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# Radiocarbon wiggle-matching of oak timbers

Alison Arnold, Robert Howard, Cathy Tyers, Silvia Bollhalder, Michael Dee, Sanne Palstra, Lukas Wacker, and Peter Marshall

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SUMMARY
Radiocarbon wiggle-matching of three undated ring-width site chronologies, STHASQ01, STHASQ02, and STHASQ03, from Southall Manor House, London, suggests their final rings formed in *cal AD 1606–1633* (*95% probability*), probably in *cal AD 1614–1628* (*68% probability*); *cal AD 1602–1620* (*95% probability),* probably in *cal AD 1604–1613* (*68% probability*), and *cal AD 1546–1568* (*11% probability*) or *cal AD 1608–1642* (*84% probability)*, probably in *cal AD 1615–1638* (*68% probability*). Even though precise calendar dating has not been achieved for the construction dates of the various elements of Southall Manor House we now know that it contains a significant amount of timber felled in the first half of the seventeenth century. This is at odds with the expected late-sixteenth-century-date and the carved AD 1587 inside the pediment of one of the windows of the west front of the main house.

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# CONTENTS



 

# INTRODUCTION

## Southall Manor

Southall Manor House (Fig 1) is thought to have been built in AD 1587 by Francis Awsiter, a City merchant and alderman living in the locality, who acquired the manor of Southall in AD 1602. The house, grade II* listed ([List Entry Number 1079419]), is timber-framed with tiled roofs, and consists of two separate elements: the main house, aligned north–south, comprising a two-storey hall with flanking cross-wings, a rear staircase wing, and gabled entrance porch; and a two-storey 'kitchen lodgings' range on its north side, aligned east–west.

## Tree-ring analysis

A major programme of ring-width dendrochronology was undertaken in AD 2004 to inform a potential revision to the building's statutory designation (Arnold *et al* 2005). This analysis produced three site chronologies, STHASQ01, STHASQ02, and STHASQ03, consisting of 18, four, and three samples respectively, and the mean ring-width series contain 86, 81, and 73 rings respectively. None of these site chronologies could be dated.

# RADIOCARBON DATING

Radiocarbon wiggle-matching of the three undated chronologies was requested by the Historic England London & South-East team as the building has been the subject of longstanding casework for the both the Development Advice and Heritage at Risk teams. Recent work has led to its conversion to a catering college and, as the building will be more commercial rather than heritage/tourism-led in operation, further information on the potential early (sixteenth-century) date will be very useful to assist with promoting care of the building owing to the rarity and significance of it within Ealing, and London as a whole.

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 Tables 1–3, 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).

## STHASQ01

The undated site chronology STHASQ01 consists of 18 samples, spanning 86 years, from five of the six components of the building sampled for ring-width dendrochronology: the north cross-wing, the south cross-wing, and the hall range of the Manor House, plus the stair tower, and the north range (the two samples from north cross-wing A13 and A14 are incorrectly labelled on the bar diagram for STHASQ01 as coming from the north range (Arnold *et al* 2005, fig 7)). Samples for radiocarbon dating come from cores STH-A27 and STH-A28. STH-A27, a south principal rafter from the north range truss 2, comprises 55 rings, including 21 complete sapwood rings and spans relative years 32–86 of STHASQ01. STH-A28, a north purlin from the north range, truss 1–2, comprises 69 rings, including nine sapwood rings and spans relative years 1–69 of STHASQ01.

### STHASQ02

The undated site chronology STHASQ02 consists of four samples, spanning 81 years, all from the 'Link Range'; timbers from this component of the building are not part of the other two undated chronologies STHASQ01 and STHASQ03. Samples for radiocarbon dating come from core STH-A26, a common rafter (west number 16) from the 'Link Range', comprising 81 rings, including 26 complete sapwood rings and spans relative years 1–81 of STHASQ02.

### STHASQ03

The undated site chronology STHASQ03 consists of three samples, spanning 73 years, from the primary south cross-wing roof. Samples for radiocarbon dating come from cores STH-A01 and STH-A05. STH-A01, north purlin, truss 2 – east gable, comprises 62 rings including three sapwood rings and spans relative years 1–62 of STHASQ03. STH-A05, north purlin, truss 2 – west gable, comprises 65 rings including 21 complete sapwood rings and spans relative years 9–73 of STHASQ03.

### Radiocarbon sampling and analysis

Twenty-three radiocarbon measurements have been obtained from single annual tree-rings from timbers STH-A27 and STH-A28 (Table 1), STH-A26 (Table 2), and STH-A01 and STH-A05 (Table 3). 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.

Radiocarbon dating was undertaken by the Laboratory of Ion Beam Physics, ETH Zürich, Switzerland and Centre for Isotope Research, University of Groningen, the Netherlands in 2021. At ETH Zürich cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (Synal *et al* 2007; Wacker *et al* 2010b). Data reduction was undertaken as described by Wacker *et al* (2010c).

At the University of Groningen each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee *et al* 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant $CO_2$ was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma *et al* 1996; Aerts-Bijma *et al* 1997). The graphite was then pressed into aluminium cathodes and dated by AMS (Synal *et al* 2007; Salehpour *et al* 2016). Data reduction was undertaken as described by Wacker *et al* (2010c).

Both facilities maintain a continual programme of quality assurance procedures (Aerts-Bijma *et al* 2021; Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Tables 1–3). The quoted $\delta^{13}C$ values measured by Isotope Ratio Mass Spectrometry at the Centre for Isotope Research, University of Groningen,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 Southall Manor, House derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 2–4.

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 2–4 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).

## STHASQ01

Figure 2 illustrates the chronological model for STHASQ01. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 1 of the measured tree-ring series (GrM-26370) was laid down 32 years before the carbon in ring 33 of the series (GrM-26371); Fig 2), with the radiocarbon measurements (Table 1) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 137.1, An: 26.7, n: 7; Fig 2), with all seven radiocarbon dates having good individual agreement (A:>60). It suggests that the final ring of STHASQ01 formed in *cal AD 1606–1633* (*95% probability*; *ring 86*; Fig 2), probably in *cal AD 1614–1628* (*68% probability*).

## STHASQ02

The two measurements on ring 5 (ETH-12755 and GrM-26387) are statistically consistent at the 5% significance level (T′=0.2, T′(5%)=3.8, ν=1; Ward and Wilson 1978) and a weighted mean (STH-A26 ring 5; 299±12 BP) was taken as providing the best estimate for its formation. Figure 3 illustrates the chronological model for STHASQ02. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 24 of the measured tree-ring series (ETH-112756) was laid down 9 years before the carbon in ring 33 of the series (ETH-112757); Fig 3), with the radiocarbon measurements (Table 2) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 76.2, An: 25.0, n: 8; Fig 3), with all but one, ETH-112762 (A:15) of the eight radiocarbon dates having good individual agreement (A:>60). It suggests that the final ring of STHASQ02 formed in *cal AD 1602–1620* (*95% probability*; *ring 81*; Fig 3), probably in *cal AD 1604–1613* (*68% probability*).

## STHASQ03

Figure 4 illustrates the chronological model for STHASQ03. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 29 of the measured tree-ring series (GrM-26382) was laid down 5 years before the carbon in ring 34 of the series (GrM-26383); Fig 4), with the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020). GrM-26385 has been excluded from the model as it is anomalously old for its position in the tree-ring sequence. The sample was pre-treated and dated twice by the laboratory, 459±16 BP and 466±12 BP, the reported age being a mean of these two independent measurements, which are statistically consistent at the 5% significance level (T′=0.1, T′(5%)=3.8, ν=1; Ward and Wilson 1978). It therefore seems that the radiocarbon measurement reflects the age of the sample material, that could be contaminated, rather than a problem in the laboratory.

The model has good overall agreement (Acomb: 51.9, An: 25.9, n: 6; Fig 4), with all but one, GrM-26379 (A:33), of the six radiocarbon dates having good individual agreement (A:>60). It suggests that the final ring of STHASQ03 formed in *cal AD 1546–1568* (*11% probability*; *ring 73*; Fig 4) or *cal AD 1608–1642* (*84% probability)*, probably in *cal AD 1615–1638* (*68% probability*).

## INTERPRETATION

### STHASQ01

Of the 18 samples in site chronology STHASQ01, 11 retain complete sapwood, that is each have the last growth ring produced by the tree represented before it was felled. In each case the last complete sapwood ring is the same relative position, ie ring 86, that we now know to have formed in *cal AD 1606–1633* (*95% probability*; *ring 86*; Fig 2), probably in *cal AD 1614–1628* (*68% probability*). Furthermore, the relative positions of the heartwood/sapwood boundaries on the other seven cross-matched samples (Arnold *et al* 2005, fig 7) would suggest these timbers were all felled at, or about, the same time. The variation in the relative date of the heartwood/sapwood boundary in this entire group is only 14 years, ranging from 54 (STH-A29) to 68 (eg STH-A14 and STH-A19) (Arnold *et al* 2005, fig 7).

### STHASQ02

Again, there is little variation in the relative dates of the heartwood/sapwood boundaries which range from relative year 53 (STH-A23) to relative year 64 (STH-A22) (Arnold *et al* 2005, fig 8). However, all four samples from site chronology STHASQ02 retain complete sapwood but, unlike STHASQ01, the positions of their last complete sapwood rings vary by up to two years. These samples were therefore not all felled at precisely the same time — their felling dates are given in Table 4 — but were likely felled as part of a single felling episode spanning a small number of years.

### STHASQ03

Of the three samples in site chronology STHASQ03, two retain complete sapwood. For both of these the last complete sapwood ring is the same relative position, ie at relative year 67, that we now know to have formed in *cal AD 1546–1568* (*11% probability*; *ring 73*; Fig 3) or *cal AD 1608–1642* (*84% probability)*, probably in *cal AD 1615–1638* (*68% probability*). Moreover, the relative position of the heartwood/sapwood boundaries on the other cross-matched sample (Arnold *et al* 2005, fig 9) would suggest this timber was also felled at the same, or similar, time. The variation in the relative date of the three samples in this group ranges from relative year 52 (STH-A05) to relative year 59 (STH-A01).

## DISCUSSION

Tree-ring analysis had previously demonstrated that a number of principal rafters, a common rafter, purlins, and wall plates in the north and south cross-wings, the hall, stair tower, and north range of Southall Manor House were all felled in the same year. Radiocarbon wiggle-matching of timbers in site chronology STHASQ01 estimates that this was in *cal AD 1606–1633* (*95% probability*; *ring 86*; Fig 2), probably in *cal AD 1614–1628* (*68% probability*). Radiocarbon wiggle-matching is only able to provide dates precise to a single calendar year, when distinct features in the atmospheric $^{14}C$ record caused by cosmic radiation events occur (Kuitems *et al* 2021; Wacker *et al* 2014).

The 'Link range' timbers, all common rafters, were not all felled in a single year and, although they do not cross-match with those of the rest of the Manor House, the radiocarbon wiggle-match of site chronology STHASQ02 suggests they could potentially be contemporary, with the earliest timber felled in *cal AD 1600–1618* (*95% probability*), probably in *cal AD 1602–1611* (*68% probability*), and the latest in *cal AD 1602–1620* (*95% probability*), probably in *cal AD 1604–1613* (*68% probability*).

The three purlins in site chronology STHASQ03 from the primary roof of the south-cross wing were felled in the same year in *cal AD 1546–1568* (*11% probability)* or *cal AD 1608–1642* (*84% probability)*, probably in *cal AD 1615–1638* (*68% probability*). Although they do not cross-match with other samples from the roof, this dating suggests they are from a different woodland source rather than being of a different date.

Even though precise calendar dating has not been achieved for the construction dates of the various elements of Southall Manor House, we now know that it contains timbers felled in the first half of the seventeenth century. This is at odds with the expected late sixteenth-century date and the carved AD 1587 inside the pediment of one of the windows of the west front of the main house (Arnold *et al* 2005, 1). The new independent scientific dating evidence suggests a revaluation of the history of the building is required, and in particular further consideration is needed of whether it was built by Francis Awsiter as previously assumed or whether the roof-level timbers dated here represent a major programme of repairs or modifications.

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# TABLES

*Table 1: Radiocarbon measurements and associated δ$^{13}$C values from oak samples STH-A27 and STH-A28, part of site chronology STHASQ01*

| Laboratory Number | Sample | Radiocarbon Age (BP) | δ$^{13}$C$_{IRMS}$ (‰) |
|---|---|---|---|
| GrM-26370 | STH-A28, ring 1, *Quercus* sp., heartwood, STHASQ01 relative year 1 | 321±18 | −23.5±0.15 |
| GrM-26371 | STH-A28, ring 33, *Quercus* sp., heartwood, STHASQ01 relative year 33 | 323±17 | −24.5±0.15 |
| GrM-26372 | STH-A28, ring 49, *Quercus* sp., heartwood, STHASQ01 relative year 49 | 336±17 | −25.3±0.15 |
| GrM-26373 | STH-A28, ring 60, *Quercus* sp., heartwood, STHASQ01 relative year 60 | 346±18 | −24.9±0.15 |
| GrM-26374 | STH-A27, ring 37, *Quercus* sp., sapwood, STHASQ01 relative year 68 | 365±18 | −24.6±0.15 |
| GrM-26375 | STH-A27, ring 44, *Quercus* sp., sapwood, STHASQ01 relative year 75 | 377±18 | −25.7±0.15 |
| GrM-26376 | STH-A27, ring 53, *Quercus* sp., sapwood, STHASQ01 relative year 84 | 340±18 | −24.6±0.15 |

*Table 2: Radiocarbon measurements and associated $\delta^{13}C$ values from oak sample STH-A26, part of site chronology STHASQ02 (replicate measurements have been tested for statistical consistency and combined before calibration as described by Ward and Wilson (1978)*

| Laboratory Number | Sample | Radiocarbon Age (BP) | $\delta^{13}C_{AMS}$ (‰) | $\delta^{13}C_{IRMS}$ (‰) |
|---|---|---|---|---|
| ETH-112755 | STH-A26, ring 5, *Quercus* sp., heartwood, STHASQ02 relative year 5 | 295±14 | −24.5 | |
| GrM-26387 | Replicate of ETH-112755 | 305±18 | | −24.3±0.15 |
| STH-A26 ring 5 | T′=0.2, T′(5%)=3.8, ν=1 | 299±12 | | |
| ETH-112756 | STH-A26, ring 24, *Quercus* sp., heartwood, STHASQ02 relative year 24 | 312±14 | −26.6 | |
| ETH-112757 | STH-A26, ring 33, *Quercus* sp., heartwood, STHASQ02 relative year 33 | 330±14 | −27.2 | |
| ETH-112758 | STH-A26, ring 39, *Quercus* sp., heartwood, STHASQ02 relative year 39 | 339±14 | −27.1 | |
| ETH-112759 | STH-A26, ring 52, *Quercus* sp., heartwood, STHASQ02 relative year 52 | 343±14 | −27.0 | |
| ETH-112760 | STH-A26, ring 60, *Quercus* sp., sapwood, STHASQ02 relative year 60 | 345±14 | −24.8 | |
| ETH-112761 | STH-A26, ring 74, *Quercus* sp., sapwood, STHASQ02 relative year 74 | 351±14 | −27.4 | |
| ETH-112762 | STH-A26, ring 79, *Quercus* sp., sapwood, STHASQ02 relative year 79 | 339±14 | −26.7 | |

*Table 3: Radiocarbon measurements and associated δ¹³C values from oak samples STH-A01 and STH-A05, part of site chronology STHASQ03*

| Laboratory Number | Sample | Radiocarbon Age (BP) | $\delta^{13}C_{IRMS}$ (‰) |
|---|---|---|---|
| GrM-26378 | STH-A01, ring 2, *Quercus* sp., heartwood, STHASQ03 relative year 2 | 340±18 | −22.9±0.15 |
| GrM-26379 | STH-A01, ring 18, *Quercus* sp., heartwood, STHASQ03 relative year 18 | 371±20 | −24.4±0.15 |
| GrM-26382 | STH-A01, ring 29, *Quercus* sp., heartwood, STHASQ03 relative year 29 | 343±18 | −25.9±0.15 |
| GrM-26383 | STH-A01, ring 34, *Quercus* sp., heartwood, STHASQ03 relative year 34 | 344±18 | −24.2±0.15 |
| GrM-26384 | STH-A01, ring 47, *Quercus* sp., heartwood, STHASQ03 relative year 47 | 349±29 | −26.0±0.15 |
| GrM-26385 | STH-A01, ring 52, *Quercus* sp., heartwood, STHASQ03 relative year 52 | 464±10 | −26.2±0.15 |
| GrM-26386 | STH-A05, ring 59, *Quercus* sp., sapwood, STHASQ03 relative year 67 | 370±20 | −27.2±0.15 |

*Table 4: Highest Posterior Density interval felling dates for samples in site chronology STHASQ02*

| Sample | *Highest Posterior Density interval (95% probability)* | *Highest Posterior Density interval (68% probability)* |
|---|---|---|
| STH-A22 | *cal AD 1601–1619* | *cal AD 1603–1612* |
| STH-A23 | *cal AD 1600–1618* | *cal AD 1602–1611* |
| STH-A24 | *cal AD 1601–1619* | *cal AD 1603–1612* |
| STH-A26 | *cal AD 1602–1620* | *cal AD 1604–1613* |

# FIGURES

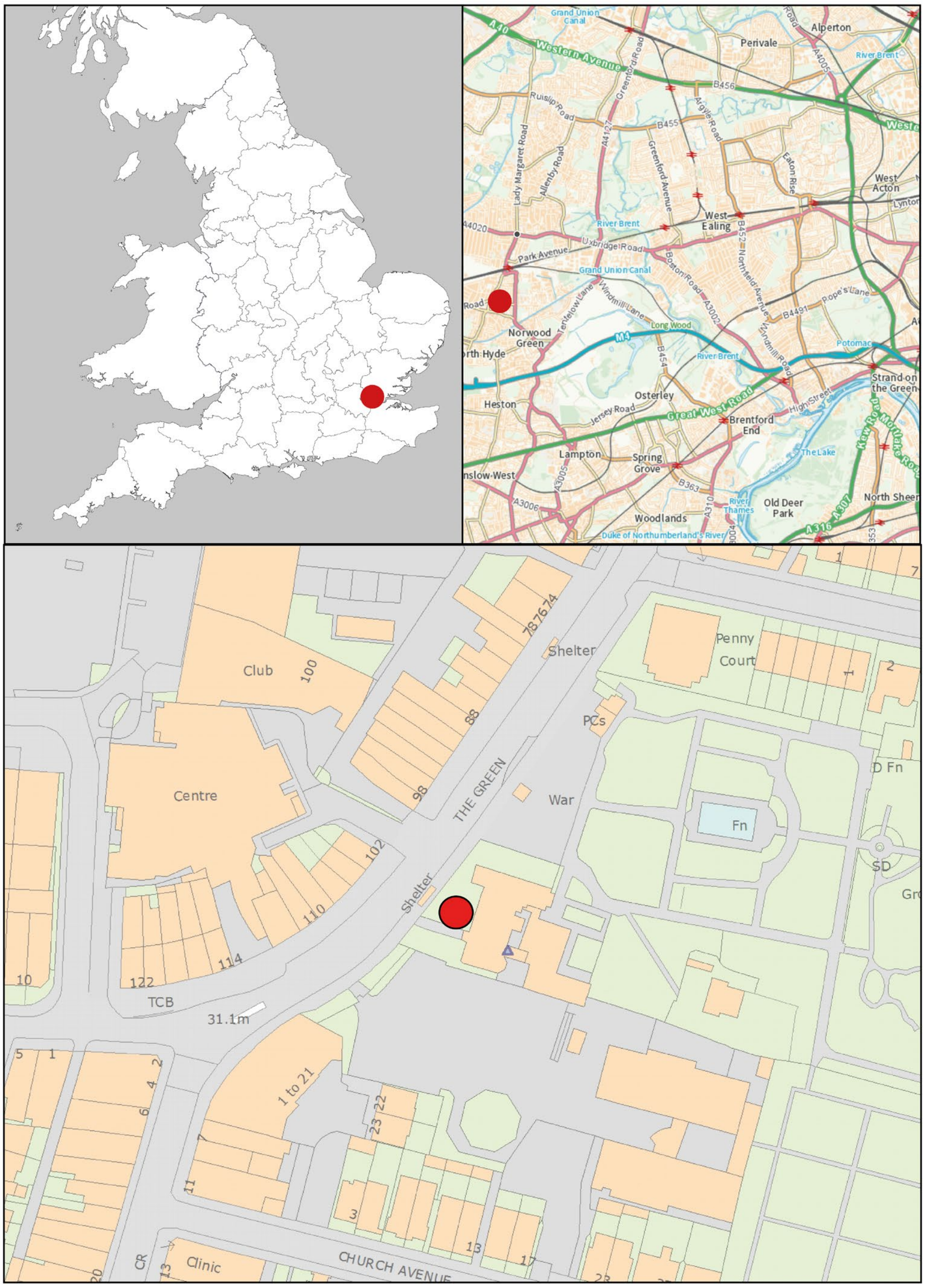



*Figure 1: The location of the Southall Manor House, marked in red. Scale: top right 1:52913; bottom 1:2500. © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Limited 2021. All rights reserved. Licence number 102006.006*

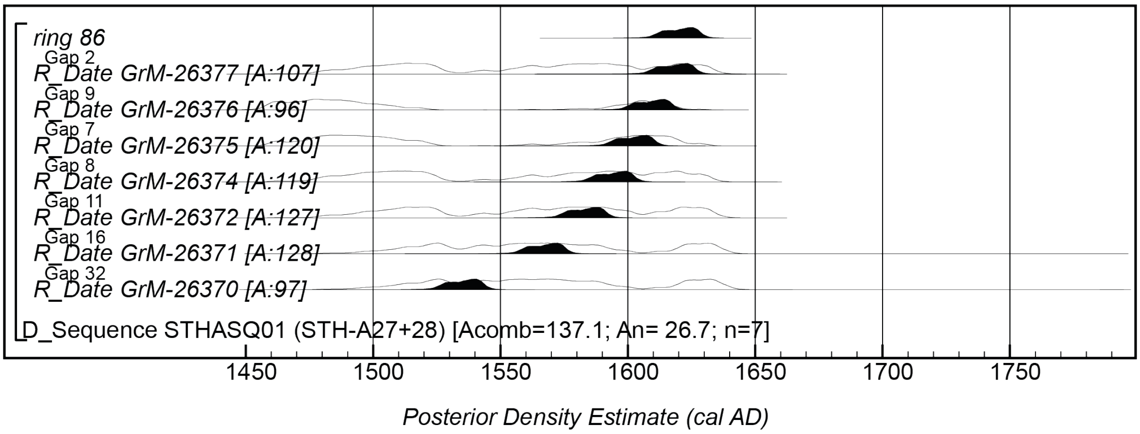



*Figure 2: Probability distributions of dates from timbers STH-A27 and STH-A28 part of site sequence STHASQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution '*ring 86*' is the estimated date when the last ring of chronology STHASQ01 formed. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly*

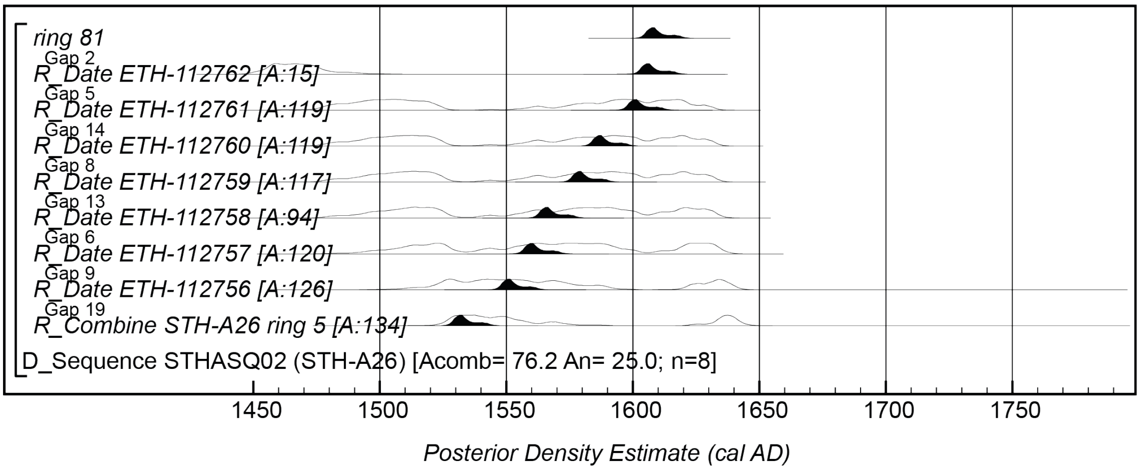



*Figure 3: Probability distributions of dates from timber STH-A26 part of site sequence STHASQ02. The format is identical to Figure 2*

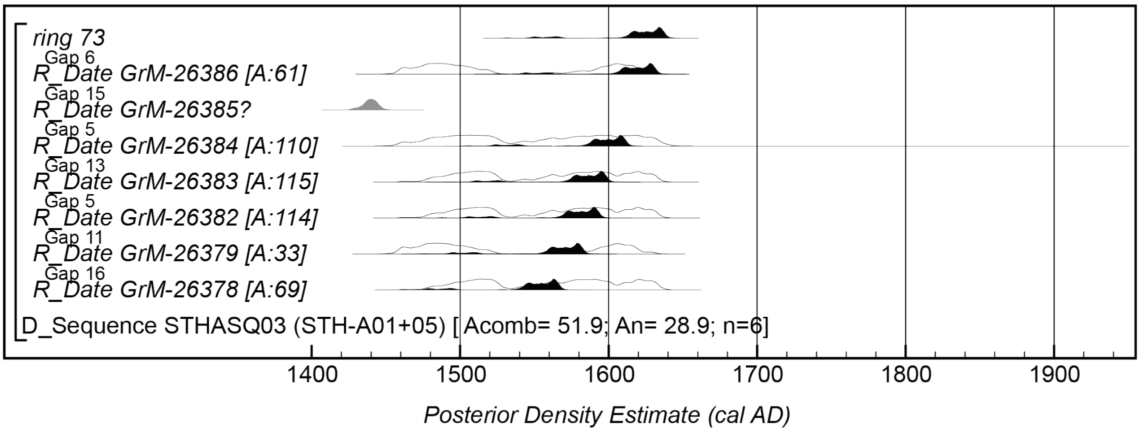
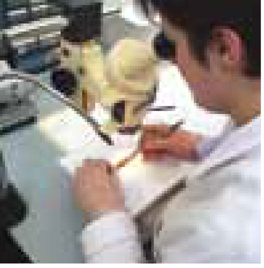
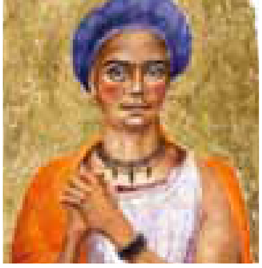
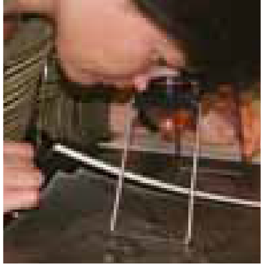



*Figure 4: Probability distributions of dates from timbers STH-A01 and STH-A05 part of site sequence STHASQ03. The format is identical to Figure 2*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