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Gunns Mill, Lower Spout Lane, Abenhall, Gloucestershire
Tree-ring Analysis and Radiocarbon Wiggle-Matching of Two Roof Trusses

Alison Arnold, Gordon Cook, Frances Healy, Robert Howard, Christopher Bronk Ramsey, and Paula Reimer

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SUMMARY

Dendrochronological analysis had been undertaken previously on samples from a number of timbers of Gunns Mill, Abenhall, Gloucestershire. Timbers from the north part of the building were dated by this method to AD 1681–82, while timbers from the south part remained ungrouped and undated individually. Six single-year samples of oak from the east queen posts of each of two roof trusses in the south of the building, GNM-A13 (truss B) and GNM-A11 (truss C), which had not been dated by dendrochronology and did not cross-match with each other, were subsequently the subject of radiocarbon dating and wiggle-matching. This analysis suggests that the timber for the east queen post of truss B was felled in the second quarter of the eighteenth century cal AD or later and that the timber for the east queen post of truss C may have been felled in the second quarter of the nineteenth century cal AD, although an eighteenth century date is also possible because of the irregularities of the calibration curve in this period. Both were later than the AD 1681–82 timbers in the north of the building identified by dendrochronology.

CONTRIBUTORS

Alison Arnold, Gordon Cook, Frances Healy, Robert Howard, Christopher Bronk Ramsey, and Paula Reimer

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INTRODUCTION

The Forest of Dean, to the west of the river Severn in Gloucestershire, has a long history of iron making, with evidence of workings dating to Roman times and possibly earlier. In the medieval period the industry expanded making the Dean one of the largest iron-producing areas of the country; by the end of the seventeenth century nearly half the furnaces working in England were located in this area. Of these, Gunns Mill, at Abenhall, near Mitcheldean (Fig 1), is believed to be the best preserved example in the country of a furnace from this period; it is listed grade II* and is designated a Scheduled Ancient Monument.

On the basis of documentary evidence, it is believed that Gunns Mill may date at least from the early part of the seventeenth century, since the Crown ordered the casting of 610 guns in the area in AD 1629. It is possible that the site might be named in commemoration of this undertaking, but it is perhaps more likely that it is named after William Gunn, who was tenant here at the start of the seventeenth century. The first certain use of the site as a furnace is in AD 1634 when 'Gunnes Mill' was listed in the ownership of Sir John Winter.

In the later seventeenth century, after the Restoration, the Crown became increasingly concerned over the deforestation of the area and the AD 1667 Dean Forest (Reafforestation) Act cut off the fuel supply to the industry. Although, by the end of the eighteenth century coke-fired blast furnaces were taking over, this new fuel was not used correctly in the Forest, leading to a decline in iron making in the area. The furnace at Gunns Mill may in fact have already gone out of use by this date, there being instructions to destroy the site in AD 1650 by order of the Parliamentary government. It is certainly recorded as being ruinous in AD 1680.

The site was bought at this time by Messers Hall and Soudamore who rebuilt the derelict furnace in AD 1682–83. This reconstruction work is recorded in the date stamped on the cast-iron upper lintel above the casting aperture. Production of iron continued intermittently at Gunns Mill through the early eighteenth century until AD 1736 when production ceased altogether. It is known, again from documentary sources, that the buildings were then converted to a paper manufactory shortly before AD 1743. It is believed that at this time an additional timber-framed structure was placed on top of the existing masonry blast-furnace structure and used as a paper drying shed. In AD 1745 the site was tenanted by Joseph Lloyd, it remaining with the Lloyds until the paper works closed in AD 1879. After this time the building was used for agricultural purposes, this use lasting well into the twentieth century. It was abandoned and unused from about AD 1960.

TREE-RING SAMPLING

By 2001 the building was once again in a ruinous condition, and in a dilapidated and dangerous state. Sampling and analysis by tree-ring dating were commissioned by English Heritage to inform a proposed programme of repair by establishing the construction date of the timber-framed portion forming the top floor of the building. The results of this exercise, which are reported elsewhere (Howard *et al* 2001), are summarised here. The seven roof trusses (A–G from south to north; Fig 2) appeared to represent two periods of work. Trusses A–C were squarely cut, well jointed, and made of timbers with relatively few growth rings. Trusses D–G were rougher in appearance, less squarely cut, and made of timber with many more growth rings; they also included some re-used timber. Ten core samples were taken from timbers of trusses D–G, those most likely to produce a date; and five were taken from trusses A–C, which were less likely to be datable. Details of the samples are given by Howard *et al* (2001, table 1).

TREE-RING ANALYSIS AND INTERPRETATION

The timbers of trusses D–G cross-matched with each other and with relevant reference chronologies to indicate a felling late in AD 1681 or early in AD 1682, corresponding to the documented reconstruction of the furnace in AD 1682–83.

The timbers of trusses A–C, however, could neither be cross-matched with each other nor dated individually, suggesting a different date or dates or, at the very least, a different timber source.

RADIOCARBON DATING SAMPLING AND ANALYSIS

This lack of dating evidence for the southern trusses hampered decisions as to the restoration and future use of the building. Thus further dating was required. To this end, two series of six single-year tree rings were subsampled from cores which retained their sapwood rings complete to the bark and did not cross-match with each other or date independently These were core GNM-A11, from the east queen post of truss C core GNM-A13 from the east queen post of truss B (Fig 3).

Sample GNM-A11, from the east queen post of truss C, is 58 rings long and includes 20 sapwood rings which are complete to the bark. Sample GNM-A13, from the east queen post of truss B, is 61 rings long and includes 18 sapwood rings which are also complete to the bark.

Six single-year growth rings were taken from each of the two core samples at intervals of either 11 or 12 rings, the first or earliest extant growth ring on the sample, and the outermost sapwood or last growth ring produced by the tree before felling being included (Fig 4). Four samples were dated by each of the Oxford Radiocarbon Accelerator Unit (ORAU), the Scottish Universities Environmental Research Centre (SUERC), East Kilbride, and ^{14}CHRONO, Queen's University Belfast. 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 an acid-base-acid pretreatment (Stenhouse and Baxter 1983) 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 2003; Scott *et al* 2007; 2010). 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 1), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986).

RADIOCARBON DATING

Radiocarbon dating is based on the radioactive decay of carbon-14 and can be used to date organic materials, including wood. A small proportion of the carbon atoms in the atmosphere are of a radioactive form, carbon-14. Living plants and animals take up carbon from the environment, and therefore contain a constant proportion of carbon-14. Once a plant or animal dies, however, its carbon-14 decays at a known rate. This makes it possible to calculate the date of formerly living material from the concentration of carbon-14 atoms remaining. Radiocarbon measurements, like those in Table 1 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 calibrated date ranges quoted for each sample in Table 1, expressed 'cal AD', were calculated by the maximum intercept method (Stuiver and Reimer 1986) and are rounded outwards to the nearest five years as recommended by Mook (1986). The graphical distributions of the calibrated dates, shown in outline in Figures 5, 7, 9, 10, and 11 are derived from the probability method (Stuiver and Reimer 1993). Figure 5 shows the effect of calibration on a radiocarbon determination.

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 from various publications by Christopher Bronk Ramsey (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.

East queen post of truss B (core GNM-A13)

The chronological model for this core includes the radiocarbon dates for the six single-year tree-ring samples with the information that there were 12 rings between each sample and the next and that the sequence was complete to the bark, as shown in Figure 4. If all six radiocarbon dates are included in the model, it falls into poor overall agreement (A_{comb}=17.9% (A_n=28.9%); n=6), UBA-23616 having the lowest individual index of agreement (A=9), which suggests that it is an outlier.

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 data 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 that would agree better with the other dates if its error term were larger and so it can be identified as an outlier. Outlier analysis (OxCal '*s-type'* model) on the sequence of dates from GNM-A13 confirms UBA-23616 as an outlier (Fig 6).

When UBA-23616 is excluded the overall agreement is good (A_{comb}=90% (A_n=31.6%), n=5). This analysis (Figure 7) suggests that the east queen post of truss B (represented by tree-ring core sample GNM-A13) was felled in *cal AD 1725–55* (*53% probability*) or *cal AD 1845–65* (*6% probability*), or *cal AD 1915–40* (*36% probability*), probably in *cal AD 1730–45* (*42% probability*), or *cal AD 1920–35* (*26% probability*; Fig 7: *OxA-28735*). The trimodality of this result and of the individual calibrated age ranges is a product of the shape of the radiocarbon calibration curve at this period (Fig 5).

East queen post of truss C (core GNM-A11)

The chronological model for this core includes the radiocarbon dates on the six single-year tree-ring samples with the information that there were 11 or 12 rings between each sample and the next and that the sequence was complete to the bark, as shown in Figure 4. If all six radiocarbon dates are included in the model, it falls into poor overall agreement (A_{comb}=24.4; (A_n=28.9); n=6), UBA-23614 having the lowest individual index of agreement (A=18). Application of the OxCal '*s-type*' (Bronk Ramsey 2009b) outlier model distinguishes UBA-23614 as an outlier (Fig 8).

When UBA-23614 is excluded the overall agreement is good (A_{comb}=101.1% (A_n=31.6%), n=5). This analysis suggests that the east queen post of truss C (represented by tree-ring core sample GNM-A11) was felled in *cal AD 1710–1730* (*11% probability*) or *cal AD 1815–1855* (*84% probability*), probably in *cal AD 1820–1845* (*68% probability*; Fig 9: *UBA-23615*).

There remains, however, the possibility of an earlier date. Because of the irregularity of the calibration curve for this period (Fig 5), most of the probability of a calibrated radiocarbon date may not always coincide with its true age. Two series of simulated radiocarbon dates are modelled in Figures 10 and 11, one culminating in a felling date of AD 1743 (the approximate date of the conversion of the site to a paper manufactory), the other in a felling date of AD 1741, only two years earlier. Both models employ exactly the same intervals and the same structure as in Figure 9, except for the fact that no dates are excluded. The most probable felling date returned by the first is cal *AD 1855–1945* (*82% probability*: Fig 10: *Ring 58 1743*), although all the simulated dates in the model lie between AD 1686 and AD 1743. The most probable felling date returned by the second is *cal AD 1720–1760* (*65% probability*: Fig 11: *Ring 58 1741*). This, unlike the estimate shown in Figure 10, is an accurate representation of the dates in the model, which lie between AD 1684 and AD 1741. In these circumstances, truss C could date from the 18th century.

Interpretation

The results obtained here show unambiguously that the two timbers dated by radiocarbon wiggle-matching are later than the other timbers from this building which have been dated by dendrochronology. There is, however, more than one possible date for each, due to the shape of the radiocarbon calibration curve between the eighteenth and early twentieth centuries AD (Fig 5).

The strongest probability for the east queen post of truss B, represented by core GNM-A13, is that it was felled in *cal AD 1725–1755 (53% probability)*; it could also, however, have been felled in *cal AD 1915–40 (36% probability)*, or, less probably, *cal AD 1845–65 (6% probability*; Fig 12: *Truss_B_OxA-28735*).

The east queen post of truss C, represented by core GNM-A11, was most probably felled in *cal AD 1820–55 (84% probability*), less probably in *cal AD 1715-30 (11% probability*; *Fig 12: Truss_C_UBA-23615)*. An eighteenth century date, comparable to the most probable date of Truss B, remains possible, however, because of the shape of the calibration curve (Figs 5, 11).

CONCLUSION

These results support the observations made as part of the general survey of the building that trusses A–C (timbers from two of which are dated here) are structurally later than trusses D–G (dated by dendrochronology to AD 1681–82). It was also noted at the time of sampling for dendrochronology that the timbers of trusses A–C are quite different from the timbers of trusses D–G, in having far fewer growth rings, and being more squarely cut. These results also accord with the absence of grouping revealed by the dendrochronological analysis between timbers from the south and the north of the building and between cores GNM-11 and -13 themselves.

The dating by radiocarbon wiggle-matching of one timber to the second quarter of the eighteenth century would fit very well with the conversion of the site to a paper manufactory shortly before AD 1743. It is believed that at this time an additional timber-framed structure was placed on top of the existing masonry blast-furnace structure and used as a paper drying shed. The radiocarbon wiggle match dating of another timber to the second quarter of the nineteenth century may represent a subsequent episode of repair.

The structural and material differences between the south and the north of the building are also chronological ones. The timbers of the north part of the building (trusses D–G) date from AD 1681–82 and can be related to the documented reconstruction of the furnace in AD 1682–83. The timbers of the south of the building were felled in the eighteenth and nineteenth centuries cal AD and probably relate to subsequent reuse and repair (Fig 12).

These conclusions might be refined by radiocarbon dating additional rings from each core to explore the reasons for the poor agreement of some dates with their positions in the sequences. In addition, it may be worth undertaking a timber characterisation survey of the south end of the building, in the course of which observations of the carpentry, tooling and timber finishing techniques might help inform their likely dates.

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TABLES

Table 1: Radiocarbon results from Gunns Mill

The date ranges in the 'Calibrated date' column were calculated by the maximum intercept method (Stuiver and Reimer 1986) and are rounded outwards to the nearest five years as recommended by Mook (1986). The highest posterior density intervals are derived from the models shown in Figures 7 and 9.

Laboratory number	Sample ID	Material	δ^{13}C (‰)	Radiocarbon age (BP)	Calibrated date - cal AD (95% confidence)	*Highest posterior density interval – cal AD (95% probability)*
GNM-A11 (truss C)						
OxA-28732	ring 1	Wood, *Quercus* sp. heartwood	−24.5	172±23	1660–1955	*1650–1675 (11%), 1760–1800 (84%)*
SUERC-49083	ring 12	Wood, *Quercus* sp. heartwood	−22.7	211±34	1640–1955	*1665–1685 (12%), 1770–1810 (84%)*
UBA-23614	ring 23	Wood, *Quercus* sp. heartwood	−25.0	49±23	1710–1910	*1695–1725 (18%), 1810–1840 (12%), 1845–1855 (1%), 1875–1920 (64%)*
OxA-28733	ring 34	Wood, *Quercus* sp. heartwood	−25.3	124±22	1675–1940	*1685–1710 (11%), 1790–1835 (84%)*
SUERC-49084	ring 46	Wood, *Quercus* sp. sapwood	−23.1	135±34	1665–1955	*1695–1720 (11%), 1805–1845 (84%)*
UBA-23615	ring 58	Wood, *Quercus* sp. sapwood, outermost ring	−25.4	92±22	1685–1930	*1710–1730 (11%)1815–1855 (84%)*
GNM-A13 (truss B)						
UBA-23616	ring 1	Wood, *Quercus* sp. heartwood	−26.9	277±24	1520–1665	*1520–1595 (48%), 1615–1665 (46%), 1785–1795 (1%)*

Laboratory number	Sample ID	Material	$\delta^{13}C$ (‰)	Radiocarbon age (BP)	Calibrated date - cal AD (95% confidence)	*Highest posterior density interval – cal AD (95% probability)*
GNM-A13 (truss B)						
SUERC-49085	ring 13	Wood, *Quercus* sp. heartwood	−24.7	156±34	1660–1955	*1675–1705 (53%), 1795–1815 (6%), 1865–1895 (36%)*
OxA-28734	ring 25	Wood, *Quercus* sp. heartwood	−27.5	108±22	1680–1935	*1690–1715 (53%),1810–1830 (6%),1875–1905 (36%)*
UBA-23617	ring 37	Wood, *Quercus* sp. heartwood	−28.4	41±29	1705–1915	*1700–1730 (53%), 1820–1840 (6%), 1890–1920 (36%)*
SUERC-49086	ring 49	Wood, *Quercus* sp. sapwood	−26.6	109±34	1670–1945	*1710–1740 (53%), 1835–1850 (6%), 1900–1930 (36%)*
OxA-28735	ring 61	Wood, *Quercus* sp. sapwood, outermost ring	−25.7	168±23	1665–1955	*1725–1755 (53%), 1845–1865 (6%), 1915–1940 (36%)*

FIGURES

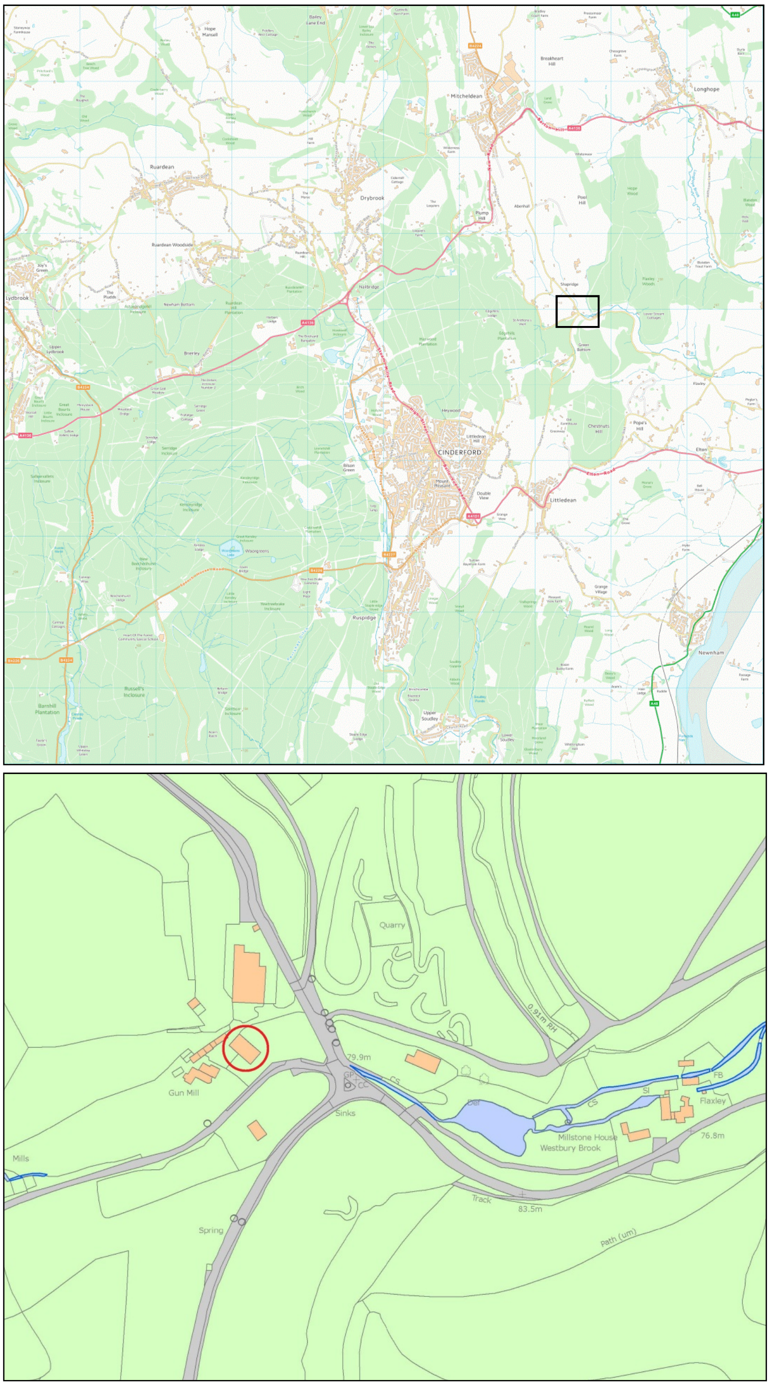

Figure 1: Location of Abenhall (above) and Gunns Mill below. © Crown copyright and database right 2014. All rights reserved. Ordnance Survey License number 100024900

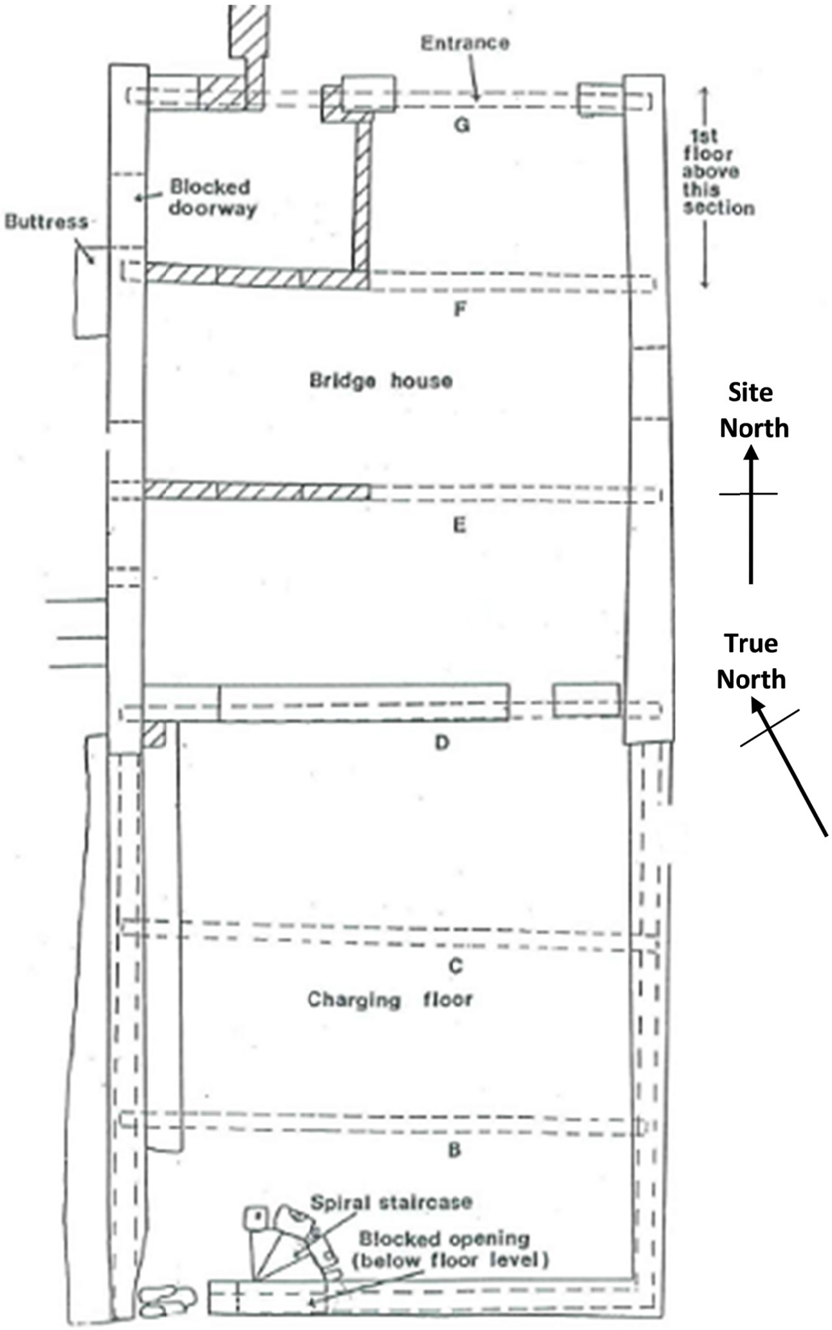

Figure 2: Plan of Gunns Mill to show layout and arrangement of trusses A–G

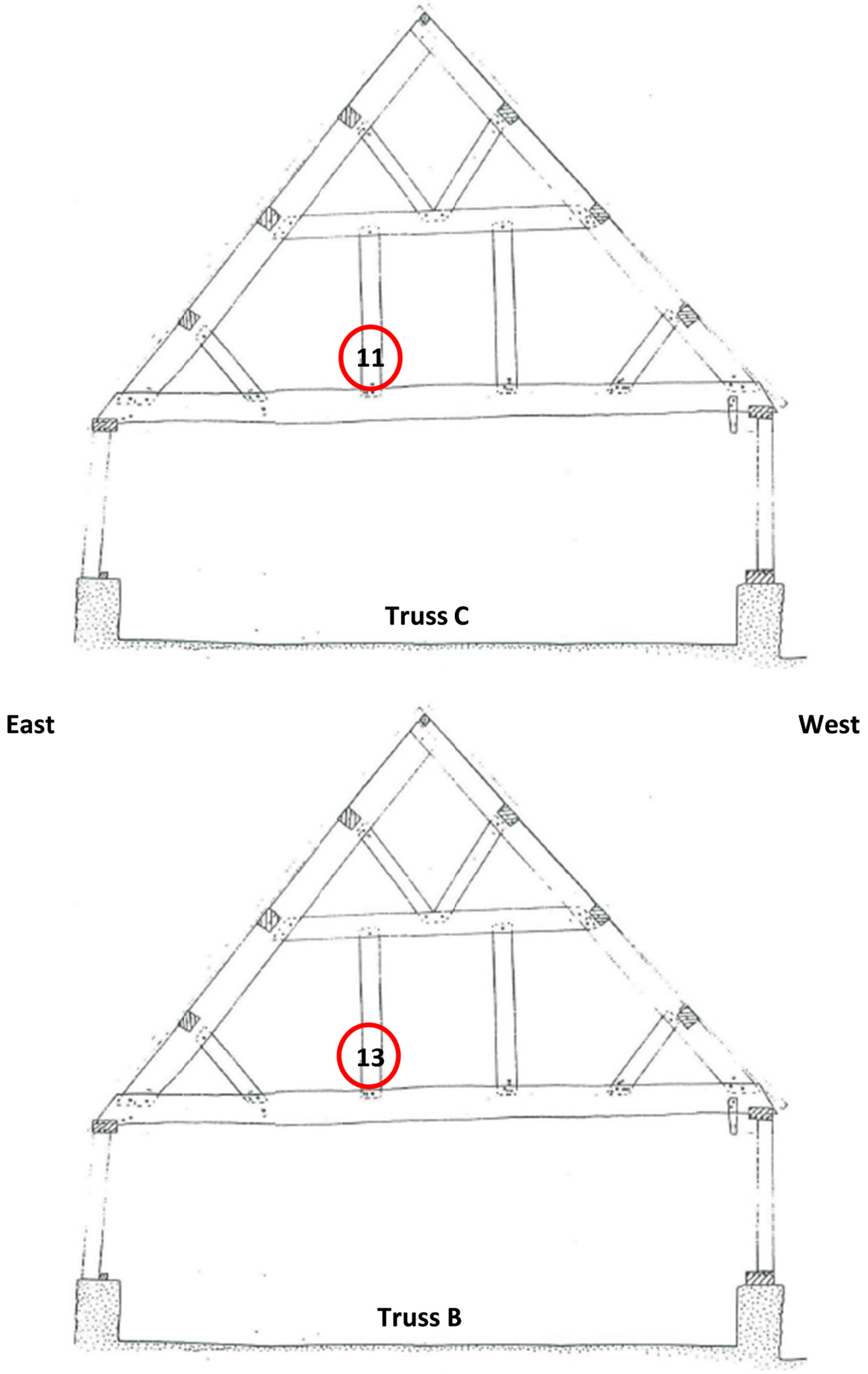

Figure 3: Sections through trusses B and C to locate sampled timbers

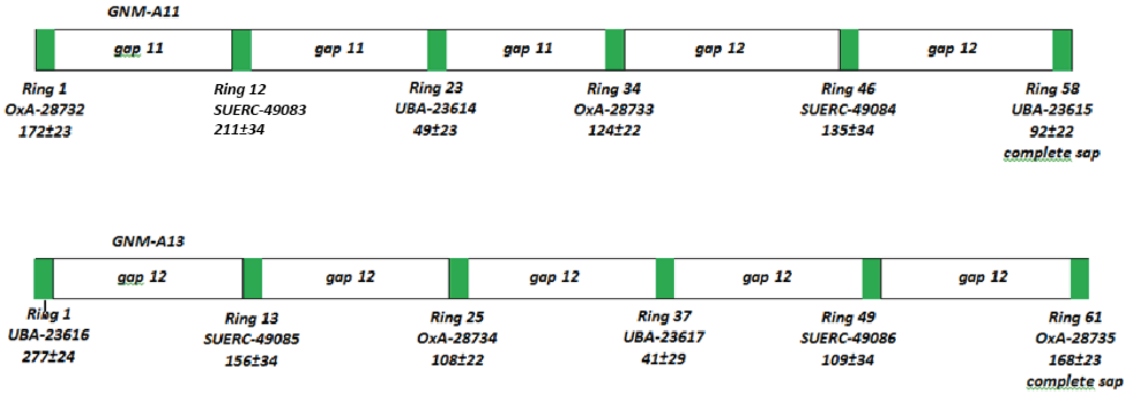

Figure 4: Schematic illustration of core samples GNM-A11 and A13 to locate the individual ring samples submitted for radiocarbon dating

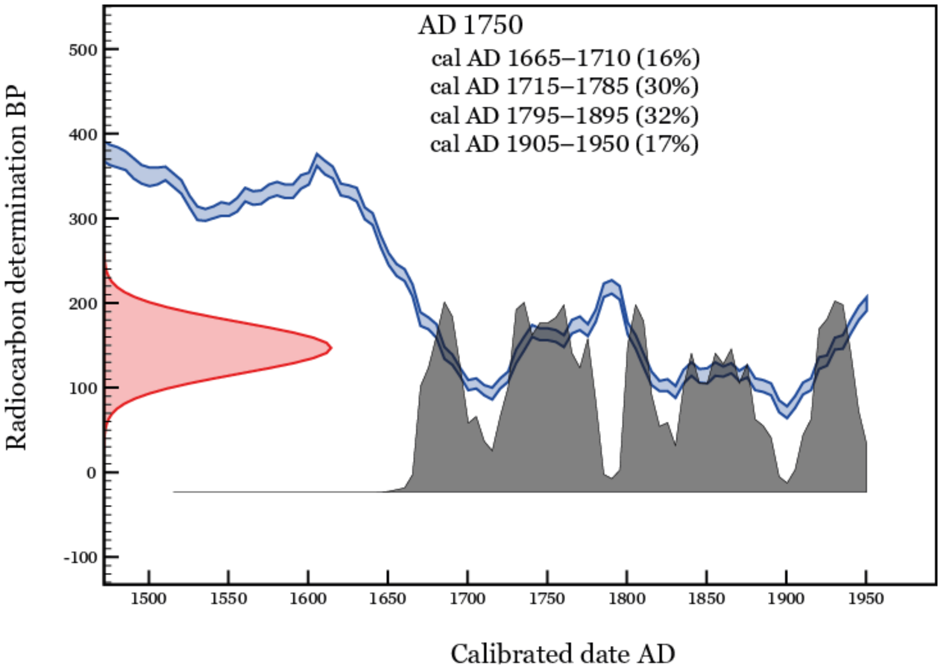

Figure 5: A simulated radiocarbon measurement for a sample with a calendar age of AD 1750 and an error on the radiocarbon measurement of ±30 years, in pink on the vertical axis, calibrated to cal AD 1665 to 1710 (16% probability), 1715 to 1785 (30% probability), 1795–1895 (32% probability) or 1905 to 1950 (17% probability), in black on the horizontal axis. The blue band is the relevant part of the calibration curve. '

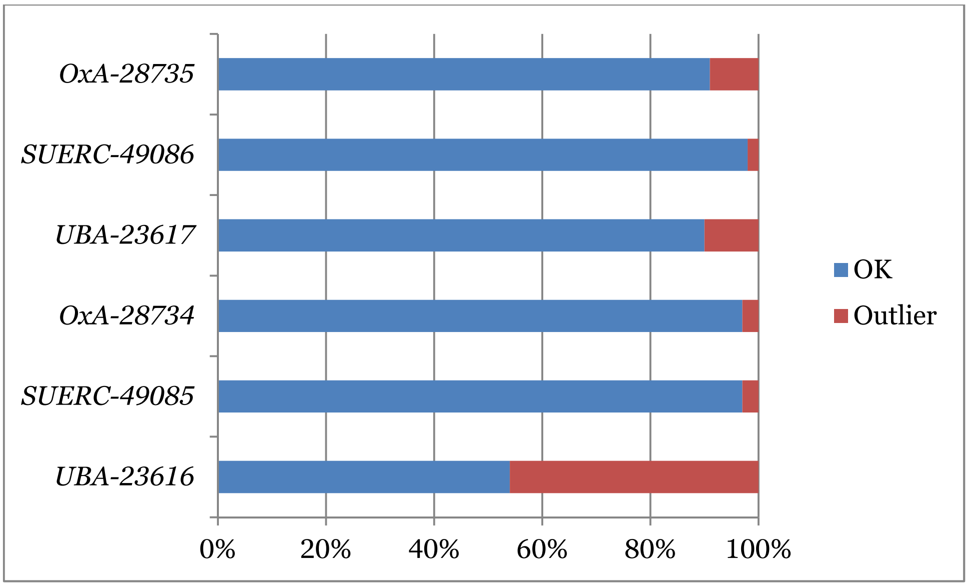

*Figure 6: The result of the application of the outlier(*s-type*) model (Bronk Ramsey 2009b; Bronk Ramsey* et al *2010, 956–7) to the sequence of dates from GNM-A13.* UBA-23616 *is distinguished as an outlier*

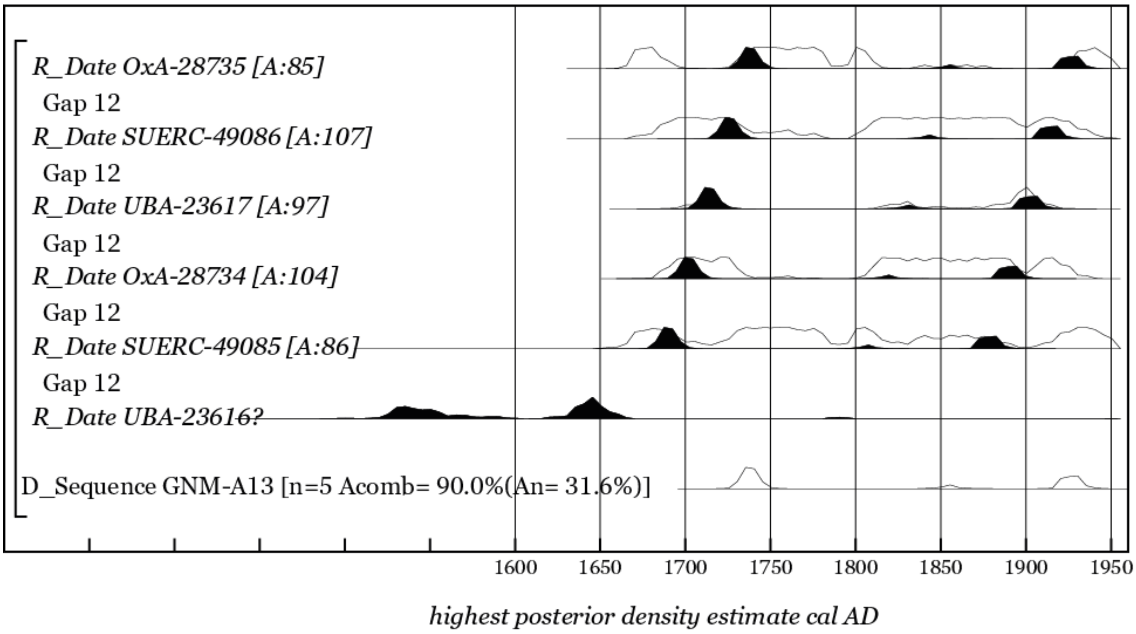

Figure 7: Probability distributions of dates from the timber GNM-A13, from roof truss B. Each distribution represents the relative probability that an event occurs at a particular time. OxA-28735*, the date for the outermost sapwood ring, is the felling date. A question mark after the laboratory number of* UBA-23616 *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*

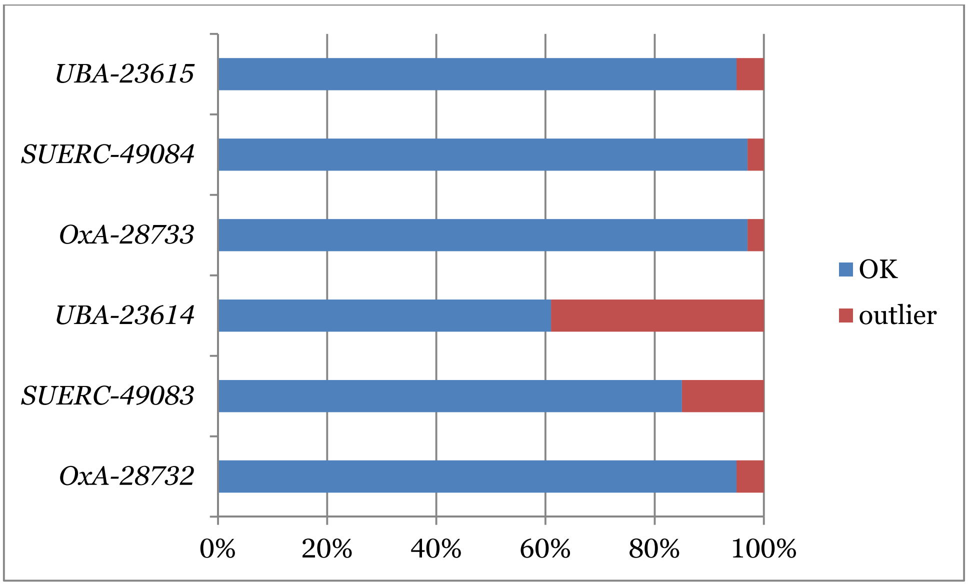

Figure 8: The result of the application of the outlier (s-type) *model ((Bronk Ramsey 2009b; Bronk Ramsey* et al *2010, 956–7)) to the sequence of dates from GNM-A11*. UBA-23614 *is distinguished as an outlier*

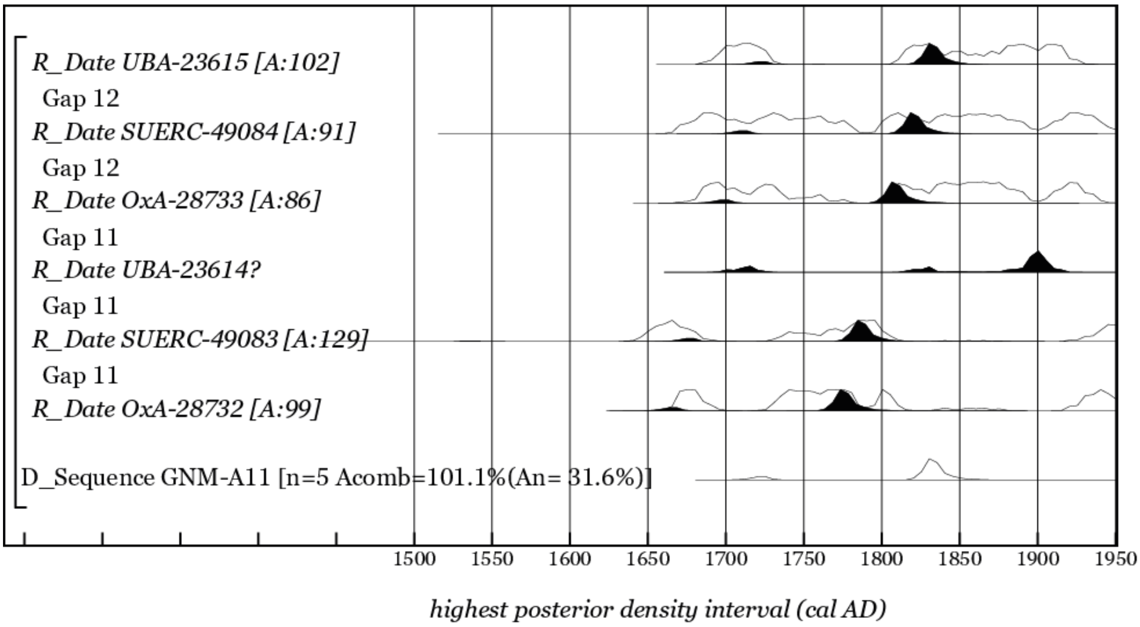

Figure 9: Probability distributions of dates from the timber GNM-A11, from roof truss C. Each distribution represents the relative probability that an event occurs at a particular time. UBA-23615*, the date for the outermost sapwood ring, is the felling date. A question mark after the laboratory number of* UBA-23614 *indicates that it 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*

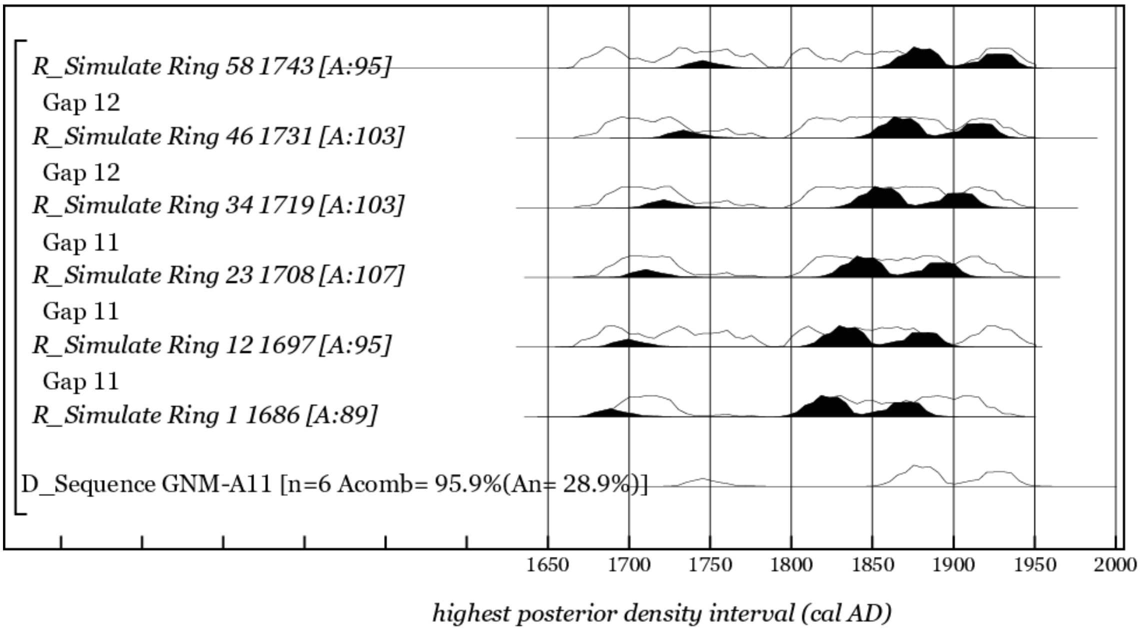

Figure 10: Probability distributions of simulated dates for the timber GNM-A11, from roof truss C, modelled with exactly the same intervals and the same structure as in Figure 9, except for the fact that no dates are excluded. The dates have been simulated to culminate in a felling date of AD 1743. The most probable estimated felling date, however is cal AD 1855–1945 *(82%* probability; Ring 58 1743*), despite the fact that all the simulated dates lie between 1686 and 1743*

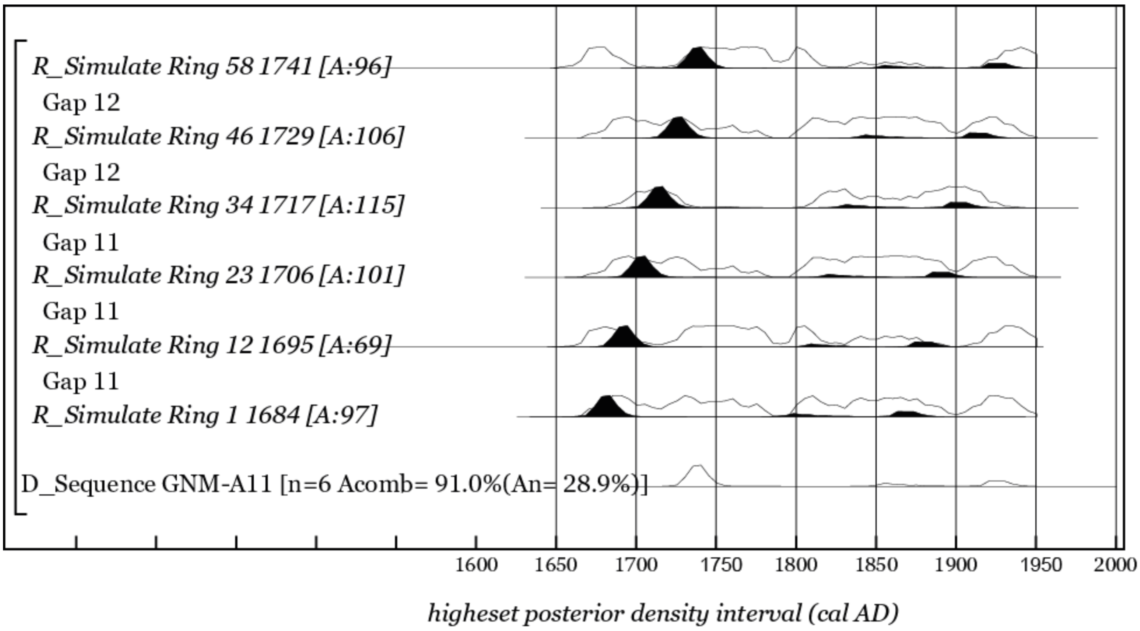

Figure 11: Probability distributions of simulated dates for the timber GNM-A11, from roof truss C, modelled with exactly the same intervals and the same structure as in Figure 9, except for the fact that no dates are excluded. The dates have been simulated to culminate in a felling date of AD 1741, which falls within the range of the most probable estimated felling date of 1720–1760 cal AD (65% probability; Ring 50 1741*). The difference between this result and that shown in Figure 10 is due to the shape of the calibration curve (Fig 5)*

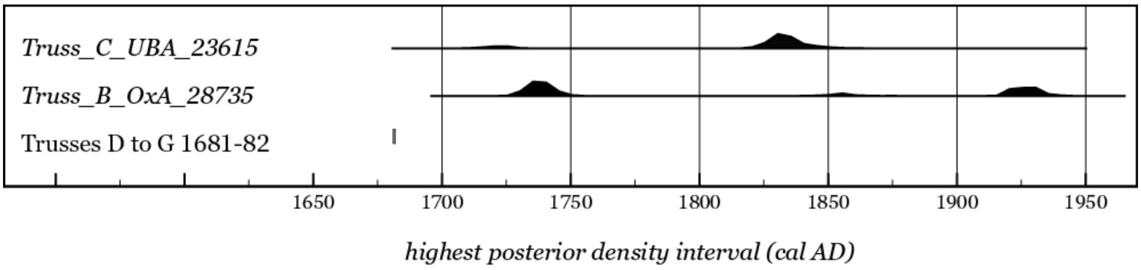

Figure 12: Probability distributions derived from wiggle-matching of radiocarbon dates of the felling dates for the east queen posts of trusses B and C in the south part of the buildings according to the models shown in Figures 7and 9, together with the dendrochronological felling date of AD 1681–82 for the timbers of the north part of the building (trusses D to G). The estimated felling dates for trusses B and C are listed in Table 1

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