Research Report Series 58/2023

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Radiocarbon Wiggle-matching of Oak Timbers

Alex Bayliss, Christopher Bronk Ramsey, Shahina Farid, Paula Reimer, Alison Arnold, Robert Howard and Cathy Tyers

Scientific Dating

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NGR: SE 52124 90658

Print: ISSN 2398-3841
Online: ISSN 2059-4453

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Summary

Ring-width tree-ring analysis was undertaken on 12 of the 23 samples taken from the mill. This resulted in the construction of a single site sequence, ARDMSQ01, which was 112 rings long and contained the ring-width series from six timbers, but could not be dated conclusively by dendrochronology (Arnold and Howard 2016).

Radiocarbon wiggle-matching of two timbers from this sequence suggests that the last ring formed in *cal AD 1835–1849 (95% probability)*. This is compatible with weak statistical cross-matching of the tree-ring master sequence, allowing this tentative cross-matching to be accepted, the rings in the chronology spanning AD 1732–1843$_{DR}$.

Five of the timbers in the site master sequence, two of which have complete sapwood, are from the mill roof. These were felled in AD 1841$_{DR}$, suggesting construction of this roof in that date or shortly thereafter. The sixth timber in the site master sequence, from the hurst frame has an estimated felling date within the range AD 1852–1877$_{DR}$.

The subscript DR indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence should not be utilised as a ring-width master sequence for dating other sites.

Contributors

Alex Bayliss, Christopher Bronk Ramsey, Shahina Farid, Paula Reimer, Alison Arnold, Robert Howard and Cathy Tyers

Acknowledgements

The front cover image shows the hurst frame and gears at Arden Mill from the north (photograph: Alison Arnold).

Archive location

Historic England Archive, The Engine House, Fire Fly Avenue, Swindon SN2 2EH

Historic environment record

North York Moors National Park Historic Environment Record, National Park Office, The Old Vicarage, Bondgate, Helmsley, North Yorkshire YO62 5BP

Date of investigation

2016–22

Contact details

Alison Arnold and Robert Howard, Nottingham Tree-ring Dating Laboratory, Mayfield Cottage, Tattle Hill, Dale Abbey, Derbyshire DE7 4RR
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Alex Bayliss, Shahina Farid and Cathy Tyers, Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA
customers@HistoricEngland.org.uk
alex.bayliss@historicengland.org.uk
shahina.farid@historicengland.org.uk
cathy.tyers@historicengland.org.uk

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

Paula J Reimer, ^{14}CHRONO Centre, Archaeology & Palaeoecology Building, Queen's University Belfast, 42 Fitzwilliam Street, Belfast BT9 6AX
p.j.reimer@qub.ac.uk

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Introduction

The Grade II* listed Arden Mill is a water-powered corn mill located to the north-west of the village of Hawnby, near Helmsley, in North Yorkshire (Fig 1; https://historicengland.org.uk/listing/the-list/list-entry/1391800). The site is thought to be medieval in origin, once serving St Andrew's Priory (the Benedictine nunnery at Arden) with the existence of a mill here being hinted at in AD 1189 and securely documented in AD 1536.

The current mill is a three-bay, single storey structure, orientated roughly north-south. The southern bay houses the waterwheel and is separated from the central bay by a stone wall. The central bay contains the driving gears, hurst frame, and millstones, whilst the northern bay was floored and was used for grain storage. Attached to the north of the mill is what remains of the miller's house, a smoke bay with inglenook fireplace with chamfered bressumer beam, and a salt box. The roof over the mill consists of two cruck trusses, between which are two tiers of staggered trenched purlins and modern common rafters.

Arden Mill is of special interest as a water-powered corn mill of possibly medieval origin that retains a near complete set of early eighteenth-century mill machinery with only minor mid nineteenth-century modifications and repairs.

Further information can be found in Harrison (2008) and Watts (2012).

Figure 1: Maps to show the location of Arden Mill (marked in red dot). Scale: top right 1:25000; bottom 1:1250. © Crown Copyright and database right 2021. All rights reserved. Ordnance Survey Licence number 100024900.

Tree-ring Analysis

A dendrochronological survey of the mill was undertaken in 2014 to inform its long-term future which included possible dismantlement and potential relocation (Arnold and Howard 2016).

In total, 23 timbers were sampled by coring (Table 1), 21 of which were oak (*Quercus* spp.) and two ash (*Fraxinus excelsior*). The 12 oak samples that had more than 40 growth rings were prepared by sanding and polishing, and their ring widths measured. These ring-width series were then compared with each other by the Litton/Zainodin grouping procedure (Laxton *et al* 1988; Litton and Zainodin 1991), resulting in six samples cross-matching each other at a minimum *t*-value of 6.0.

These six ring-width series were combined at the relevant offset positions to form ARDMSQ01, a site sequence of 112 rings (Fig 2). Attempts to date this site sequence and the ungrouped samples by comparing them against a series of relevant reference chronologies for oak, initially from throughout the British Isles and subsequently from elsewhere in Europe and the United States and Canada, failed to produce any conclusive cross-matching and all remain undated by ring-width dendrochronology.

Some low but consistent cross-matching was noted, however, against a number of reference chronologies from England when the site master chronology spans AD 1732–1843 (Table 2).

Table 1: Details of samples from Arden Mill, Hawnby, North Yorkshire.

Sample Number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Roof & structure						
ARD-M01	East principal rafter, truss 1	81	19C	1761$_{DR}$	1822$_{DR}$	1841$_{DR}$
ARD-M02	West principal rafter, truss 1	100	15	1736$_{DR}$	1820$_{DR}$	1835$_{DR}$
ARD-M03	Tiebeam, truss 1	NM	--	----	----	----
ARD-M04	East principal rafter, truss 2	61	h/s	1763$_{DR}$	1823	1823$_{DR}$
ARD-M05	West principal rafter, truss 2	95	03	1732$_{DR}$	1823$_{DR}$	1826$_{DR}$
ARD-M06	Tiebeam, truss 2	NM	--	----	----	----
ARD-M07	East upper purlin, wall to truss 2	99	11C	1743$_{DR}$	1830$_{DR}$	1841$_{DR}$
ARD-M08	Lower lintel, south wall	99	h/s	----	----	----
ARD-M09	Window lintel, east wall	NM	--	----	----	----
ARD-M10	Bresummer, mill house	NM	--	----	----	----
ARD-M11	Joist 4 – not oak	NM	--	----	----	----
ARD-M12	Joist 8 – not oak	NM	--	----	----	----
Hurst frame						
ARD-M13	Top beam	108	19	----	----	----
ARD-M14	Axial beam	70	15	----	----	----
ARD-M15	East post	NM	--	----	----	----
ARD-M16	West post	64	--	----	----	----
ARD-M17	Cross rail	107	06	1737$_{DR}$	1837$_{DR}$	1843$_{DR}$
Waterwheel pit						
ARD-M18	Horizontal beam	NM	--	----	----	----
ARD-M19	Spoke 1	NM	--	----	----	----
ARD-M20	Spoke 2	63	--	----	----	----
ARD-M21	Spoke 3	NM	--	----	----	----
ARD-M22	Rim 1	64	--	----	----	----
ARD-M23	Rim 2	NM	--	----	----	----

Key: NM = not measured, h/s = heartwood/sapwood boundary is the last-measured ring, C = complete sapwood retained on sample, last measured ring is the felling date, $_{DR}$ = dates spanning derive from tentative ring-width cross-dating, supported independently by radiocarbon wiggle-matching.

Table 2: Results of the cross-matching of site sequence ARDMSQ01 and relevant reference chronologies when the first-ring date is AD 1732 and the last-ring date is AD 1843.

Reference chronology	***t* – value**	**Span of chronology**	**Reference**
Monk Wood trees, Northumberland	5.9	AD 1748–1980	Briffa *et a*l. 1986 #473
Bradgate trees, Leicestershire	5.3	AD 1595–1975	Laxton and Litton 1988
Old Smithy, Mainstone, Shropshire	5.3	AD 1722–1804	Bridge and Miles 2015
Castle Howard trees, North Yorkshire	5.0	AD 1708–1972	Morgan 1973 unpubl.
Sherwood trees	4.7	AD 1426–1981	Laxton and Litton 1988
Ty Mawr Castell, Caereinion, Wales	4.7	AD 1707–1808	Miles and Worthington 2001 #1442
Mill Pond, Stowe, Buckinghamshire	4.6	AD 1712–1891	Miles *et al*. 2004
Helesyside Hall trees, Northumberland	4.5	AD 1753–1980	Briffa *et al.* 1986 #473
Savenake Forest trees, Wiltshire	4.4	AD 1651–1982	Briffa *et al.* 1986 #473
Cannock Chase trees, Staffordshire	4.3	AD 1639–1979	Briffa *et al* 1986 #473

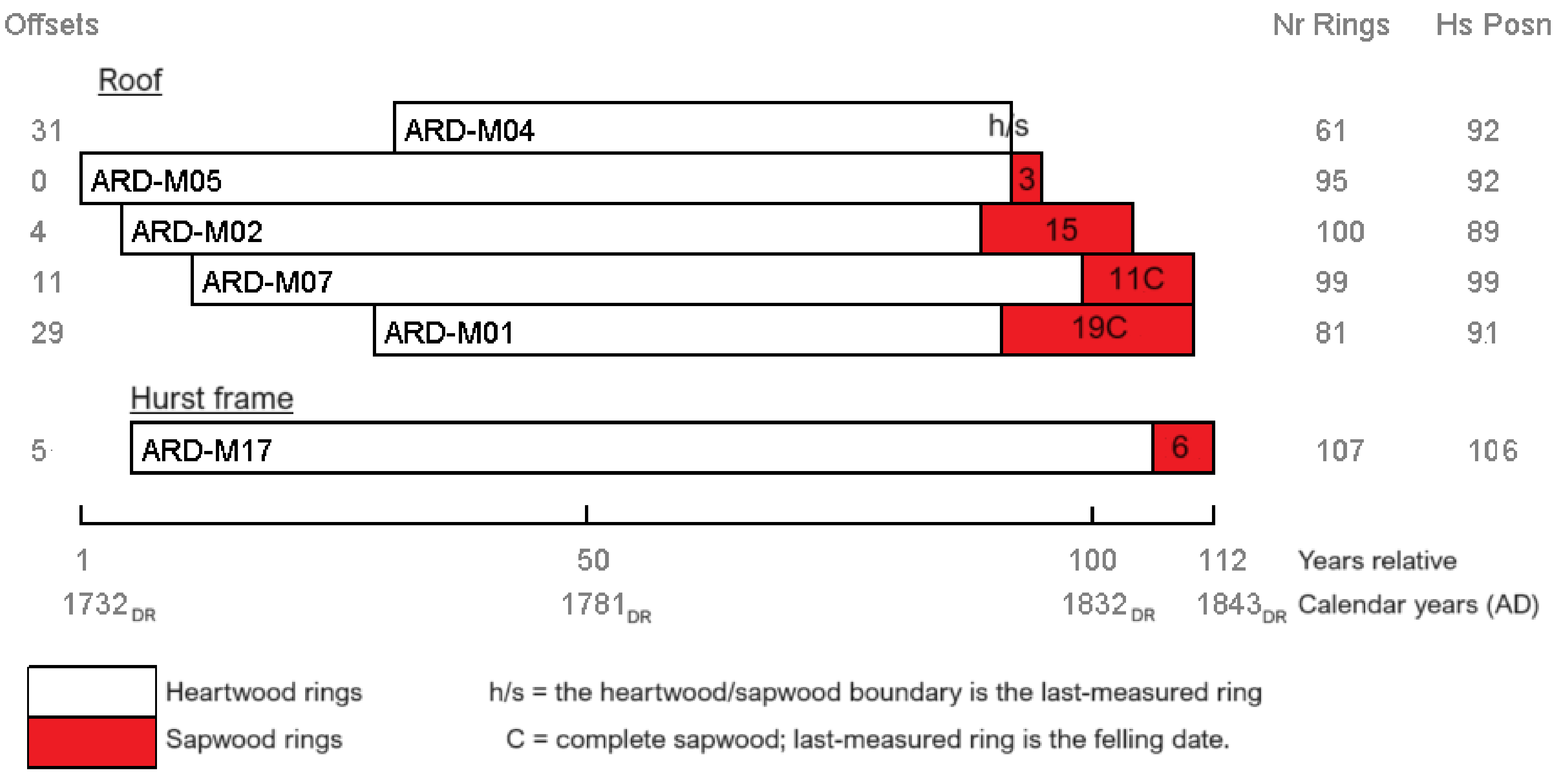

Figure 2: Bar diagram of samples in site sequence ARDMSQ01 using the radiocarbon supported dendrochronological date spans identified.

Radiocarbon Dating

Following the failure of the dendrochronology to provide secure calendar dating for the timbers from Arden Mill contained in ARDMSQ01 and given the potential significant survival of historic fabric in the building and the future value of this chronology as ring-width reference data, a series of single ring samples were taken from two of the core samples in this reference chronology (ARD-M01 and ARD-M05).

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 3, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Table 3: Radiocarbon measurements and associated $\delta^{13}C$ values from oak samples ARD-M01 and D-M05, components of site chronology ARDMSQ01 (replicate measurements have been tested for statistical consistency and combined before calibration using the methods of Ward and Wilson (1978)).

Laboratory Number	**Sample**	**Radiocarbon Age (BP)**	**$\delta^{13}C_{IRMS}$ (‰)**
UBA-28560	ARD-M05, ring 85, *Quercus* spp, heartwood	68±26	−25.4±0.22
OxA-35077	ARD-M05, ring 69, *Quercus* spp, heartwood	175±22	−24.1±0.2
OxA-35160	ARD-M05, ring 60a, *Quercus* spp, heartwood	198±26	−23.8±0.2
UBA-28559	ARD-M05, ring 60b, *Quercus* spp, heartwood	238±37	−25.4±0.22
Weighted mean	*T'=0.8, T'(5%)=3.8, v=1*	*211±22*	
UBA-28558	ARD-M05, ring 50, *Quercus* spp, heartwood	299±36	−25.7±0.22
UBA-31427	ARD-M05, ring 40, Quercus spp, heartwood	290±26	−25.7±0.22
UBA-28557	ARD-M05, ring 30a, *Quercus* spp, heartwood	87±37	−24.9±0.22
OxA-35159	ARD-M05, ring 30b, *Quercus* spp, heartwood	109±26	−23.6±0.2
Weighted mean	*T'=0.2, T'(5%)=3.8, v=1*	*102±22*	
OxA-33687	ARD-M05, ring 20, *Quercus* spp, heartwood	195±26	−26.6±0.2
OxA-35158	ARD-M05, ring 10, *Quercus* spp, heartwood	176±26	−24.6±0.2
UBA-31426	ARD-M05, ring 1, *Quercus* spp, heartwood	237±27	−25.2±0.22
OxA-33689	ARD-M01, ring 80, *Quercus* spp, sapwood	138±26	−25.2±0.2
UBA-31428	ARD-M01, ring 56, *Quercus* spp, heartwood	221±28	−26.6±0.22
OxA-33688	ARD-M01, ring 31, *Quercus* spp, heartwood	236±25	−25.6±0.2

Initially, three radiocarbon measurements were obtained from single annual tree-rings from each of the two timbers (Table 3; Fig 3) but, following the first series of results, another six single-ring samples were submitted from core ARD-M05. Two of these single rings were divided and dated in both laboratories. Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

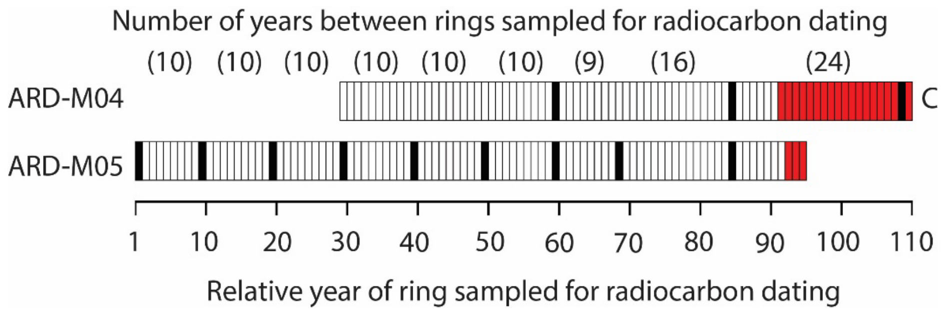

Figure 3: Schematic illustration of samples ARD-M01 and ARD-M05 to locate the single-ring sub-samples submitted for radiocarbon dating (C = complete sapwood; red = sapwood).

The samples were dated at the Oxford Radiocarbon Accelerator Unit (OxA-) and the ^{14}Chrono Centre, Queen's University Belfast (UBA-). In Oxford the first set of samples underwent an acid-base-acid pretreatment followed by bleaching (Brock et al. 2010, table 1 (UW)); in Belfast the first set of samples simply received an acid-base-acid pretreatment (Reimer et al. 2015). In Oxford the second set of samples were processed to α-cellulose and treated with a series of solvent rinses (Brock et al. 2010, 106). In Belfast the second set of samples received an organic solvent Soxhlet extraction (Bruhn et al. 2001) before acid-base-acid treatment (Reimer et al. 2015). In Oxford all the samples were then combusted and graphitized as described by Dee and Bronk Ramsey (2000) and dated by Accelerator Mass Spectrometry (AMS) as described by Bronk Ramsey et al. (2004). The samples dated at Queen's University Belfast were graphitised and measured by AMS as described in Reimer et al. (2015).

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by AMS (Stuiver and Polach 1977; Table 3). These $\delta^{13}C$ values may deviate from the natural $\delta^{13}C$ of the sample by a few per mille, because sample preparation and the ion source of the AMS may lead to fractionation during the dating process, but this value is most appropriate for correcting for $^{14}C/^{12}C$ fractionation in dating. The quoted $\delta^{13}C$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Wiggle-matching

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al*. 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from ARD-M01 and ARD-M05, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 4–5.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al.* (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al*. 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 4–5 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

A model for timber ARD-M01 that incorporates the gaps between each dated annual ring known from tree-ring counting (e.g. that the carbon in ring 31 of the measured tree-ring series (OxA-33688) was laid down 25 years before the carbon in ring 56 of the series (UBA-31428; Fig 3), with the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer et al. 2020) has good overall agreement (Acomb: 83.8, An: 40.8, n: 3), and all three dates have good individual agreement (A: > 60.0).

A similar model for timber ARD-M05, however, that incorporates only the three measurements undertaken in the first round of sampling (UBA-31426–7 and OxA-33687) has poor overall agreement (Acomb: 11.5, An: 40.8, n: 3), and two dates have poor individual agreement (UBA-31426, A: 22 and UBA-31427, A: 8). Chemical contamination of the timber from which core ARD-M05 had been retrieved was suspected, and for this reason a further six single-ring samples were submitted for dating from this core. Two rings were split and dated at both laboratories. As described above, more rigorous pretreatment protocols were employed on the second batch of samples, and both replicate pairs are statistically consistent (Ward and Wilson 1978; Table 3). A model for timber ARD-M05 that incorporates only the results from the second batch of samples, however, again has poor overall agreement (Acomb: 10.6, An: 28.9, n: 6), with two dates having poor individual agreement (UBA-28558, A: 7 and ARD-M05 ring 30, A: 3). Omitting UBA-28558, which is clearly anomalously old, produces a model that has good overall agreement (Acomb: 42.8, An: 31.6, n: 5), although ARD-M05 ring 30 still has poor individual agreement (A: 10).

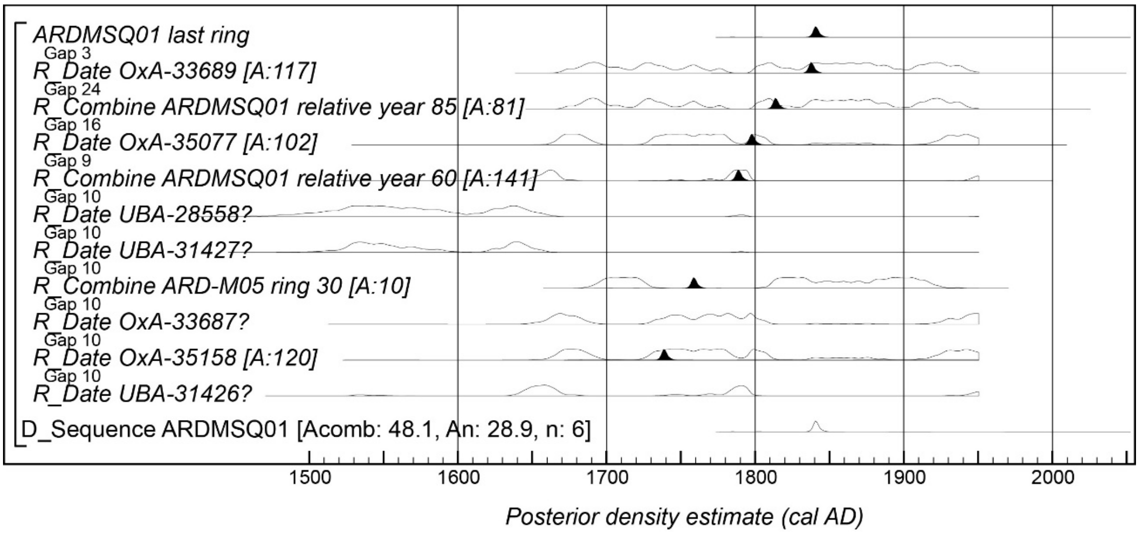

Figure 4: Probability distributions of dates from site master chronology ARDMSQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Dates followed by a '?' have been excluded from the model. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'ARDMSQ01 last ring' is the estimated date when the last ring in site chronology ARDMSQ01 formed. The model is defined by the CQL2 OxCal keywords and brackets on the left-hand side of the diagram.

Figure 4 shows a chronological model for ARDMSQ01. This combines the radiocarbon dates from ARD-M01 and those from the second batch of samples dated from ARD-M06 using the more rigorous pretreatment protocols (except for UBA-28558), with the relative sequence for the sampled rings suggested by the ring-width dendrochronology (Fig 3). This model has good overall agreement (Acomb: 48.1, An: 28.9, n: 6), although ARD-M05 ring 30 still has poor individual agreement (A: 10). This model suggests that the final ring of site chronology ARDMSQ01 formed in *cal AD 1835–1849 (95% probability; ARDSQ01 last ring*; Fig 4), or in *cal AD 1838–1844 (68% probability)*.

When the last ring of ARDMSQ01 is constrained to have formed in AD 1843, as suggested tentatively by the ring-width dendrochronology (Table 2), the model again has good overall agreement (Acomb: 35.9, An: 26.7, n: 7; Fig 5), although two rings have poor individual agreement (A > 60).

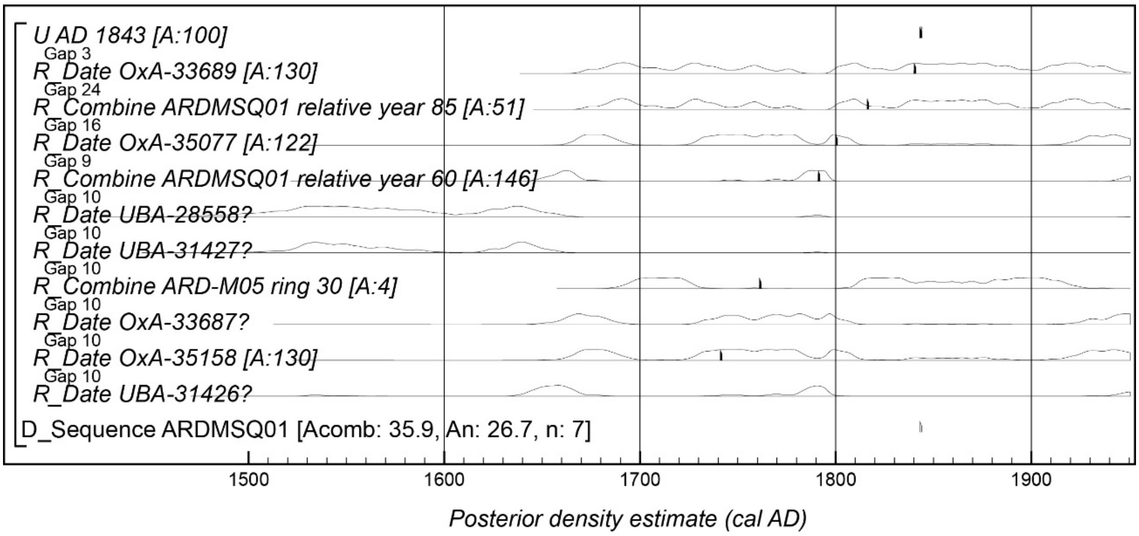

Figure 5: Probability distributions of dates site master chronology ARDMSQ01, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1843. The format is identical to that of Fig 4. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly.

Discussion

The site master chronology formed by the ring-width dendrochronology at Arden Mill, ARDMSQ01, only provides tentative cross-matching with the existing corpus of reference chronologies (Table 2). The radiocarbon wiggle-matching, however, includes the end date for the site master chronology tentatively identified by ring-width dendrochronology (Fig 4), and when the last ring of the wiggle-match sequence is constrained to have formed in AD 1843, the model has good overall agreement (Acomb: 35.9; An: 26.7; n: 7; Fig 5). This allows the tentative dating provided by the ring-width dendrochronology to be considered as a radiocarbon supported dendrochronological date, with the growth rings in the timbers contained within the site master sequence forming in AD 1732–1843$_{DR}$. The subscript $_{DR}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, ARDMSQ01, should not be utilised as a ring-width master sequence for dating other sites.

It is clear that the five samples from the roof included in site sequence ARDMSQ01 are coeval with heartwood/sapwood boundaries varying by only nine years. Two of these samples, representing a principal rafter and a purlin, have complete sapwood and, thus, based on the high level of cross-matching, it is possible to suggest that all five of the timbers represented were felled in AD 1841$_{DR}$. It is notable that the cross-matching between ARD-M01 and ARD-M02 (t = 10.7) and ARD-M04 and ARD-M05 (t = 12.0) raises the possibility that each pair of principal rafters was derived from a single tree.

The sixth sample, ARD-M17, included in site sequence ARDMSQ01 represents a cross rail in the hurst frame. With a last measured ring which formed in AD 1843$_{DR}$, it was clearly felled at a later date than the roof timbers. This timber does not have complete sapwood but does have the heartwood/sapwood transition and therefore, using a sapwood estimate of 15–40 rings (the usual 95% confidence interval for this area), it can be estimated that this timber was felled sometime within the range AD 1852–1877$_{DR}$. This indicates that this cross rail was felled some years later than the dated timbers in the roof.

It is interesting that ARDMSQ01 could not be dated conclusively by ring-width dendrochronology. Generally, the longer and better replicated a site sequence is, the greater the chance of successful dating. Site sequence ARDMSQ01 contains six samples and is 112 rings long and so might usually be expected to have a good chance of dating. The timbers represented, however, clearly belong to the late post-medieval period, a period less well represented within the network of reference chronologies. In addition, it may be that the trees used were subject to highly localised conditions which have unduly influenced the growth pattern necessary for matching against reference chronologies. The mill is located in an area which is not well represented in the chronological network and an area that has previously proven problematic with respect to successful dendrochronological analysis.

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ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)