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NAVE ROOF AND CEILING, CATHEDRAL CHURCH OF ST PETER AND ST WILFRED, RIPON, NORTH YORKSHIRE
WIGGLE-MATCH RADIOCARBON DATING OF TIMBERS

SCIENTIFIC DATING REPORT

Alex Bayliss, Christopher Bronk Ramsey, Gordon Cook, Stewart Freeman, W Derek Hamilton, Johannes van der Plicht, and Cathy Tyers

INTERVENTION AND ANALYSIS

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SUMMARY

Tree-ring analysis was undertaken on a total of 30 core samples from the principal oak timbers of the roof and ceiling ribs of the nave of Ripon Cathedral. This produced two major site chronologies, one of six samples, 226 rings long (RIPCSQ01), and another of nine samples, 117 rings long (RIPCSQ02). Two other site chronologies each containing two samples were also created. None of these site chronologies, nor any individual samples, could be dated by dendrochronology.

A series of ten contiguous decadal blocks of wood from the two main site chronologies were submitted for radiocarbon dating by Accelerator Mass Spectrometry. Two different cores from each site chronology were sent for dating to two different laboratories. Analysis of these results by wiggle-matching suggests that the timbers in site sequence RIPCSQ01 were felled in *cal AD 1855–1870 (95% probability*), and the timbers in site sequence RIPCSQ02 were felled in *cal AD 1850–1870 (95% probability)*.

This dating suggests that the truncated trusses of the nave roof, both those with single larger principal rafters and those with two very slightly smaller principal rafters in close-set pairs, as well as the ceiling ribs, date to the alterations undertaken under the direction of Sir Gilbert Scott in AD 1862–72

CONTRIBUTORS

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INTRODUCTION

Ripon Cathedral (Figs 1 and 2) was originally part of a Celtic monastery. This was reorganised by St Wilfrid in AD 660. Between then and AD 1050 it was refounded as a college of secular canons under the patronage of the Archbishop of York. It remained as a parish church even after the dissolution of the college in AD 1547. In AD 1604 the college was refounded under James I, dissolved during the Commonwealth, but founded yet again in AD 1660. It was elevated to Cathedral status in AD 1836.

The oldest fabric surviving in the Cathedral is the Anglo-Saxon crypt, dating from the seventh century AD. Major rebuilding work was begun under Archbishop Roger (AD 1154–81) and completed by Walter Gray (AD 1215–55). The eastern bays of the choir and the upper storey of the present chapter house were added in the fourteenth century, with further alterations occurring in the fifteenth century. The nave is believed to have undergone substantial alternations in the early sixteenth century, with the aisles added at this time. The works in AD 1514 and again in AD 1520–1 were in the charge of Christopher Scure, previously master mason at Durham Cathedral. In AD 1615 the spire on the crossing tower collapsed and in AD 1664 the spires on the two western towers were taken down. Nineteenth-century repairs were undertaken in AD 1829–31 by Edward Blore and in AD 1843–4 by William Railton, with more drastic alterations being made by Sir Gilbert Scott in AD 1862–72.

The nave roof (Fig 3) consists of 15 'truncated' trusses, consisting alternately of single larger principal rafters (trusses 1, 3, 5, etc, numbering from west to east) or of two very slightly smaller principal rafters in close set pairs (trusses 2, 4, 6, etc). All such principal rafters, both single and double, are of oak. Apart from slight differences in dimension, there are other very slight variations between the timbers of the two types of truss. The larger single rafters are more squarely cut and have more regular saw-marks on their faces. The smaller 'double' rafters are less well worked, being less well trimmed, and appear slightly more uneven in their sawing. It thus appears that there may be two sets of timbers within the principal trusses. The apex of each truss seems to have been cut off (if indeed the original ever extended to the ridge) and replaced in softwood. In addition to the apex sections, the collars, purlins, and other roof timbers are also of softwood. These softwood timbers, on the basis of the carpentry, appear to be nineteenth century in date.

Set to the underside of the principal roof timbers are the beams of the ceiling vault. These consist of ridge and vault ribs, from which spring diagonal and intermediate ribs. These timbers are all of oak. Some of them retain carpenters' marks in the form of Roman numerals.

The tree-ring analysis of the nave roof and ceiling was undertaken in 2004 to inform a programme of repairs grant-aided by English Heritage. It was uncertain, for example, how much sixteenth-century (or even earlier) fabric remained in its original position or had been reused in the nineteenth-century reconstruction of the roof. In 2005 a series of samples was submitted for radiocarbon dating by Accelerator Mass Spectrometry (AMS) in an attempt to date the floating tree-ring master sequences by wiggle-matching. By this time the repairs to the nave roof were largely complete, and so the principal aim of the project was to test the inter-laboratory comparability and accuracy of measurements produced by our collaborating radiocarbon laboratories in support of English Heritage's wider research programmes. Accelerator Mass Spectrometry had only recently achieved the precision needed for wiggle-matching, and so a subsidiary aim was to field test the technique to determine whether it can offer, on a routine basis, the accuracy required for applications relating to historic buildings.

This research and report was largely completed by the end of 2008. We had hoped to be able to include further discussion of how the dating of these timbers from the nave roof relates to the documentary and archaeological study of the Gilbert Scott campaigns. Unfortunately, this has been prevented by the untimely illness and death of the Cathedral Archaeologist, Dr Richard Hall, and so further historical analysis into the impact of this study on the understanding of the development of Ripon Cathedral must await future research.

TREE-RING SAMPLING AND ANALYSIS

Sampling and analysis by tree-ring dating of timbers from the nave at Ripon Cathedral were commissioned by English Heritage, and undertaken by the Nottingham University Tree-ring Dating Laboratory (Arnold *et al* 2005). Thirty core samples were taken, including principal rafters and double rafters from along the length of the nave and from both the north and south slopes of the roof, and ceiling ribs from bay 1 (at the western end) and bays 11 and 12. Sampling of the ceiling ribs was confined to the bays at each end of the nave because of health-and-safety concerns. Details of these samples are provided in Arnold *et al* (2005, table 1). Their locations are shown on Figure 4.

Tree-ring analysis of the ring series from these samples was undertaken using the grouping procedure described by Litton and Zainodin (1991). At a minimum *t*-value of 4.5, four site chronologies were produced. RIPCSQ01 contains six samples from principal rafters and has 226 rings (Fig 5), RIPCSQ02 contains nine samples, including five 'double' rafters and two ceiling ribs from each end of the nave (Fig 6) and has 117 rings. RIPCSQ03 and RIPCSQ04 each contain two samples from ceiling ribs (Arnold *et al* 2005, figs 6–7). Unfortunately none of these site chronologies, or any of the individual samples, can be conclusively dated by dendrochronology. It is unusual for oak chronologies of such length from English buildings to remain undated. At Lincoln Cathedral, for example, only 23% of samples with between 80 and 170 rings failed to date (and all samples with more than 170 rings dated), whereas 75% of samples with between 55 and 65 rings remain undated (Laxton *et al* 2001, fig 16).

Despite the lack of calendar dates, information about the chronology of these roofs is available from this tree-ring analysis. It is certain that some timbers represent a single phase of felling. All the samples with complete sapwood in RIPCSQ01 were felled in the same year. All the samples with complete sapwood in RIPCSQ02 were also felled in the same year. However we do not know whether the trees represented in each of these chronologies were felled in the same year. The chronologies may fail to cross-match because they have no temporal overlap between each other, or because they are from different sources.

Two other points are noteworthy from this analysis. First, a number of timbers from the nave at Ripon Cathedral have in excess of 150 rings. Whilst it is not unusual for oaks to live this long, the presence of such timber in an English building of late-medieval or post-medieval date is relatively uncommon. Second, the number of sapwood rings on these timbers is unusually low for English material, ranging from 9 to 18 rings on the 22 samples with complete sapwood. Such low numbers of sapwood rings are more common on material from eastern England and Continental Europe.

RADIOCARBON SAMPLING AND ANALYSIS

Following the failure of the tree-ring analysis to produce felling dates, the outer parts of two of the cores taken for dendrochronology from each of the two principal undated site chronologies from Ripon Cathedral (RIPCSQ01 and RIPCSQ02) were divided into ten contiguous blocks, each containing wood of ten-year's growth (Fig 7). Cores RIP-C08 and RIP-C11 were used from site sequence RIPCSQ01 (Fig 8), and cores RIP-C14 and RIP-C29 were used from site sequence RIPCSQ02 (Fig 9). Two series of ten contiguous decadal samples were taken to mimic the shorter ring series which usually remain undated from English buildings. It is often most effective to sample decades from floating tree-ring chronologies as widely spaced in time as possible (ie from the innermost and outermost sections of the sequence). This allows the wiggle-match to fit against a longer stretch of the calibration curve, which is therefore more likely to include significant variations in the atmospheric radiocarbon concentration. Unfortunately, it is usually the short tree-ring series which remain undated from English buildings, preventing this sampling strategy (cf Bayliss *et al* 2006).

Ten decadal blocks from sample RIP-C08 were dated in replicate at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride using Accelerator Mass Spectrometry (AMS). They were prepared using methods outlined in Hoper *et al* (1998), and measured as described by Xu *et al* (2004). The dated rings comprise rings 127–226 in the undated site chronology, RIPCSQ01.

Ten decadal blocks from sample RIP-C11 were dated by AMS at the Centre of Isotope Research, Rijksuniversiteit Groningen. The dated rings from this core also comprise rings 127–226 in the undated site chronology, RIPCSQ01. Another ten decadal blocks from sample RIP-C14 were also dated by AMS at Groningen. The dated rings from this sample comprise rings 18–117 in the undated site chronology, RIPCSQ02. Procedures used for dating these samples are described by Aerts-Bijma *et al* (1997; 2001) and van der Plicht *et al* (2000).

Ten decadal blocks from sample RIP-C29 were dated by AMS at the Oxford Radiocarbon Accelerator Unit. These were processed using methods outlined in Hedges *et al* (1989) and dated as described by Bronk Ramsey *et al* (2004).The dated rings also comprise rings 18–117 in the undated site chronology, RIPCSQ02.

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Tables 1 and 2), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986). Replicate results have been quoted for each decadal block. Of the twenty groups of measurements, 16 are statistically consistent at two standard deviations (Ward and Wilson 1978; Tables 1 and 2). In two other cases the results are consistent at three standard deviations, although in the other two cases they are not (see below).

All three laboratories maintain continual programmes of quality assurance procedures, in addition to participation in international inter-comparisons (Scott 2003). These tests indicate no laboratory offsets and demonstrate the validity of the precision quoted.

CALIBRATION

The calibrations of these results, relating the radiocarbon measurements directly to calendar dates, have been calculated using the calibration curve of Reimer *et al* (2004) and the computer program OxCal (v3.10) (Bronk Ramsey 1995; 1998; 2001). The calibrated date ranges for each sample given in Table 1 have been calculated using the maximum intercept method (Stuiver and Reimer 1986). They are quoted in the form recommended by Mook (1986), with the end points rounded outwards to 5 years. The graphical distributions of the calibrated dates, given in outline in Figures 10–15 and 19, are derived from the probability method (Stuiver and Reimer 1993). All calculations have been undertaken at a bin-width of one year.

WIGGLE-MATCHING

Wiggle-matching is the process of matching a series of radiocarbon determinations which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of different blocks of wood submitted for dating is known precisely by counting the rings in the timber.

Radiocarbon wiggle-matching of tree-ring sequences that cannot be absolutely dated through dendrochronology is not new (eg Clarke and Renfrew 1972; Clarke and Morgan 1983; Baillie 1995, 69–70), although until now it has been confined largely to assemblages of waterlogged wood (eg van der Plicht *et al* 1995; Bayliss and Pryor 2001; Bayliss *et al*

2003). This is because large samples of wood were required for high-precision radiocarbon dating by Liquid Scintillation Spectrometry or Gas Proportional Counting. Recent advances in the accuracy and precision of radiocarbon measurements produced by Accelerator Mass Spectrometry (eg Bronk Ramsey *et al* 2004; Dellinger *et al* 2004), however, now make this approach feasible for small wood samples, such as those available from cores taken for tree-ring dating. An excellent summary of the history and variety of approaches employed for wiggle-matching is provided by Galimberti *et al* (2004).

A variant of the wiggle-matching approach has also been applied to validate, or choose between, different matching positions of a floating tree-ring sequence against the absolutely dated master chronologies (Bayliss *et al* 1999). This is useful in situations where possible cross-matching positions have been identified by the tree-ring analysis, but where these are not strong enough statistically to be accepted without independent, confirmatory, evidence.

A BAYESIAN APPROACH TO WIGGLE-MATCHING

The first method of wiggle-matching which has been applied to these data, is using a Bayesian approach to combine the radiocarbon dates with the relative dating provided by the tree-ring analysis. This is a probabilistic approach, which determines which parts of the calibrated radiocarbon date are most likely given the tree-ring evidence. This results in a reduced date range, known as a posterior density estimate, which is shown in black in Figures 10–15 and 19, and given in italics in the text. 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) and Bronk Ramsey *et al* (2001).

The technique used is a form of numerical integration, and has been applied using the program OxCal v3.10 (http://www.rlaha.ox.ac.uk/orau/). Details of the algorithms employed for this application are available from the on-line manual or in Bronk Ramsey (1995; 1998; 2001). The algorithms used in the models described below can be derived from the structure shown in Figures 10–15 and 19.

The chronological model for the dating of samples RIP-C08/C11 (site sequence RIPCSQ01) is shown in Figure 10. This includes the weighted mean of the replicate radiocarbon measurements on each of the decadal blocks of wood from the cores, the information that the centre ring of block 10 is 10 years earlier than the centre ring of block 9 etc, and the information that after the centre point of block 1 there were five years to the bark edge.

This analysis suggests that samples RIP-C08/C11, and so all the samples from principal rafters whose tree-ring series form site chronology RIPCSQ01, were felled in *cal AD 1855–1870 (95% probability; RIPCSQ01 bark edge*; Fig 10), or *cal AD 1860–1865 (68% probability*). This model has good overall agreement (Aoverall = 166.3%, An= 22.4%;

Bronk Ramsey 1995). This means that the radiocarbon measurements are compatible with the tree-ring sequence of the timber samples.

The chronological model for the dating of samples RIP-C14/C29 (site sequence RIPCSQ02) is shown in Figure 11. This includes the weighted mean of the replicate radiocarbon measurements on each of the decadal blocks of wood from the cores, the information that the centre ring of block 10 is 10 years earlier than the centre ring of block 9 etc, and the information that after the centre point of block 1 there were five years to the bark edge.

This analysis suggests that samples RIP-C14/C29, and so all the samples from 'double rafters' and ceiling ribs whose tree-ring series form site chronology RIPCSQ02, were felled in *cal AD 1850–1870 (95% probability; RIPCSQ02 bark edge*; Fig 11), or *cal AD 1855–1865 (68% probability*). This model also has good overall agreement (Aoverall = 69.7%, An= 22.4%; Bronk Ramsey 1995).

Although both these models show good overall agreement, suggesting that the radiocarbon dating information is compatible with the relative dating series provided by the tree-ring analysis, three of the ten pairs of radiocarbon measurements in the series for RIPCSQ01 are statistically inconsistent (Table 1). This is more than would be expected simply on the grounds of statistical scatter.

For this reason, it was decided to wiggle-match the results from cores RIP-C08 and RIP-C11 separately. Figure 12 shows the analysis of RIP-C08, which suggests that this timber was felled in *cal AD 1855–1870 (95% probability; bark edge C08*), or *cal AD 1855–1865 (68% probability*). This model has good overall agreement (Aoverall =46.0%, An=22.4; Bronk Ramsey 1995), although four of the replicate pairs of measurements from this core are statistically inconsistent at 95% confidence (SUERC-8971 and SUERC-11442, T'=4.1; SUERC-8972 and SUERC-11443, T'=6.3; SUERC-8974 and SUERC-11445, T'=4.5; and SUERC-8975 and SUERC-11449, T'=5.4; T'(5%)=3.8 and ν=1 for all; Ward and Wilson 1978). None of the pairs is inconsistent at 99% confidence, and in all four cases the younger measurement is statistically consistent with that produced by the Groningen laboratory on the same decade from core RIP-C11 (SUERC-11442 and GrA-30761, T'=2.0; SUERC-11443 and GrA-30762, T'=0.2; SUERC-11445 and GrA-30765, T'=0.3; and SUERC-11449 and GrA-30766, T'=0.8; T'(5%)=3.8 and ν=1 for all; Ward and Wilson 1978). This suggests that SUERC-8971–2 and SUERC-8974–5 are slightly older than would be expected on purely statistical grounds. Figure 13 shows the analysis of RIP-C11, which suggests that this timber was felled in *cal AD 1860–1885 (90% probability; bark edge C11*) or *cal AD 1930–1945 (5% probability)*, or *cal AD 1870–1885 (68% probability*). This model also has good overall agreement (Aoverall =58.1%, An=22.4; Bronk Ramsey 1995).

This analysis suggests that the wiggle-matching of site sequence RIPCSQ01 is robust. Reproducible results are produced by the analysis of the measurements from the master sequence (Fig 10), and by the analyses of the measurements from each tree-ring core independently (Figs 12 and 13).

A BAYESIAN APPROACH TO VALIDATING TENTATIVE TREE-RING MATCHES

Despite exhaustive cross-checking for potential matches with an extensive set of reference data from Great Britain, northern Europe, and North America, conclusive dating of the tree-ring series from Ripon Cathedral by dendrochronology has not been possible (Arnold *et al* 2005). An unproven potential tree-ring match was suggested by the dendrochronology for each of the main site sequences, however, where the final ring of both RIPCSQ01 and RIPCSQ02 falls in AD 1868. A selection of the highest *t*-values for each potential match against a range of reference chronologies is given in Table 3, although in neither case are the results sufficiently strong for acceptance in the absence of confirmatory evidence, and in both cases they are barely replicated elsewhere. Although still inadequate, the statistical evidence for placing RIPCSQ02 at this date is slightly stronger than that for RIPCSQ01 as it produces potential matches against a wider selection of reference data.

Figure 14 shows the chronological model for the dating of samples RIP-C08/C11 (site sequence RIPCSQ01) where the last ring of the sequence is constrained to be AD 1868, as tentatively suggested by the tree-ring analysis (Table 3). This model includes the weighted mean of the replicate radiocarbon results on each of the decadal blocks of wood from the cores, the information that the centre of one block is 10 years earlier than the centre of the next block in the sequence, and the information that the centre point of block 1 is five years earlier than the bark edge date of AD 1868. This model has good overall agreement (Aoverall =68.3%; An=21.3%; Bronk Ramsey 1995). This suggests that the dating of this sequence, cautiously suggested by tree-ring analysis, may be correct.

A similar chronological model for the dating of samples RIP-C14/C29 (site sequence RIPCSQ02), where the last ring of the sequence is also constrained to be AD 1868, is shown in Figure 15. This model also has good overall agreement (Aoverall =22.2%; An=21.3%; Bronk Ramsey 1995). This suggests that the dating of this sequence, cautiously suggested by tree-ring analysis, may also be correct.

THE 'LEAST-SQUARES' METHOD OF WIGGLE-MATCHING

The second approach used to fit the radiocarbon measurements from cores RIP-C08/C11 and RIP-C14/C29 to the radiocarbon calibration curve places the weighted means of the results from each decadal block in a position that minimises the differences between the radiocarbon results from the tree-ring series and those forming the calibration curve. This method is described by Pearson (1986) and Bronk Ramsey *et al* (2001).

At Ripon Cathedral, we know that the mid-point of each wood sample submitted for radiocarbon dating is 10 years earlier or later than the next sample in the sequence, and that the outermost sample was complete to bark edge. Consequently, the timbers were felled five years after the date provided by the wiggle-matching (Figs 8 and 9).

This approach has been applied using a non-distributed version of the computer program CAL25 (van der Plicht 1993). The specific algorithm implemented is described in Bronk Ramsey *et al* (2001).

The least-squares 'best fit' for the first sequence of radiocarbon results against the calibration curve of Reimer *et al* (2004) indicates a date for the bark edge of the mean sequence RIP-CSQ01 of AD 1865 (χ^2 fit value=0.47; Fig 16). The result is in accordance with posterior density estimate of *cal AD 1855–1870 (95% probability; RIPCSQ01 bark edge*) provided by the Bayesian analysis shown in Figure 10.

The least-squares 'best fit' for the second sequence of radiocarbon results against the calibration curve of Reimer *et al* (2004) indicates a date for the bark edge of the mean sequence RIP-CSQ02 of AD 1866 (χ^2 fit value=1.09; Fig 17). This result is also compatible with the posterior density estimate of *cal AD 1850–1870 (95% probability; RIPCSQ02 bark edge*) provided by the Bayesian analysis shown in Figure 11. The consistency of the results produced by the two methods is not surprising, since it has been shown that the least-squares fit gives the highest point in the probability density function derived by the Bayesian method described above (Bronk Ramsey *et al* 2001, table 1), although the least-squares method provides a single date with no estimate of error.

WIGGLE-MATCHING RIPON CATHEDRAL AND THE RADIOCARBON CALIBRATION CURVE

At the time this analysis was undertaken, the internationally accepted calibration curve for radiocarbon dating was IntCal04 (Reimer *et al* 2004). This is the dataset used for the all analyses so far presented in this report.

IntCal04 adopts a more sophisticated approach to the estimation of the errors on the curve than previous datasets, interpolating data points at 5-year bin widths using a smoothing function based on the year by year trend in atmospheric radiocarbon concentration observed in annual data (Buck and Blackwell 2004). Because the data points in this curve are interpolated using a smoothing function, they are not statistically independent. This is a fundamental assumption of the statistical approaches to wiggle-matching adopted at present.

To assess the practical effect of the statistical dependency between the data points in the IntCal04 calibration curve, the analyses for the mean site sequences (RIPCSQ01 and RIPCSQ02; Figs 10 and 11) were repeated using the IntCal98 calibration dataset (Stuiver *et al* 1998). During the period in question, this curve contains exactly the same radiocarbon measurements as IntCal04 (Fig 18), although in this case decadal data points have been produced by averaging the relevant measurements at each calendar date. The posterior density estimates for the outer ring dates of these mean sequences are shown in Table 4. In both cases they are identical to those produced by IntCal04. It should be noted that the single-year data used to produce the smoothing function for IntCal04 is included in the calibration data of relevance to these datasets from Ripon Cathedral. Consequently other wiggle-match applications beyond the extent of this single-year data may not be as robust.

Finally, the analyses for the mean site sequences (RIPCSQ01 and RIPCSQ02; Figs 10 and 11) were repeated using the raw single-year calibration data of Stuiver (1993). Although, as a single record, there is considerable random noise in this data (Figs 18–20), it does allow posterior density estimates to be calculated with rounding only to the year (Table 4). These are again consistent with the results from the analyses using the multi-dataset curves, and with the dates tentatively suggested by dendrochronology.

INTERPRETATION AND DISCUSSION

The combined results of the radiocarbon dating and tree-ring analysis presented above provide an estimated felling date for the timbers in RIPCSQ01, comprising samples from the principal rafters of the nave of Ripon Cathedral, of AD 1868 (Fig 14; Table 3). The estimated felling date for the timbers in RIPCSQ02, comprising samples from the 'double rafters' and ceiling ribs of the nave of Ripon Cathedral, is also AD 1868 (Fig 15; Table 3).

This suggests that the entire roof structure of the nave was reconstructed as part of the works designed by Sir Gilbert Scott and undertaken between AD 1862 and AD 1872. It seems that the nave vault was completed just before the service in the Cathedral to celebrate the completion of the 10-year restoration programme on October 24th AD 1872 (Anon 1873, 25), but had been inserted beneath the existing roof. The roof itself seems to have been replaced shortly afterwards, a scheme "delayed for want of funds" (Scott 1874, 318). The original designs by Scott for the nave roof survive and, although his drawing for the vault does show what was actually built, his drawings for the roof trusses do not seem to relate to the extant structure. Further work is required to determine whether the roof was actually completed to Scott's design or whether another architect became involved. A pencil note on the Scott design states,

"NB. The Ribs, Bosses, Boarding, Cornice and Plates to be Dantzic oak. The constructional timbers behind to be of Memel fir…The old timbers to be used as far as possible… The oak to be left its natural colour, not oiled or varnished".

The scientific dating currently available does not provide evidence for significant numbers of reused oak timbers being salvaged and incorporated into the replacement roof and vault. Perhaps these were too rotten for reuse. New oak, and perhaps also the softwood, seems to have been procured for construction in AD 1868 or shortly thereafter, but to have been in stock for use until at least 1873. The documentary evidence agrees with the tentative cross-matching suggested by dendrochronology (Table 3), in suggesting that this timber may have been imported from the eastern Baltic.

The consistency of the results provided by the statistical analyses of the radiocarbon data from Ripon Cathedral (Table 4) suggests that the proposed dating is probably robust against further refinements in radiocarbon calibration data and the methodology of wiggle-matching. This application may be unusual in this respect, simply because of the presence of single-year calibration data in the relevant part of the radiocarbon calibration curve and its use for determining the form of that curve. Further research is required to clarify these issues.

The accuracy and precision required for the radiocarbon measurements produced for this application is challenging, particularly for AMS technology. For reasons that are unclear, some of the results from core RIP-C08 seem biased towards slightly older radiocarbon ages. Because of the degree of replication available for this study, this has no practical influence on the accuracy of the results produced by the analyses. It does illustrate, however, that even slight bias, which under normal circumstances would have little practical influence on archaeological interpretation, can be significant when attempting applications of this sort.

CONCLUSIONS

Bayesian wiggle-matching of radiocarbon measurements from tree-ring sequences from Ripon Cathedral suggests that the timbers in site sequence RIPCSQ01 were felled in *cal AD 1855–1870 (95% probability; RIPCSQ01 bark edge*; Fig 10), and the timbers in site sequence RIPCSQ02 were felled in *cal AD 1850–1870 (95% probability; RIPCSQ02 bark edge*; Fig 11). These radiocarbon results are consistent with weak statistical tree-ring matches tentatively suggesting that each sequence ends in AD 1868 (Table 3).

This application demonstrates that sophisticated statistical approaches to the integration of radiocarbon dating with information from dendrochronology can produce results which are sufficiently precise and accurate to be of utility to buildings historians. Such precision and accuracy is currently challenging for the radiocarbon community, and more research may be required before such applications can be undertaken on a routine basis.

BIBLIOGRAPHY

Aerts-Bijma, A T, Meijer, H A J, and van der Plicht, J, 1997 AMS sample handling in Groningen. *Nuclear Instruments and Methods in Physics Research B,* **123**, 221–5

Aerts-Bijma, A T, van der Plicht, J, and Meijer, H A J, 2001 Automatic AMS sample combustion and CO_2 collection, *Radiocarbon*, **43**, 293–8

Anon, 1873 Re-opening of Ripon Cathedral, *The Church Builder*, **45** (**January 1873**), 25

Arnold, A J, Howard, R E, and Litton, C D, 2005 *Tree-ring analysis of timbers from the nave roof and ceiling of the Cathedral Church of St Peter and St Wilfred, Ripon, North Yorkshire*, Centre for Archaeol Rep, **44/2005**

Baillie, M G L, 1995 *A Slice through time*, London (Batsford)

Bartholin, T S, 1973 *Undersøgelse af muligheden for dendrokronologisk datering af egetræ i Danmark, specielt sønderjylland, Beretning*, **265**, 215–41

Bayliss, A, and Pryor, F, 2001 Radiocarbon and absolute chronology, in *The Flag Fen Basin: archaeology and environment of a Fenland landscape* (F Pryor), English Heritage Archaeol Rep, 390–9

Bayliss, A, Groves, C, McCormac, G, Baillie, M, Brown, D, and Brennard, M, 1999 Precise dating of the Norfolk timber circle, *Nature*, **402**, 479

Bayliss, A, Groves, C, McCormac, F G, Bronk Ramsey, C, Baillie, M G L, Brown, D, Cook, G T, and Switsur, R V, 2003 Dating, in *The Dover Bronze Age Boat* (P Clark), English Heritage Archaeol Monograph, 250–5

Bayliss, A, Bronk Ramsey, C, Hamilton, D, and van der Plicht, J, 2006 *Radiocarbon wiggle-matching of the second floor of the bell tower at the church of St Andrew, Wissett, Suffolk*, English Heritage Research Dept Rep Ser, **32/2006**

Becker, B, 1981 *Fällungsdaten Römischer Bauhölzer, Fundberichte aus Baden-Wurtemberg*, **6**, 369–86

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

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

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

Bronk Ramsey, C, van der Plicht, J, and Weninger, B 2001 'Wiggle matching' radiocarbon dates, *Radiocarbon*, **43**, 381–9

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

Buck, C E, and Blackwell, P G, 2004 Formal statistical models for radiocarbon calibration curves, *Radiocarbon*, **46**, 1093–1102

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

Christen, J A, and Litton, C D, 1995 A Bayesian Approach to Wiggle-Matching, *J Archaeol Sci*, **22**, 719–25

Clarke, R M, and Morgan, R A, 1983 An alternative statistical approach to the calibration of floating tree-ring chronologies: two sequences from the Somerset levels, *Archaeometry*, **25**, 3–15

Clarke, R M, and Renfrew C, 1972 A statistical approach to the calibration of floating tree-ring chronologies using radiocarbon dates, *Archaeometry*, **14**, 5–19

Dellinger, F, Kutschera, W, Nocolussi, K, Schiessling, P, Steier, P, and Wild, E M, 2004 A 14C calibration with AMS from 3500 – 3000 BC, derived from a new high-elevation stone-pine tree-ring chronology, *Radiocarbon*, **46**, 969–78

Delorme, A, 1972 *Dendrochronologische Untersuchungen an Eichen des Südlichen Weser- und Leineberglandes*, unpubl PhD thesis Göttingen Univ

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

Hedges, R E M, Bronk, C R, and Housley, R A, 1989 The Oxford Accelerator Mass Spectrometry facility: technical developments in routine dating, *Archaeometry*, **31**, 99–113

Hollstein, E, 1980 *Mitteleuropäische Eichenchronologie*, Mainz am Rhein

Hoper, S T, McCormac, F G, Hogg, A G, Higham, T F G, and Head, M J, 1998 Evaluation of wood pretreatments on oak and cedar, *Radiocarbon*, **40**, 45–50

Laxton, R R, Litton, C D, and Howard, R E, 2001 *Dendrochronology of roof timbers at Lincoln Cathedral*, English Heritage Research Trans, **7**

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

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

Pearson, G W, 1986 Precise calendrical dating of known growth-period samples using a 'curve fitting' technique, *Radiocarbon*, **28**, 292–9

van der Plicht, J, 1993 The Groningen radiocarbon calibration program, *Radiocarbon*, **35**, 231–7

van der Plicht, J, Jansma, E, and Kars, H, 1995 The "Amsterdam Castle": a case study of wiggle matching and the proper calibration curve, *Radiocarbon*, **37**, 965–8

van der Plicht, J, Wijma, S, Aerts, A T, Pertuisot, M H, and Meijer, H A J, 2000 Status report: the Groningen AMS facility, Nuclear Instruments and Methods in *Physics Research B*, **172**, 58–65

Reimer, P J, Baillie, M G L, Bard, E, Bayliss, A, Beck, J W, Bertrand, C J H, Blackwell, P G, Buck, C E, Burr, G S, Cutler, K B, Damon, P E, Edwards, R L, Fairbanks, R G, Friedrich, M, Guilderson, T P, Hogg, A G, Hughen, K A, Kromer, B, McCormac, G, Manning, S, Bronk Ramsey, C, Reimer, R W, Remmele, S, Southon, J R, Stuiver, M, Talamo, S, Taylor, F W, van der Plicht, J, and Weyhenmeyer, C E, 2004 IntCal04 Terrestrial radiocarbon age calibration, 0–26 Cal Kyr BP, *Radiocarbon*, **46**, 1029–58

Scott, E M (ed), 2003 The Third International Radiocarbon Intercomparison (TIRI) and the Fourth International Radiocarbon Intercomparison (FIRI) 1990–2002: results, analysis, and conclusions, *Radiocarbon*, **45**, 135–408

Scott, Sir G G, 1874 Ripon Minster, *Archaeol J*, **31**, 309–19

Stuiver, M, 1993 A note on single-year calibration of the radiocarbon time scale, AD 1510–1954, *Radiocarbon*, **35**, 67–72

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

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

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

Stuiver, M, and Reimer, P J, 1993 Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program, *Radiocarbon*, **35**, 215–30

Stuiver, M, Reimer, P J, Bard, E, Beck, J W, Burr, G S, Hughen, K A, Kromer, B, McCormac, F G, van der Plicht, J and Spurk, M 1998 INTCAL98 radiocarbon age calibration, 24,000–0 cal BP, *Radiocarbon*, **40**, 1041–84

Ward, G K, and Wilson, S R, 1978 Procedures for comparing and combining radiocarbon age determinations: a critique, *Archaeometry*, **2**, 19–31

Wazny, T, 1990 *Aufbau und Anwendung der Dendrochronologie für Eichenholz in Polen*, unpubl PhD thesis Hamburg Univ

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

TABLES

Table 1: Radiocarbon determinations from contiguous 10-year blocks of wood from cores RIP-C08 and RIP-C11, both comprising rings 126–226 of the 226-ring undated tree-ring sequence RIPCSQ01. A weighted mean has been taken of replicate radiocarbon measurements prior to calibration (Ward and Wilson 1978)

Laboratory Number	Sample ID	Material	$\delta^{13}C$ (‰)	Radiocarbon Age (BP)	Calibrated Date (95% confidence)	*Posterior Density Estimate (95% probability)* (see Fig 10)
SUERC-8963	RIP-C08(1)	*Quercus* spp.	−24.0	100±35		
SUERC-11434	RIP-C08 (1)	*Quercus* spp.	−23.9	140±35		
GrA-30753	RIP-C11(1)	*Quercus* spp.	−25.7	150±30		
mean rings 217–226: T'=1.2; T'(5%)=6.0; ν=2				132±19	cal AD 1675–1955*	*cal AD 1850–1865*
SUERC-8964	RIP-C08(2)	*Quercus* spp.	−23.6	135±35		
SUERC-11435	RIP-C08(2)	*Quercus* spp.	−23.5	160±35		
GrA-30755	RIP-C11(2)	*Quercus* spp.	−25.9	115±30		
mean rings 207–216: T'=1.0; T'(5%)=6.0; ν=2				135±19	cal AD 1670–1955*	*cal AD 1840–1855*
SUERC-8965	RIP-C08(3)	*Quercus* spp.	−23.4	145±35		
SUERC-11439	RIP-C08(3)	*Quercus* spp.	−23.7	135±35		
GrA-30756	RIP-C11(3)	*Quercus* spp.	−26.1	115±30		
mean rings 197–206: T'=0.5; T'(5%)=6.0; ν=2				130±19	cal AD 1675–1955*	*cal AD 1830–1845*
SUERC-8969	RIP-C08(4)	*Quercus* spp.	−23.5	150±35		
SUERC-11440	RIP-C08(4)	*Quercus* spp.	−23.6	110±35		
GrA-30757	RIP-C11(4)	*Quercus* spp.	−25.3	65±30		
mean rings 187–196: T'=3.4; T'(5%)=6.0; ν=2				104±19	cal AD 1680–1955*	*cal AD 1820–1835*
SUERC-8970	RIP-C08(5)	*Quercus* spp.	−23.5	155±35		
SUERC-11441	RIP-C08(5)	*Quercus* spp.	−23.3	85±35		
GrA-30635	RIP-C11(5)	*Quercus* spp.	−27.2	95±30		
mean rings 177–186: T'=2.4; T'(5%)=6.0; ν=2				110±19	cal AD 1680–1955*	*cal AD 1810–1825*
SUERC-8971	RIP-C08(6)	*Quercus* spp.	−23.7	240±35		
SUERC-11442	RIP-C08(6)	*Quercus* spp.	−23.5	140±35		

GrA-30761	RIP-C11(6)	*Quercus* spp.	−26.3	75±30		
mean rings 167–176: T'=12.8; T'(5%)=6.0; ν=2				144±19	cal AD 1665–1955*	*cal AD 1800–1815*
SUERC-8972	RIP-C08(7)	*Quercus* spp.	−23.4	270±35		
SUERC-11443	RIP-C08(7)	*Quercus* spp.	−23.3	145±35		
GrA-30762	RIP-C11(7)	*Quercus* spp.	−27.0	165±30		
mean rings 157–166: T'=7.6; T'(5%)=6.0; ν=2				191±19	cal AD 1655–1955*	*cal AD 1790–1805*
SUERC-8973	RIP-C08(8)	*Quercus* spp.	−23.3	275±35		
SUERC-11444	RIP-C08(8)	*Quercus* spp.	−23.2	230±35		
GrA-30763	RIP-C11(8)	*Quercus* spp.	−25.6	210±30		
mean rings 147–156: T'=2.0; T'(5%)=6.0; ν=2				235±19	cal AD 1640–1950	*cal AD 1780–1795*
SUERC-8974	RIP-C08(9)	*Quercus* spp.	−23.2	245±35		
SUERC-11445	RIP-C08(9)	*Quercus* spp.	−23.4	140±35		
GrA-30765	RIP-C11(9)	*Quercus* spp.	−25.1	165±30		
mean rings 137–146: T'=5.0; T'(5%)=6.0; ν=2				182±19	cal AD 1660–1955*	*cal AD 1770–1785*
SUERC-8975	RIP-C08(10)	*Quercus* spp.	−23.3	275±35		
SUERC-11449	RIP-C08(10)	*Quercus* spp.	−24.1	160±35		
GrA-30766	RIP-C11(10)	*Quercus* spp.	−25.4	120±30		
mean rings 127–136: T'=11.7; T'(5%)=6.0; ν=2				179±19	cal AD 1660–1955*	*cal AD 1760–1775*

Table 2: Radiocarbon determinations from contiguous 10-year blocks of wood from cores RIP-C14 and RIP-C29, both comprising rings 126–226 of the 226-ring undated tree-ring sequence RIPCSQ02. A weighted mean has been taken of replicate radiocarbon measurements prior to calibration (Ward and Wilson 1978)

Laboratory Number	Sample ID	Material	$\delta^{13}C$ (‰)	Radiocarbon Age (BP)	Calibrated Date (95% confidence)	*Posterior Density Estimate (95% probability)* (see Fig 11)
GrA-30767	RIP-C14(1)	*Quercus* spp.	−23.9	115±30		
OxA-15406	RIP-C29(1)	*Quercus* spp.	−23.8	132±25		
mean rings 108–17: T'=0.2; T'(5%)=3.8; ν=1				126±20	cal AD 1675–1955*	*cal AD 1845–1865*
GrA-30768	RIP-C14(2)	*Quercus* spp.	−24.5	100±30		
OxA-15497	RIP-C29(2)	*Quercus* spp.	−24.0	155±23		
mean rings 98–07: T'=2.1; T'(5%)=3.8; ν=1				135±19	cal AD 1675–1955*	*cal AD 1835–1855*
GrA-30770	RIP-C14(3)	*Quercus* spp.	−24.1	95±30		
OxA-15407	RIP-C29(3)	*Quercus* spp.	−22.8	143±26		
mean rings 88–97: T'=1.5; T'(5%)=3.8; ν=1				123±20	cal AD 1680–1955*	*cal AD 1825–1845*
GrA-30772	RIP-C14(4)	*Quercus* spp.	−24.5	60±30		
OxA-15408	RIP-C29(4)	*Quercus* spp.	−23.1	141±25		
mean rings 78–87: T'=4.3; T'(5%)=3.8; ν=1				109±20	cal AD 1680–1955*	*cal AD 1815–1835*
GrA-30773	RIP-C14(5)	*Quercus* spp.	−24.1	85±30		
OxA-15409	RIP-C29(5)	*Quercus* spp.	−23.2	147±26		
mean rings 68–77: T'=2.4; T'(5%)=3.8; ν=1				121±20	cal AD 1680–1955*	*cal AD 1805–1825*
GrA-30775	RIP-C14(6)	*Quercus* spp.	−24.4	155±35		
OxA-15410	RIP-C29(6)	*Quercus* spp.	−23.1	171±25		
mean rings 58–67: T'=0.1; T'(5%)=3.8; ν=1				166±21	cal AD 1665–1955*	*cal AD 1795–1815*
GrA-30776	RIP-C14(7)	*Quercus* spp.	−24.1	170±30		
OxA-15411	RIP-C29(7)	*Quercus* spp.	−22.3	208±26		
mean rings 48–57: T'=0.9; T'(5%)=3.8; ν=1				192±20	cal AD 1655–1955*	*cal AD 1785–1805*
GrA-30777	RIP-C14(8)	*Quercus* spp.	−25.4	150±30		
OxA-15412	RIP-C29(8)	*Quercus* spp.	−22.6	221±25		
mean rings 38–47: T'=3.3; T'(5%)=3.8; ν=1				192±20	cal AD 1655–1955*	*cal AD 1775–1795*

GrA-30779	RIP-C14(9)	*Quercus* spp.	−24.4	189±30		
OxA-15413	RIP-C29(9)	*Quercus* spp.	−23.3	188±25		
mean rings 28–37: T'=0.0; T'(5%)=3.8; ν=1				189±20	cal AD 1660–1955*	*cal AD 1765–1785*
GrA-30780	RIP-C14(10)	*Quercus* spp.	−23.7	220±30		
OxA-15414	RIP-C29(10)	*Quercus* spp.	−23.7	211±25		
mean rings 18–27: T'=0.1; T'(5%)=3.8; ν=1				215±20	cal AD 1645–1955*	*cal AD 1755–1775*

*Table 3: Potential tree-ring cross-matches for RIPCSQ01 and RIPCSQ02 against independent reference chronologies (**please note**: these sequences remain undated by dendrochronology)*

Reference chronology	Start date	End date	*t*-value
RIPCSQ01 (AD 1643–1868)			
Germany: Niedersachsen Nord (Leuschner pers comm)	AD 915	AD 1873	4.73
Germany: South (Becker 1981)	370 BC	AD 1950	3.37
Germany: Trier region (Hollstein 1980)	546 BC	AD 1975	3.12
Germany: Weserbergland (Delorme 1972)	AD 1004	AD 1970	4.48
Poland: Dolny Slask (Krapiec pers comm)	AD 1319	AD 1994	5.93
Poland: Hajnowka (Wazny pers comm)	AD 1720	AD 1984	3.42
RIPCSQ02 (AD 1752–1868)			
Denmark: modern (Bartholin 1973)	AD 1630	AD 1971	4.13
Germany: Niedersachsen Nord (Leuschner pers comm)	AD 915	AD 1873	3.70
Germany: South (Becker 1981)	370 BC	AD 1950	3.72
Lithuania: Stakliskes (Kairaitis and Pukiene pers comm)	AD 1721	AD 1969	4.59
Poland: Hajnowka (Wazny pers comm)	AD 1720	AD 1984	4.09
Poland: East Pomerania (Wazny 1990)	AD 996	AD 1985	5.00

Table 4: posterior density estimates for the outer rings of RIPCSQ01 and RIPCSQ02, according to the models defined in Figures 10 and 11; calculated using the calibration curves of Reimer et al *(2004) and Stuiver* et al *(1998), and the single-year data of Stuiver (1993)*

	IntCal04 (Reimer *et al* 2004)	IntCal98 (Stuiver *et al* 1998)	Single-year data (Stuiver 1993)
RIPCSQ01			
95% probability	*cal AD 1855–1870*	*cal AD 1855–1870*	*cal AD 1856–1871*
68% probability	*cal AD 1860–1865*	*cal AD 1860–1865*	*cal AD 1857–1863 (45%) or cal AD 1864–1868 (23%)*
RIPCSQ02			
95% probability	*cal AD 1850–1870*	*cal AD 1850–1870*	*cal AD 1741–1750 (10%) or cal AD 1853–1871 (85%)*
68% probability	*cal AD 1855–1865*	*cal AD 1855–1865*	*cal AD 1855–1870*

FIGURES

Figure 1: Map showing the location of Ripon and Ripon Cathedral (shown in blue). This map is based upon Ordnance Survey © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

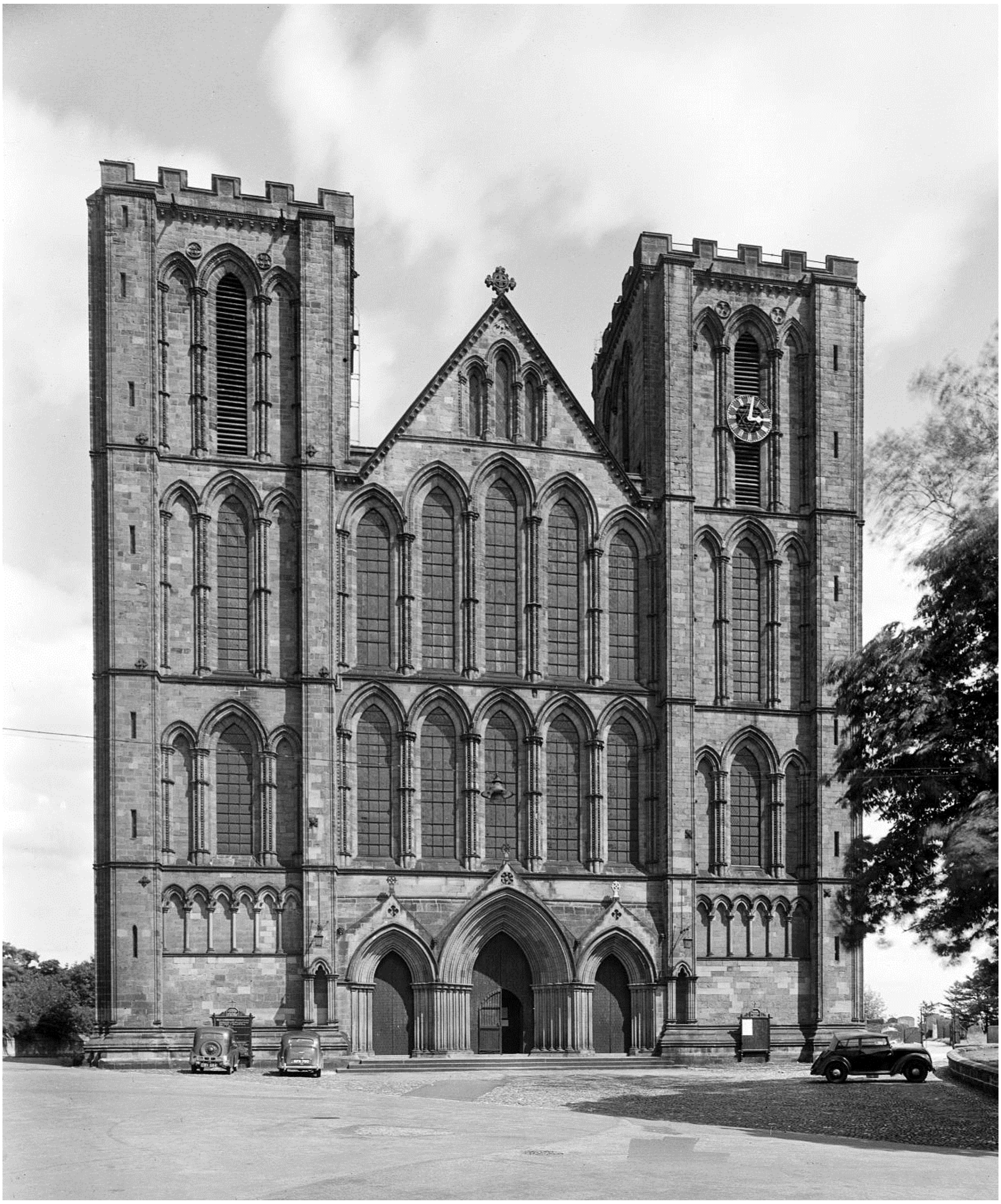


Figure 2: West front of Ripon Cathedral. © English Heritage/NMR AA72/942)

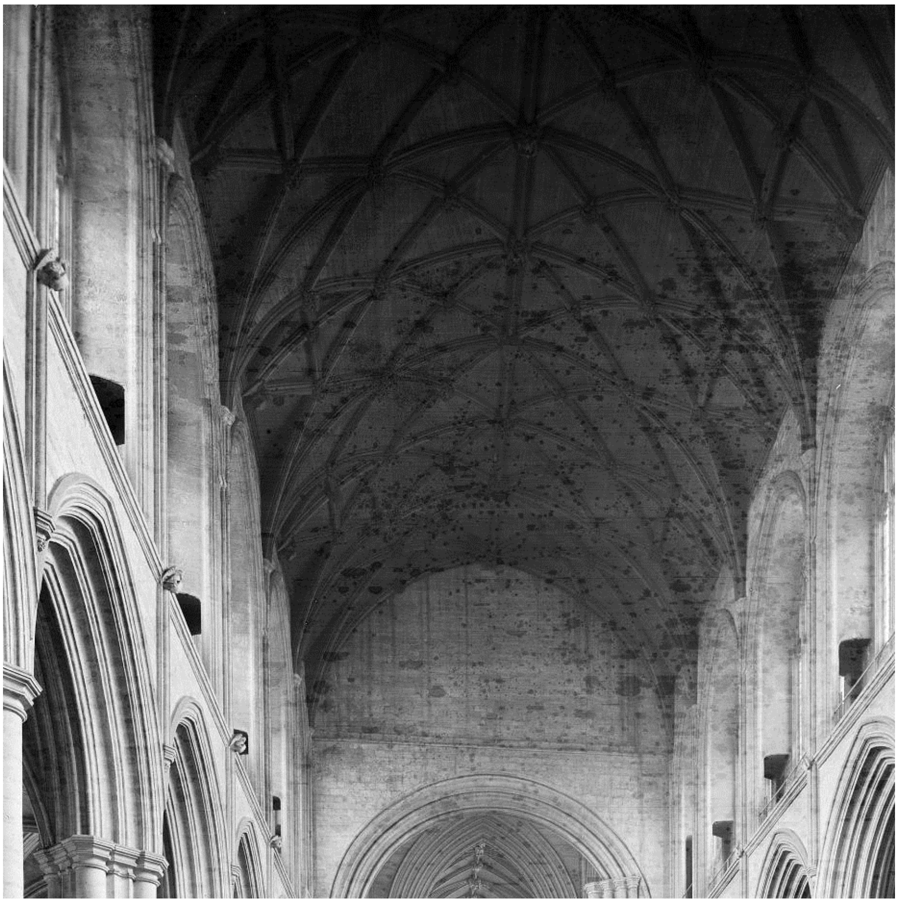


Figure 3: Ripon Cathedral, Nave looking east. © English Heritage/NMR CC66/157)

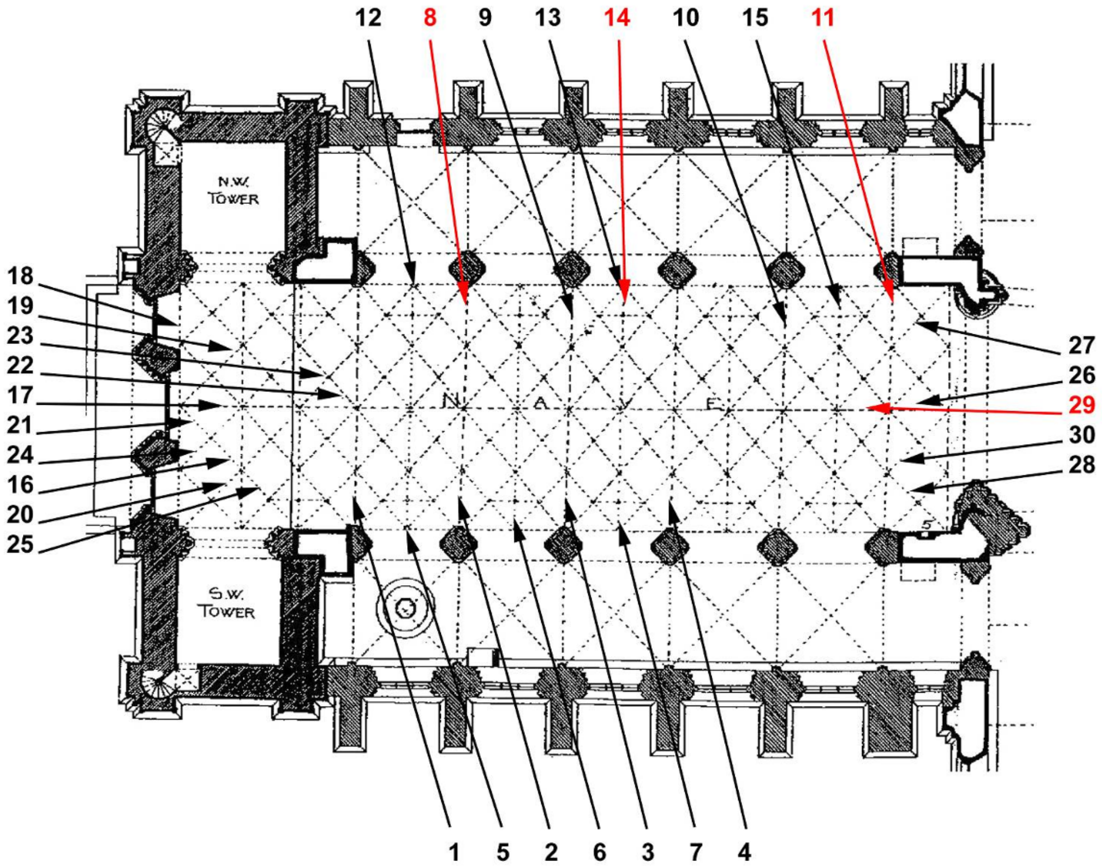
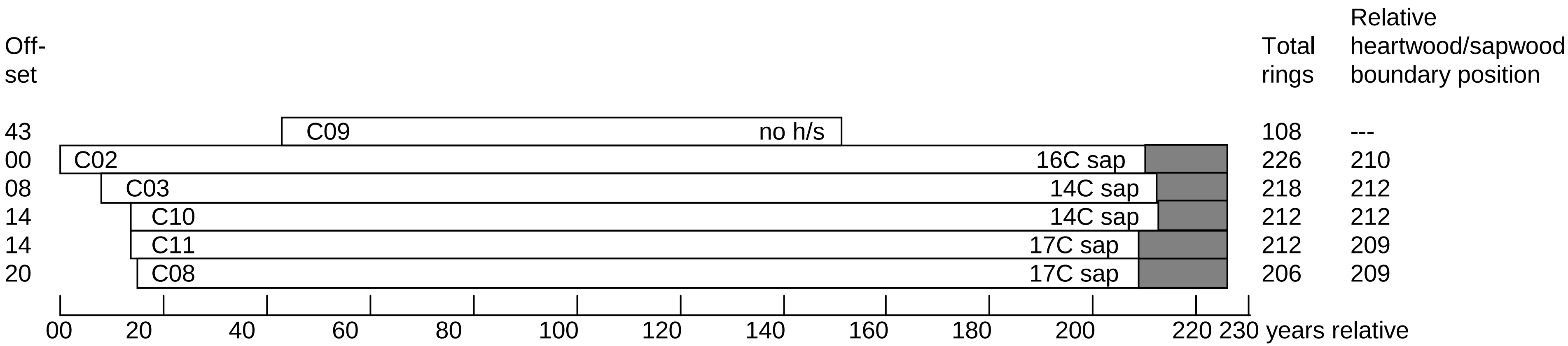
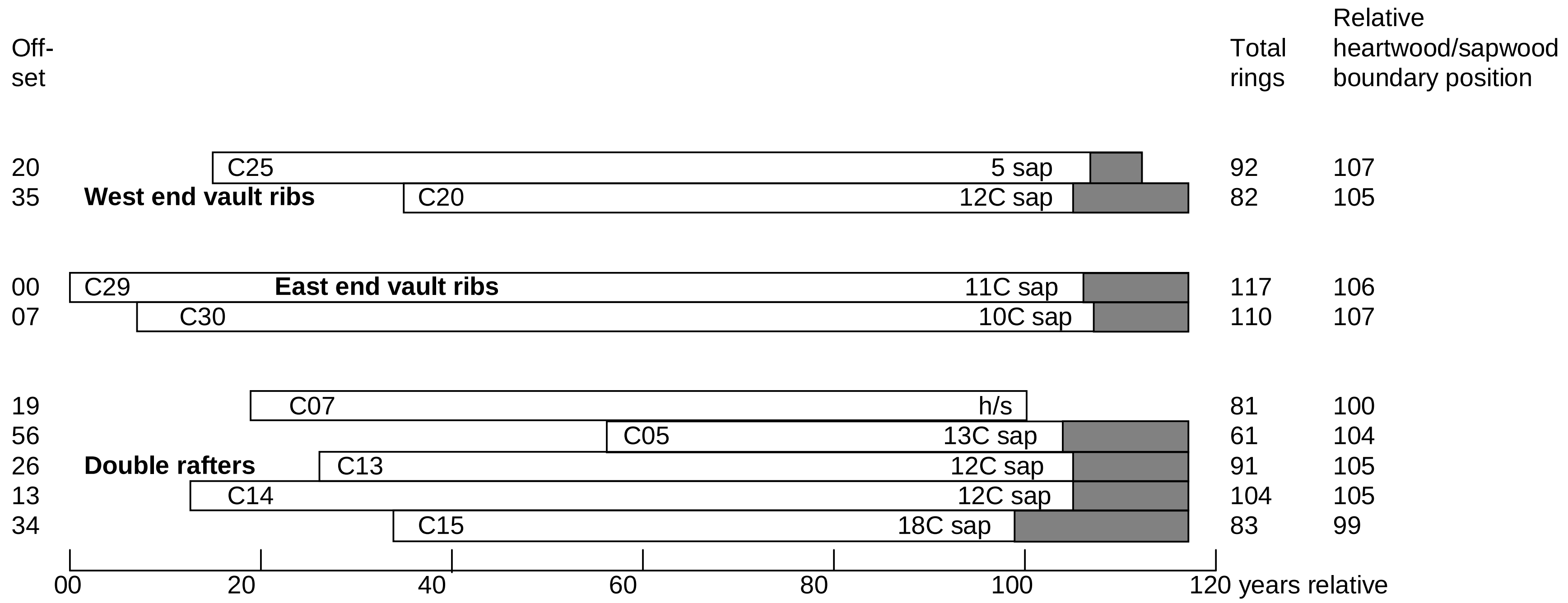


Figure 4: Plan of the nave of Ripon Cathedral, showing timbers sampled for dendrochronology (black) and dendrochronology and radiocarbon dating (red). © English Heritage/NMR 9317827



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 5: Bar diagram of the samples in site chronology RIPCSQ01



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Figure 6: Bar diagram of the samples in site chronology RIPCSQ02

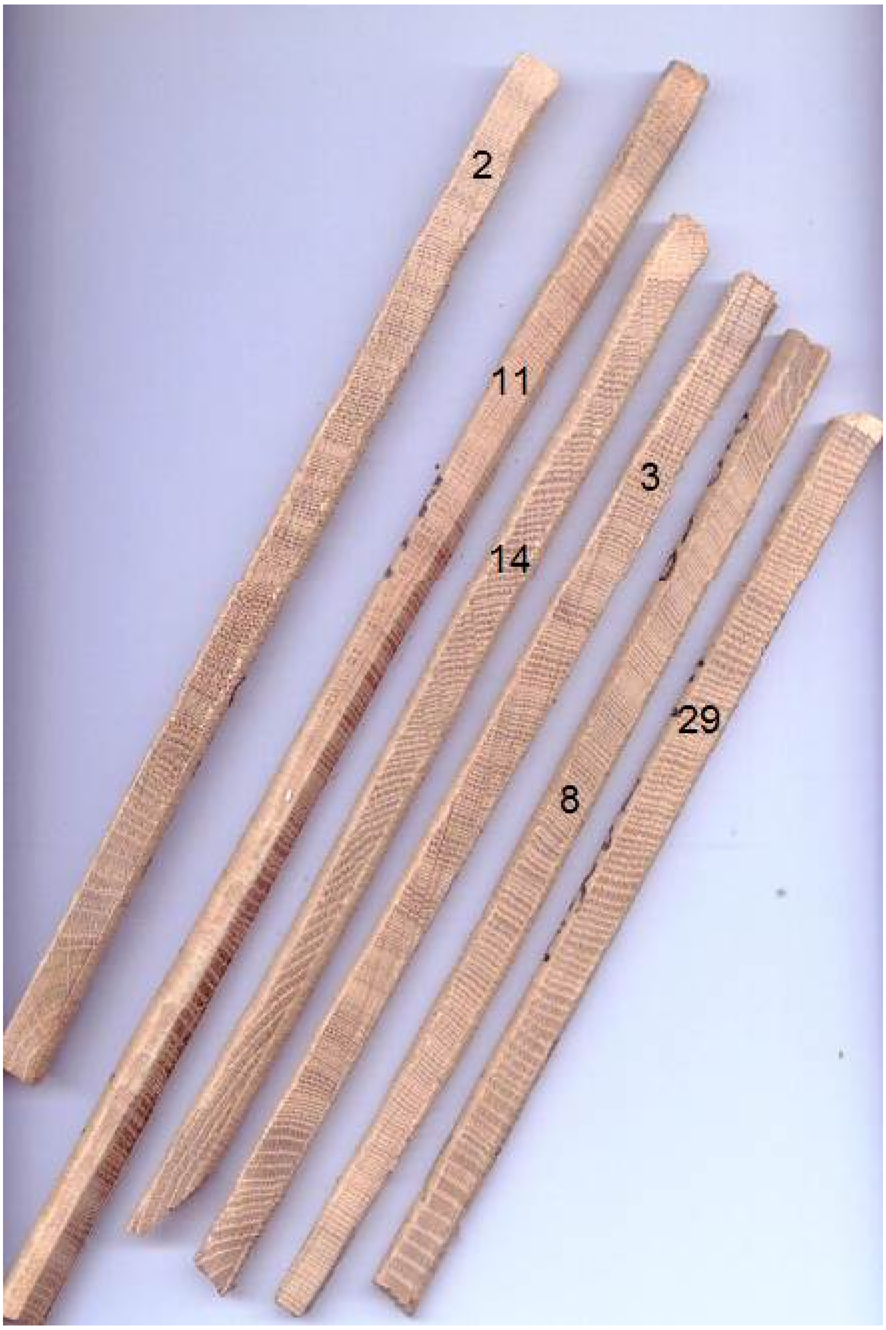


Figure 7: Dendrochronology cores used in this study (photo: Robert Howard)

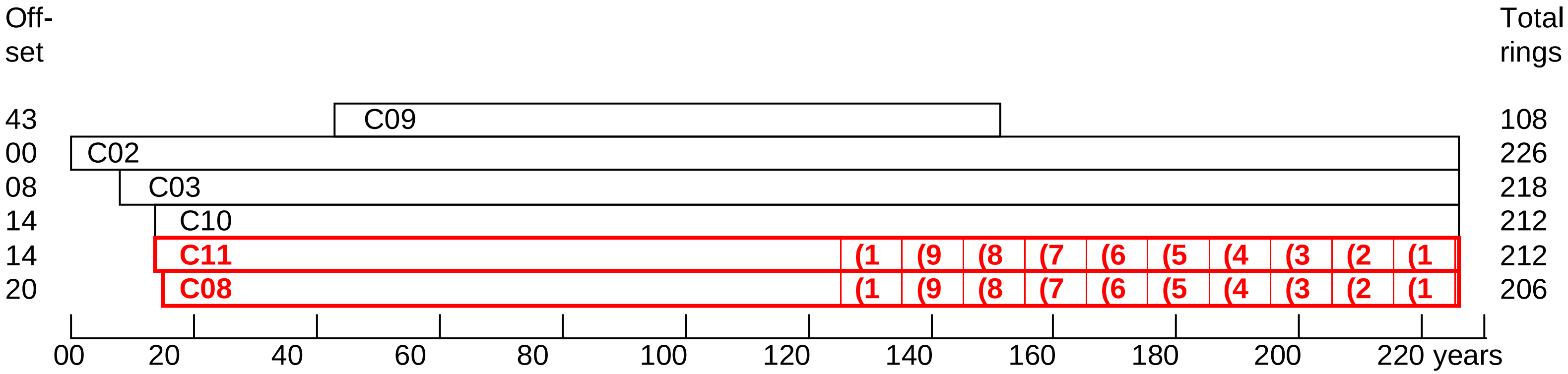


Figure 8: Schematic showing radiocarbon sampling (RIPCSQ01)

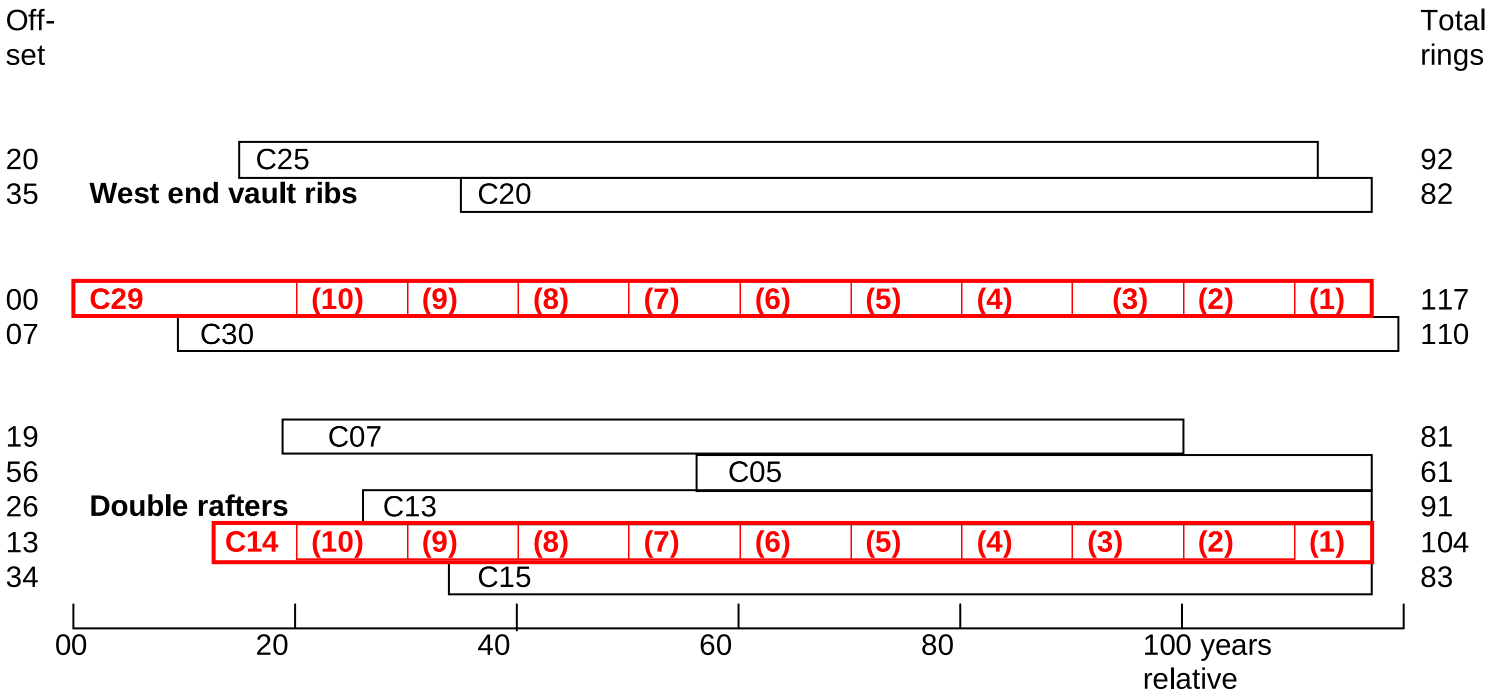


Figure 9: Schematic showing radiocarbon sampling (RIPCSQ02)

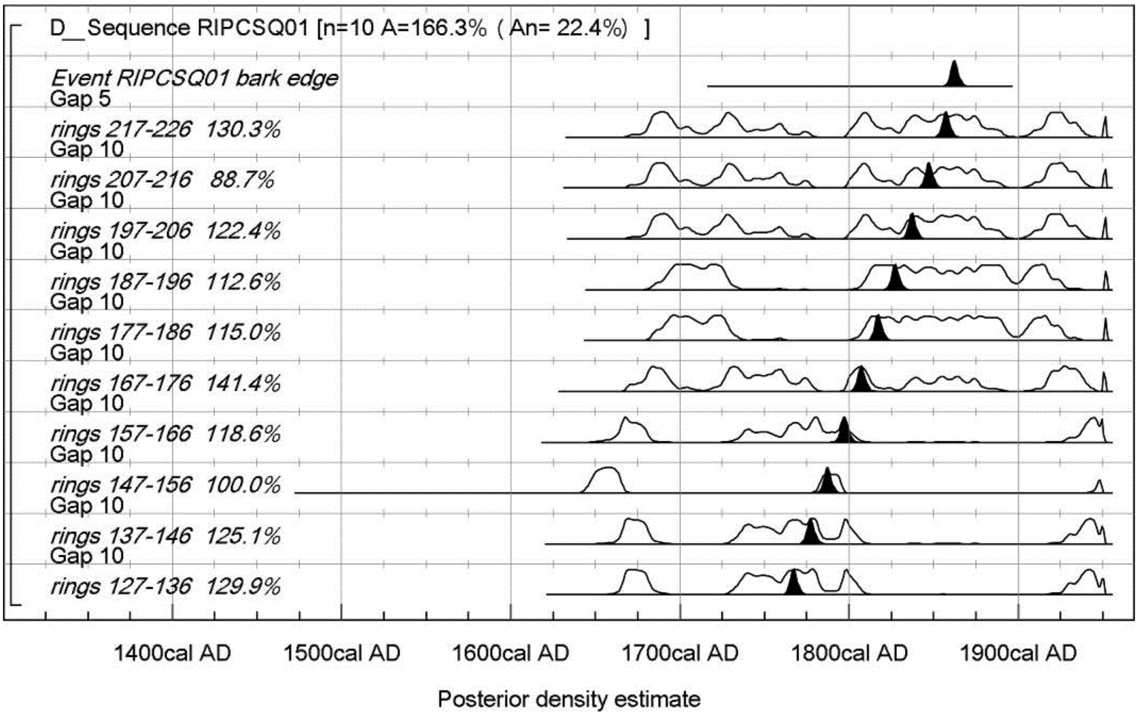


Figure 10: Probability distributions of dates from cores RIP-C08/C11 (site mean sequence RIPCSQ01). Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples, correspond to aspects of the model. For example, the distribution 'RIPCSQ01 bark edge' is the estimated date when the timbers retaining bark edge from this chronology were felled. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

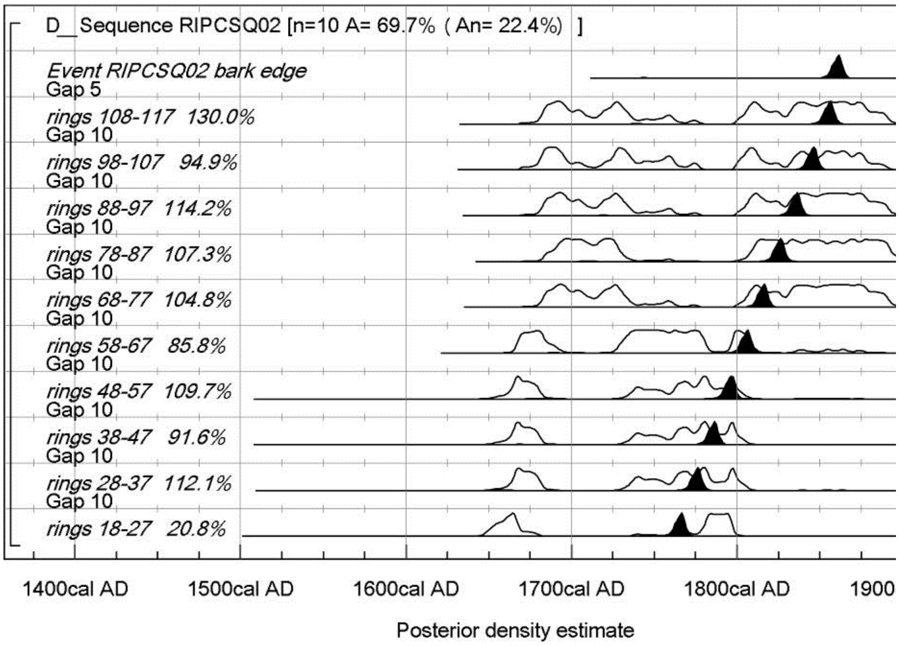


Figure 11: Probability distributions of dates from cores RIP-C14/C29 (site mean sequence RIPCSQ02). The format is identical to that of Figure 10. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

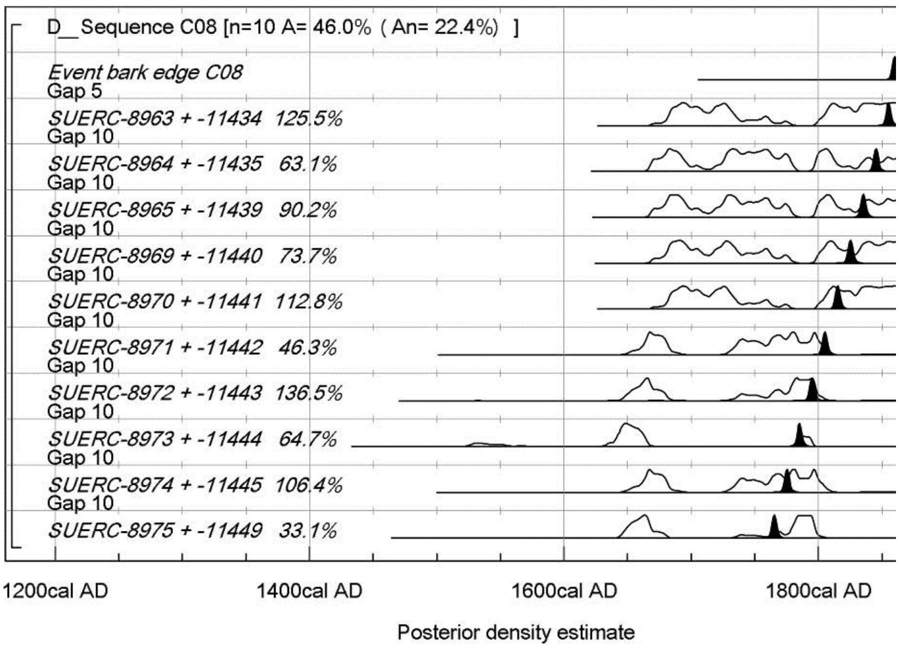


Figure 12: Probability distributions of dates from core RIP-C08. The format is identical to that of Figure 10. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

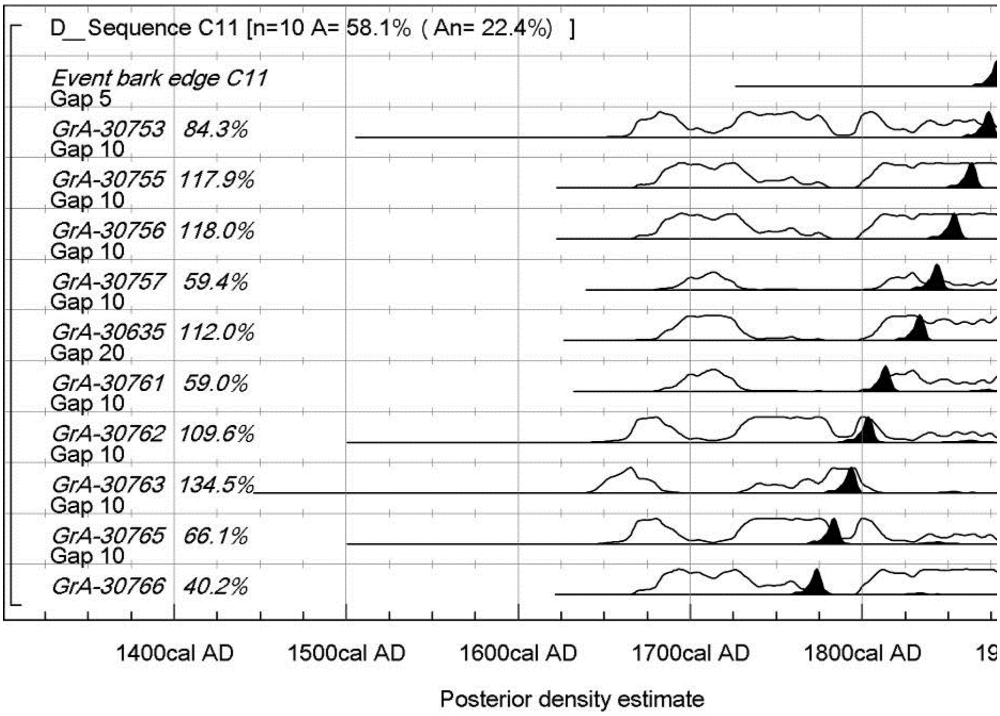


Figure 13: Probability distributions of dates from cores RIP-C11. The format is identical to that of Figure 10. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

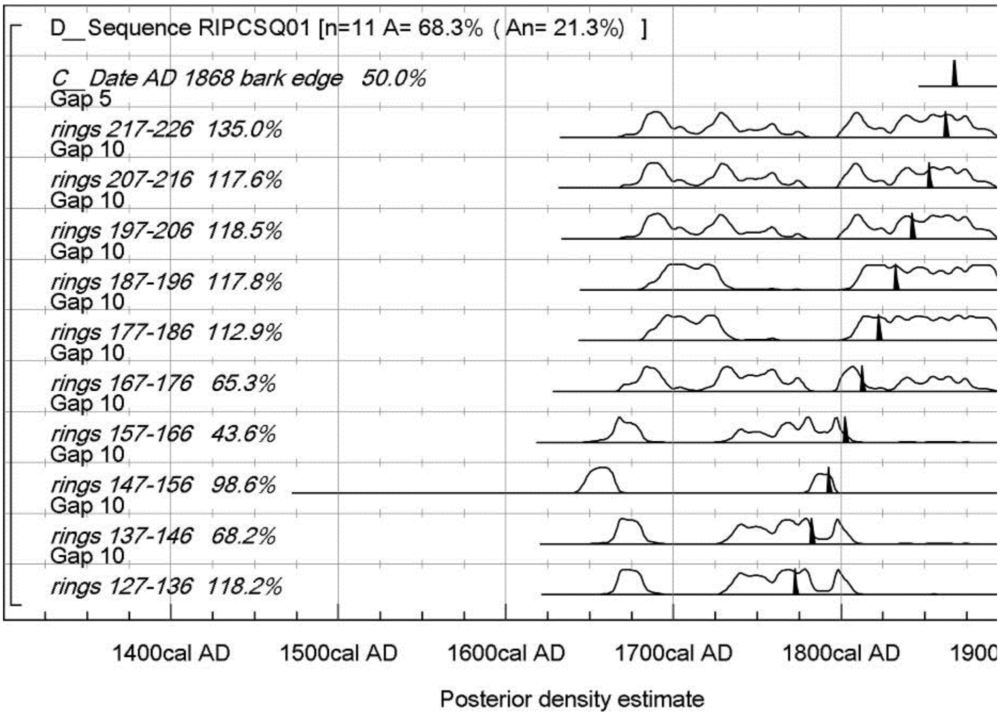


Figure 14: Probability distributions of dates from RIPCSQ01. The format is identical to that of Figure 10. C_Date AD 1868 bark edge has been included to test whether the radiocarbon dates agree with the weak match provided by tree-ring analysis at this date. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

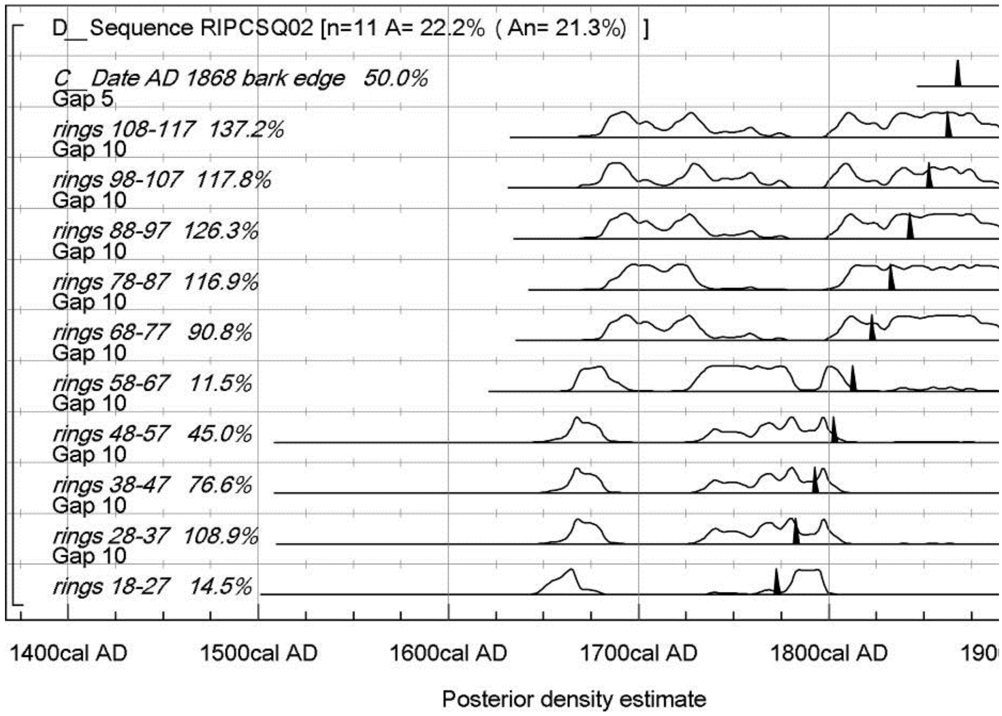


Figure 15: Probability distributions of dates from RIPCSQ02. The format is identical to that of Figure 10. C_Date AD 1868 bark edge has been included to test whether the radiocarbon dates agree with the weak match provided by tree-ring analysis at this date. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

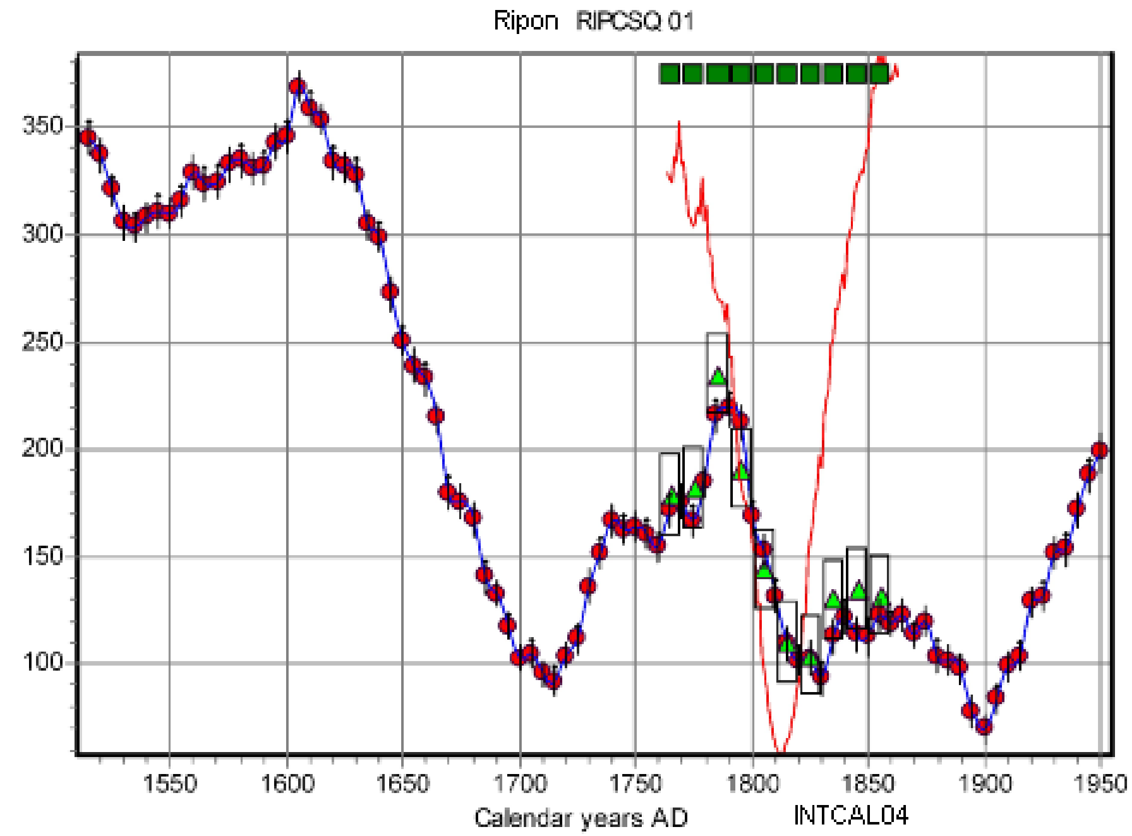


Figure 16: Least-squares wiggle-match, which provides a date for the last ring of RIPCSQ01 of AD 1865 (χ^2 fit value=0.47)

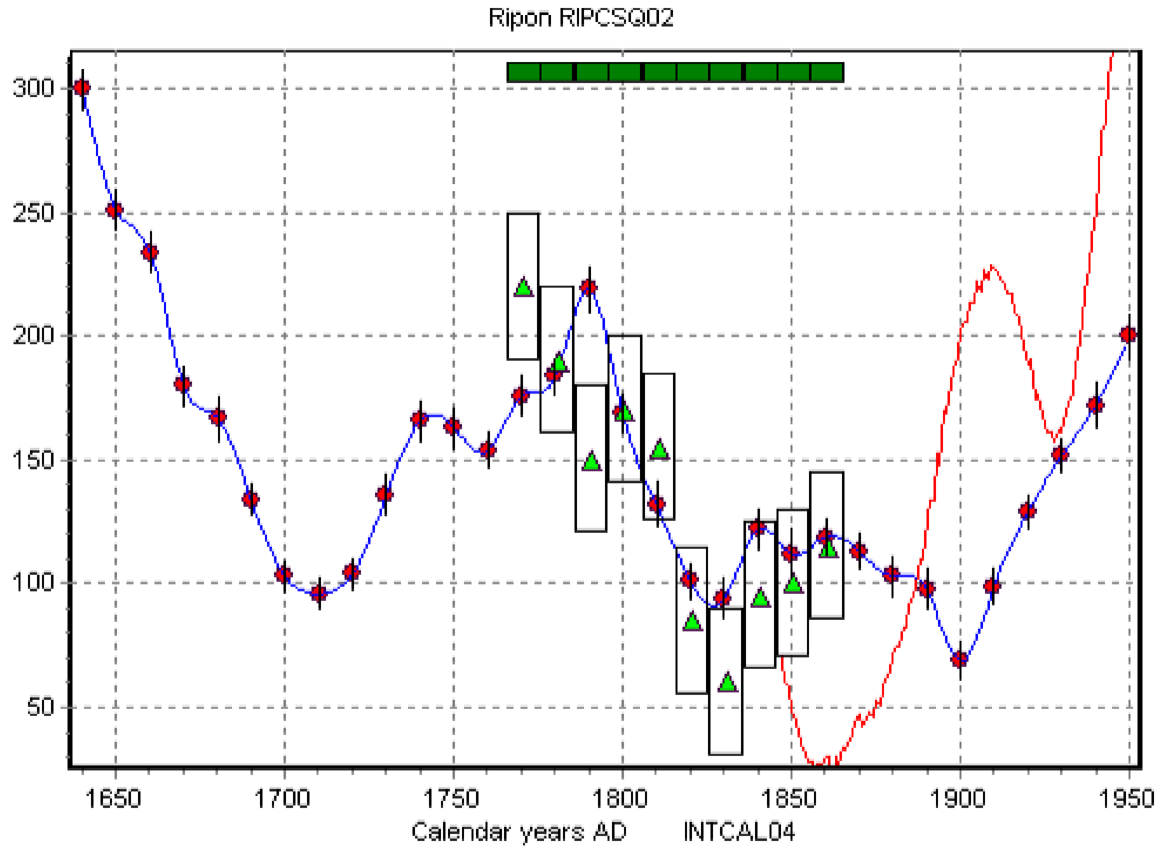


Figure 17: Least-squares wiggle-match, which provides a date for the last ring of RIPCSQ02 of AD 1866 (χ^2 fit value=1.1)

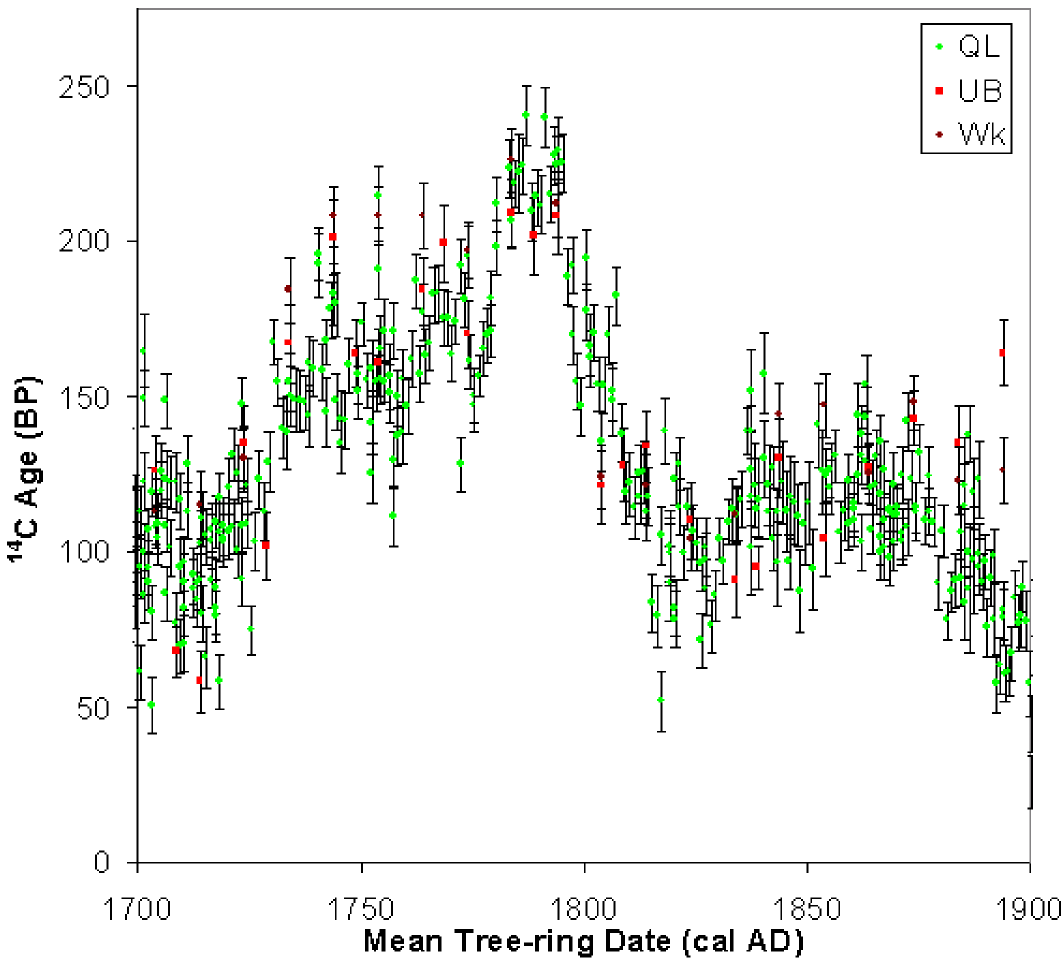


Figure 18: Graphical representation showing the data-points and their 1 σ errors in the radiocarbon calibration datasets, AD 1700–1900 (QL=University of Washington at Seattle; UB=The Queen's University, Belfast; Wk=University of Waikato)

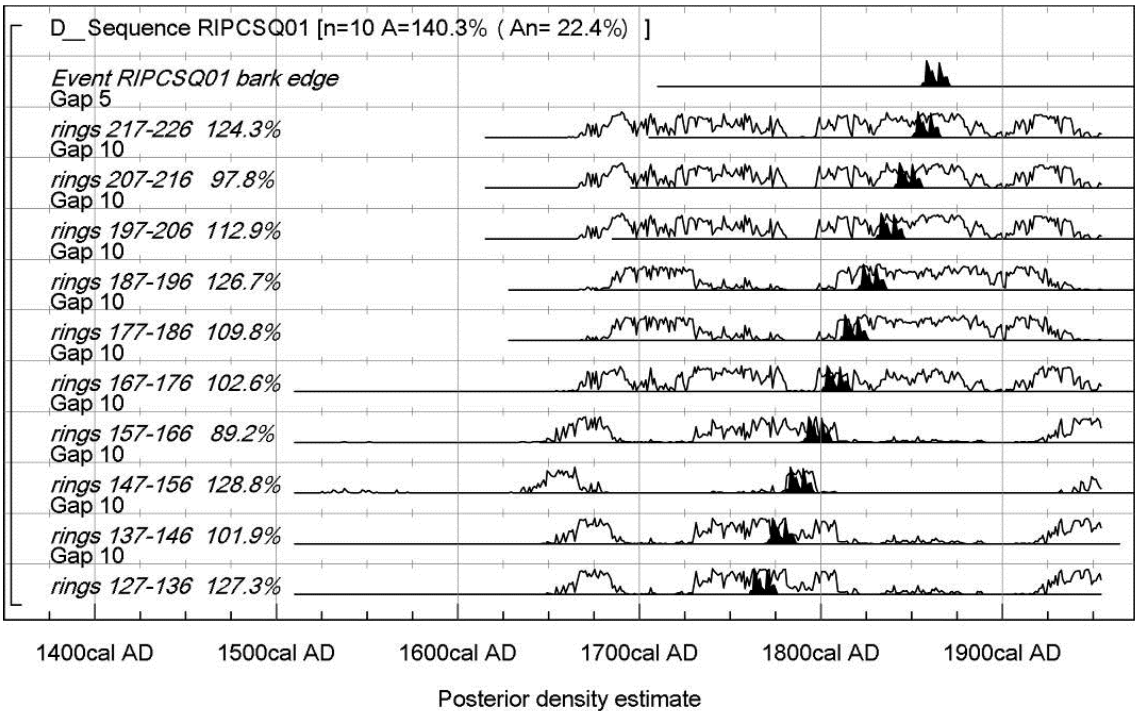


Figure 19: Probability distributions of dates from cores RIP-C01/C11 (site mean sequence RIPCSQ01), calculated using the single-year calibration data of Stuiver (1993). The format is identical to that of Figure 10. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

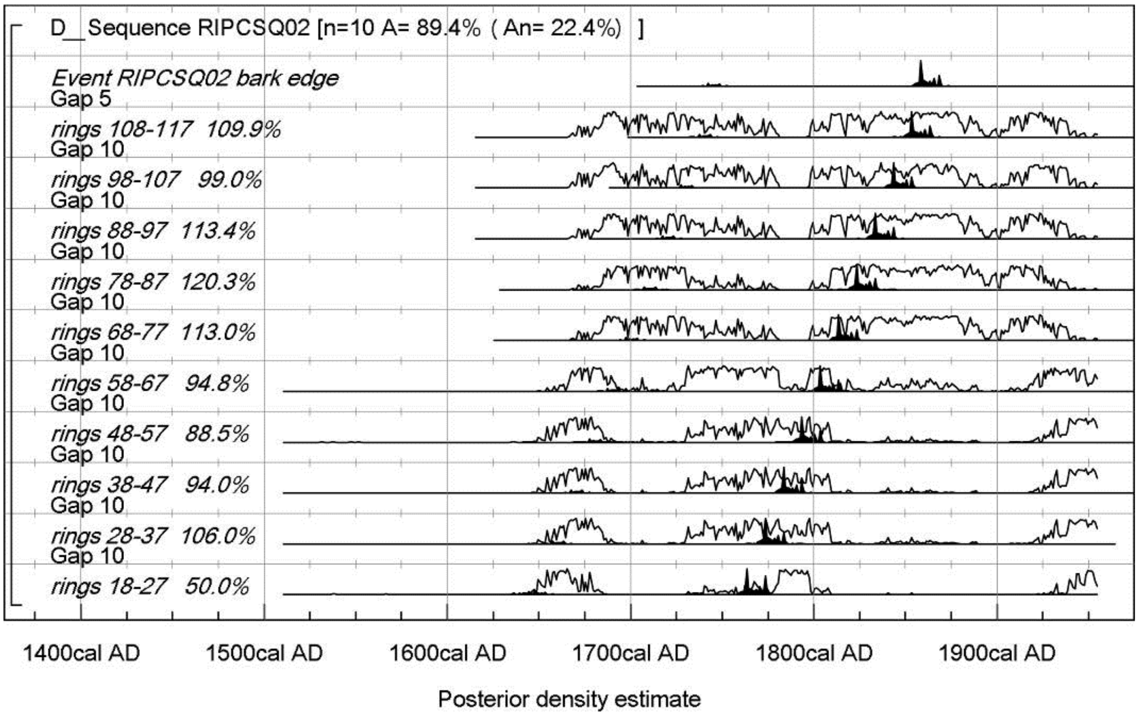
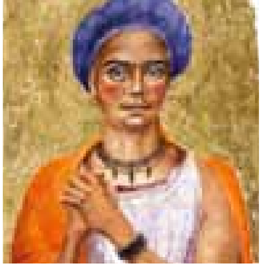
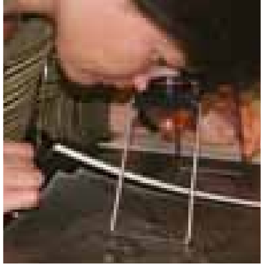


Figure 20: Probability distributions of dates from cores RIP-C14/C29 (site mean sequence RIPCSQ02), calculated using the single-year calibration data of Stuiver (1993). The format is identical to that of Figure 11. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly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- Assessment (including Archaeological and Architectural Investigation, the Blue Plaques Team and the Survey of London)
- Imaging and Visualisation (including Technical Survey, Graphics and Photography)
- Remote Sensing (including Mapping, Photogrammetry and Geophysics)

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