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Barn North-West of Burncliffe, Tow House, Henshaw, Northumberland

Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Michael Dee, and Sanne Palstra

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Front Cover: The Cruck-Framed Barn, Burncliffe, Tow House from the south-west (2011). Photograph by Peter Ryder.

BARN NORTH-WEST OF BURNCLIFFE, TOW HOUSE, HENSHAW, NORTHUMBERLAND

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SUMMARY

A combination of tree-ring analysis and radiocarbon wiggle-matching has resulted in the successful dating of seven timbers from this building.

A single timber has been dated to the winter of AD 1590/91 with a further six having last ring dates compatible with felling in the first quarter of the eighteenth century. These results suggest construction occurred in the first quarter of the eighteenth century and incorporated potentially reused timber of the late-sixteenth century.

CONTRIBUTORS

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Michael Dee, and Sanne Palstra

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ARCHIVE LOCATION

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

HISTORIC ENVIRONMENT RECORD LOCATION

Northumberland Historic Environment Record
Conservation Team
Development Services
Planning and Economy Directorate
Northumberland County Council
County Hall
Morpeth
Northumberland NE61 2EF

CONTACT DETAILS

Historic England,
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA
020 7973 3700
customers@HistoricEngland.org.uk

DATE OF INVESTIGATION

2014–22

OTHER CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Alex Bayliss and Cathy Tyers
Historic England
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA
alex.bayliss@historicengland.org.uk
cathy.tyers@historicengland.org.uk

Michael Dee and Sanne Palstra
Centre for Isotope Research
University of Groningen
Nijenborgh 6
9747 AG Groningen
The Netherlands
m.w.dee@rug.nl
s.w.l.palstra@rug.nl

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INTRODUCTION

This Grade II* barn (List Entry Number 1045243 https://historicengland.org.uk/listing/the-list/list-entry/1045243), is situated in the hamlet of Tow House, north-west of Burncliffe, in the county of Northumberland (Fig 1). The origin of the barn is unclear but, on the evidence of Ordnance Survey maps, it appears to have been the south-east end of a longer range of buildings and in contrast to the rest of the building, which is constructed in rubble, the extant north-west end is brick.

The single-storey building with heather thatched roof is rectangular in plan and orientated north-west to south-east, parallel to the road. There is a central pair of doors to the north-east (or roadside) elevation, with an opposite doorway to the rear (or south-west) elevation (Fig 2). Internally, there are four cruck trusses, dividing the building into five bays. Each truss has a pair of curved blades carrying the ridge and a tiebeam half-lapped onto the south-east faces of the blades set high to carry the purlins. There are more recent tiebeams at a lower level (Fig 3).

The building is believed to be one of only three surviving traditional heather-thatched buildings in Northumberland and one of a handful of full-cruck buildings north of the Tees (Ryder 2011). It is thought to be late-seventeenth or eighteenth century in date.

TREE-RING SAMPLING

In 2006, English Heritage commissioned sampling of the roof structure of the barn and 15 core samples were obtained. These were given the site code TWH-A and numbered 01–15. Analysis of 11 of these (four proving to have too few rings for secure dating and were rejected prior to analysis) resulted in no grouping and no dating (Arnold and Howard 2006). In 2013, English Heritage commissioned a further programme of sampling as renewal of the thatch allowed greater accessibility of timbers and the present owners were in receipt of a grant for repairs.

This latest programme of work resulted in a further four core samples and five slices being obtained. These were also given the code TWH-A and, continuing on from the 2006 samples, numbered 16–24. The location of all core samples was noted at the time of sampling and has been marked on Figures 2 and 4–7. Further details relating to the samples can be found in Table 1, including which of them showed obvious signs of reuse. Since the initial sampling some of the rafters have been removed and were piled up in the barn; it was from these that the slices were taken.

When the original sampling was undertaken in 2006 it was without the benefit of Peter Ryder's survey. With this to hand some amendments to the 2006 work have been made; what were described as collars in 2006 are now called tiebeams and trusses now follow his numbering (north-west to south-east).

TREE-RING ANALYSIS AND RESULTS

The nine new samples were prepared by sanding and polishing and their growth-ring widths measured; the data of all measurements are given at the end of the report. These, together with the 11 measured samples from 2006, were then compared with each other by the Litton/Zainodin grouping programme (see Appendix) resulting in eight samples matching to form two groups.

Firstly, six samples grouped at a minimum *t*-value of 4.4 and were combined at the relevant offset positions to form TWHASQ01, a site sequence of 130 rings (Fig 8). Two further samples cross-matched at a *t*-value of 13.9 and were combined to form TWHASQ02, a site sequence of 127 rings (Fig 9).

Comparison of these two site sequences with the extensive database of relevant reference chronologies failed to identify conclusive cross-dating positions and thus these timbers remain undated by ring-width dendrochronology. However, some low but consistent cross-dating was noted against a number of reference chronologies when site sequence TWHASQ01 spans AD 1595–1724 (Table 2).

Attempts were then made to date the remaining ungrouped samples by comparing them individually against the reference chronologies. Despite tentative dates being identified for a number of these, only sample TWH-A17 can be said to be securely dated. This sample was found to match at a first-ring date of AD 1530 and a last-measured ring date of AD 1590. The evidence for this dating is given in Table 3.

RADIOCARBON DATING

Following the extended programme of tree-ring analysis from the barn, only a single timber had been dated securely by ring-width dendrochronology. This sample, TWH-A17, is from an *ex situ* rafter felled in AD 1590. It is unclear whether this timber was reused, although structural evidence of reuse was visible on several elements of the roof frame. Site sequence TWHASQ01 contains six timbers, five of which were sampled *in situ* and none of which showed obvious evidence of reuse. Site sequence TWHASQ02, however, contained only two timbers, one being sampled *ex situ* and the other being reused. Radiocarbon wiggle-matching was therefore confined to site sequence, TWHASQ01.

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 4, 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).

Seven radiocarbon measurements have been obtained from single tree-rings from TWH-A08, a core sample containing 122 growth rings, including 26 complete sapwood rings, from the south-west cruck blade of truss 3 (Table 4; Fig 10). This is the longest tree-ring series in site sequence TWHASQ01. 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 Centre for Isotope Research, University of Groningen (GrM-), the Netherlands in 2022. 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 Accelerator Mass Spectrometry (AMS) (Synal *et al* 2007; Salehpour *et al* 2016).

Data reduction was undertaken as described by Wacker *et al* (2010), and the facility maintains a continual programme of quality assurance procedures (Aerts-Bijma *et al* 2021), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). The two results on ring 2 (GrM-29035 and GrM-29052; Table 4) are statistically consistent (T'=0.0, T'(5%)=3.8, ν=1) and a weighted mean has been taken of them before calibration and incorporation in the model (Ward and Wilson 1978). 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; Table 4). The $\delta^{13}C$ values presented in Table 4 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 the barn, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 11–12.

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 11–12 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agrees 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 with its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 11 illustrates the chronological model for TWH-A08. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 20 of the measured tree-ring series (GrM-29036) was laid down 17 years before the carbon in ring 37 of the series (GrM-29037); Fig 10). It also incorporates the radiocarbon measurements from TWH-A08 (Table 4) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

This model has good overall agreement (Acomb: 107.6, An: 28.9, n: 6), and all the dates on the single rings have good individual agreement (A > 60) with their positions in the sequence. It suggests that the final surviving ring of TWH-A08 formed in *cal AD 1717–1731 (95% probability; TWH-A08 felling*; Fig 11), probably in *cal AD 1720–1727 (68% probability)*.

The last ring of TWH-A08 is two years before the end of site sequence TWHASQ01 and so, if the low but consistent cross-dating noted when site sequence TWHASQ01 spans AD 1595–1724 (Table 2) is correct, the last ring of TWH-A08 would have formed in AD 1722. A model which constrains the last ring of the wiggle-match sequence to form in AD 1722 also has good overall agreement (Acomb: 112.2; An: 26.7; n: 7; Fig 12), and all the individual dates again have good individual agreement (A > 60).

This allows the tentative dating provided by the tree-ring analysis to be considered as a radiocarbon supported dendrochronological dating, with the site sequence spanning AD 1595–1724$_{DR}$. The subscript $_{DR}$ indicates that these are not dates determined independently by ring-width dendrochronology, and that the master sequence, TWHASQ01, should not be utilised as a ring-width master sequence for dating other sites.

INTERPRETATION

A combination of traditional tree-ring analysis and radiocarbon wiggle-matching has resulted in the successful dating of two samples. One of these samples, TWH-A08, is a component of site sequence TWHASQ01 and, therefore, by association the other five samples in this site sequence are also dated (Fig 13).

Four of the dated samples have complete sapwood, allowing felling dates to be given for the timbers represented. The earliest sample, TWH-A17, has the last-measured ring date of AD 1590. The final ring on this sample has both spring and summer growth cells which gives the timber represented a felling of winter AD 1590/91. The other three samples with complete sapwood have last-measured ring dates of AD 1717$_{DR}$ (TWH-A22), AD 1722$_{DR}$ (TWH-A08), and AD 1724$_{DR}$ (TWH-A24). The final ring on samples TWH-A22 and TWH-A24 can also be seen to have both spring and summer growth cells, giving the timbers represented felling dates of winter AD 1717/18$_{DR}$ and winter AD 1724/25$_{DR}$, respectively. This ring cannot be checked on sample TWH-A08 as radiocarbon dating has been undertaken on the core so this sample is given the felling date of AD 1722$_{DR}$ without specification of season.

One of the other dated samples does not have any sapwood but the last-measured ring (AD 1698 $_{DR}$) is the heartwood/sapwood boundary, giving the timber represented an estimated felling date within the range AD 1713–38$_{DR}$ (using a sapwood estimate of 15–40 rings, this being the 95% confidence range for mature oak timbers in this area), consistent with this timber having been felled at a similar time to the other eighteenth century timbers identified above. The final two dated samples do not have the heartwood/sapwood boundary and so estimated felling dates cannot be calculated for them, except to say that with last-measured ring dates of AD 1678$_{DR}$ (TWH-A16) and AD 1692$_{DR}$ (TWH-A23), the timbers represented have *termini post quem* for felling dates of AD 1693$_{DR}$ and AD 1707$_{DR}$, respectively.

DISCUSSION

Prior to scientific dating being undertaken the barn was thought to be late-seventeenth or eighteenth century in date. These results have now demonstrated that it is likely to belong to the latter part of the first quarter of the eighteenth century, when the majority of the dated timbers utilised were felled.

It has also been shown that the roof incorporated at least one timber from the late-sixteenth century. Although no obvious signs of reuse were noted on the dated timber, it could be seen that a large number of the main beams did show signs of previous use (Table 1) making it quite likely that some of the smaller ones, such as rafters, were also salvaged from other structures but during their conversion had all signs of reuse removed.

The two sample components of undated site sequence TWHASQ02 (Fig 9) match each other at t=13.9, a level to suggest both samples are likely to represent the same tree. Indeed, sample TWH-A15 is one of the 2006 samples taken from a rafter which upon revisiting in 2013 could not be identified within the roof structure thus making it quite possible that it is actually the same timber from which the sliced sample TWH-A19 was removed. Alternatively, it could simply mean that two rafters were cut from the same tree, not an unlikely scenario.

Following the unsuccessful analysis in 2006 it was suggested that the failure to securely date any of the samples (or even identify any grouping between them) might be due to the roof being constructed from a disparate group of timbers of varying dates and/or sources. Peter Ryder's survey in 2011, identifying a number of reused timbers within the roof structure, would appear to lend support to this suggestion. Indeed, the three timbers, thought to be primary to the building, with absolute felling dates (TWH-A08, TWH-A22, and TWH-A24) were felled in different years (winter AD 1717/18$_{DR}$, AD 1722$_{DR}$, and winter AD 1724/25$_{DR}$), which for such a modest building might be considered slightly unusual.

Given that TWHASQ01 is a reasonably well replicated site sequence of 130 rings it was disappointing when it could not be securely dated by tree-ring analysis. At the time (2013) it was felt that this might be due to a number of the samples having bands of restricted growth, possibly the result of non-climatic influences, which would mask the climatic signal necessary for successful matching against the reference chronologies. Alternatively, with the possibility that the barn was late in date, it could have been simply due to a lack of suitable reference chronologies of the right date with which to compare it. It can be seen that five of the best reference chronologies against which this site sequence now matches (Table 2) have been constructed after the original analysis in 2013 and were not available at that time, demonstrating the importance of having good coverage in reference databanks both regionally and chronologically.

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TABLES

Table 1: Details of tree-ring samples from the Barn north-west of Burncliffe, Tow House, Henshaw, Northumberland

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
2006 samples						
TWH-A01	North-east blade, truss 1 – reused	60	--	----	----	----
TWH-A02	South-west blade, truss 1 – reused	156	h/s	----	----	----
TWH-A03	Tiebeam, truss 1 – reused	90	15	----	----	----
TWH-A04	North-east blade, truss 2 – reused	NM	--	----	----	----
TWH-A05	South-west blade, truss 2	NM	--	----	----	----
TWH-A06	Tiebeam, truss 2 – reused	NM	--	----	----	----
TWH-A07	North-east blade, truss 3	72	05	----	----	----
TWH-A08	South-west blade, truss 3	122	26C	1601_{DR}	1696_{DR}	1722_{DR}
TWH-A09	Tiebeam, truss 3 - reused	88	18C	----	----	----
TWH-A10	South-west blade, truss 4	NM	--	----	----	----
TWH-A11	Tiebeam, truss 4	88	24	----	----	----
TWH-A12	North-east purlin, trusses 1-2	55	h/s	----	----	----
TWH-A13	South-west purlin, trusses 3-4	55	h/s	----	----	----
TWH-A14	South-west rafter, bay 1 – reused	56	05	----	----	----
TWH-A15	South-west rafter, bay 4 – reused	99	--	----	----	----

2013 samples						
TWH-A16	Rafter – slice	80	--	1599$_{DR}$	----	1678$_{DR}$
TWH-A17	Rafter - slice	61	17C	1530	1573	1590
TWH-A18	Rafter - slice	57	h/s	----	----	----
TWH-A19	Rafter - slice	127	h/s	----	----	----
TWH-A20	Rafter - slice	61	h/s	----	----	----
TWH-A21	North-east rafter, bay 4	70	h/s	1629$_{DR}$	1698$_{DR}$	1698$_{DR}$
TWH-A22	North-east rafter, bay 2	88	32C	1630$_{DR}$	1685$_{DR}$	1717$_{DR}$
TWH-A23	North-east rafter, bay 4	98	--	1595$_{DR}$	----	1692$_{DR}$
TWH-A24	North-east rafter, bay 4	118	29C	1607$_{DR}$	1695$_{DR}$	1724$_{DR}$

*NM = not measured

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

C = complete sapwood retained on sample, last-measured ring is the felling date

$_{DR}$ = radiocarbon-supported dendrochronological date

Table 2: Results of the cross-matching site sequence TWHASQ01 and the reference chronologies when the first-ring date is AD 1595 and the last-measured ring date is AD 1724

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Durham Cathedral (refectory/librarian's loft), County Durham	5.6	1431–1683	Arnold *et al* 2007
Snitterton Hall, nr Matlock, Derbyshire	5.3	1588–1696	Arnold and Howard 2020a unpubl
Teversall Church (bellframe), Nottinghamshire	5.2	1587–1697	Arnold *et al* 2016
Grandy's Knowe, Bardon Mill, Northumberland	5.1	1585–1714	Arnold and Howard 2009a
Upper Millshaw Farm, Near Hepworth, Yorkshire	4.9	1568–1697	Arnold and Howard 2020b unpubl
St Mary's Chare, Hexham, Northumberland	4.9	1536–1689	Arnold *et al* 2004
Cappleside Barn, Rathmell, North Yorkshire	4.6	1571–1711	Arnold *et al* 2018
The Chantry, Morpeth, Northumberland	4.6	1336–1651	Arnold and Howard 2009b
Cheddleton Grange, Cheddleton, Staffordshire	4.6	1551–1682	Arnold *et al* 2008
Shaw House Farm, Yorkshire	4.5	1577–1695	Arnold and Howard 2017

Table 3: Results of the cross-matching of sample TWH-A17 and the reference chronologies when the first-ring date is AD 1530 and the last-measured ring date is AD 1590

Reference chronology	t-value	Span of chronology (AD)	Reference
Sinai Farm, Burton on Trent, Staffordshire	6.8	1445–1635	Arnold *et al* 2008
Clumpcliff Farm, Methley Lane, Rothwell, West Yorkshire	6.5	1452–1613	Howard *et al* 2000
Astley Castle, Warwickshire	6.5	1495–1627	Howard and Litton 1997
Bolsover Castle (Riding School), Derbyshire	6.3	1494–1744	Howard *et al* 2005
Whiston Barn, Rotherham, South Yorkshire	6.1	1374–1622	Tyers 2002
Pontefract Castle, West Yorkshire	5.9	1507–1656	Arnold and Howard 2005
Bolsover (Little Castle), Derbyshire	5.8	1532–1749	Arnold *et al* 2003
Bishops House, Sheffield	5.8	1359–1591	Morgan 1980
Beverley Gate, Hull, East Yorkshire	5.7	1475–1614	Groves 1990
Howley Hall Farm, Morley, West Yorkshire	5.6	1415–1635	Arnold and Howard 2013

Table 4: Radiocarbon and stable isotope measurements from the Barn north-west of Burncliffe, Tow House, Henshaw (replicate measurements have been compared and combined as described by Ward and Wilson 1978)

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)
GrM-29035	TWH-A08, ring 2 (Quercus sp. heartwood)	368±17	−24.85±0.15
GrM-29052	replicate of GrM-29035	368±18	−24.58±0.15
^{14}C: T′=0.0; $\delta^{13}C$: T′=1.6; T′(5%)=3.8, ν=1 for both		368±13	−24.72±0.11
GrM-29036	TWH-A08, ring 20 (Quercus sp. heartwood)	344±17	−25.38±0.15
GrM-29037	TWH-A08, ring 37 (Quercus sp. heartwood)	313±18	−25.75±0.15
GrM-29039	TWH-A08, ring 53 (Quercus sp. heartwood)	224±18	−25.11±0.15
GrM-29040	TWH-A08, ring 66 (Quercus sp. heartwood)	204±18	−24.35±0.15
GrM-29041	TWH-A08, ring 79 (Quercus sp. heartwood)	146±17	−25.96±0.15

FIGURES

Figure 1: Maps to show the location of the Barn north-west of Burncliffe, Tow House, Henshaw in Northumberland with red dot. Scale: top right 1:10000; bottom 1:1000. © Crown Copyright and database right 20204. All rights reserved. Ordnance Survey Licence number 100024900.

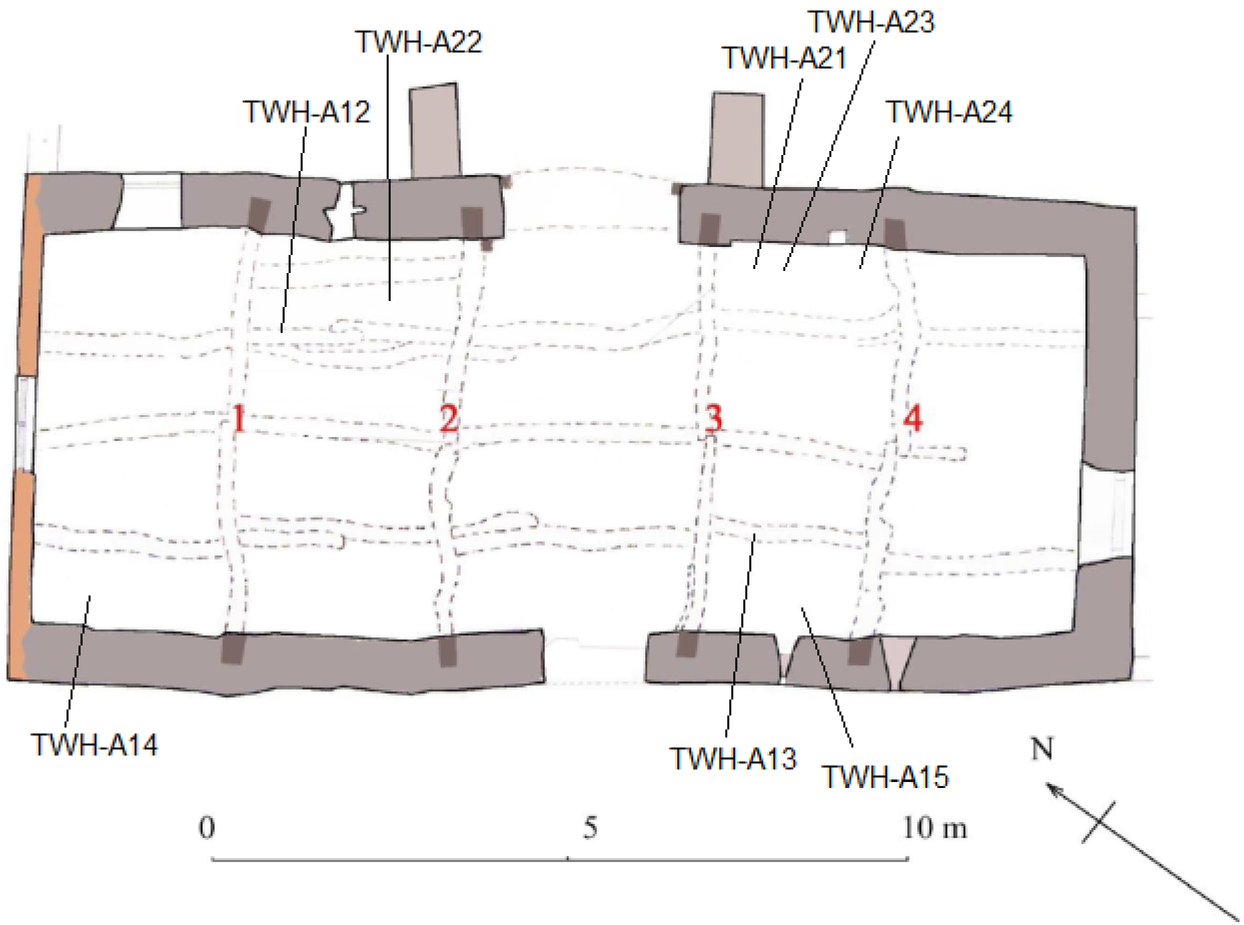


Figure 2: Plan, showing the location of samples TWH-A12–15 and TWH-A21–24 (Ryder 2011)

Figure 3: Photograph of the roof, with truss 2 in the foreground, photograph taken from the south-east (Alison Arnold)

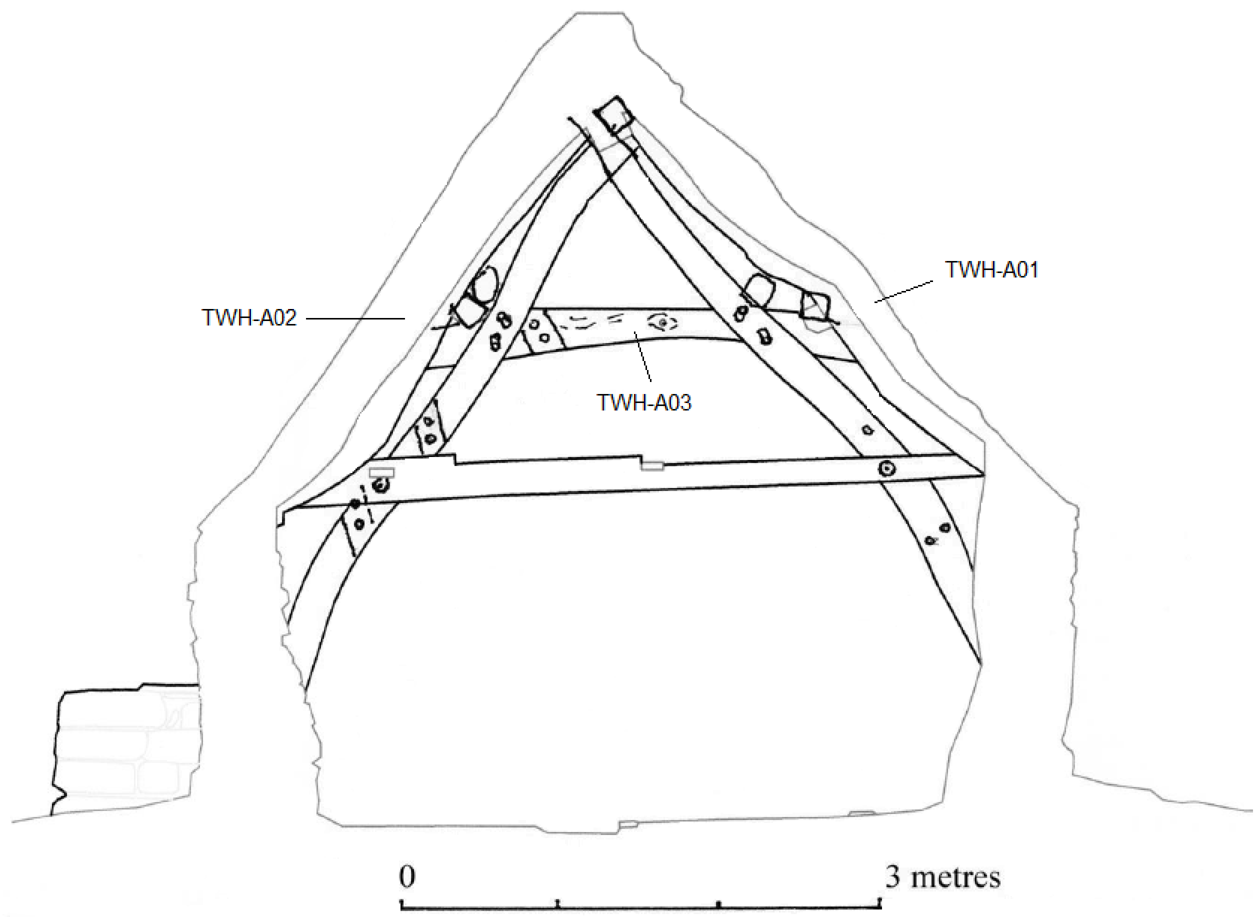


Figure 4: Truss 1 (north-west face), showing the location of samples TWH-A01–03 (Ryder 2011)

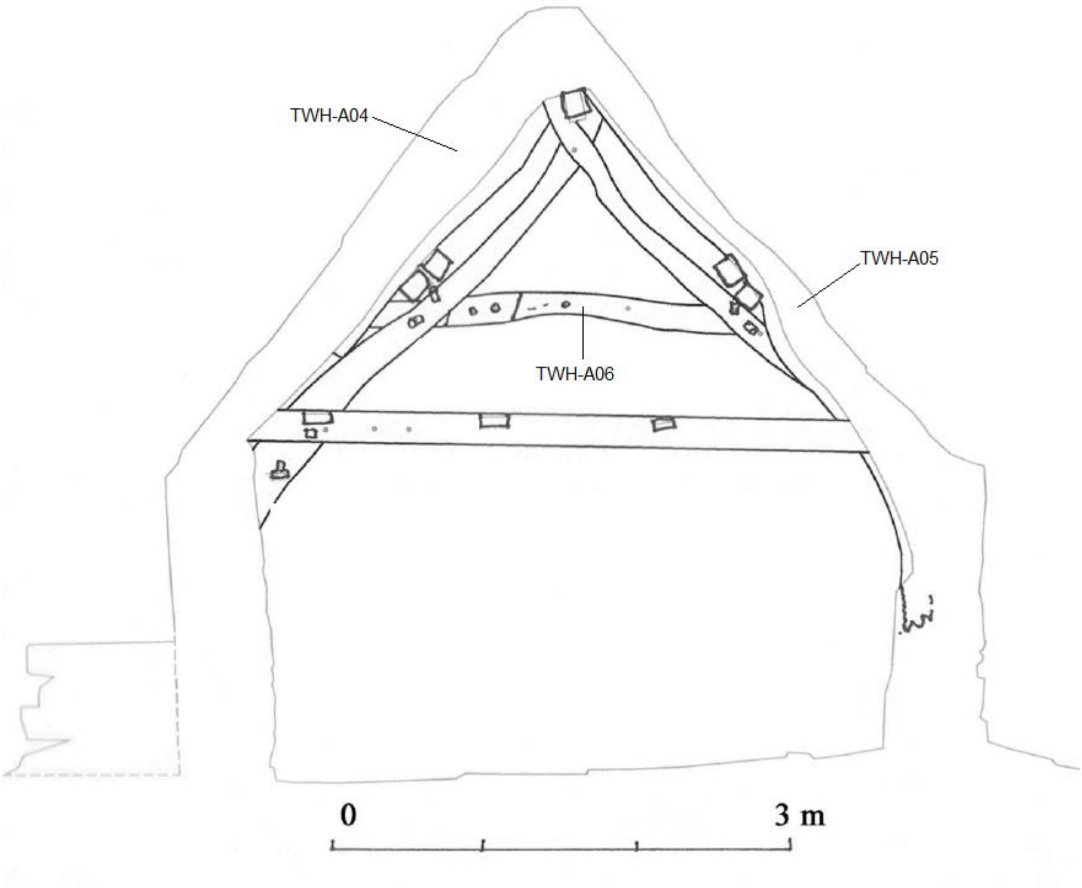


Figure 5: Truss 2 (north-west face), showing the location of samples TWH-A04 and TWH-A05 (Ryder 2011)

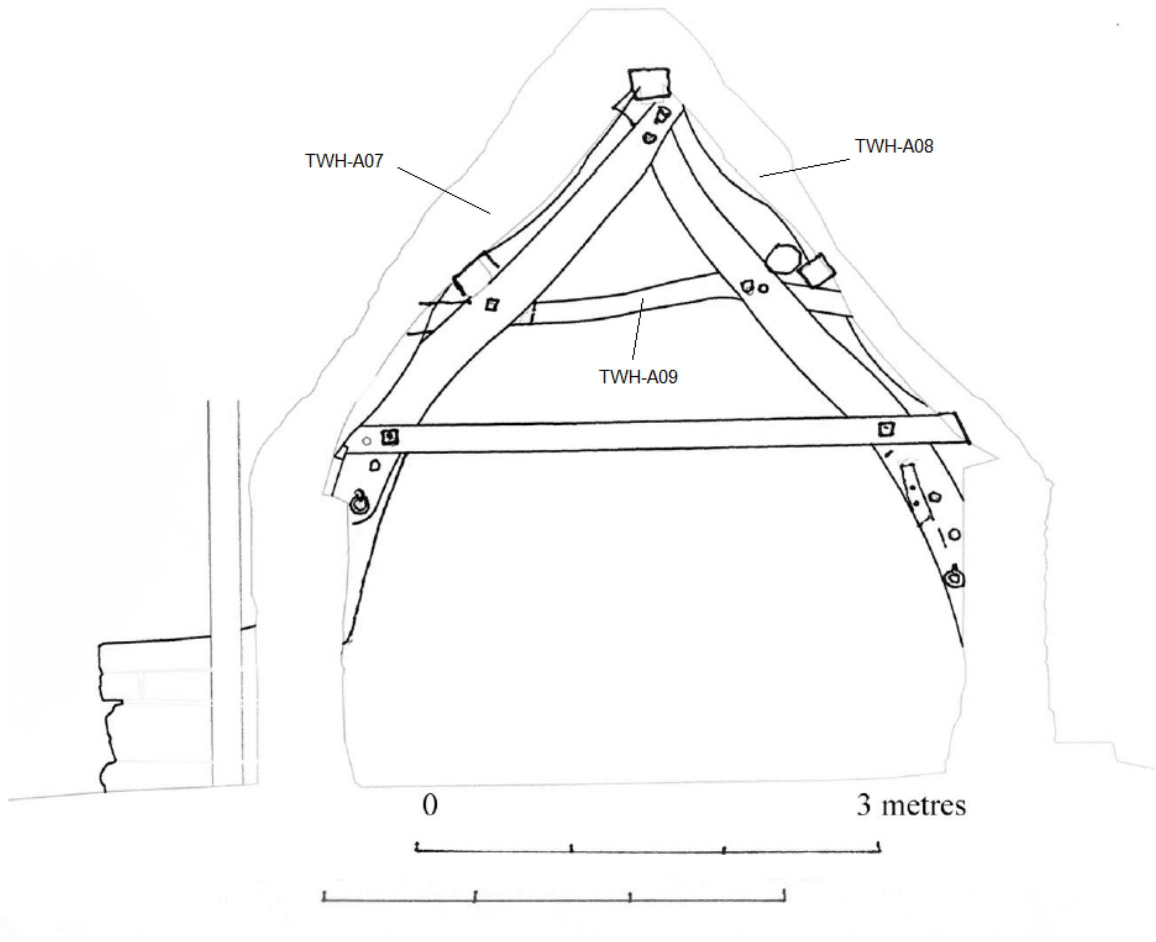


Figure 6: Truss 3 (north-west face), showing the location of samples TWH-A07–09 (Ryder 2011)

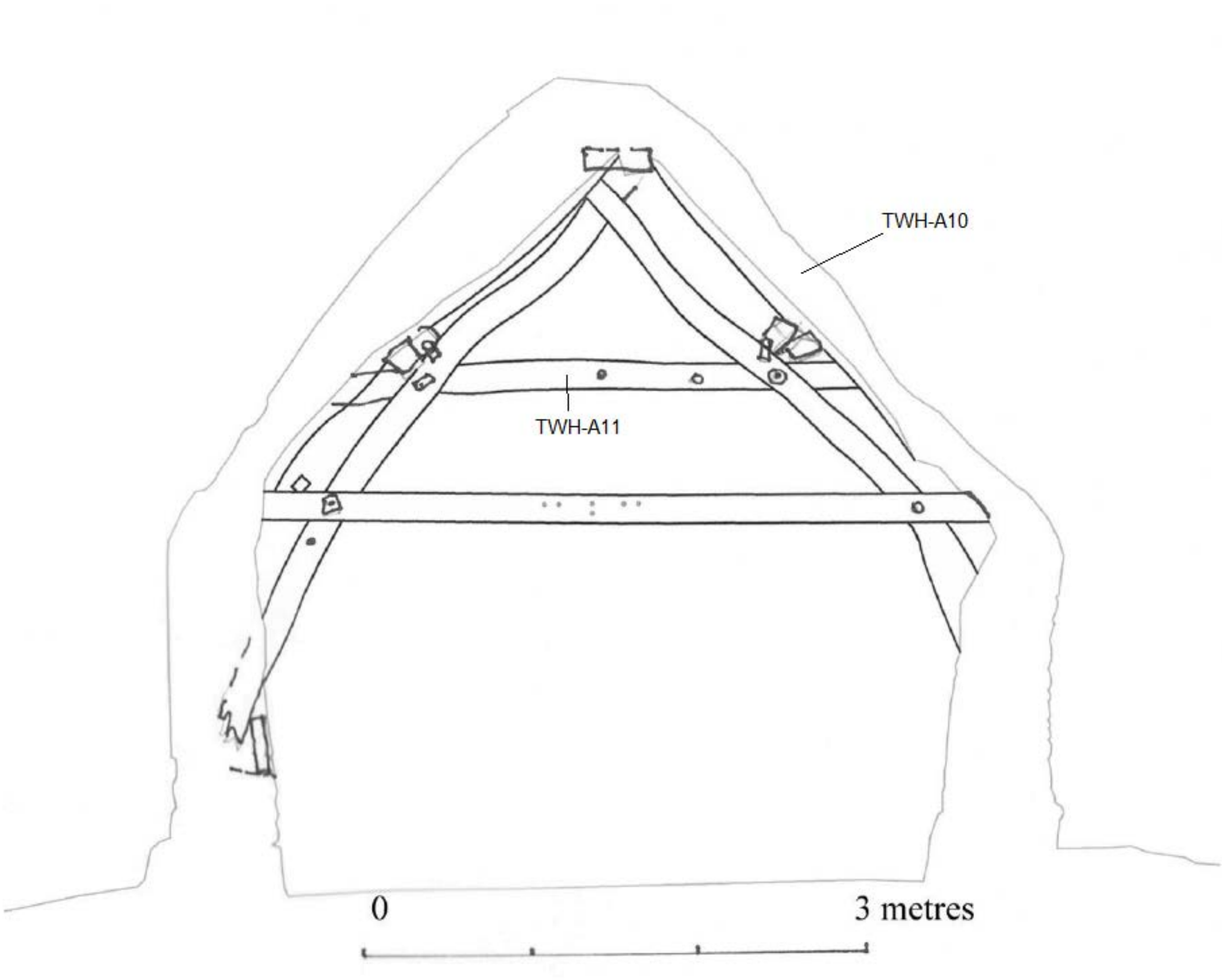


Figure 7: Truss 4 (north-west face), showing the location of samples TWH-A10 and TWH-A11 (Ryder 2011)

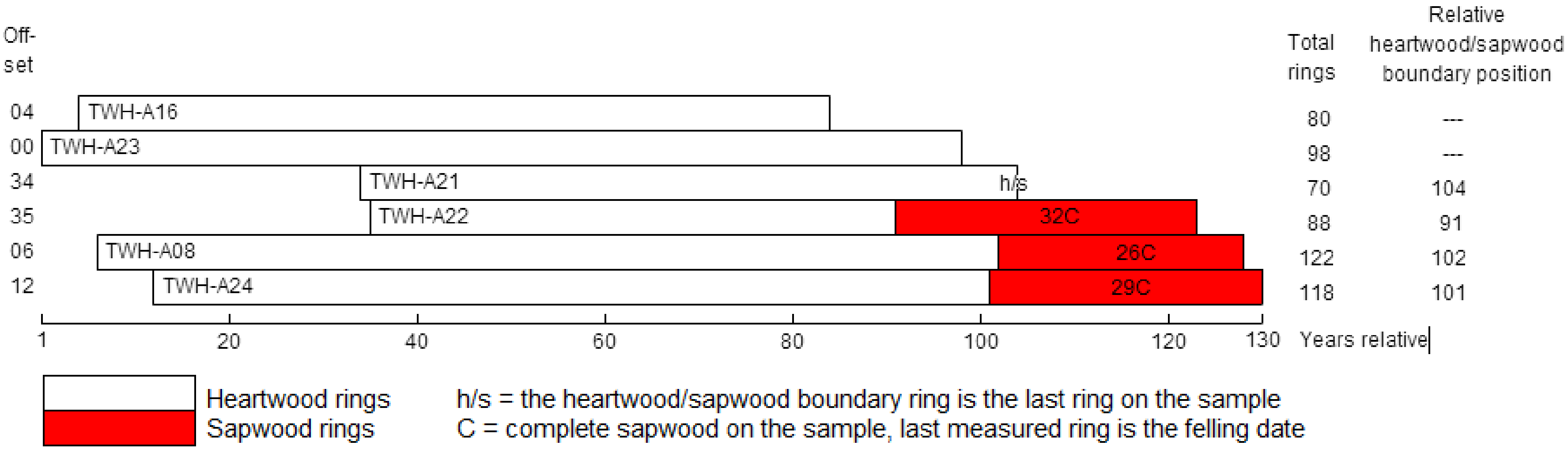


Figure 8: Bar diagram of samples in undated site sequence TWHASQ01

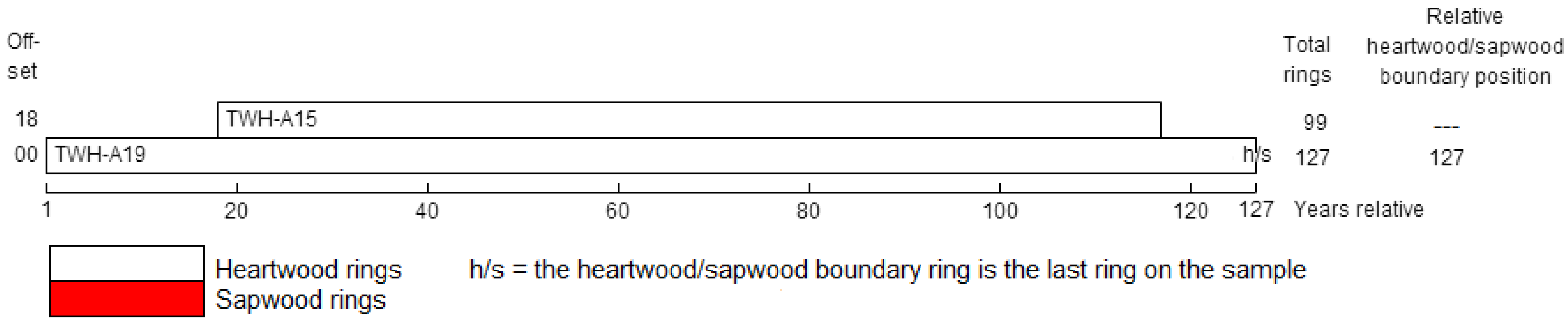


Figure 9: Bar diagram of samples in undated site sequence TWHASQ02

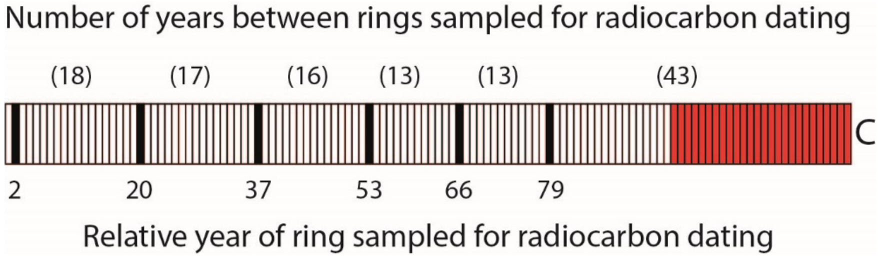


Figure 10: Schematic illustration of sample TWH-A08 to locate the single-ring sub-samples submitted for radiocarbon dating (red = sapwood rings; C = complete sapwood)

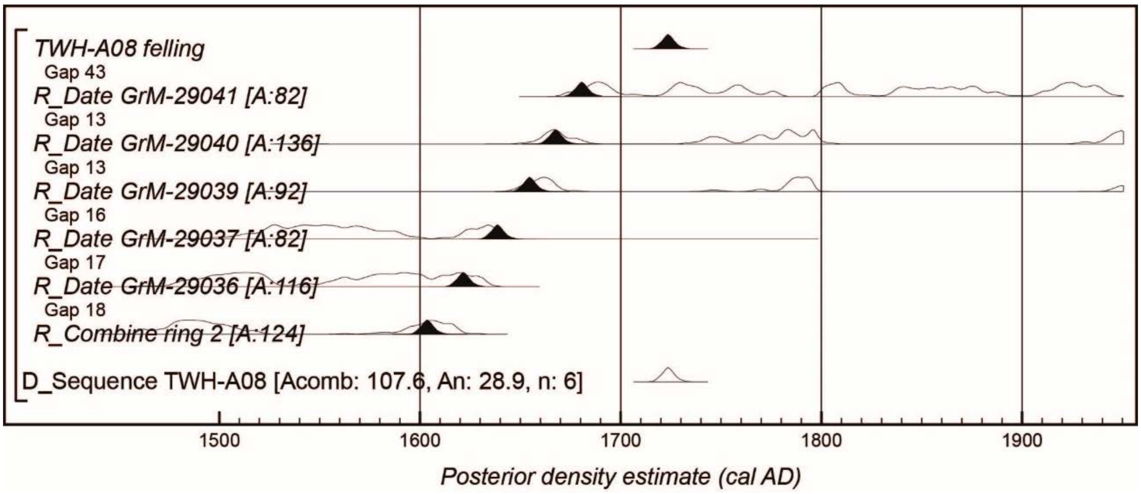


*Figure 11: Probability distributions of dates from sample TWH-A08. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution '*TWH-A08 felling*' is the estimated date when the tree which produced timber TWH-A08 was felled. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly*

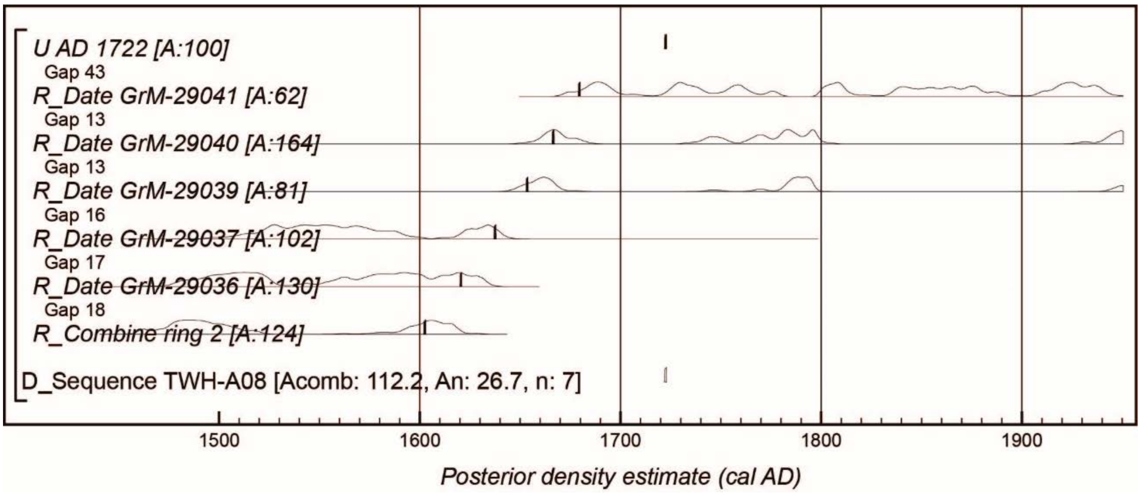


Figure 12: Probability distributions of dates from TWH-A08, including the tentative date produced by ring-width dendrochronology for the formation of the last ring in AD 1722. The format is identical to that of Figure 11. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

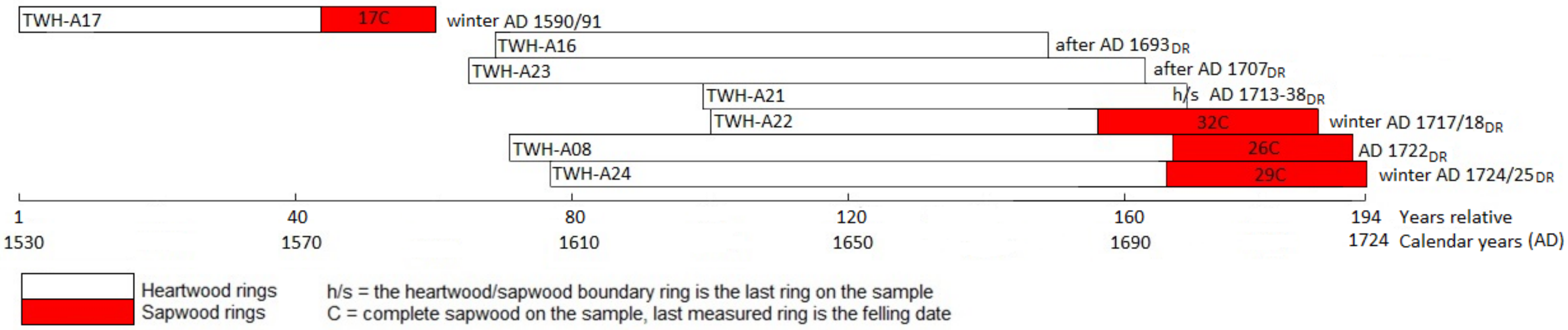


Figure 13: Bar diagram showing radiocarbon-supported dendrochronological dates (AD_{DR}) of samples in site sequence TWHASQ01, and the independent tree-ring date (AD) of sample TWH-A17

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units
TWH-A01A 60
266 455 312 453 275 381 380 442 397 400 453 309 213 90 107 168 217 197 179 272
293 377 393 325 303 234 224 342 233 199 134 74 78 87 54 89 180 281 284 130
132 110 124 133 168 228 208 296 345 442 388 384 182 154 166 175 93 135 123 85
TWH-A01B 60
259 464 313 460 326 367 398 447 392 379 417 301 203 97 100 166 222 193 183 271
298 381 393 324 294 245 233 354 244 185 138 75 81 84 59 86 169 294 286 127
139 108 117 133 173 228 207 295 343 436 394 384 186 158 172 158 97 127 120 79
TWH-A02A 156
143 180 173 165 174 144 180 119 131 131 159 127 108 111 104 71 79 75 119 85
73 70 77 109 99 121 61 71 76 98 117 94 78 91 76 87 88 85 92 102
72 98 73 68 63 110 82 99 88 76 84 83 111 71 75 49 78 75 105 59
56 66 65 95 72 110 101 113 129 106 103 84 90 60 90 52 71 90 70 66
54 52 66 49 81 71 82 87 84 66 98 98 74 72 47 80 87 84 65 64
92 102 81 65 96 116 87 89 94 89 80 73 75 69 71 86 84 97 94 93
73 71 74 73 46 84 65 90 79 76 99 100 88 106 113 107 76 70 52 78
106 63 81 51 68 68 78 77 78 72 40 53 78 82 92 88
TWH-A02B 156
151 172 172 173 171 148 160 112 127 141 152 130 98 106 99 61 80 72 115 90
71 72 82 97 105 122 57 73 81 97 119 90 74 94 69 89 87 84 99 110
71 95 78 67 63 112 86 89 88 76 74 95 108 68 71 57 65 84 89 66
62 64 62 93 71 113 108 120 135 110 103 90 95 66 82 52 74 84 77 64
49 53 65 56 80 67 82 86 82 68 100 93 75 63 50 76 86 83 66 85
83 98 78 72 90 105 85 96 84 92 77 68 81 63 73 86 85 92 98 83
79 71 70 80 46 82 61 95 77 74 97 101 89 108 104 103 85 63 58 72
108 57 85 50 70 65 74 81 78 78 44 50 81 78 93 85
TWH-A03A 90
270 347 372 318 412 212 198 230 232 259 126 132 208 268 258 231 223 155 123 103
122 127 174 204 154 181 159 158 118 86 96 84 92 68 60 78 73 42 47 67
44 61 83 108 110 85 89 70 52 50 77 71 123 162 162 124 131 189 165 183
222 193 164 190 76 112 89 87 98 77 96 78 58 69 96 90 127 113 139 180
135 127 104 83 94 153 138 124 174 166
TWH-A03B 90
258 351 365 321 404 209 200 231 230 266 119 133 194 272 260 237 233 140 122 100
94 128 173 224 158 176 152 147 125 84 99 82 100 62 65 74 63 54 49 66
43 64 91 104 114 72 97 66 54 51 69 74 122 161 168 124 123 200 168 183
217 192 164 191 84 107 96 74 100 85 95 67 77 61 93 89 130 101 137 186
140 131 100 84 92 156 144 184 147 177
TWH-A07A 72
271 504 395 361 260 258 256 246 285 232 281 222 203 178 165 169 175 200 249 137
127 104 90 96 108 130 136 150 158 132 167 153 186 166 151 174 55 34 36 22
27 42 44 28 46 57 73 67 46 42 32 41 41 39 49 36 49 41 47 41
36 61 61 68 46 52 51 51 78 60 73 53
TWH-A07B 72
291 505 389 367 249 266 261 255 291 272 251 220 208 181 166 165 179 203 247 148
118 106 97 89 111 121 141 154 157 155 166 153 180 169 154 165 56 35 31 22
25 49 33 32 45 59 71 64 50 39 36 43 45 40 51 36 52 40 42 43
39 59 55 69 48 50 45 50 78 67 64 53
TWH-A08A 122
279 263 269 189 140 183 219 187 200 234 204 239 215 205 284 228 247 293 294 301

144 85 99 127 139 121 104 72 98 102 116 78 44 40 45 51 73 110 76 84
84 70 84 87 94 139 135 97 55 58 67 88 108 72 82 95 85 92 81 94
80 111 123 93 102 84 77 86 90 99 85 88 101 86 87 79 96 101 96 87
66 114 129 40 36 49 48 48 39 47 55 55 59 62 57 70 59 55 58 48
55 54 35 41 30 24 25 27 15 25 29 23 26 27 19 19 23 24 19 21
20 26
TWH-A08B 122
272 255 282 193 146 185 224 187 198 246 200 233 222 200 270 246 251 276 299 302
149 89 99 129 138 124 100 75 97 102 98 78 44 39 44 39 79 118 76 78
83 75 88 91 95 137 128 101 58 59 65 84 109 70 87 93 85 92 81 94
80 111 123 97 95 86 88 97 99 109 81 82 98 92 90 84 94 97 105 80
76 122 134 40 37 50 51 44 37 52 57 51 60 60 65 65 62 59 56 42
49 65 31 46 27 24 21 20 22 22 25 24 24 18 17 21 23 22 26 26
22 26
TWH-A09A 88
82 147 207 143 189 219 214 273 224 195 210 177 112 103 104 138 103 88 76 41
78 91 72 80 94 139 148 116 95 96 52 86 114 140 199 189 150 175 223 134
119 72 99 128 114 128 148 145 133 158 130 138 98 115 84 120 85 81 94 100
169 89 70 69 65 55 53 65 93 151 72 140 96 45 41 63 65 106 90 68
66 63 82 65 127 117 100 77
TWH-A09B 88
58 174 215 151 194 198 210 274 220 193 215 182 127 127 127 169 108 88 78 34
87 84 82 68 101 132 141 130 95 100 44 94 107 142 199 170 162 177 219 136
117 63 110 135 108 134 160 148 128 159 119 146 99 113 86 113 94 75 100 94
165 98 56 85 53 45 73 49 106 188 82 129 108 60 35 55 76 84 90 60
73 68 82 70 122 117 91 68
TWH-A11A 88
538 735 407 468 359 236 257 233 224 177 201 172 221 244 194 151 103 135 143 119
126 144 138 163 163 178 260 359 377 207 208 212 185 155 129 109 89 56 55 92
106 109 70 95 161 62 75 78 57 74 55 43 45 67 60 57 66 66 83 77
84 67 36 59 58 87 91 60 42 38 40 46 62 61 55 59 75 111 87 51
93 95 101 134 82 35 49 51
TWH-A11B 88
516 734 406 459 360 246 252 229 224 180 195 175 214 245 197 145 99 128 151 118
121 145 132 139 155 185 261 356 380 207 211 210 184 160 126 78 72 50 65 96
132 116 95 108 171 78 81 71 58 53 42 43 38 54 50 49 62 56 79 70
63 76 45 51 68 95 83 63 42 43 43 52 50 65 55 60 76 108 91 53
90 90 106 135 80 28 41 47
TWH-A12A 55
100 46 89 143 197 303 106 211 224 228 184 166 178 154 171 185 135 91 103 158
143 123 185 149 154 199 128 181 187 120 151 189 171 198 209 199 115 109 157 178
169 188 157 145 204 162 150 99 113 87 77 131 193 206 122
TWH-A12B 55
110 52 77 138 200 309 103 245 226 231 185 152 181 153 178 183 136 88 96 163
147 127 176 142 153 190 133 175 195 130 150 193 166 213 215 192 107 101 141 166
175 182 156 143 203 162 150 98 119 92 84 122 188 213 151
TWH-A13A 55
155 101 87 121 132 92 81 94 121 113 111 84 75 81 111 123 144 156 168 237
227 228 217 145 115 94 101 71 154 143 156 120 114 97 61 102 76 59 52 44
30 37 28 31 32 36 29 27 23 26 16 21 22 30 37
TWH-A13B 55
157 107 92 122 130 93 70 96 117 110 114 78 77 79 117 117 141 155 152 228
208 240 221 150 106 101 100 74 159 138 137 136 125 81 74 90 87 55 48 49

32 31 27 29 35 37 33 24 20 23 19 24 31 32 43
TWH-A14A 53
194 138 212 259 248 231 146 139 145 148 154 155 91 132 181 233 220 181 174 108
135 99 97 106 117 141 72 83 147 97 118 95 90 48 52 48 46 54 49 60
71 48 45 50 60 53 101 101 110 91 116 132 89
TWH-A14B 51
232 123 190 183 129 189 276 260 217 138 109 129 110 144 152 98 101 181 172 173
163 159 110 130 90 83 86 104 117 84 70 151 104 111 93 107 50 47 50 57
52 56 71 67 55 65 58 49 62 88 116
TWH-A15A 99
155 146 113 97 88 116 150 186 77 72 93 120 123 149 102 122 137 139 172 98
79 78 115 91 109 114 91 88 72 87 84 100 93 75 84 83 116 70 88 81
83 64 75 75 58 75 72 70 59 58 64 80 98 149 120 84 138 164 153 150
148 133 95 82 75 86 73 71 55 44 62 71 42 35 32 51 50 51 39 59
40 54 77 57 59 70 34 53 104 90 81 66 86 67 73 42 47 35 54
TWH-A15B 99
156 147 118 87 94 118 147 181 88 57 100 119 122 152 109 117 129 149 166 100
81 77 109 86 111 120 86 95 63 97 76 105 89 79 76 93 105 87 75 92
72 71 71 78 65 67 76 64 59 59 60 80 104 150 113 81 141 152 142 137
138 134 93 64 69 91 68 68 59 36 55 83 35 32 37 47 49 57 43 42
36 55 80 61 66 72 31 53 103 102 76 75 82 74 72 40 48 33 59
TWH-A16A 80
170 180 103 63 48 71 55 65 54 53 60 83 66 58 53 80 113 76 120 117
119 139 49 37 56 53 47 48 41 42 49 75 76 68 34 39 23 27 29 53
23 45 38 42 49 48 53 82 82 82 84 75 59 42 21 21 19 20 22 30
31 47 38 45 81 80 76 71 96 217 114 166 70 130 139 163 127 95 215 159
TWH-A16B 80
171 178 107 55 42 89 45 66 71 40 57 85 62 61 53 75 115 76 125 114
114 134 46 37 53 54 50 48 38 41 55 69 80 66 33 38 26 30 32 46
23 49 38 39 50 49 58 75 82 83 80 76 58 33 29 24 16 18 29 23
31 46 41 46 77 79 70 79 94 197 115 165 70 129 141 158 115 81 239 169
TWH-A17A 61
215 203 280 351 452 385 555 523 475 287 294 254 174 168 184 225 174 89 146 144
199 172 184 168 230 269 105 92 92 151 127 106 116 98 101 76 66 95 125 150
172 129 107 115 128 114 75 75 82 126 115 91 78 104 104 169 177 166 164 158
61
TWH-A17B 61
206 184 294 285 402 403 512 446 335 279 285 250 185 170 191 245 177 93 143 143
194 177 181 169 233 268 111 88 93 151 125 107 116 96 100 74 71 92 126 152
165 130 106 115 131 108 74 70 94 114 127 65 83 98 123 146 180 161 161 157
100
TWH-A18A 57
282 248 207 114 86 93 143 181 162 133 161 138 230 307 211 199 160 109 177 216
333 181 229 176 83 55 56 45 46 43 51 54 59 68 84 92 74 152 134 111
153 163 88 100 96 152 170 164 160 122 132 132 165 158 153 120 154
TWH-A18B 57
272 244 210 114 80 99 137 159 175 133 177 138 222 307 210 224 204 167 285 295
380 203 249 155 94 56 58 47 40 46 47 46 74 56 75 78 90 118 116 96
120 116 86 87 72 109 132 128 148 130 149 138 180 165 180 128 148
TWH-A19A 127
193 208 139 148 184 207 222 213 160 196 63 65 58 62 90 134 139 155 208 277
207 177 163 177 227 296 157 86 157 178 205 214 159 156 172 185 216 171 103 84
136 113 149 146 126 104 83 112 104 132 118 116 101 121 124 104 107 119 99 96

96 97 72 84 89 87 67 71 77 103 105 112 94 86 75 121 122 127 133 142
106 98 112 124 112 92 81 70 89 99 56 45 31 42 41 60 46 63 53 54
75 62 59 67 52 59 73 86 61 62 56 51 59 43 46 35 33 37 37 37
34 26 31 32 27 34 39
TWH-A19B 105
180 190 161 148 176 212 230 218 164 183 58 71 54 59 101 130 142 176 213 298
207 176 166 178 228 284 154 97 156 185 201 209 159 162 187 186 211 141 98 113
134 105 137 144 119 108 81 110 105 142 119 115 103 121 124 100 112 119 90 81
105 88 82 83 93 78 71 69 81 89 95 108 89 75 89 100 120 112 133 130
106 89 98 103 89 84 67 62 81 78 59 42 35 54 53 71 73 75 56 65
76 71 67 61 48
TWH-A20A 61
93 93 118 83 113 95 151 115 171 141 198 179 140 163 198 266 287 273 303 322
223 211 189 132 135 139 105 97 115 89 78 102 87 57 80 94 128 119 82 79
54 37 18 13 14 17 34 30 77 108 94 108 116 88 78 64 69 111 121 98
76
TWH-A20B 61
85 99 111 95 107 96 152 112 180 136 216 200 195 184 271 219 333 321 335 299
228 164 176 110 119 145 137 99 119 93 117 117 87 66 84 93 113 119 88 80
57 32 16 16 16 19 33 31 77 112 91 108 117 86 81 65 68 112 123 94
82
TWH-A21A 69
70 49 44 39 35 31 41 41 52 68 31 29 45 31 56 49 70 123 107 123
91 69 60 57 90 64 67 77 55 57 64 75 74 107 184 184 222 187 157 134
136 264 104 160 170 150 113 81 116 100 139 64 84 133 114 152 91 118 112 167
152 80 94 103 133 84 91 49 49
TWH-A21B 70
87 34 39 42 39 30 37 43 61 59 24 35 53 28 48 48 77 121 102 131
88 75 56 58 80 62 75 75 58 57 63 80 67 114 185 186 215 185 157 138
138 240 117 185 197 164 126 74 127 98 134 63 82 141 114 156 90 121 112 166
150 81 98 97 131 89 86 50 56 55
TWH-A22A 88
25 33 26 25 22 23 22 32 44 34 28 25 29 36 27 38 82 60 78 52
40 28 27 32 45 41 44 68 65 54 97 63 109 117 105 77 77 76 76 78
131 80 129 168 114 83 68 83 92 119 83 59 135 123 208 103 170 164 246 228
108 99 109 132 74 68 44 35 29 22 17 28 19 25 25 32 24 18 14 15
25 22 23 15 22 13 16 30
TWH-A22B 88
31 32 29 25 25 22 21 32 45 35 22 27 31 39 26 41 80 61 74 52
43 30 22 37 38 45 46 68 68 51 88 70 93 121 93 79 79 78 74 80
133 76 123 184 120 85 70 85 74 125 86 58 141 118 220 103 174 163 244 231
111 94 107 129 83 67 28 39 33 27 17 27 28 21 25 21 23 14 20 25
23 27 23 12 27 20 20 22
TWH-A23A 98
359 304 333 258 264 365 159 97 169 225 216 286 283 250 186 186 138 108 105 93
92 77 83 98 98 106 87 55 83 66 73 81 76 71 77 73 40 40 25 28
32 35 42 59 49 47 66 35 48 51 33 63 61 45 42 46 40 50 79 66
69 71 69 74 69 56 62 49 56 63 87 66 105 125 120 106 120 133 138 112
108 93 110 107 128 98 88 115 104 72 78 111 90 89 80 64 83 88
TWH-A23B 98
360 302 329 270 272 357 165 91 172 224 240 300 307 230 172 176 143 107 106 100
83 84 78 97 109 107 81 55 85 67 78 75 75 65 78 80 45 38 31 32
26 38 47 56 36 43 75 33 41 54 35 62 62 49 42 39 39 57 73 71

64 70 74 70 63 63 66 51 55 58 72 73 111 122 113 106 128 126 141 98
108 84 104 103 122 102 85 118 108 72 75 113 88 88 84 59 78 77
TWH-A24A 118
189 150 65 78 63 90 90 105 92 48 54 59 69 84 71 66 72 73 80 73
70 69 73 80 59 60 45 51 57 50 61 111 62 73 73 50 65 75 62 83
91 78 47 40 37 41 64 58 61 67 72 79 68 79 85 109 157 124 141 116
138 141 130 145 110 111 128 115 114 92 111 112 133 129 106 150 128 104 101 144
138 161 150 100 86 82 80 60 68 67 59 50 30 32 31 37 31 33 28 24
23 59 49 35 26 23 30 24 19 22 20 24 28 23 25 23 27 30
TWH-A24B 118
189 152 64 79 62 87 94 105 89 45 59 60 65 87 67 70 71 73 78 76
70 64 75 81 55 67 47 46 58 52 54 117 52 76 70 55 66 70 60 92
88 80 47 41 35 36 64 60 56 69 73 82 68 84 79 107 156 129 135 113
128 132 118 137 94 108 123 121 123 93 107 109 123 120 104 133 130 106 99 145
143 162 153 88 87 85 82 59 64 66 52 55 36 31 29 30 34 29 31 31
26 52 44 37 32 30 28 32 30 26 23 21 24 25 23 21 34 37

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer

rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

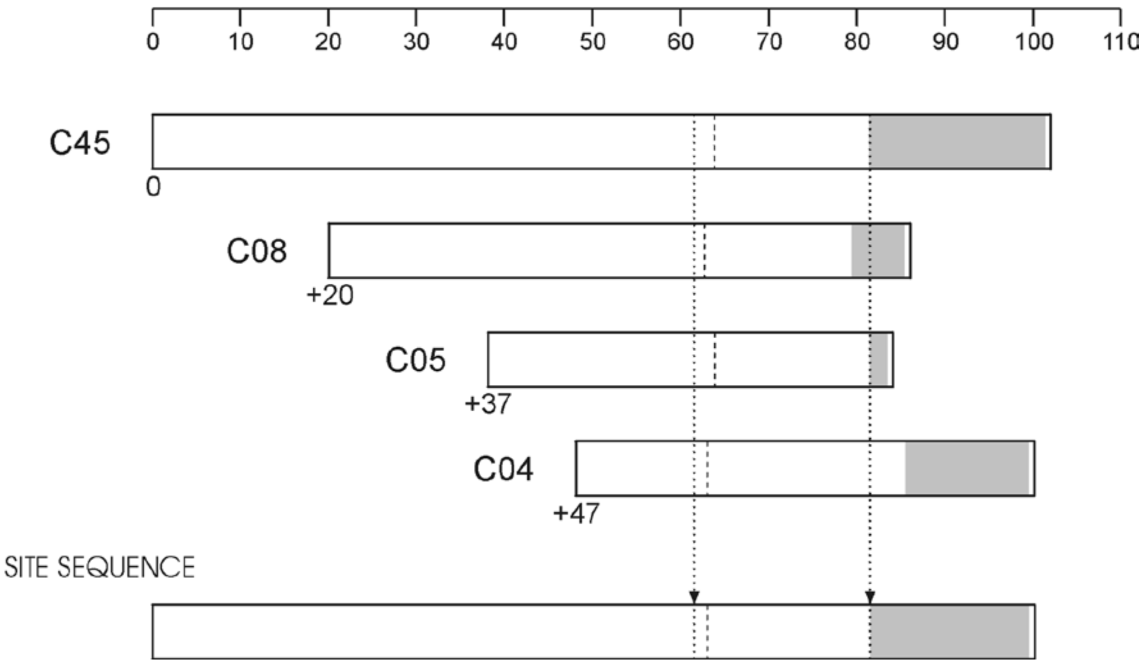


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

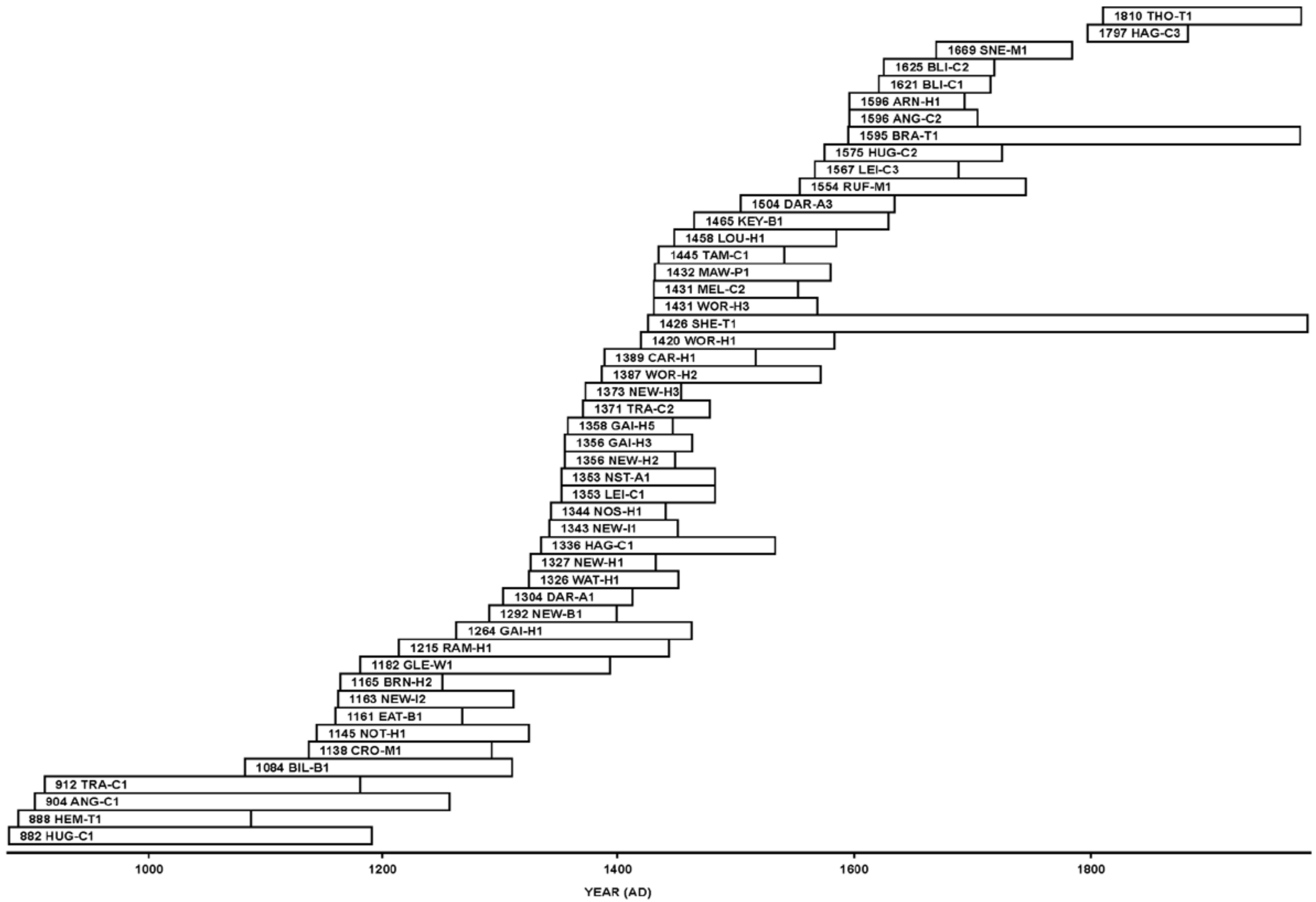
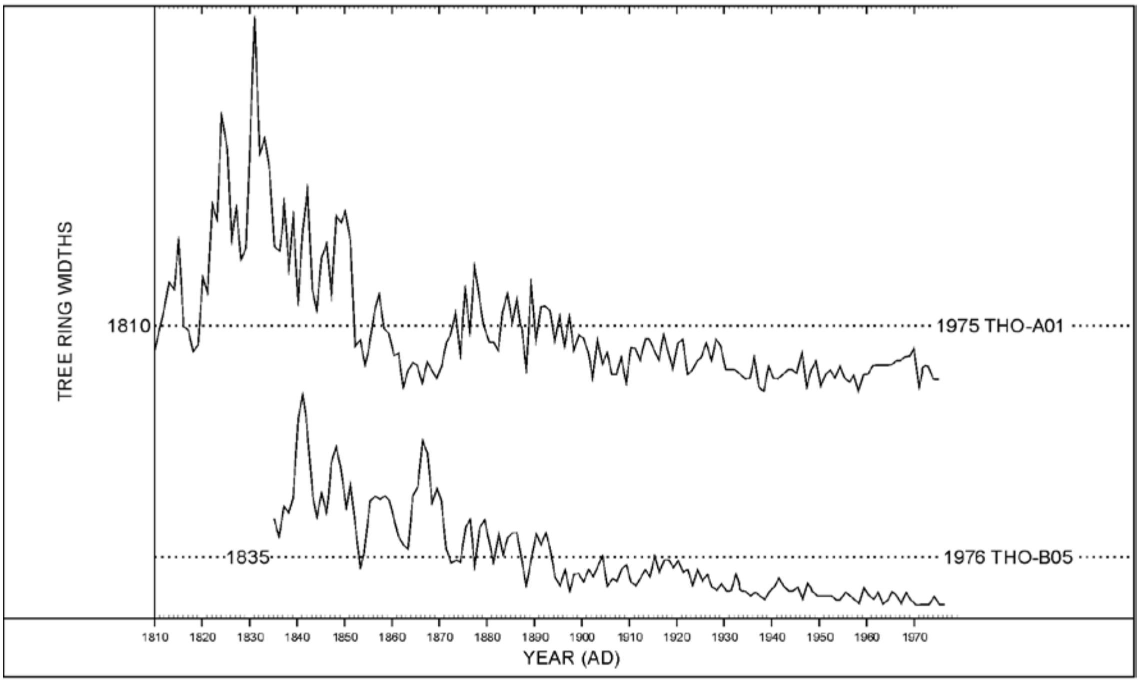


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

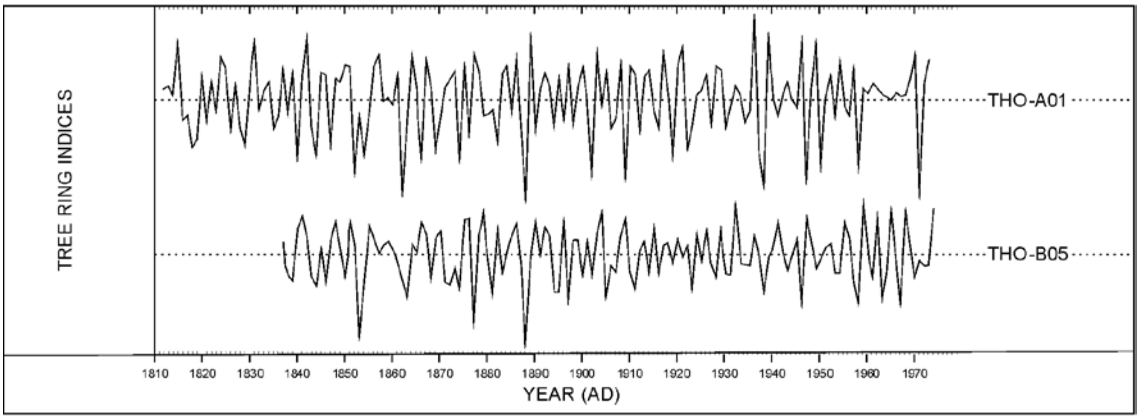


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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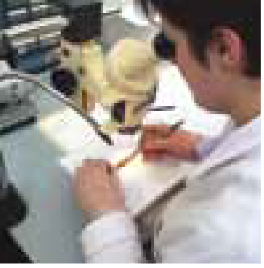
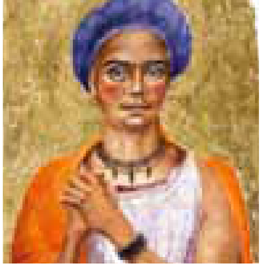


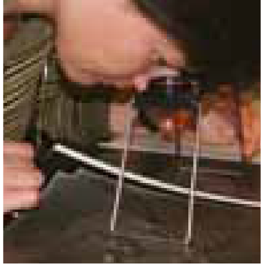


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