar diagram of the samples in site chronology CPHASQ02

White bars =heartwood rings
Red bars = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary

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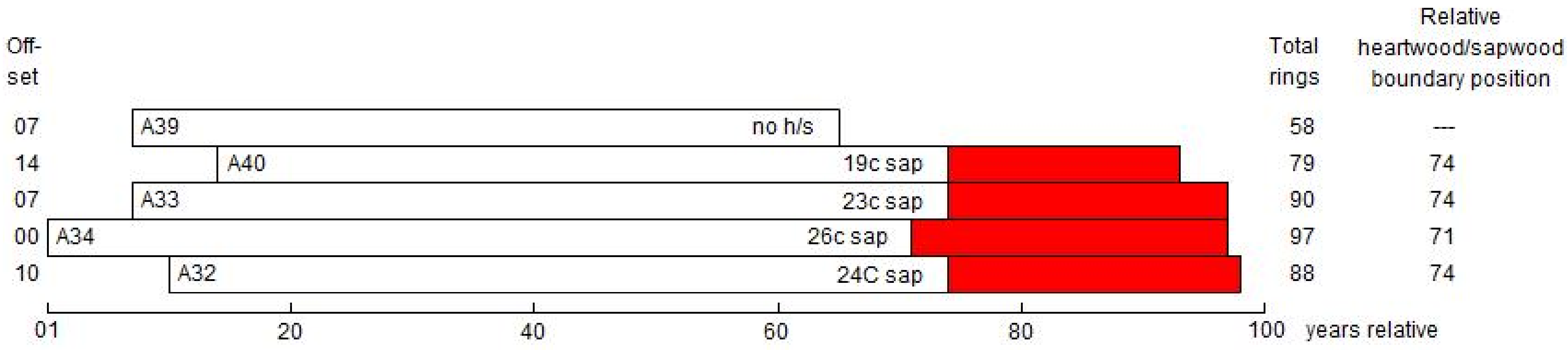

Figure 11c: Bar diagram of the samples in site chronology CPHASQ03

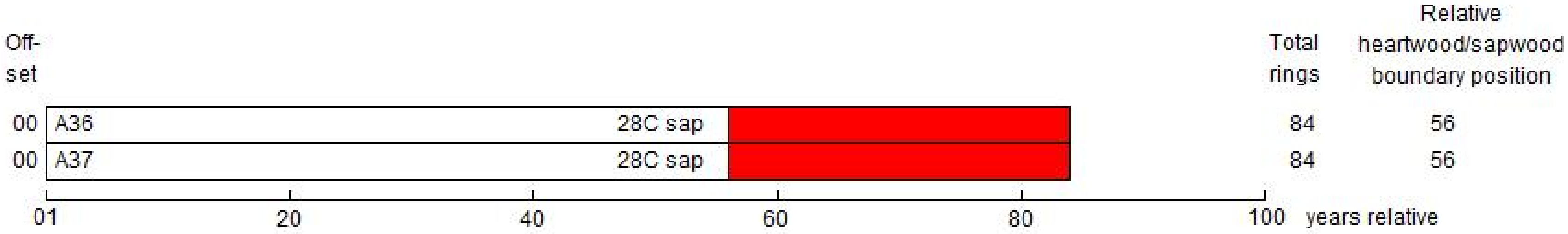

Figure 11d: Bar diagram of the samples in site chronology CPHASQ04

White bars =heartwood rings
Red bars = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary
c = complete sapwood is found on the timber, but all or part has been lost from the sample in coring
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented

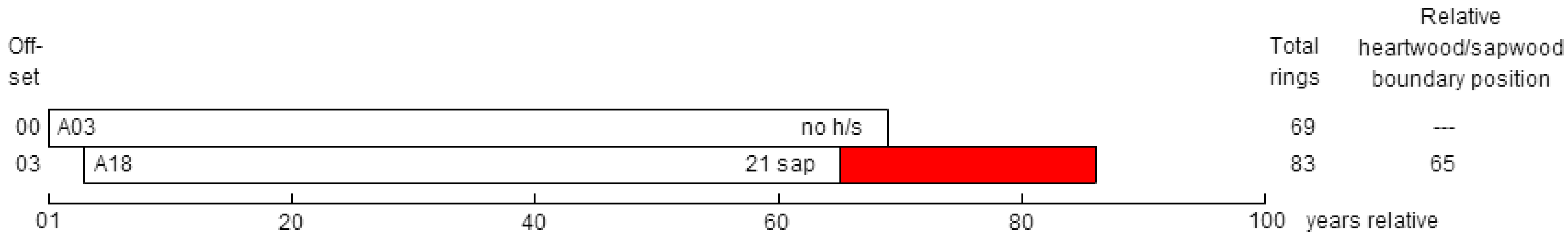

Figure 11e: Bar diagram of the samples in site chronology CPHASQ05

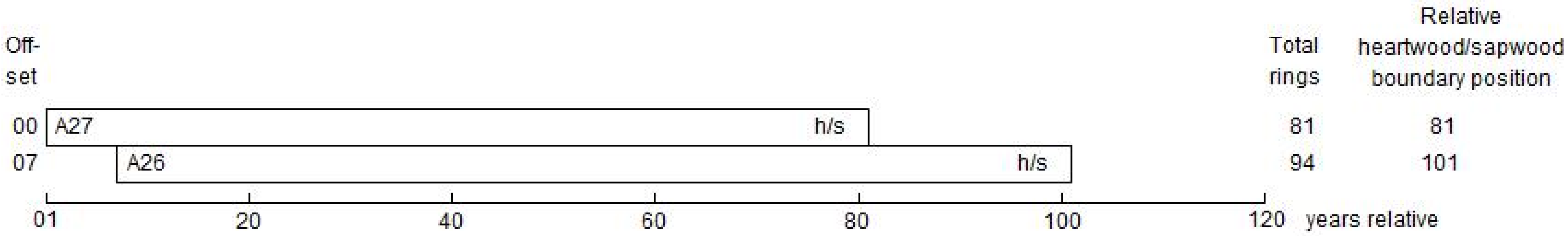

Figure 11f: Bar diagram of the samples in site chronology CPHASQ06

White bars =heartwood rings
Red bars = sapwood rings
h/s = the last ring on the sample is at the heartwood/sapwood boundary

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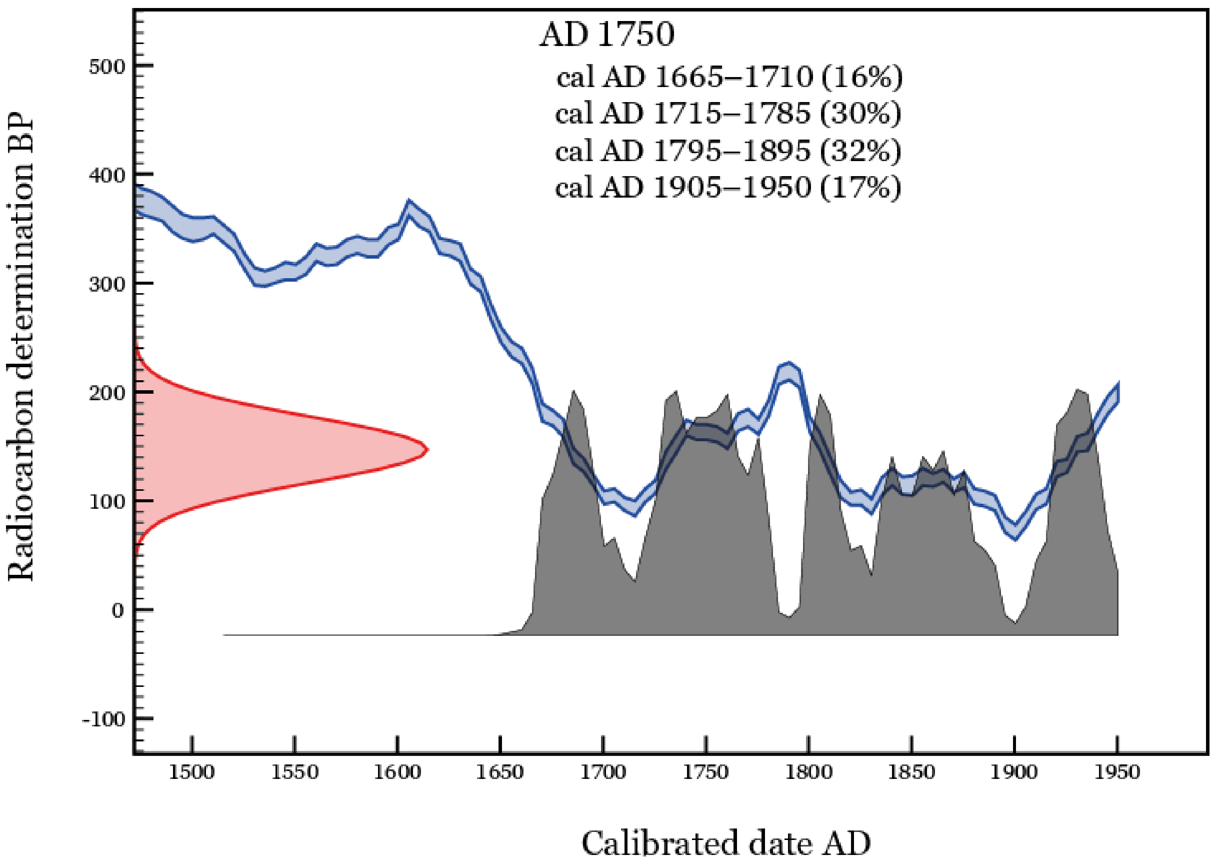

Figure 12: A simulated radiocarbon measurement for a sample with a calendar age of AD 1750 and an error on the radiocarbon measurement of ±30 years, in pink on the vertical axis, calibrated to cal AD 1665 to 1710 (16% probability), 1715 to 1785 (30% probability), 1795–1895 (32% probability) or 1905 to 1950 (17% probability), in black on the horizontal axis. The blue band is the relevant part of the calibration curve.

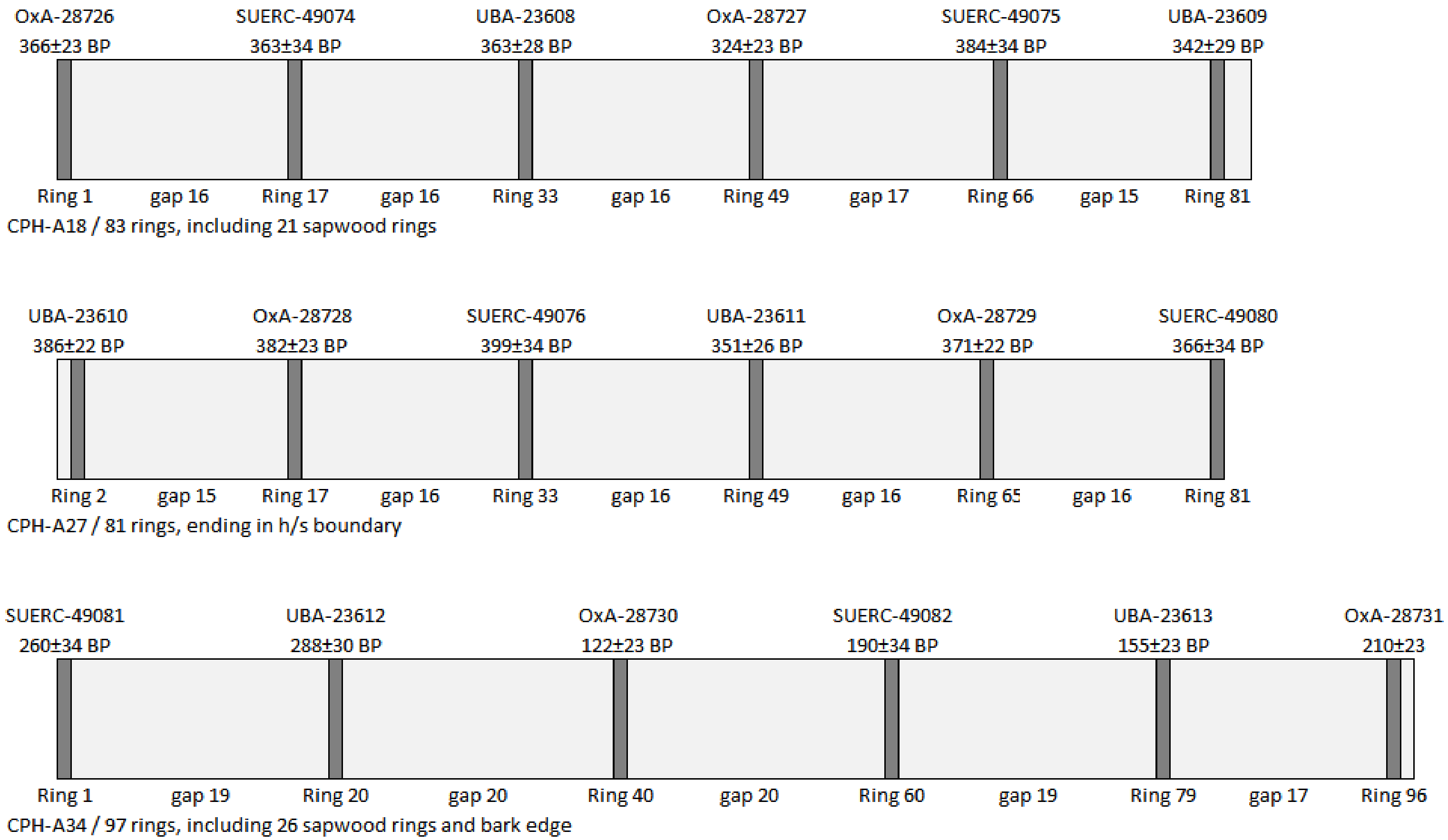

Figure 13: Schematic illustration of core samples CPH-A18, CPH-A27, and CPH-A34 indicating the location of the individual growth ring samples submitted for radiocarbon dating

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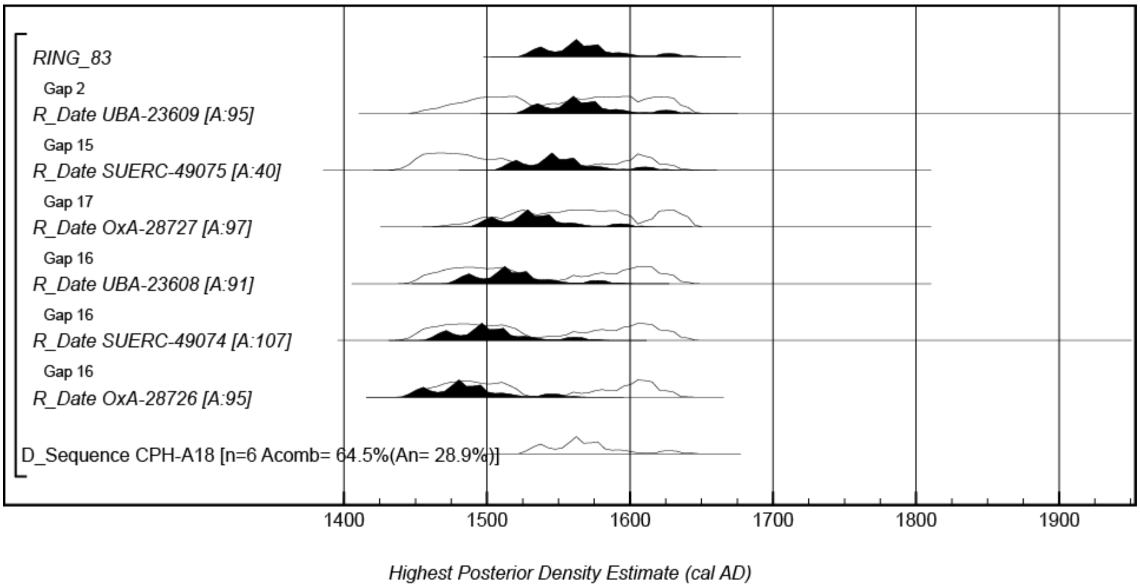

Figure 14: Probability distributions of dates from the timber purlin CPH-A18. Each distribution represents the relative probability that an event occurs at a particular time. RING_83 is the date of the last surviving sapwood ring. For each of the dates two distributions have been plotted: one in outline, 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

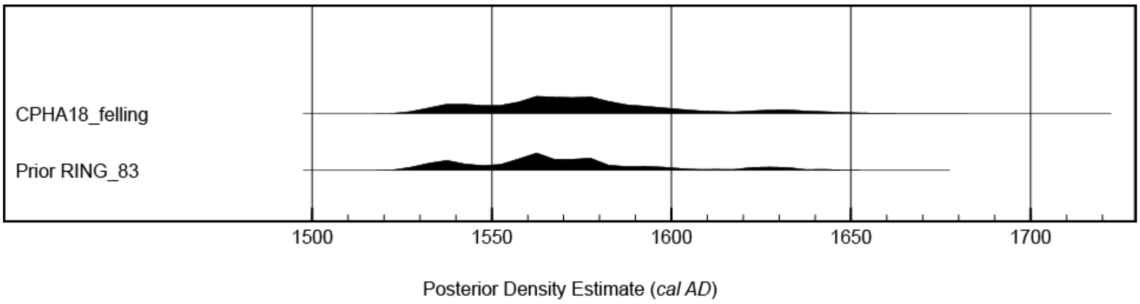

Figure 15: Probability distribution for the felling date estimate of purlin CPH-A18 using the expected number of additional sapwood rings for ancient oak samples in England

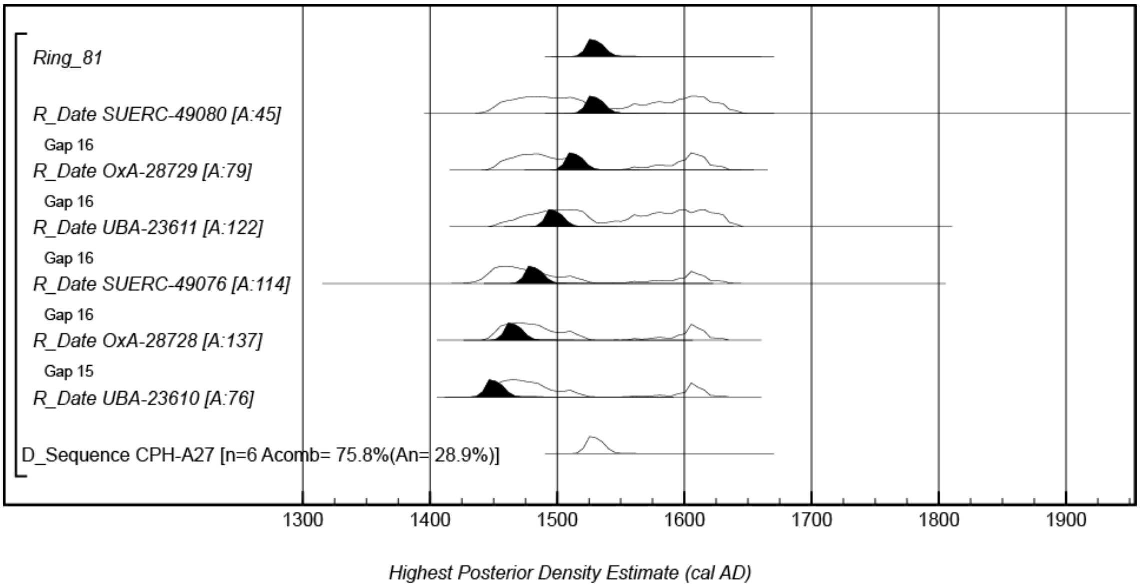

Figure 16: Probability distributions of dates from the timber purlin CPH-A27. Each distribution represents the relative probability that an event occurs at a particular time. RING_81 is the date of the heartwood/sapwood boundary ring. For each of the dates two distributions have been plotted: one in 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

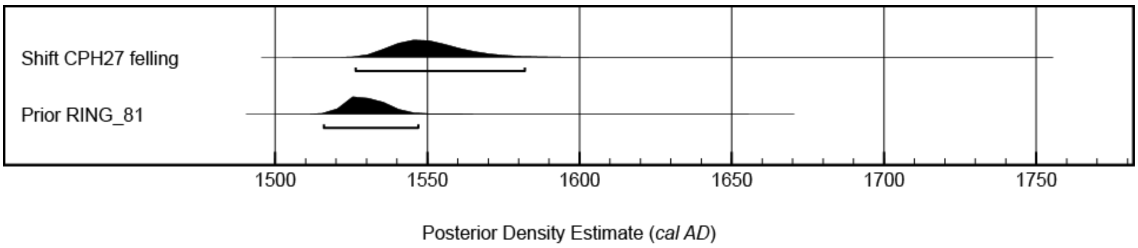

Figure 17: Probability distribution for the felling date estimate of purlin CPHA27 using the expected number of additional sapwood rings for ancient oak samples in England

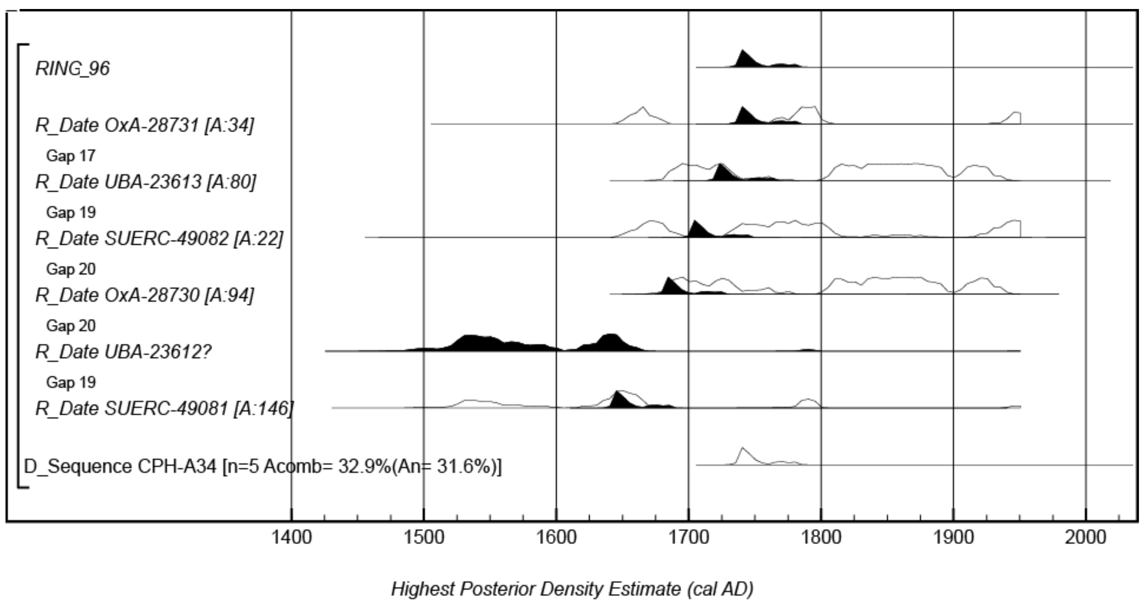

Figure 18: Probability distributions of dates from the timber CPH-A34, the north principal rafter from truss 2 from the Present Farmhouse. Each distribution represents the relative probability that an event occurs at a particular time. Ring 96 dates the outermost surviving sapwood ring. A question mark after the laboratory number of UBA-23612 indicates that this date is excluded from the model, for reasons explained in the text, although still shown on the graph. 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

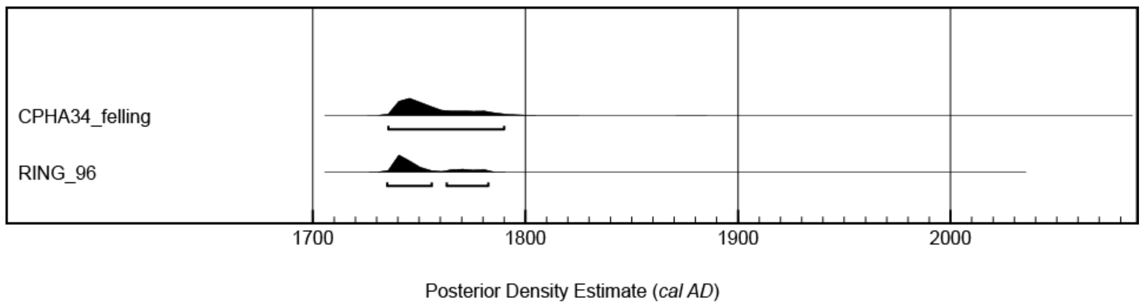

Figure 19: Probability distribution for the felling date estimate of rafter CPH-A34 using the expected number of additional sapwood rings for ancient oak samples in England

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

CPH-A01A 132
289 260 273 385 369 287 262 193 233 212 339 418 160 111 152 163 166 160 214 265
222 271 305 371 352 264 334 394 91 55 47 48 38 35 34 39 90 84 100 70
86 78 82 120 165 171 117 52 47 50 44 59 60 57 77 81 93 120 149 150
185 206 205 110 60 40 35 46 33 45 45 61 45 52 60 67 92 150 193 203
113 130 77 76 53 43 49 36 41 50 54 70 78 84 56 62 61 51 74 51
46 74 88 50 40 31 28 43 49 41 48 41 39 42 42 43 31 38 39 46
24 16 23 15 26 24 23 23 32 47 32 44
CPH-A01B 132
287 264 270 382 366 296 251 180 219 221 328 431 159 108 144 159 164 150 222 267
214 286 289 381 333 282 326 392 93 50 45 42 46 35 41 44 85 82 93 82
85 81 99 123 151 170 107 52 54 46 44 56 63 53 84 74 103 115 144 154
170 206 226 102 48 43 38 41 32 36 55 56 54 64 67 71 96 158 226 205
111 128 75 91 42 42 58 38 39 44 56 72 70 92 55 70 53 53 66 55
40 82 90 41 37 35 32 43 43 43 42 52 40 47 33 40 33 34 47 44
14 17 21 17 32 23 22 26 29 50 40 48
CPH-A02A 104
173 165 118 151 284 227 174 175 200 224 220 208 302 248 274 278 228 318 278 250
329 333 301 321 321 290 185 251 341 367 352 355 321 295 337 326 325 313 41 61
72 86 100 103 170 150 151 143 144 159 76 105 107 44 61 66 106 91 86 131
185 158 222 185 251 292 196 98 53 43 48 74 75 119 159 136 192 172 144 113
159 140 28 32 39 60 69 121 110 191 130 113 80 82 95 117 149 120 79 100
105 82 98 128
CPH-A02B 104
159 167 108 154 293 217 172 174 198 230 233 207 299 232 271 267 239 298 282 257
320 332 294 332 326 294 173 242 345 372 349 327 317 328 402 312 309 299 59 70
61 102 95 98 184 127 143 149 148 166 65 103 119 54 52 74 88 92 78 133
185 159 242 187 251 296 196 106 52 50 50 77 74 107 174 141 199 168 144 117
164 148 24 29 32 62 71 115 117 191 120 115 80 83 100 121 145 118 86 89
107 74 100 128
CPH-A03A 69
424 472 493 595 477 389 321 298 337 334 465 630 636 549 448 503 362 424 304 345
311 347 378 473 95 51 39 40 50 38 49 88 167 173 199 117 91 123 157 248
89 49 56 43 60 91 81 102 131 131 115 152 178 183 172 65 45 54 43 66
77 126 92 95 137 102 92 104 122
CPH-A03B 68
471 464 516 504 394 312 299 335 344 456 625 653 538 459 501 360 424 295 339 310
349 383 483 93 52 38 40 51 40 48 89 169 165 169 119 97 134 174 232 95
50 54 47 62 88 81 99 122 140 131 147 171 192 162 75 40 56 57 56 72
132 90 98 128 110 92 106 115
CPH-A04A 126
189 152 145 212 230 336 314 256 249 329 265 271 234 225 130 99 156 228 331 345
414 251 331 398 318 388 260 237 297 370 342 355 59 48 65 58 69 70 110 111
153 186 188 227 259 271 257 282 326 202 283 88 79 77 71 98 81 60 115 133
175 167 247 207 229 217 68 72 68 82 68 70 60 74 73 36 30 30 36 34
61 36 34 58 33 55 29 70 28 37 40 39 56 62 91 134 57 30 39 40
35 52 84 52 60 55 58 83 98 109 49 22 21 49 36 39 36 39 65 49
72 52 70 97 94 143

CPH-A04B 126
189 174 151 241 246 353 316 245 249 325 275 266 239 231 129 78 142 233 316 354
408 250 326 399 321 384 262 244 308 380 351 349 65 43 58 61 73 79 115 101
130 184 199 223 255 271 257 285 324 195 292 92 66 78 69 90 80 66 105 115
170 161 237 208 211 218 61 72 68 76 77 69 58 71 77 39 32 26 37 36
56 44 35 49 38 57 32 67 26 40 38 43 52 65 90 136 61 28 39 43
23 59 76 57 61 59 53 87 106 115 43 24 23 50 32 41 32 39 62 55
70 55 68 101 91 129
CPH-A11A 56
183 157 122 147 170 250 225 149 111 158 254 327 303 213 252 199 188 201 148 159
215 203 234 263 252 190 147 185 215 175 190 169 188 201 154 148 123 153 122 111
102 112 99 120 165 141 145 151 177 144 108 136 134 125 153 91
CPH-A11B 56
173 158 121 141 169 239 223 144 111 153 248 326 308 218 246 194 199 204 148 159
221 201 232 271 215 183 160 174 213 182 193 166 189 200 158 155 119 155 126 109
114 102 102 123 172 132 158 144 179 158 115 138 122 118 127 56
CPH-A12A 75
265 348 405 316 178 226 197 249 201 176 175 218 212 174 261 230 249 215 212 178
160 157 191 172 100 103 151 136 156 134 180 164 127 129 150 226 191 145 120 179
170 136 147 133 159 162 69 54 38 28 40 38 44 46 39 42 63 47 41 51
54 60 68 60 61 69 51 65 65 55 146 113 98 103 83
CPH-A12B 75
275 341 404 303 175 244 189 251 177 165 217 207 235 193 241 228 249 212 216 181
172 154 189 160 102 99 148 137 147 146 188 160 129 129 143 222 192 149 127 181
171 143 161 117 160 157 68 56 30 36 40 40 39 48 44 42 63 44 47 44
52 59 75 55 61 67 54 70 63 60 145 118 109 85 81
CPH-A14A 80
66 35 27 54 77 151 170 357 203 196 166 160 138 178 177 152 137 122 138 132
147 132 128 93 99 78 86 71 68 97 97 116 107 131 104 76 102 87 116 95
107 135 154 133 144 142 126 168 117 63 38 36 35 41 34 28 53 59 56 78
56 45 67 73 86 123 99 101 115 121 118 121 112 231 190 141 158 152 150 144
CPH-A14B 80
85 34 36 38 72 143 166 354 209 198 172 166 144 178 178 157 147 141 146 138
143 134 124 91 99 77 92 73 77 88 99 114 105 133 110 89 89 90 124 94
113 129 141 139 149 146 129 153 126 78 37 35 37 45 33 33 48 69 49 72
57 50 71 62 87 130 105 100 122 123 113 119 123 223 191 153 141 172 156 142
CPH-A15A 94
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520 296 91 89 77 109 183 160 228 173 274 253 294 111 88 47 88 115 123 139
137 145 204 239 174 356 428 88 46 81 81 87 83 148 175 164 188 70 58 73
71 125 142 109 87 128 281 77 83 83 79 120 120 188 45 37 56 82 101 97
193 183 262 187 190 76 56 67 69 204 231 256 287 422
CPH-A15B 94
642 879 133 95 100 106 141 196 259 545 302 498 64 76 87 102 173 251 311 282
518 297 88 90 74 109 175 171 234 170 277 256 285 124 76 53 90 111 121 136
151 149 196 230 186 386 428 98 49 61 71 79 84 119 169 175 192 80 56 69
74 115 116 122 84 127 285 69 87 75 75 120 121 179 51 39 59 76 97 110
183 182 251 193 185 88 71 67 81 199 241 310 279 415
CPH-A16A 62
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54 120 147 237 231 242 207 161 161 87 57 107 280 376 356 383 246 218 307 205
331 193 210 179 137 129 155 236 257 363 343 366 237 194 108 100 112 92 130 128
94 127

CPH-A16B 62
216 246 203 64 35 23 73 115 222 171 378 472 539 392 334 279 339 250 127 60
78 125 153 252 248 233 205 138 212 86 66 111 292 380 327 379 183 196 245 239
280 188 197 180 138 124 172 219 293 359 331 343 241 173 122 98 107 122 122 148
103 136
CPH-A17A 71
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36 46 38 49 45 60 38 35 39 40 40 39 97 50 52 80 54 65 76 78
111 103 92 96 113 159 117 147 107 241 174
CPH-A17B 71
235 293 311 218 326 321 249 271 266 234 218 235 297 415 289 352 301 252 222 154
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105 93 97 91 130 143 126 139 107 239 170
CPH-A18A 83
141 150 176 203 266 291 212 244 191 222 218 203 249 284 225 367 316 331 219 278
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28 27 36 46 40 64 69 58 83 122 85 114 35 54 46 56 81 55 80 61
86 75 62
CPH-A18B 83
132 133 185 198 260 285 201 228 191 225 222 197 244 276 229 365 301 322 214 284
263 126 64 76 63 101 75 91 82 118 121 120 168 203 237 245 262 101 75 55
87 64 82 51 46 55 77 93 131 104 136 62 39 30 45 35 43 59 58 37
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88 76 62
CPH-A19A 93
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226 220 183 166 136 122 95 99 281 372 369 251 220 175 161 149 166 141 129 169
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188 223 214 253 81 71 43 48 55 47 54 75 62 69 83 61 68 102 115 128
126 109 101 83 87 83 96 83 135 146 117 131 121
CPH-A19B 93
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225 222 188 160 133 143 80 92 283 383 375 262 228 161 159 151 166 129 137 155
129 88 133 208 232 194 168 175 176 152 118 105 161 218 182 187 235 232 183 161
183 225 211 251 86 60 45 51 57 44 59 67 66 75 76 64 67 106 108 128
139 94 106 92 79 86 92 84 137 146 116 128 120
CPH-A20A 142
308 226 216 179 131 235 164 169 239 149 190 197 168 193 162 206 142 221 176 122
72 69 62 81 113 40 31 28 30 31 33 42 42 47 40 59 43 72 57 67
57 74 55 63 72 60 68 84 105 82 85 97 69 79 79 79 84 85 85 147
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65 66 70 70 79 68 108 100 110 101 82 86 108 103 93 100 97 124 93 98
135 138

CPH-A20B 142
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65 69 66 70 75 74 106 106 102 107 75 85 115 110 102 98 96 117 102 84
127 140
CPH-A21A 78
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CPH-A24A 98
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130 123 161 108 117 195 114 129 256 205 146 144 145 138 129 89 65 62 52 70
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114 131 163 106 120 177 121 143 215 192 135 146 144 136 140 64 76 62 66 52
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132 102 128 102 130 83 72 102 118 111 154 127 127 146 227 141 165 226 97 108
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CPH-A26A 94
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277 354 243 314 356 401 421 239 276 474 427 161 205 386 76 52 42 42 54 53
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CPH-A26B 94
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CPH-A27A 81
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132 210 205 151 270 255 202 83 112 119 94 109 99 61 34 41 49 39 41 79
101 89 152 100 180 202 265 303 385 247 305 329 306 294 254 233 319 336 165 190
343 96 83 74 90 116 88 66 52 54 69 45 65 54 71 49 53 130 81 94
159
CPH-A27B 81
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132 214 191 177 255 241 187 79 111 123 104 115 88 54 43 35 51 42 48 65
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CPH-A28A 97
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CPH-A28B 97
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98 60 48 84 96 113 131 97 81 127 101 102 90 83 110 146 127 87 88 118
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CPH-A29A 108
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CPH-A29B 108
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CPH-A30A 62
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233 247 180 202 183 166 102 81 157 157 165 139 127 123 158 112 105 91 74 92
78 126 143 138 42 72 52 59 54 54 82 76 103 144 124 146 178 253 117 95
92 73
CPH-A30B 62
122 161 134 92 107 117 108 135 157 198 291 202 186 194 215 248 253 246 230 183
197 244 205 187 173 165 94 81 131 176 179 164 152 153 149 115 94 91 74 84
94 114 130 139 55 77 61 48 52 59 88 75 105 148 125 143 178 257 127 90
89 70
CPH-A31A 58
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207 210 274 230 167 107 102 132 137 129 168 172 126 130 135 110 98 90 92 94
174 148 175 87 76 38 63 58 57 84 74 75 105 82 151 163 257 169

CPH-A31B 58
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210 202 281 227 161 103 105 143 130 125 168 168 132 138 127 110 92 93 102 93
165 142 180 95 73 41 63 61 51 88 67 85 98 87 154 162 251 155
CPH-A32A 88
263 266 282 252 264 342 207 195 112 136 117 115 97 75 140 136 124 122 197 224
210 197 225 187 140 139 132 91 204 198 220 187 165 129 150 141 127 139 179 187
86 128 138 125 80 133 160 105 104 132 47 95 122 135 161 180 214 141 110 80
58 84 85 167 123 148 117 91 186 150 71 103 194 166 172 155 134 114 113 106
127 114 108 90 109 112 100 124
CPH-A32B 88
227 264 282 247 280 340 208 189 116 128 108 135 81 82 136 135 120 129 208 207
210 196 230 179 141 128 134 102 210 189 212 184 167 131 142 164 118 125 188 170
93 132 131 130 88 122 162 99 110 137 52 84 130 138 160 175 213 96 104 81
56 80 72 179 140 140 131 82 181 157 74 97 189 180 167 141 134 150 100 102
115 131 91 100 105 131 85 124
CPH-A33A 90
161 229 180 179 177 210 213 245 293 256 273 142 165 143 139 118 77 138 135 103
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172 155 109 88 117 116 195 145 96 112 89 163 137 96 94 157 183 180 151 162
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CPH-A33B 90
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134 189 260 209 283 211 203 190 158 141 177 211 167 203 169 141 127 154 180 123
158 149 158 98 121 165 160 133 138 188 116 126 127 66 104 122 132 146 221 238
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160 123 139 161 145 151 99 160 149 153
CPH-A34A 97
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130 131 106 79 107 120 87 110 137 216 178 244 211 168 147 111 92 130 155 118
128 100 115 102 136 171 119 172 139 143 100 97 137 122 94 120 131 86 104 69
39 69 96 90 94 147 179 110 114 73 65 86 77 117 102 79 88 72 96 123
107 151 132 101 114 107 101 95 85 105 91 94 66 99 103 84 80
CPH-A34B 97
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122 129 105 72 119 116 84 123 126 210 192 233 217 169 154 104 89 136 155 111
128 104 117 107 134 164 126 172 138 145 98 96 142 116 93 132 141 84 99 74
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CPH-A36A 84
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86 48 91 89 113 135 101 104 153 160 180 174 127 156 148 84 137 132 109 78
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96 97 123 80 81 104 97 133 146 107 131 84 123 117 58 91 85 127 159 147
126 143 145 151
CPH-A36B 84
112 142 66 146 211 133 145 191 98 105 150 81 107 78 86 121 112 121 134 153
83 38 90 81 126 128 95 106 149 162 165 168 128 156 158 82 147 135 121 77
80 94 133 109 95 152 114 91 158 159 264 146 184 184 129 212 215 121 92 150
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150 132 163 150

CPH-A37A 84
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117 119 121 65 89 102 73 118 125 98 145 91 102 94 58 70 92 100 105 94
121 123 173 137
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67 87 136 121 76 140 120 78 119 121 174 96 133 151 96 127 175 118 94 149
121 115 120 78 82 120 73 106 119 109 136 96 102 92 49 75 78 101 125 101
102 134 163 136
CPH-A39A 58
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118 139 224 234 229 260 235 171 109 92 76 160 143 128 117 113 95 130 150 73
83 114 97 57 75 85 69 53 103 120 81 94 97 35 59 105 111 107
CPH-A39B 58
231 270 250 187 192 184 228 214 321 198 167 82 79 93 103 81 64 127 113 76
114 141 231 251 241 254 230 177 120 107 73 161 145 125 128 118 104 124 132 71
84 115 97 35 80 74 73 53 100 116 82 104 93 27 57 122 113 106
CPH-A40A 79
212 283 163 148 95 94 103 116 79 74 120 116 98 118 155 234 227 200 214 185
145 99 114 79 166 145 130 132 125 106 161 150 84 108 130 108 60 98 100 96
80 128 154 107 120 104 40 77 155 145 130 136 169 120 82 69 55 83 94 192
123 120 109 93 160 147 72 110 204 184 192 154 162 127 101 117 180 108 123
CPH-A40B 79
215 285 159 156 86 102 86 112 94 71 128 95 97 112 154 239 218 199 211 197
137 112 127 92 170 134 127 117 127 102 135 148 91 93 144 125 59 95 102 105
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125 125 115 88 167 153 78 97 207 217 204 124 172 147 120 106 165 112 131
CPH-A42A 52
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112 85 142 195 141 182 157 246 220 255 251 352
CPH-A42B 52
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189 201 203 158 135 151 134 153 140 117 132 208 153 173 153 156 131 108 111 110
105 83 157 194 144 184 151 236 224 258 253 350
CPH-A43A 60
285 288 301 259 260 299 263 240 271 141 174 272 262 234 225 169 179 232 205 173
170 179 146 120 132 142 139 124 142 128 125 174 158 157 203 193 175 154 156 158
121 85 143 172 130 182 121 195 178 166 169 166 151 159 114 104 121 130 147 163
CPH-A43B 60
312 267 304 271 252 310 251 229 266 155 195 255 249 217 228 169 196 250 203 150
164 185 146 118 126 144 126 114 143 117 113 202 188 172 204 182 166 150 162 142
117 93 145 163 129 176 146 169 166 156 174 213 133 150 123 94 131 120 158 166
CPH-A44A 58
333 306 397 354 308 365 318 361 390 330 333 255 347 293 373 392 373 298 321 351
308 449 215 280 372 391 215 183 274 270 244 83 62 58 60 44 35 41 44 49
62 53 67 85 91 84 88 107 63 27 26 46 52 68 104 89 120 156

CPH-A44B 58
331 301 390 355 309 358 323 363 378 320 347 259 328 293 374 406 390 294 323 356
297 472 231 266 386 391 213 189 271 253 251 82 66 59 55 50 41 34 43 53
58 52 68 85 95 78 86 102 65 34 24 44 45 72 103 95 116 153
CPH-A45A 62
151 299 293 333 263 287 269 314 234 213 263 180 162 225 231 254 249 225 146 217
194 169 242 180 256 243 211 233 243 188 180 201 210 132 188 167 174 162 170 163
115 103 135 92 93 170 180 143 111 146 124 136 172 115 150 146 152 147 122 117
77 87
CPH-A45B 62
158 306 306 337 260 291 272 286 244 166 262 184 165 243 241 262 252 209 184 277
194 176 242 176 253 249 199 230 237 195 176 208 193 142 188 166 164 186 152 160
109 116 141 96 83 179 178 162 124 114 130 147 159 124 142 129 153 151 102 123
74 92
CPH-A48A 92
145 310 306 363 248 251 215 153 251 251 196 224 235 165 93 83 106 165 107 173
202 120 147 156 117 138 190 171 151 153 118 198 140 182 140 159 106 109 93 115
124 119 159 109 160 102 113 77 80 99 90 124 89 106 111 95 96 83 86 99
89 105 115 145 139 105 112 65 82 89 43 47 51 75 113 126 74 85 79 112
95 63 49 64 107 75 76 91 78 62 71 105
CPH-A48B 92
152 320 311 348 241 246 212 163 247 262 186 220 257 161 88 88 105 162 119 165
242 115 141 156 113 141 196 170 144 156 104 213 135 184 138 157 111 101 106 127
103 132 172 97 154 106 101 92 78 94 100 122 96 111 114 99 90 89 84 96
84 113 117 149 129 114 104 67 74 93 45 42 59 77 106 125 75 78 74 114
95 49 59 70 105 73 67 91 82 68 75 107
CPH-A49A 101
220 208 234 306 244 237 333 235 240 196 165 122 154 229 205 265 201 196 164 149
206 191 140 192 243 196 128 114 174 210 160 230 279 179 159 171 153 159 163 145
154 175 106 190 137 164 159 181 169 159 111 152 152 179 202 138 188 130 153 95
140 116 113 161 102 113 161 107 139 95 118 112 105 110 134 194 154 133 148 121
103 142 80 71 114 137 115 154 92 91 98 136 107 83 100 138 187 144 94 115
134
CPH-A49B 100
204 207 238 304 246 231 321 250 244 189 159 120 151 271 214 255 197 191 167 138
207 193 160 195 220 180 130 138 171 209 157 227 293 185 167 161 139 167 160 138
158 179 140 188 122 169 152 193 173 153 120 153 160 175 185 132 193 142 145 107
131 125 109 153 109 111 162 108 143 95 119 110 103 101 135 196 156 120 141 115
116 139 78 74 118 143 104 154 95 95 99 133 102 92 92 153 182 133 94 119
CPH-A50A 84
65 133 90 98 216 166 126 86 36 93 105 132 133 152 126 111 155 175 240 244
198 244 218 217 119 142 150 124 241 154 130 134 154 155 135 80 70 64 43 45
44 24 44 48 104 99 107 187 204 231 162 241 354 454 565 484 392 486 403 301
273 212 152 118 159 103 37 43 65 57 49 47 46 57 39 40 32 34 30 30
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CPH-A50B 84
57 126 81 101 208 141 129 85 33 94 111 122 151 144 130 106 157 179 235 227
182 235 217 220 137 147 165 123 206 155 128 136 155 142 142 75 68 58 51 42
40 30 44 46 104 102 104 200 196 221 166 249 329 472 570 487 389 493 397 297
276 200 153 113 157 104 32 52 74 51 49 42 45 57 40 37 33 29 40 26
22 27 28 28

CPH-A51A 70
253 186 170 157 137 117 177 56 47 81 58 66 63 45 42 44 34 37 62 69
57 55 41 60 27 31 26 33 29 36 47 80 42 32 45 42 27 34 24 40
69 62 71 41 51 37 38 35 45 81 80 89 145 158 108 105 93 141 101 108
112 101 94 66 31 32 30 21 31 41
CPH-A51B 70
239 188 165 160 130 109 185 58 47 74 61 72 56 43 45 30 41 33 70 76
62 53 38 51 36 36 28 26 36 32 54 69 45 41 45 37 35 28 30 36
68 63 75 49 48 42 37 35 42 83 79 84 155 157 105 112 99 151 97 113
123 109 111 70 30 41 39 20 31 40
CPH-A53A 72
103 121 170 243 167 175 99 57 64 112 158 71 149 190 301 225 175 133 213 132
170 199 218 231 211 152 211 193 163 184 155 173 208 216 174 166 199 176 186 143
221 163 181 163 163 54 46 51 64 95 110 107 138 149 82 137 179 144 133 103
45 72 63 80 100 70 59 98 95 127 112 167
CPH-A53B 72
83 128 159 270 158 164 95 51 69 109 146 50 137 186 290 233 134 127 223 114
159 229 190 220 209 153 210 195 165 177 162 169 198 195 168 174 189 168 189 150
224 160 168 163 174 52 48 40 65 95 110 106 136 143 100 135 177 141 139 90
38 82 66 79 96 76 60 106 91 134 100 148
CPH-A54A 103
08 14 12 13 18 17 15 12 08 10 12 10 08 06 07 08 09 12 15 16
20 16 23 11 08 12 19 08 11 08 04 11 10 09 10 10 11 16 26 29
19 07 17 17 12 20 13 08 09 08 15 18 16 11 10 13 25 25 20 28
10 05 05 04 03 04 03 04 05 06 05 04 05 05 05 05 06 07 10 08
07 05 04 05 04 08 05 07 07 08 08 07 07 05 05 05 04 04 06 06
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APPENDIX: 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.

t-value/offset Matrix

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

Bar Diagram

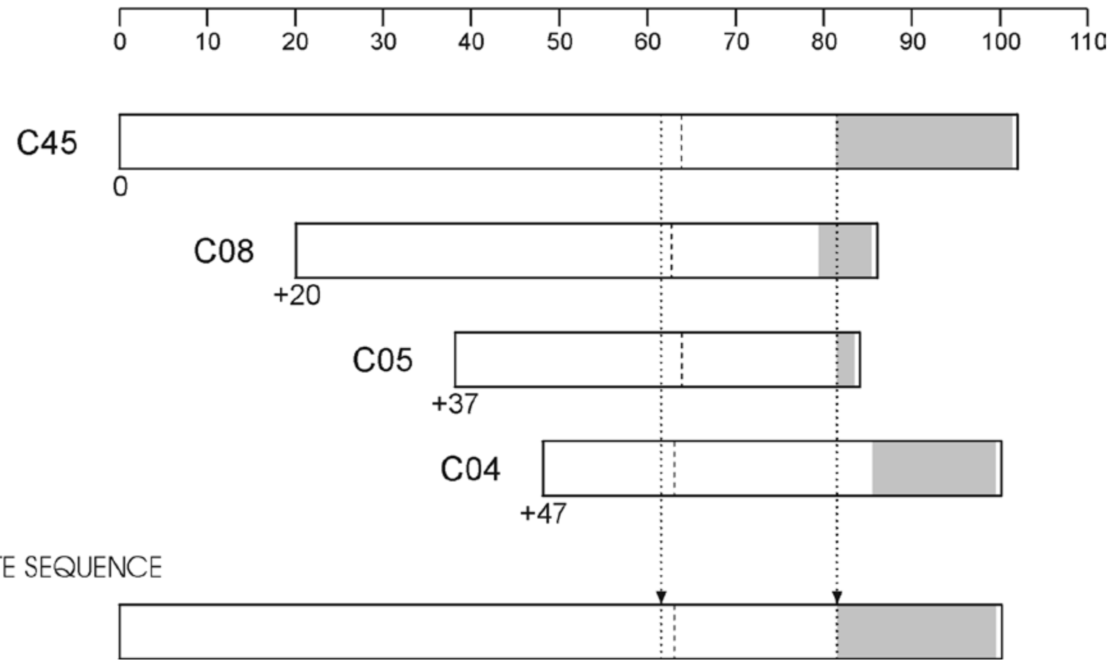


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

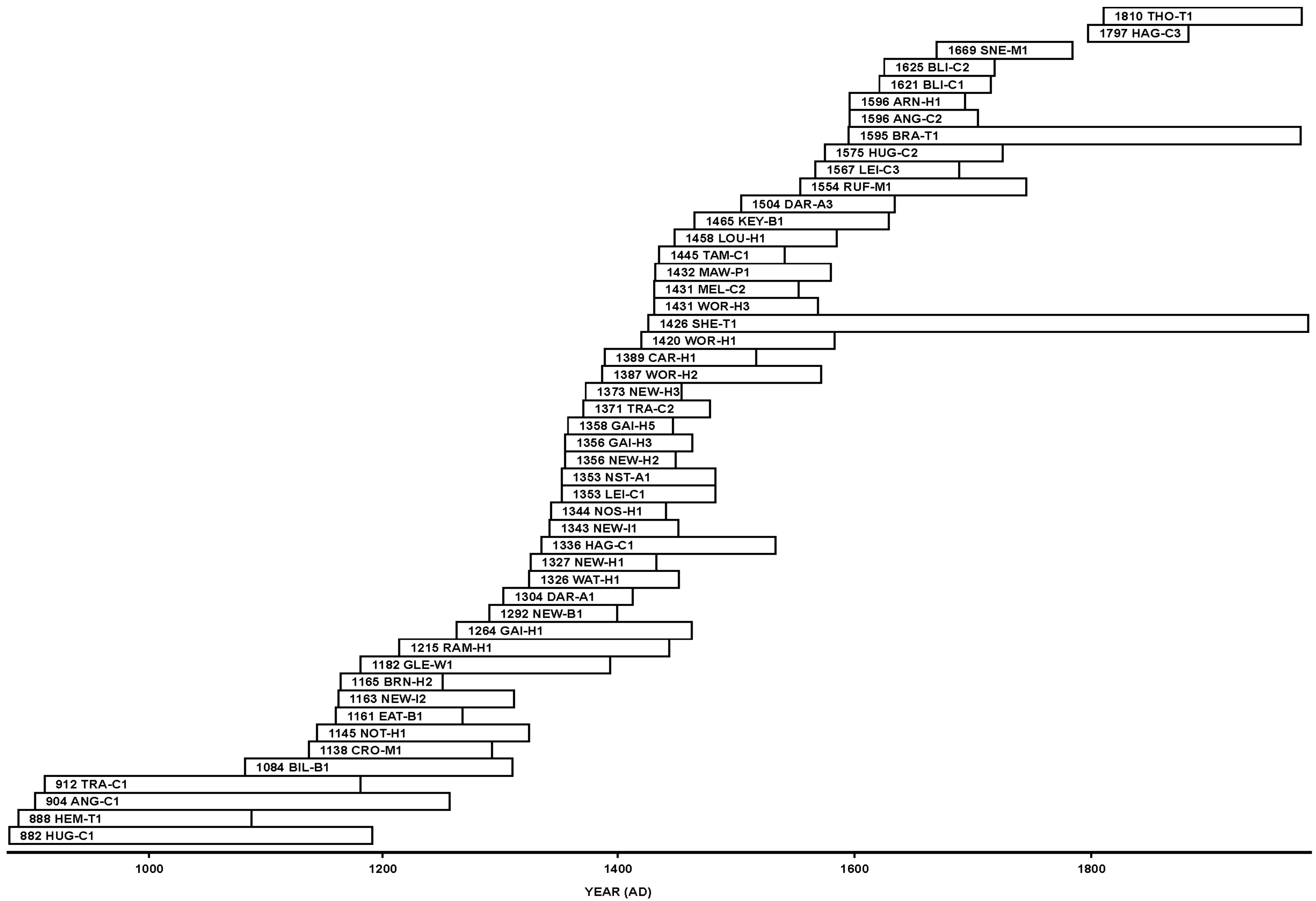
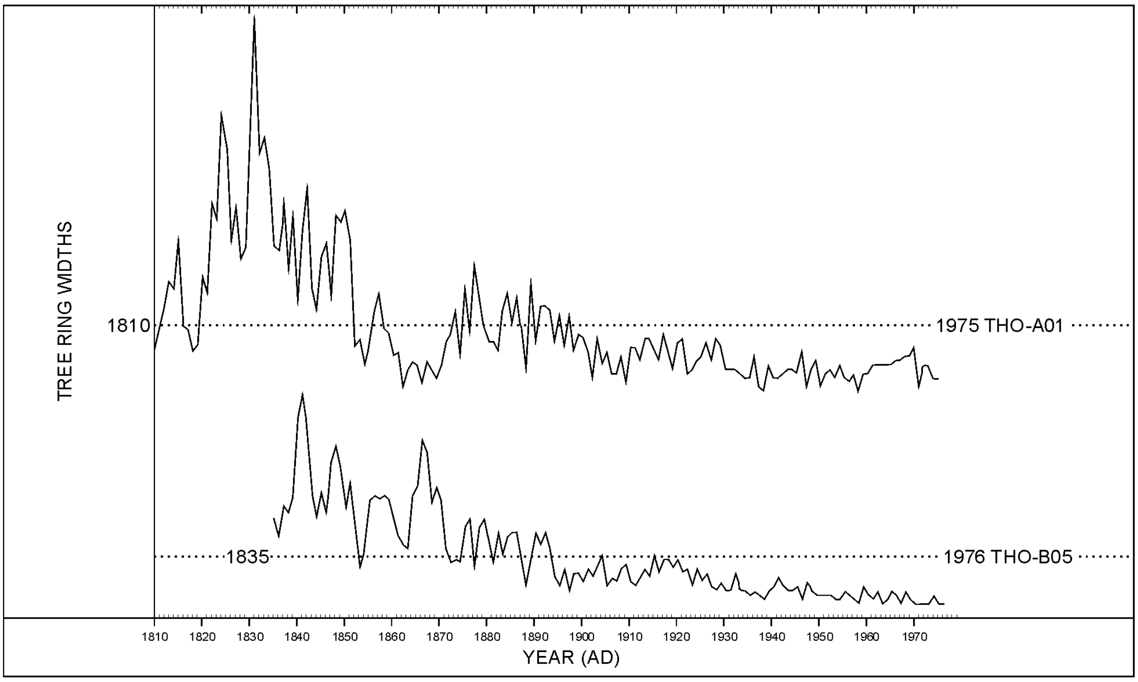


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

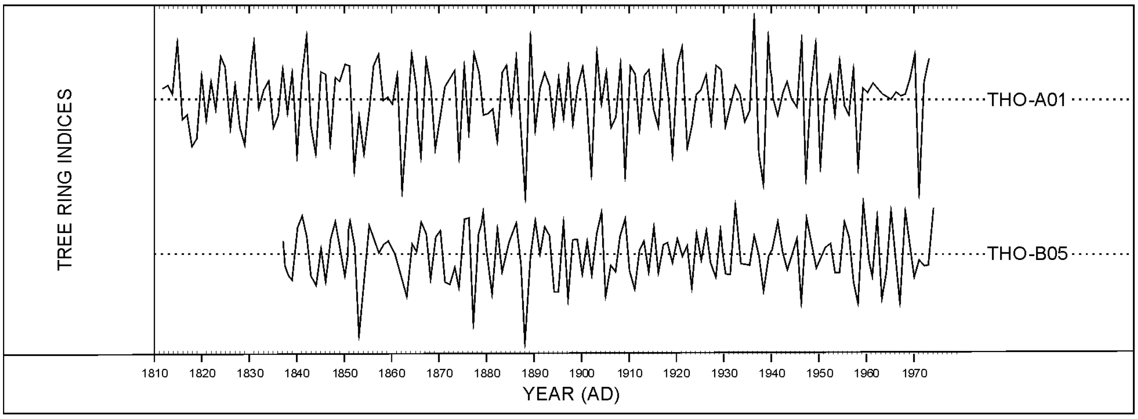


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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