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Oughtibridge Hall, Oughtibridge Lane, Bradfield, South Yorkshire

Tree-ring Analysis, Radiocarbon Wiggle-matching and Oxygen Isotope Dendrochronology of Oak Timbers

Alison Arnold, Robert Howard, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, Lukas Wacker, Neil J Loader, Danny McCarroll, Darren Davies, Giles HF Young, and Daniel Miles

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Front Cover: Oughtibridge Hall. Photograph by Robert Howard

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SUMMARY
Tree-ring analysis was undertaken on cores from 41 of the 51 timbers sampled, these timbers being associated with the hall range, east and west cross-wings, and an outbuilding at Oughtibridge Hall. This analysis produced four site chronologies accounting for 28 samples: two of these were dated by ring-width dendrochronology, a third by radiocarbon-supported oxygen isotope dendrochronology, and the fourth remains undated. A total of 13 measured samples remain both ungrouped and undated.

No samples could be dated from timbers associated with the primary construction of the open hall and east cross-wing. Interpretation of the sapwood and the heartwood/sapwood boundary on the 26 dated samples show that a group of eight timbers from the primary construction phase of the west cross-wing were felled in the late-sixteenth century, that the re-roofing of the hall and east cross-wing is likely to have taken place shortly after AD 1707 (although there may have been further modifications in the roof of the east cross-wing a few years later, and the roof over the hall includes at least one reused timber), and that the outbuilding in the driveway contains timbers felled in the early seventeenth and the early nineteenth centuries.

CONTRIBUTORS
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ARCHIVE LOCATION
Historic England Archive
The Engine House
Fire Fly Drive
Swindon SN2 2EH

HISTORIC ENVIRONMENT RECORD
South Yorkshire Historic Environment Record
South Yorkshire Archaeology Service
City Growth Service
Howden House
1 Union Street
Sheffield S1 2SH

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INTRODUCTION

The Grade II listed Oughtibridge Hall (LEN 1314571 https://historicengland.org.uk/listing/the-list/list-entry/1314571) lies to the eastern edge of Oughtibridge, which is itself approximately 8km north-west of Sheffield (Fig 1). This complex includes a number of associated farm buildings but is centred on the original house which, along with an outbuilding of potential historic interest, is the focus of this investigation (Fig 2).

The following information is summarised from Jones (1994 unpubl). Although the building runs broadly north-east to south-west, for the purposes of this report it has been deemed to run east–west. The central hall, running east-west, with cross-wings at either end forms an H-plan house (Figs 2 and 3). The extant two-bay central open hall range and three-bay east cross-wing are thought likely to be coeval and represent the primary construction phase, which is thought to date to around AD 1400. The west cross-wing is thought to be a later addition, potentially dating to the second half of the sixteenth century, and was distinctive in having a stone-built ground storey surmounted by an upper storey of timber framing. It is thought that this later cross-wing replaced one or more bays of the original open hall range. The primary roofs over the hall and east cross-wing, possibly of crown-post or king-post form, were subsequently replaced, this potentially coinciding with other seventeenth-century alterations which included the encasing of the timber framing in stone, the insertion of a floor in the open hall, and the provision of a large chimney-hood and hearth at a central point. Further improvements included a lateral chimney-stack added to the east wing and the addition of a small extension to the east of the east cross-wing. The extension to the west of the west cross-wing was formerly a barn probably dating to the eighteenth or nineteenth century. Further, more recent, alterations have seen the removal of the central hearth and stack and the insertion of a new staircase and new windows.

Although timber framing at the upper-storey level of both the hall range and east cross-wing has been exposed during recent repair and conservation works, there is, as Jones (ibid) indicated, little surviving original timber in the hall and nothing in the east cross-wing above tiebeam level. The central tiebeam truss, truss 7, of the hall range has moulded braces forming an open semi-circular arch with spandrel struts. The tiebeam, braces, and wall posts form the constituent parts of the primary-phase truss. The principal rafters are from the re-roofing phase and the apex of this truss, above the collar, is filled with close-set studs and plaster of potentially post-medieval date (Fig 4a). At the west end of the hall range, the tiebeam, wall posts, and arch braces remain of the former closed truss, truss 8, but the principal rafters, purlins, ridge beam, and possibly a 'collar', are again from the re-roofing phase, although the 'collar' may be a reused older timber (Fig 4b). Truss 6 at the east end of the hall appears to have entirely disappeared above wall plate/tiebeam level, with a number of the lower wall timbers also possibly having been replaced at some later date, along with the wall plate. The extant hall range roof trusses carry single purlins to each pitch of the roof, with the ridge beam being diamond set.

The present roof to the east wing comprises three central trusses of principal-rafter with tiebeam form, the trusses again carrying single purlins to each pitch. The ridge is also set diamond fashion. The extant trusses are not uniformly spaced.

The four trusses of the west cross-wing are of principal-rafter and tiebeam type, each apparently filled from floor to apex with close-set studding, presumably with openings for doorways (Fig 4c). Although some of the stud infill has been removed, a substantial quantity of timbering still remains.

In addition to the main building, there is a further stone-built structure to the driveway (Figs 2 and 4d) of which little is known. This comprises a simple three-bay building with two king-post trusses along with purlins, wall plates, and bridging beams. It would appear that these timbers are potentially of different dates to each other, some clearly showing evidence of reuse and a variety of redundant joints and mortices.

TREE-RING SAMPLING

Dendrochronological analysis was requested by Nicola Wray, Historic England Listing Adviser, with the aim of obtaining independent dating evidence to inform a potential listing upgrade. It was hoped that tree-ring analysis would provide a date for the original construction of the open hall and east cross-wing and indicate when the major re-roofing was undertaken, as well as providing more precise dating evidence for the construction of the west cross-wing. In addition, it was hoped to enhance the understanding and significance of the outbuilding.

Thus, from the timbers available, a total of 51 were sampled by coring, each sample being given the code OTI-B (for 'Oughtibridge') and numbered 01–51 (Table 1). All samples were from oak (*Quercus* sp.) timbers. The sampling strategy targeted potentially original timbers and timbers associated with the later re-roofing in both the open hall and the east cross-wing, whereas only apparently original timbers in the west cross-wing were sampled, all timbers here seeming to be of the one original phase of construction. No timbers remain in trusses 1 and 5 in the east wing, the extant end walls being stone, and no samples were obtained from truss 6, many timbers here being both potentially later replacements and unsuitable for ring-width dendrochronology. Samples were also obtained from both primary and reused timbers in the outbuilding to the driveway, the latter of which, it was thought, could potentially represent reused primary-phase timbers from the hall or east cross-wing.

The sampled timbers have been located on annotated photographs, on the plans provided by Historic England from Jones (ibid) or, if necessary, on simple sketch plans made at the time of sampling (Figures 5a–g, 6, and 7).

RING-WIDTH DENDROCHRONOLOGY

Each of the cores obtained from the 51 timbers sampled in the various parts of the Oughtibridge Hall complex was prepared by sanding and polishing. It was seen at this time that 10 samples had fewer than the 40 rings here deemed necessary for reliable dating by ring-width dendrochronology, and they were rejected from this programme of analysis. The annual growth ring-widths of the remaining samples from 41 timbers were, however, measured, these data being given at the end of this report. In one case, OTI-B07, duplicate cores were taken in order to maximise the numbers of growth rings available, and the number of rings on the two core samples are thus different. They do, however, cross-match with a value of t=12.9, and the mean of the two ring-width series was used in subsequent analysis. The 41 series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process resulting in the production of four groups of cross-matching samples.

The first group comprises 13 samples, these being combined at their indicated offset positions to form OTIBSQ01 (minimum t-value of 3.2), a site chronology with an overall length of 201 rings (Fig 8). Site chronology OTIBSQ01 was then compared to an extensive corpus of reference chronologies for oak, this indicating a consistent and repeated match with a series of these when the date of its first ring is AD 1424 and the date of its last measured ring is AD 1624 (Table 2).

The second group comprises five samples, these being combined at their indicated offset positions to form OTIBSQ02 (minimum *t*-value of 3.7), a site chronology with an overall length of 68 rings (Fig 9). Site chronology OTIBSQ02 was also compared to an extensive corpus of reference chronologies for oak, this indicating a consistent and repeated match when the date of its first ring is AD 1745 and the date of its last measured ring is AD 1812 (Table 3).

The third group comprises eight samples, these being combined at their indicated offset positions to form site chronology OTIBSQ03 (minimum *t*-value of 4.6) with an overall length of 56 rings (Fig 10). This site chronology was also compared to an extensive corpus of reference chronologies for oak, but there was no consistent and reliable cross-matching identified and thus, this site chronology must, therefore, remain undated by ring-width dendrochronology.

The fourth and final group comprises two samples, these each being combined at their indicated offset positions to form site chronology OTIBSQ04 (*t*-value of 10.7) with an overall length of 173 rings (Fig 11). This site chronology was again compared to the extensive corpus of reference chronologies, but again there was no consistent and reliable cross-matching identified and again this site chronology must also remain undated.

Each of the 13 remaining measured but ungrouped series were then compared individually with the full corpus of reference chronologies for oak, but again there was no cross-matching, and these individual series must also remain undated by ring-width dendrochronology.

This analysis may be summarised thus;

Site chronology/ sample	Number of Samples	Length	Date span (where dated)
OTIBSQ01	13	201	AD 1424–1624
OTIBSQ02	5	68	AD 1745–1812
OTIBSQ03	8	56	Undated
OTIBSQ04	2	173	Undated
Undated/ungrouped individuals	13	---	---
Unmeasured	10	---	---

RADIOCARBON DATING

Following the failure of the ring-width dendrochronology to provide calendar dating for the well-replicated (eight timbers) but short (56 rings), site master chronology, OTIBSQ03, sample OTI-B10 was selected for radiocarbon dating and wiggle-matching as this was one of the cores with the longest ring sequence (55 annual growth-rings) in this site master chronology (Table 1; Fig 10).

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).

Eleven radiocarbon measurements have been obtained from single annual tree-rings from timber OTI-B10 (Table 4; Fig 12). 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 in 2019–20. 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). The facility maintains a continual programme of quality assurance procedures (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; Table 4).

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 OTI-B10, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 13.

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 v4.3 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figure 13 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).

Figure 13 illustrates the chronological model for OTI-B10. 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 (ETH-96733) was laid down four years before the carbon in ring 5 of the series (ETH-104569; Fig 12), with the radiocarbon measurements (Table 4) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 37.3, An: 21.3, n: 11; Fig 13), with three radiocarbon dates having poor individual agreement (A > 60): ETH-96733 (A:12), ETH-96737 (A: 53), and ETH-10457 (A:43). It suggests that the final ring of OTI-B10 formed in *cal AD 1701–1707 (95% probability; ETH-96739 (felling)*; Fig 13), probably in *cal AD 1702–1706 (68% probability)*.

OXYGEN ISOTOPE DENDROCHRONOLOGY

In addition to the radiocarbon dating and wiggle-matching of core OTI-B10 from site master chronology, OTIBSQ03, two other core samples (OTI-B01 and OTI-B14) from this chronology were selected for oxygen isotope analysis (Fig 14). Oxygen isotope dendrochronology shares many of the fundamental principles, and assumptions, of conventional (ring-width-based) dendrochronology. However, rather than using ring-width measurements it uses the ratio of heavy to light oxygen isotopes (McCarroll and Loader 2004) in the latewood cellulose ($\delta^{18}O$). The isotopes can have a higher signal to noise ratio than ring-width measurements and preservation of a strong dating signal does not require the trees to be growing under any environmental stress (Young *et al* 2015).

The method relies on matching individual isotopic series with others from the same structural phase, and on matching against a regional master chronology (Loader *et al* 2019) that has been constructed using dendrochronologically-dated oak timbers sourced from across a *c* 45,200km^2 (20,000 mile^2) region centred on Oxfordshire, in south-central England. The chronology was developed as part of a Leverhulme Trust funded project (RPG-2014-327) and currently covers a period from AD 1200 – 2000 with annual replication (sample depth) of 10 trees throughout the chronology period.

Of the two core samples selected for oxygen isotope analysis, OTI-B01 comprised 51 measured ring-widths including three sapwood rings, and sample OTI-B14 had 55 measured ring-widths including 15 sapwood rings (Table 1). Sample OTI-B14i had an additional partial ring, consisting of latewood only preserved at the start of the core (pith end). As oxygen isotope analysis only requires preparation of the latewood, it could be excised and prepared for isotopic analysis (ring 0). Where the sample was degraded or showed signs of possible contamination, isotopic analyses were either not attempted or the measured data were excluded from the cross-matching. For OTI-B14 the last complete ring formed (ring 55) was too degraded for a reliable isotopic measurement. Similarly, rings 0–9 of OTI-B01 exhibited cracks which had been glued and marked with ink. As this intervention could be a source of potential contamination for isotopic analysis these rings were excluded from the dating exercise. A total of 42 and 55 rings were measured isotopically for samples OTI-B01i and OTI-B14i respectively (Table 5; see below).

A thin slice (4mm) was removed from the base of the sample cores selected for isotopic analysis to retain the original measured surface and ensure its preservation for future ring-width dendrochronology and archiving.

Several physiological studies of oak trees have shown that the earlywood is partially formed from carbohydrates fixed in previous years (Richardson *et al* 2013; McCarroll *et al* 2017). To avoid this chemical carry-over effect in oak, only the latewood of each tree-ring is prepared for chemical analysis and dating. Each latewood ring is carefully removed as thin slivers (*c* 40μm thick) using a scalpel and dissecting microscope. Wood samples are converted to α-cellulose using an acidified sodium chlorite solution with removal of hemicelluloses by sodium hydroxide (Loader *et al* 1997). Samples are homogenised using an ultrasonic probe and vacuum-dried at −50˚C for 48 hours. 0.30–0.35mg of dry α-cellulose are weighed into individual silver foil capsules for pyrolysis to carbon monoxide (CO) at 1400°C (Woodley *et al* 2012). The resulting carbon monoxide is analysed using a Delta V isotope-ratio mass spectrometer. Duplicate stable isotopic measurements are typically undertaken on aliquots of the prepared cellulose from each ring. Data are expressed as per mille (‰) deviations relative to the Vienna Standard Mean Ocean Water (VSMOW) international standard. Analytical precision is typically 0.30‰ (σ_{n-1}, n=10) (Loader *et al* 2015).

The master chronology used for dating was prepared as two independent pools of five trees to ensure quality control and the resulting data combined to form the ten-tree master chronology. Individual samples for dating are prepared and analysed separately, using identical preparation protocols. The resulting stable isotopic data are presented as chronologies (time series).

Tree-ring oxygen isotope data have statistical properties that are quite different from ring-widths, requiring different pre-treatment. The Baillie-Pilcher filter that works well for ring width dating (Baillie and Pilcher 1973) is not appropriate for isotope data and would result in unrealistically high *t*-values (Loader *et al* 2019). The isotope data are filtered using a simple nine-year rectangular filter, with indices derived by subtraction. Degrees of freedom are corrected for autocorrelation and filtering resulting in *t*-values that conform to a Student's *t*-distribution and can be used to calculate one-tail probabilities of error. The probabilities are corrected for multiple testing by division by the number of possible matches against the master chronology (a 'Bonferroni' correction) (Dunn 1959; 1961). The ratio of probabilities for the first and second highest *t*-values provides an 'isolation factor'. Potential dates are only considered for acceptance when the corrected probability of error is less than one in a hundred and the probability for the best match is more than an order of magnitude less likely to be in error than the next best match. All *t*-values pertaining to isotope data in this report are Student's *t*-values.

Cross-matching between isotope samples is achieved using the same approach, with the number of possible matches determined by setting a minimum size of overlap. Student's *t*-values, corrected one-tail probabilities and the isolation factor are reported as well as the highest correlation coefficient, offset in ring number, and size of overlap.

In isotope dendrochronology it is not always necessary or possible to measure isotopically each tree-ring, in which case the last ring measured isotopically must be placed within the context of the entire sample. This may require addition of years identifiable in the sample, but not measured isotopically. Once a date for the last ring has been calculated, a felling date or sapwood estimate may be assigned using identical methods to those in ring-width dendrochronology (see Appendix).

Results

The oxygen isotope series from OTI-B01i comprises isotopic measurements from 42 rings (ring 10 to ring 51). The series from OTI-B14i comprises isotopic measurements from 55 rings (ring 0 to ring 54). Ring 55 of OTI-B14 did not yield a sample for isotope analysis, and the isotopic measurements from rings 0–9 of OTI-B01 were excluded from the dating exercise as these rings had been glued and marked prior to isotopic analysis. The oxygen isotope measurements from these timbers are listed below.

Oxygen-isotope series OTI-B01i cross-matches with OTI-B14i with an offset of 1 year and overlap of 51 rings (r = 0.744, df = 34, Student's *t* = 6.50; Table 6; Fig 15).

This is consistent with the ring-width cross-matching (Table 1; Fig 10), when accounting for the last ring of OTI-B14 that could not be measured isotopically. A 56-year mean oxygen isotope series (OTI-Bx) was compiled, which, when compared against the south-central England oxygen isotope master chronology (Loader *et al* 2019), produced the strongest cross-matching where the last ring of the mean isotopic series dates to AD 1705 (Table 7; Fig 16). This cross-matching ($r = 0.62$, df = 47, Student's $t = 5.42$, 1/p=1350, IF>1000; Table 7) passes the thresholds for consideration as dated suggested by Loader *et al* (2019). Individually, the oxygen isotope series from these timbers match the reference chronology at positions that are consistent with the suggested dating of the mean isotopic series, but with lower matching statistics (Table 7).

The last ring of the mean oxygen isotope series is ring 55 of site master sequence OTIBSQ03 (Fig 10). The oxygen isotope dendrochronology suggests that this ring formed in AD 1705, and thus that the final ring of OTIBSQ03, ring 56, formed in AD 1706. This dating is clearly compatible with the date estimate for the formation of the ring produced independently by radiocarbon wiggle-matching of *cal AD 1701–1707 (95% probability; ETH-96739 (felling)*; Fig 13), probably in *cal AD 1702–1706 (68% probability)*. When the last ring of OTI-B10 is constrained to have formed in AD 1706, the radiocarbon wiggle-match again has good overall agreement (Acomb: 50.3, An: 26.7, n: 7; Fig 17), with two radiocarbon dates having poor individual agreement (A > 60): ETH-96733 (A:47) and ETH-96735 (A: 15).

Since the levels of the statistical thresholds necessary for oxygen isotopic dating to have equivalent confidence to traditional ring-width dendrochronology are currently uncertain, the dating of the timbers contained in site master sequence OTIBSQ03 are reported as a radiocarbon-supported oxygen isotope dates (denoted by the subscript IR). OTIBSQ03 is dated as spanning AD 1651–1706$_{IR}$ (Fig 18).

INTERPRETATION

Dendrochronological analysis of a series of samples of timbers from the main house and an outbuilding at Oughtibridge Hall has produced four site chronologies, of which two have been successfully dated by ring-width dendrochronology, one has been dated by radiocarbon-supported isotope dendrochronology, and one remains undated. To aid interpretation, the results are presented area by area below and in Figures 8–9 and 18. In each case, where sapwood is not complete (ie the sample does not have the last ring produced before the tree was felled), the estimated felling date is calculated on the basis of the 95% confidence interval for the amount of sapwood the trees are likely to have had which is 15–40 rings.

Hall - re-roofing phase

A single sample, OTI-B11, from a stud post to the apex of the central truss (truss 7) in the open hall, thought to be associated with the re-roofing, has a last measured heartwood ring date of AD 1513 (Fig 7). However, the felling date of the timber represented cannot be determined because, in the absence of the heartwood/sapwood boundary, it has lost not only all of its sapwood rings, but an unknown number of heartwood rings as well. If an allowance is made for the usual minimum number of sapwood rings, a *terminus post quem* date for felling (a felled after date) of AD 1528 is obtained.

Five other samples from both principal rafters of truss 7 and three purlins, all thought to be associated with the re-roofing, are clearly coeval (Fig 18). The presence of complete sapwood on two samples, OTI-B08 and OTI-B10, means that they have the last rings produced by the trees represented before they were felled. These final complete growth-rings formed in AD 1705$_{IR}$ and AD 1706$_{IR}$

respectively, but the presence of spring and partial summer growth on the outside of both timbers means that they were felled respectively in the summer of AD 1706IR and summer AD 1707IR. The relative dates of the heartwood/sapwood boundaries on the other three samples suggest that they were felled as part of the same episode of felling and that all five timbers are coeval with some of the timbers from the re-roofing of the east cross-wing (see below).

East cross-wing - re-roofing

Three samples from two tiebeams and a purlin, all thought to be associated with the re-roofing, are broadly coeval but probably represent more than one episode of felling (Fig 18). The final complete ring of OTI-B02 formed in AD 1705IR, and retains complete sapwood, including spring and partial summer growth of the following year, and thus derives from a tree felled in the summer of AD 1706IR. OTI-B04 also has a last measured ring that formed in AD 1705IR, although as it has incomplete sapwood it must be felled later than this. However, with a heartwood/sapwood boundary date within one year of that of OTI-B02, it appears likely that OTI-B04 was felled only shortly after AD 1705. The tiebeam represented by sample OTI-B01 has a somewhat later heartwood/sapwood boundary ring, formed in AD 1702IR, and was thus probably felled a couple of decades later in AD 1717–42IR.

West cross-wing – primary phase

Eight samples, representing three principal rafters, two wall plates, two wall posts, and a tiebeam, from the west cross-wing were dated (Fig 8). One of these samples, OTI-B32, retains complete sapwood. This last sapwood ring is dated AD 1581, although the presence of the spring and partial summer growth of the following year suggests that it was felled in the summer of AD 1582. Five of the other samples from the west cross-wing are from timbers which have complete sapwood present. However, due to its soft and fragile nature, part of the sapwood, usually only a few millimetres, was lost from the samples during coring. In each case it is therefore estimated that the small amounts of lost sapwood represent relatively few rings, which, if allowed for, would suggest that these trees were also felled in, or around, AD 1582. The remaining two samples, OTI-B30 and OTI-B31, retain only the heartwood/sapwood boundary. As the date of these heartwood/sapwood boundaries are very similar to the other samples, the entire group having an overall variation of heartwood/sapwood boundary date of 16 years (OTI-B38 at AD 1544; OTI-B37 at AD 1560) it likely that these two timbers were also felled in, or about, AD 1582.

Two other timbers from the west cross-wing, both tiebeams, appear broadly coeval (Fig 11). The level of similarity of the two ring series (t-value = 9.7) suggests that they were likely to be from trees felled at the same time and possibly even derived from the same tree, although this site chronology, OTIBSQ04, remains undated.

Outbuilding

The nine dated samples from this building represent two distinct felling episodes.

Four samples from three purlins and a tiebeam appear coeval (Fig 8). Of these, two (OTI-B40 and OTI-B48) retain complete sapwood. In the case of OTI-B48 the last sapwood ring is dated to AD 1623, whereas the last sapwood ring on OTI-B40 is dated AD 1624. Again, the outer surfaces of both timbers retain the spring and partial summer growth of the following year, and so these trees were felled in the summer of AD 1624 and the summer of AD 1625 respectively. Of the two remaining samples in this group, OTI-B46 retains the heartwood/sapwood boundary, and OTI-B50 retains 15 measured sapwood rings, plus approximately a further 25 unmeasured sapwood rings (the latest extant growth on the tree represented thus dating to *c* AD 1612). Given that the relative position and date of the heartwood/sapwood boundary on these two samples is similar to that on the other samples in this group, the entire group having an overall variation of heartwood/sapwood boundary date of 16 years (OTI-B48 at AD 1571; OTI-B40 at AD 1577) it likely that these two timbers were also felled in the early AD 1620s.

Another group of five samples from four purlins and a principal rafter also appear coeval (Fig 9). One of these samples, OTI-B45, retains complete sapwood. In this case the last sapwood ring is dated to AD 1812, but the outer surface of the timber only retains signs of the spring growth of the following year, suggesting this tree was felled in the spring of AD 1813. The four other samples in this group retain some sapwood or at least the heartwood/sapwood boundary. Again given that the relative position and date of the boundary on these four samples is similar to that on OTI-B45, and that of the group varies by only three years (OTI-B51 at AD 1792; OTI-B44, OTI-B45, and OTI-B49 at AD 1794) it is likely that these four timbers represented were felled at, or about, the same time in the early AD 1810s.

DISCUSSION AND CONCLUSION

Analysis by ring-width dendrochronology has dated 18 of the 41 samples that were measured as part of two dated site chronologies, whilst another eight measured samples have been dated by radiocarbon-supported oxygen isotope dendrochronology, and two more have relative dating provided by ring-width dendrochronology as part of an undated site chronology.

Six timbers have been dated from the re-roofing of the hall (Figs 8 and 18), five of these were felled in AD 1706 and AD 1707 and the roof was probably constructed very shortly after this date. The other dated timber from this roof has a *terminus post quem* date for felling of AD 1528 (Fig 8). Taking into account the growth characteristics of timbers across the site, it seems unlikely that this stud post represents the innermost rings of a very heavily trimmed tree that was particularly long-lived and thus is seems most likely that this timber was derived from a tree felled after AD 1528 but probably no later than the early seventeenth century.

The eight dated timbers from the west cross-wing are coeval and all appear likely to have been felled in, or around, AD 1582 (Fig 8), indicating a likely construction date for the west cross-wing in the late-sixteenth century. This dating confirms the date anticipated on architectural grounds (Jones 1994 unpubl). Four of the dated timbers from the outbuilding are also coeval and were felled in the early AD 1620s (Fig 8) and hence are not, as had been mooted, reused from somewhat earlier stages of the development of the H-plan main house. What is noticeable about this group of samples is that the two with complete sapwood, OTI-B40 and OTI-B48, have more sapwood rings than expected, both lying outside of the usual 95% range of 15–40 rings with 47 and 52 sapwood rings respectively. A further five timbers from the outbuilding have been dated to having been felled in, or around, AD 1813 (Fig 9), and could either represent the date of construction of this extant roof or the date of significant repairs/alterations.

It is unfortunate that none of the timbers from the primary construction phase of the hall and east cross-wing have been successfully dated, nor indeed successfully grouped and hence relatively dated with each other. The three dated timbers from the re-roofing of the east cross-wing were felled at different times in the first half of the eighteenth century (Fig 18), possibly suggesting that this roof was further modified following the re-roofing that occurred shortly after AD 1707$_{IR}$.

The only other two timbers which have been proven to be coeval are two tiebeams from the west cross-wing (Fig 11). The lack of dating however, does not necessarily indicate that they are of a different date to the successfully dated west cross-wing timbers.

Woodland sources

The level of cross-matching observed between dated samples from the west cross-wing is such that it suggests that the trees represent a single woodland source and indeed, with some very high *t*-values suggesting possible same-tree derivation for some timbers (eg OTI-B31/OTI-B32 *t*-value = 11.2; OTI-B36/OTI-B37 *t*-value = 12.0; OTI-B38/OTI-B39 *t*-value = 15.6). Similarly, the dated timbers (three purlins and a tiebeam) from the earlier outbuilding felling episode have very high levels of similarity, with *t*-values ranging from 9.5 to 15.9. The relevant site chronology, OTIBSQ01, cross-matches best with reference chronologies made up of timbers from other sites in surrounding areas, particularly those in Yorkshire (Table 2). Although dendro-provenancing to any fine degree is highly problematic, this does suggest that at least some of the timbers used in Oughtibridge Hall were of relatively local origin.

Such a distinction is not so clear with the later timbers used in the outbuilding dating to the early-nineteenth century, and represented by site chronology OTIBSQ02. At this late date, however, the database contains far fewer reference chronologies, and those that are available are much more widely dispersed and thus less regionally representative.

The samples forming site chronology OTIBSQ03, subsequently dated by radiocarbon-supported oxygen isotope dendrochronology, appear to match sufficiently well as to suggest that a single woodland source is represented, as do the two undated samples forming site chronology OTIBSQ04. However, being undated by ring-width dendrochronology, the likely source of the timbers cannot be identified.

The overall characteristics of the trees used in the late-sixteenth and early seventeenth centuries are notably different from those used in the early eighteenth and early nineteenth centuries, with the earlier timbers being derived from much longer-lived and slower grown trees.

Timbers undated by ring-width dendrochronology

The successful dating of only 18 of the 41 measured samples is disappointing and is well below the expected success rate for ring-width dendrochronology of around 70-80% of apparently suitable samples. Thirteen of these undated samples are also ungrouped, showing no clear similarities with the growth patterns of any of the other measured timbers from the site. Some of these, including all of those associated with the primary construction phase of the hall, have ring numbers towards the lower limit of acceptability for reliable dating purposes, and some show some disturbance to their growth patterns which may mask the general climatic signal needed for successful matching and dating against reference chronologies. The dating of individual ring series against reference chronologies is far less successful than the dating of replicated site chronologies formed from a group of cross-matched samples.

The grouped but undated samples forming OTIBSQ03, associated with the re-roofing of the hall and east cross-wing, show no growth disturbances but all have relatively short ring sequences which are again towards the lower limit of suitability for reliable dating purposes. The pair of samples forming OTIBSQ04 have significantly more rings but these show periodic narrow bands indicating growth suppression events which will adversely affect their dating potential. Such growth reduction events, followed by a period of recovery, could be the result of anthropogenic, local environmental, and general environmental effects. Causal factors include management regimes or at least some form of human intervention, such as pollarding or shredding, localised defoliation by pests, possible responses to localised flooding, or more generalised environmental effects such as severe weather conditions (eg drought, or long hard winters and late frosts). No definitive answer can be provided from the tree-ring analysis.

Radiocarbon-supported oxygen isotope dendrochronology

Cross-matching of the stable isotopes was obtained against the south-central England master chronology which pass the thresholds for consideration as dated suggested by Loader *et al* (2019)(Table 7) but, since the levels of the statistical thresholds necessary for oxygen isotopic dating to have equivalent confidence to traditional ring-width dendrochronology are currently uncertain, the dating of the timbers contained in site master sequence OTIBSQ03 are reported as a radiocarbon-supported oxygen isotope dates (denoted by the subscript $_{IR}$). This is a cautious approach, which may be reconsidered in the light of future work.

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TABLES

Table 1: Details of tree-ring samples from Oughtibridge Hall, Oughtibridge Lane, Bradfield, Sheffield, South Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	East cross wing – re-roofing					
OTI-B01	Tiebeam, truss 2	51	3	1655_{IR}	1702_{IR}	1705_{IR}
OTI-B02	East purlin, truss 2–3	43	16C	1663_{IR}	1689_{IR}	1705_{IR}
OTI-B03	Tiebeam, truss 3	55	4	------	------	------
OTI-B04	Tiebeam, truss 4	47	17	1659_{IR}	1688_{IR}	1705_{IR}
OTI-B05	East principal rafter, truss 4	nm	---	------	------	------
OTI-B06	West principal rafter, truss 4	nm	---	------	------	------
	Open hall – re-roofing					
OTI-B07	North purlin, truss 6–7	44	6	1653_{IR}	1690_{IR}	1696_{IR}
OTI-B08	South purlin, truss 6–7	50	15C	1656_{IR}	1690_{IR}	1705_{IR}
OTI-B09	North principal rafter, truss 7	45	15	1659_{IR}	1688_{IR}	1703_{IR}
OTI-B10	South principal rafter, truss 7	55	24C	1652_{IR}	1682_{IR}	1706_{IR}
OTI-B11	Stud post 5 (from north), truss 7	85	no h/s	1429	------	1513
OTI-B12	Stud post 6, truss 7	107	5	------	------	------
OTI-B13	Stud post 7, truss 7	68	no h/s	------	------	------
OTI-B14	North purlin, truss 7–8	55	15	1651_{IR}	1690_{IR}	1705_{IR}
OTI-B15	South purlin, truss 7–8	nm	---	------	------	------
OTI-B16	South principal rafter, truss 8	nm	---	------	------	------
OTI-B17	Intermediate bressummer beam	138	h/s	------	------	------
	Open hall – primary construction					
OTI-B18	Tiebeam, truss 7	50	4	------	------	------
OTI-B19	South main wall post, truss 7	53	no h/s	------	------	------
OTI-B20	South brace, truss 7	56	no h/s	------	------	------
OTI-B21	North brace, truss 7	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Open hall – primary construction					
OTI-B22	North strut, truss 7	nm	---			
OTI-B23	Tiebeam, truss 8	52	h/s			
	East cross wing – primary construction					
OTI-B24	West main wall post, truss 2	50	8	------	------	------
OTI-B25	West wall plate, truss 1 – 2	57	h/s	------	------	------
OTI-B26	Stud post 2 (from east) truss 3	nm	---	------	------	------
OTI-B27	Stud post 3, truss 3	79	h/s	------	------	------
	West cross wing – primary construction					
OTI-B28	Tiebeam, truss 9	114	no h/s	1[SQ04]	------	114[SQ04]
OTI-B29	West main wall post, truss 10	nm	---	------	------	------
OTI-B30	Tiebeam, truss 10	111	h/s	1437	1547	1547
OTI-B31	East principal rafter, truss 10	126	h/s	1486	1553	1553
OTI-B32	West principal rafter, truss 10	96	26C	1424	1555	1581
OTI-B33	East main wall post, truss 11	140	h/s	------	------	------
OTI-B34	West main wall post, truss 11	118	22c	1454	1549	1571
OTI-B35	Tiebeam, truss 11	154	18	20[SQ04]	155[SQ04]	173[SQ04]
OTI-B36	East principal rafter, truss 11	84	12c	1487	1558	1570
OTI-B37	East main wall post, truss 12	90	11c	1482	1560	1571
OTI-B38	West wall plate, truss 10–11	154	33c	1424	1544	1577
OTI-B39	West wall plate, truss 11–12	106	25c	1466	1546	1571
	Outbuilding to driveway					
OTI-B40	Tiebeam truss 1	197	47C	1428	1577	1624
OTI-B41	Tiebeam truss 2	62	18	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
OTI-B42	West principal rafter, truss 1	nm	---	------	------	------
OTI-B43	East principal rafter, truss 2	nm	---	------	------	------
	Outbuilding to driveway					
OTI-B44	West principal rafter, truss 2	44	h/s	1751	1794	1794
OTI-B45	East lower purlin, truss 1 to north gable	55	18C	1758	1794	1812
OTI-B46	East upper purlin, truss 1 to north gable	106	h/s	1467	1572	1572
OTI-B47	West lower purlin, truss 1 to north gable	51	15	1758	1793	1808
OTI-B48	East lower purlin, truss 1 – 2	166	52C	1458	1571	1623
OTI-B49	East upper purlin, truss 1 – 2	57	13	1751	1794	1807
OTI-B50	West lower purlin, truss 1 – 2	120+25nm	15 +25nm	1468	1572	1587
OTI-B51	West upper purlin, truss 1 – 2	63	15	1745	1792	1807

C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented
c = complete sapwood is found on the timber, but a portion of this has been lost from the sample in coring
h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured
$_{IR}$ = radiocarbon-supported oxygen isotope dendrochronological date
^{SQ04} = relative date span within site master chronology OTIBSQ04

Table 2: Results of the ring-width cross-matching of site chronology OTIBSQ01 and relevant reference chronologies when the first-ring date is AD 1424 and the last-ring date is AD 1624

Reference chronology	Span of chronology	*t*-value	Reference
Bishops House, Sheffield, South Yorkshire	AD 1399 – 1579	9.1	Arnold and Howard 2017 unpubl
Lane Head Farm, Dodworth Lane, Barnsley, South Yorkshire	AD 1385 – 1627	8.9	Tyers 2006
Raynor House, Bradfield, South Yorkshire	AD 1468 – 1593	8.5	Howard *et al* 1994
Stayley Hall, Stalybridge, Greater Manchester	AD 1387 – 1565	8.3	Nayling 2000
Auckland Castle, Bishop Auckland, Co Durham	AD 1425 – 1698	7.9	Arnold and Howard 2013
Manor Farm, Bradfield, South Yorkshire	AD 1380 – 1550	7.8	Howard *et al* 1996
Kent House, Ridgeway, Derbyshire	AD 1431 – 1646	7.8	Groves and Hillam 1990
Westgate End House, Kemps Bridge, Wakefield, West Yorkshire	AD 1377 – 1567	7.7	Arnold and Howard 2015
Offerton Hall, Offerton, Derbyshire	AD 1401 – 1592	7.4	Howard *et al* 1995
Grange Farm, Norton, Sheffield, South Yorkshire	AD 1436 – 1599	7.4	Arnold and Howard 2007

Table 3: Results of the ring-width cross-matching of site chronology OTIBSQ02 and relevant reference chronologies when the first-ring date is AD 1745 and the last-ring date is AD 1812

Reference chronology	Span of chronology	*t*-value	Reference
Savernake Forest, Wiltshire	AD 1651 – 1982	6.8	Briffa *et al* 1986 unpubl
Great Gransden Windmill, Cambridgeshire	AD 1706 – 1836	6.7	Bridge 2015
Castle Farm, Marshfield, Gloucestershire	AD 1706 – 1797	6.7	Howard *et al* 1998 unpubl
Endcliffe Park Wood, Sheffield, South Yorkshire	AD 1759 – 2003	6.5	Tyers 2004
Eastcote Manor, Hillingdon, Middlesex	AD 1720 – 1820	6.5	Arnold and Howard 2012
Coombe Warren, Coventry, Warwickshire	AD 1747 – 1830	6.2	Arnold and Howard 2015 unpubl
Church of St Giles bellframe, Mountnessing, Essex	AD 1747 – 1899	6.1	Tyers 1996
Jessops Riverside, Sheffield, South Yorkshire	AD 1709 – 1842	5.8	Tyers 2001 unpubl
Moat Bridges, Tattershall Castle, Lincolnshire	AD 1759 – 1981	5.6	Arnold *et al* 2018
Bradgate Trees, Bradgate Park, Leicestershire	AD 1595 – 1975	5.5	Laxton and Litton 1988

Table 4: Radiocarbon measurements and associated δ^{13}C values from oak sample OTI-B10 (south principal rafter from the re-roofing of the open hall)

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{AMS}$ (‰)
ETH-96733	OTI-B10, ring 1 (*Quercus* sp., heartwood)	224±11	−24.9
ETH-104569	OTI-B10, ring 5 (*Quercus* sp., heartwood)	254±13	−25.2
ETH-96734	OTI-B10, ring 10 (*Quercus* sp., heartwood)	233±11	−24.9
ETH-96735	OTI-B10, ring 16 (*Quercus* sp., heartwood)	237±14	−22.7
ETH-96736	OTI-B10, ring 19 (*Quercus* sp., heartwood)	184±11	−25.9
ETH-96737	OTI-B10, ring 28 (*Quercus* sp., heartwood)	156±11	−25.6
ETH-104571	OTI-B10, ring 34 (*Quercus* sp., sapwood)	169±13	−24.3
ETH-96738	OTI-B10, ring 40 (*Quercus* sp., sapwood)	136±11	−25.3
ETH-104572	OTI-B10, ring 45 (*Quercus* sp., sapwood)	135±13	−26.1
ETH-104573	OTI-B10, ring 50 (*Quercus* sp., sapwood)	130±13	−26.1
ETH-96739	OTI-B10, ring 55 (*Quercus* sp., sapwood)	112±11	−25.4

Table 5: Sample description: timber type and position, material analysed, number of complete tree rings (N), number (N_i) and range of rings for which $\delta^{18}O$ measurements were undertaken, and laboratory code. The presence of a zero ring indicates that latewood only was preserved at the pith-end of the sample, this was measured isotopically but not included in the ring-width analyses

Sample	Timber and Position	Species	N	N_i	$\delta^{18}O$ (Measured rings)	Code
OTI-B01i	Tiebeam, truss 2 (3)	Latewood α-cellulose *Quercus* spp	51	42	10–52	SWAN-71a
OTI-B14i	North purlin, truss 7–8 (15C)	Latewood α-cellulose *Quercus* spp	55	55	0–54	SWAN-71b

Key: (3) = number of sapwood rings preserved; C = sapwood complete (bark edge).

Table 6: Cross-dating matrix for samples OTI-B01i and OTI-B14i identifying number of rings [N_i] for which $\delta^{18}O$ measurements have been undertaken. Upper right: significant Student's t*-value and position (offset; OTI-B14i isotopic series ends 1 year before that of oti-B01i). Lower left (shaded cell): Pearson's correlation coefficient and degrees of freedom for position of best match (series compared column versus row). Statistics presented for position of full overlap.*

	OTI-B01i [42]	OTI-B14i [55]
OTI-B01i [42]	-	6.50 −1
OTI-B14i [55]	0.744 34	-

Table 7: Stable oxygen isotope dating of the composite and individual samples from Oughtibridge Hall against the south-central England master chronology (Loader et al *2019) over the period AD 1200–AD 2000. Number of whole rings present in core sample (N), number of rings on which $\delta^{18}O$ measurements were undertaken (N_i), Pearson's correlation coefficient (r), degrees of freedom (adjusted for autocorrelation and multiple sampling), Student's* t*-value, probability (1/p), isolation factor (IF), and date. Rings 0-9 were omitted from the cross-matching process due to the presence of glue and ink on the core provided for isotopic analysis.*

Sample	Description	N	N_i	R	df	*T*	1/p	IF	Date
OT-Bx	Mean of OTI-B01i & OTI-B14i	55	56	0.620	47	5.42	1350	>1000	1705
OTI-B01i	Tiebeam, truss 2 (3)	51	42	0.645	35	4.99	158	18	1705
OTI-B14i	North purlin, truss 7–8 (15C)	55	55	0.557	46	4.55	69	51	FAIL

Key: (3) = number of sapwood rings preserved; C = sapwood complete (bark edge).

FIGURES

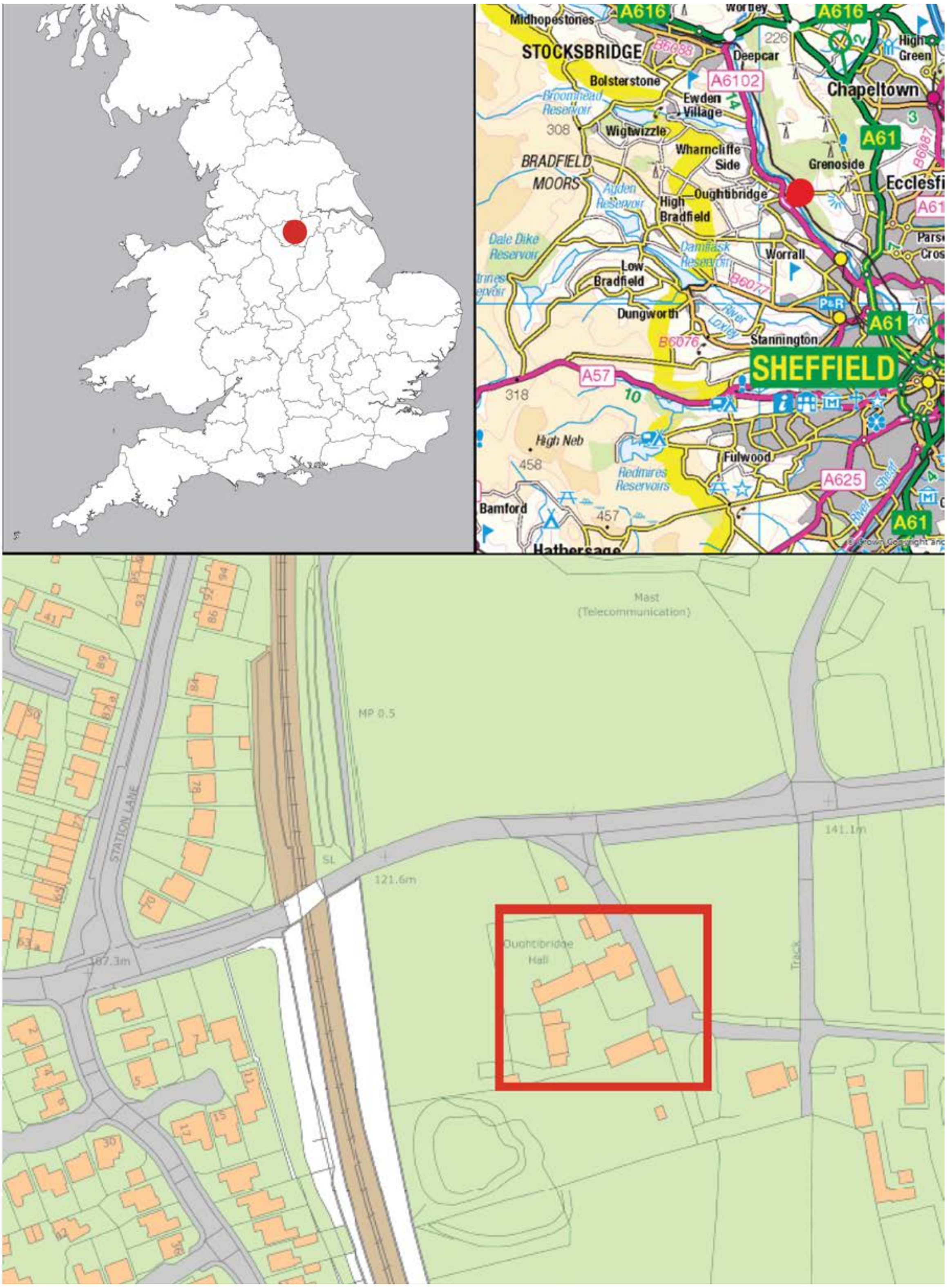


Figure 1: Maps to show the location of Oughtibridge Hall, Bradfield in South Yorkshire marked in red. Scale: top right 1:105,000; bottom: 1:1800. (© Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900)

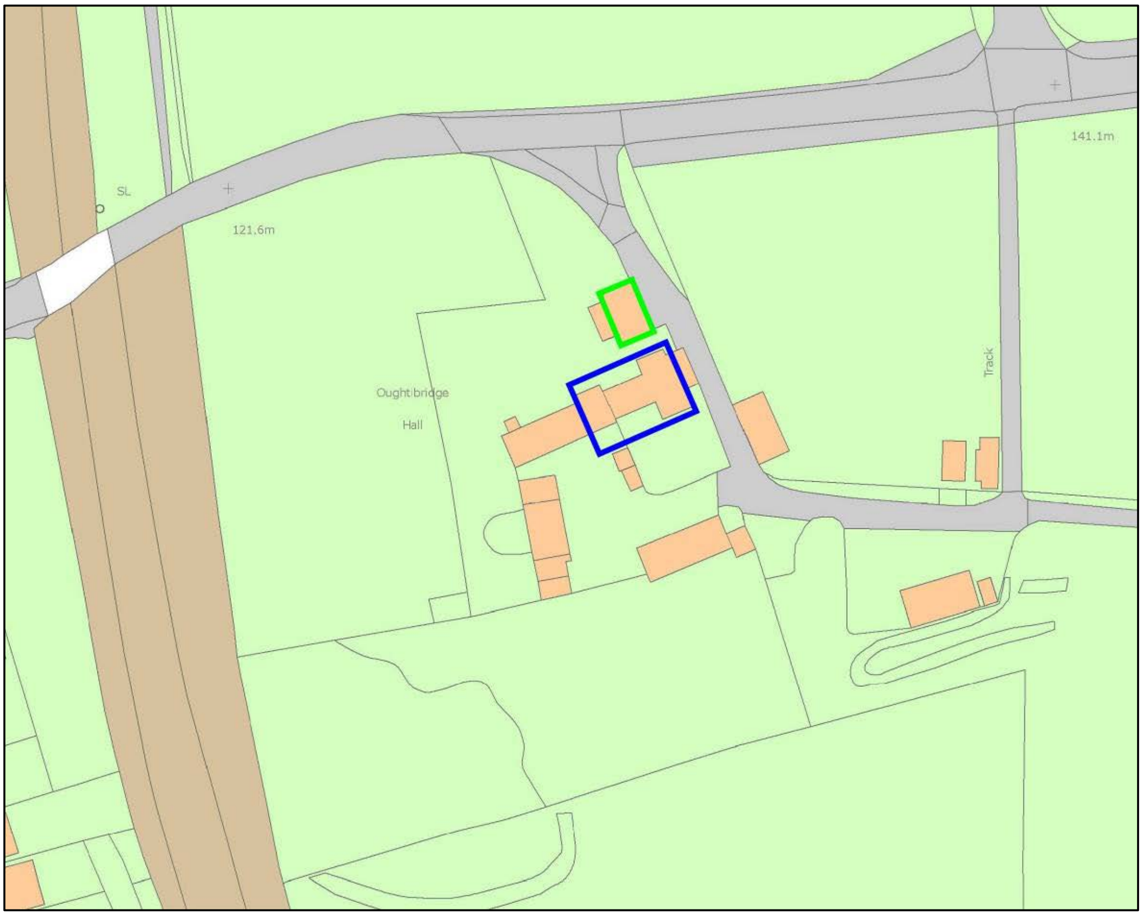


Figure 2: Map highlighting the location of the buildings investigated at Oughtibridge Hall. (© Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900)

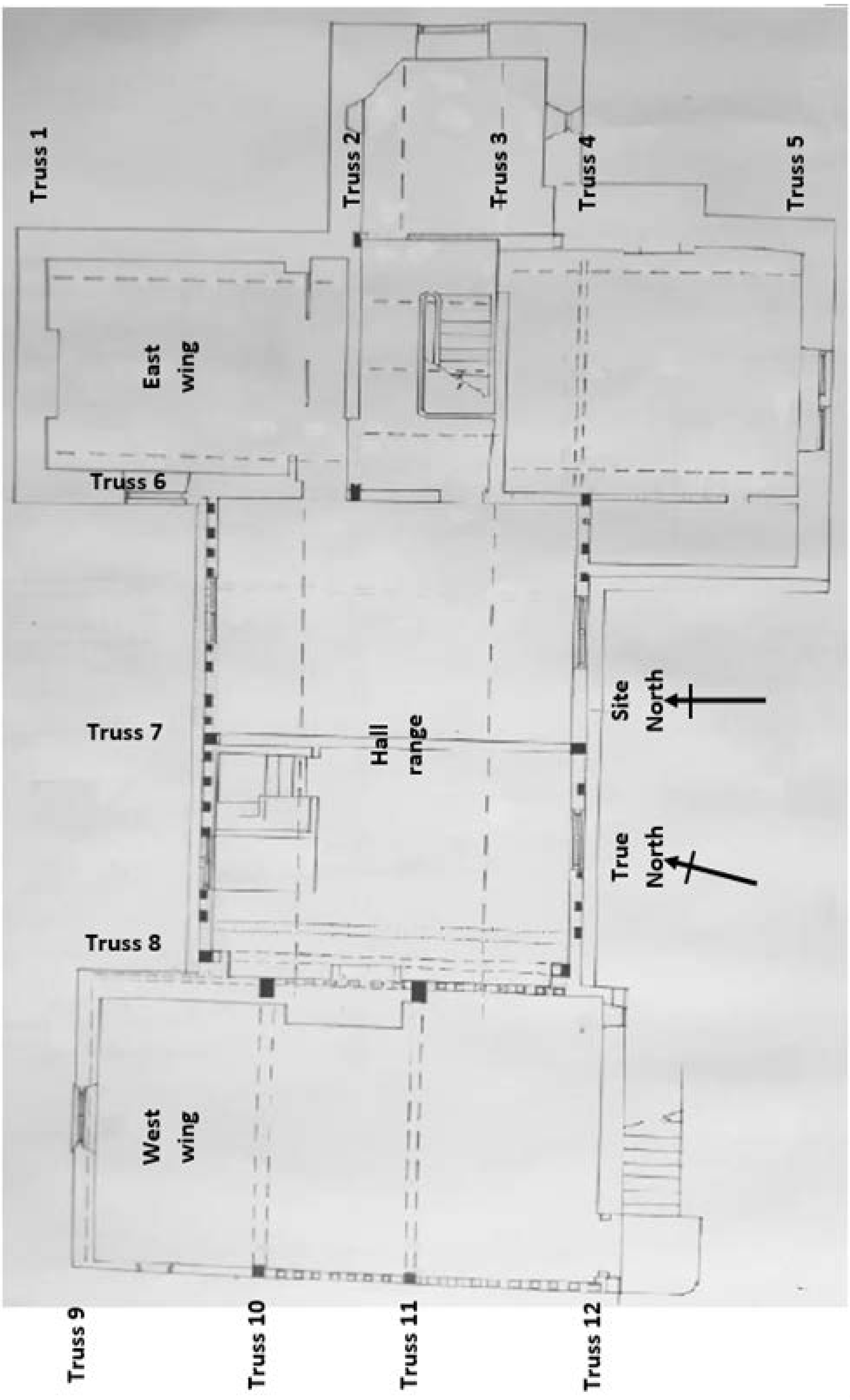


Figure 3: Plan to show layout of Oughtibridge Hall and the truss positions (after Jones 1994)

Figure 4a/b: Views of the open hall trusses, truss 7 (top), truss 8 (bottom) (photographs Robert Howard)

Figure 4c/d; Views of the open trusses to the west cross wing with truss 11 in the foreground (top) and the building to the driveway (bottom) (photographs Robert Howard)

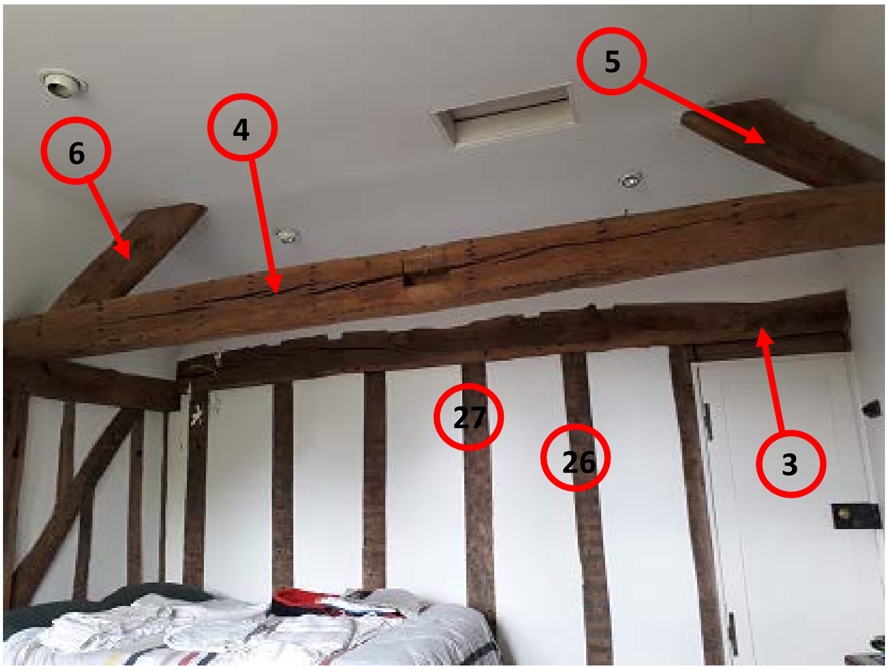


Figure 5a/b: Annotated photographs to help locate sampled timbers; east cross-wing, truss 2 (top), and trusses 3 and 4 (bottom), all viewed from the south looking north (photographs Robert Howard)

Figure 5c/d: Annotated photographs to help locate sampled timbers; open hall viewed looking east towards truss 6 (top), and east cross-wing, truss 2, viewed from the south (bottom) (photographs Robert Howard)

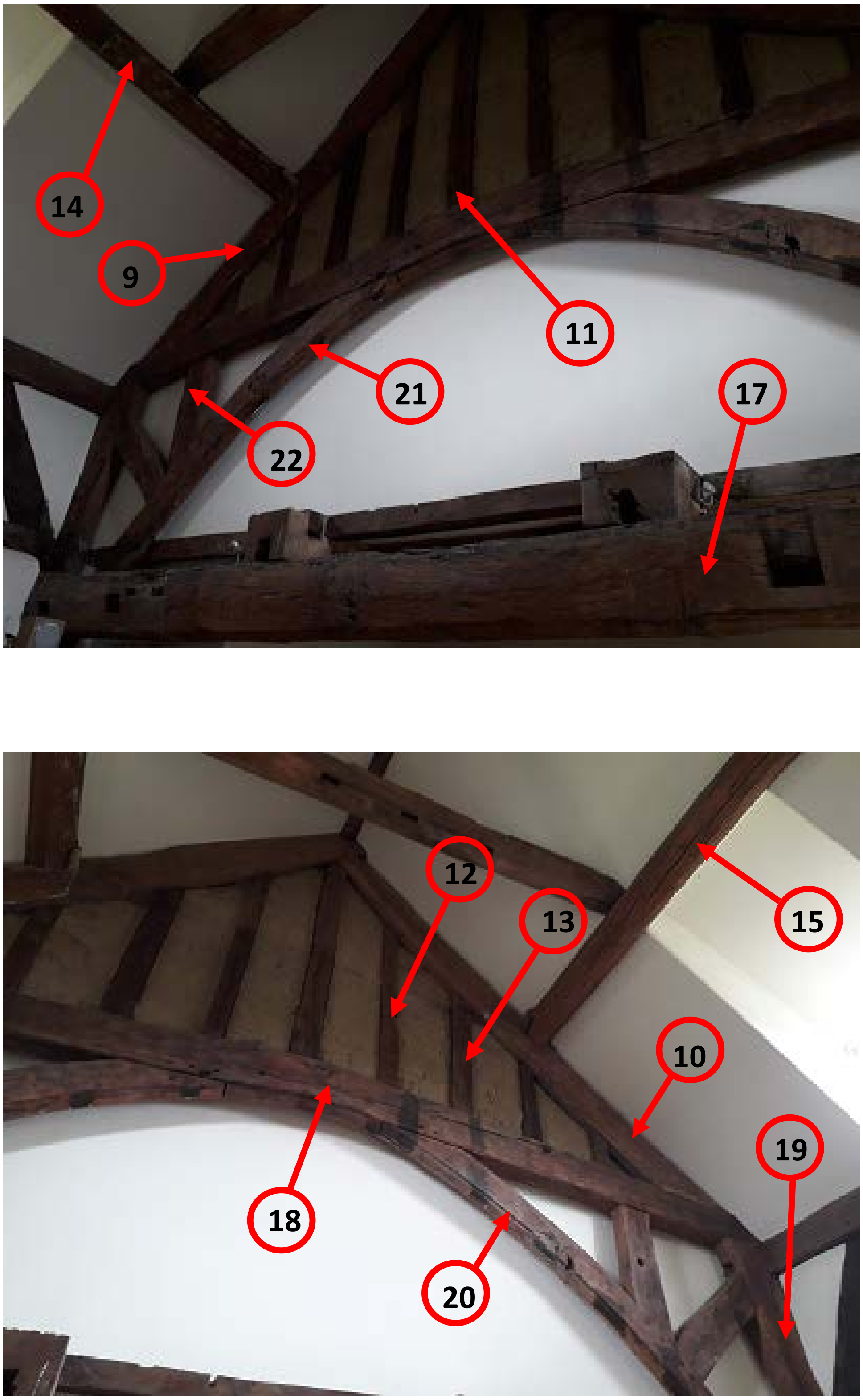


Figure 5e/f: Annotated photographs to help locate sampled timbers; open hall truss 7, viewed from west looking east (photographs Robert Howard)

Figure 5g: Annotated photograph to help locate sampled timbers; open hall truss 8 viewed from east looking west (photographs Robert Howard)

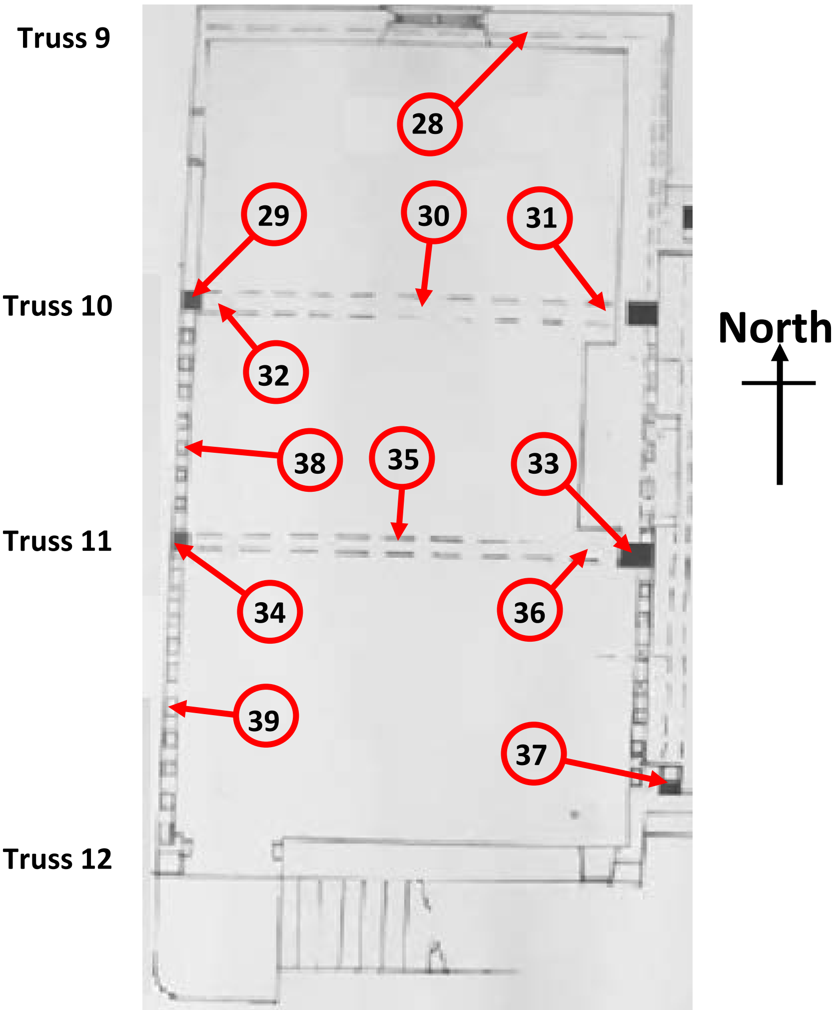


Figure 6: Outline plan of the west cross wing to help locate sampled timbers (after Jones 1994)

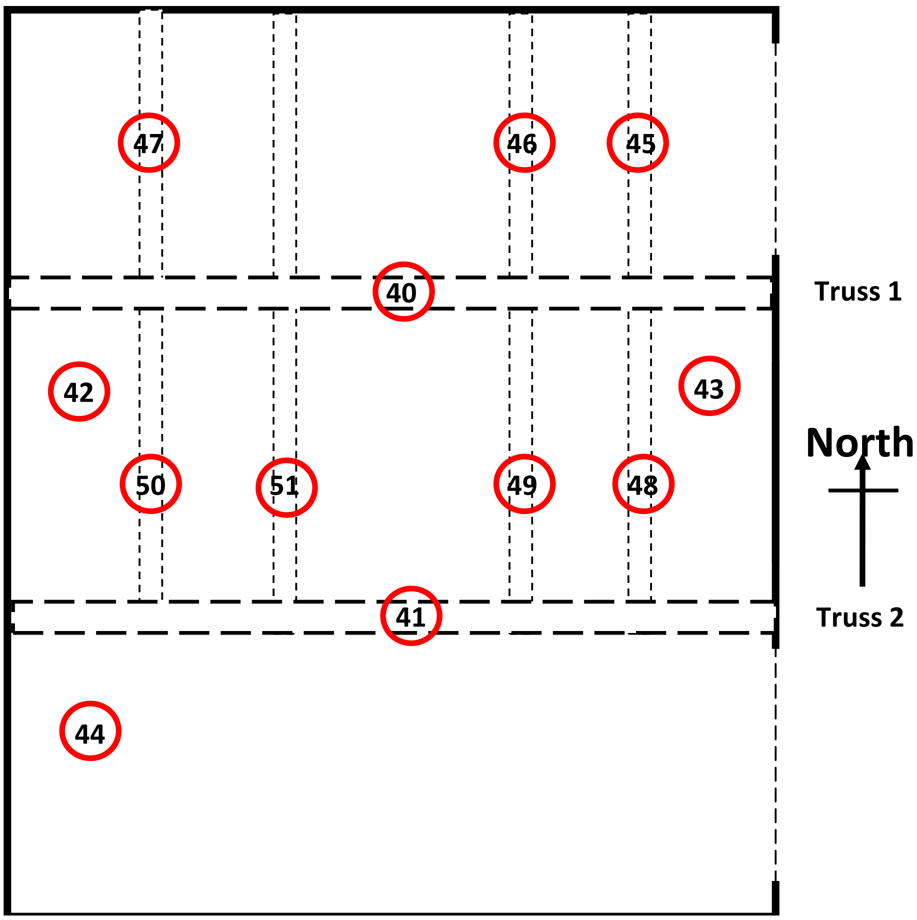
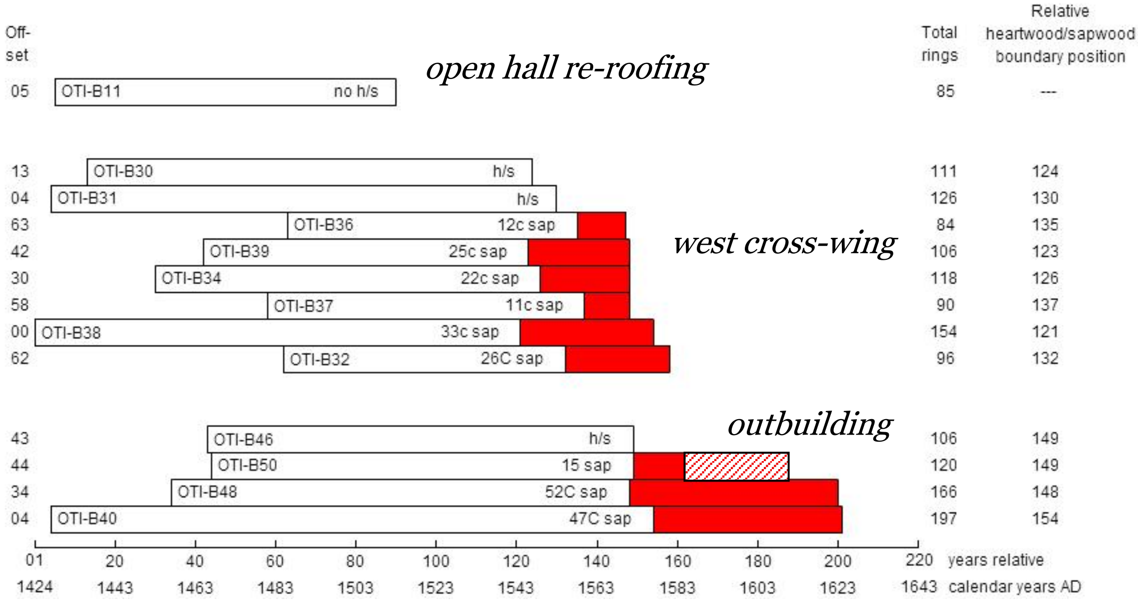
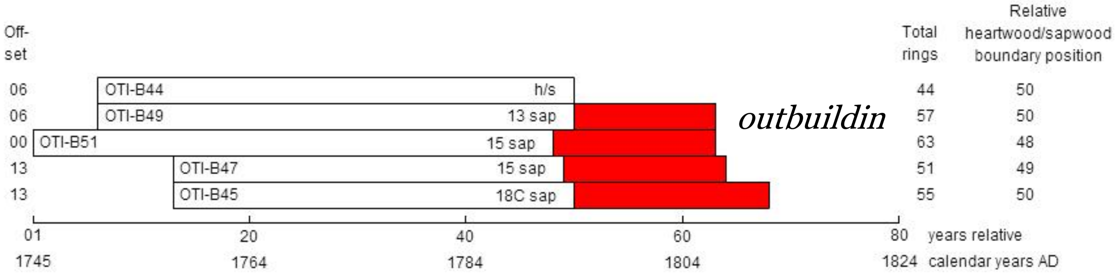


Figure 7: Sketch plan of the building to the driveway to help locate sampled timbers (Robert Howard)



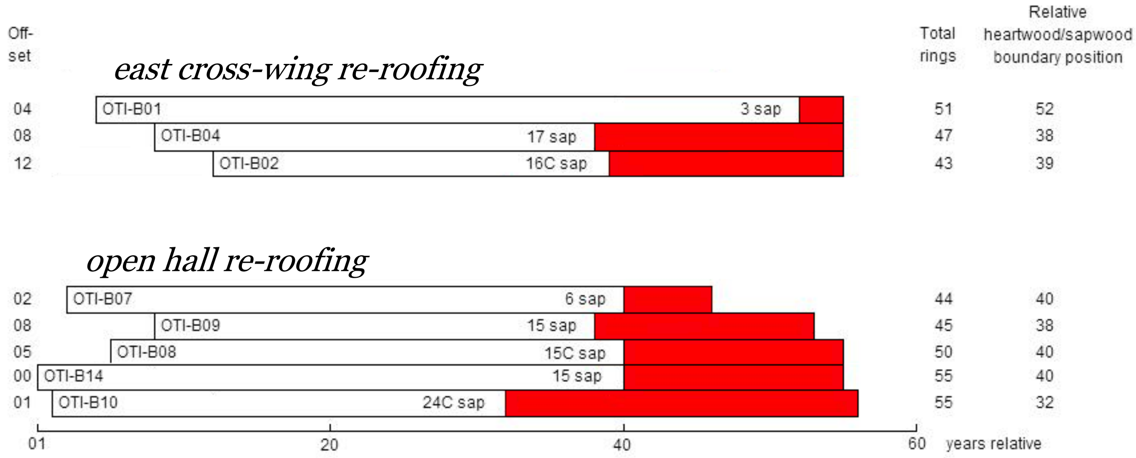
White bars = heartwood rings; red bars = sapwood rings; hatched bars = unmeasured sapwood rings; h/s = heartwood/sapwood boundary; C = sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented; c = complete sapwood is found on the timber but all or part has been lost from the sample in coring

Figure 8: Bar diagram of the samples in site chronology OTIBSQ01



White bars = heartwood rings; red bars = sapwood rings; h/s = heartwood/sapwood boundary; C = sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented

Figure 9: Bar diagram of the samples in site chronology OTIBSQ02



White bars = heartwood rings; red bars = sapwood rings; C = sapwood is retained on the sample

Figure 10: Bar diagram of the samples in site chronology OTIBSQ03

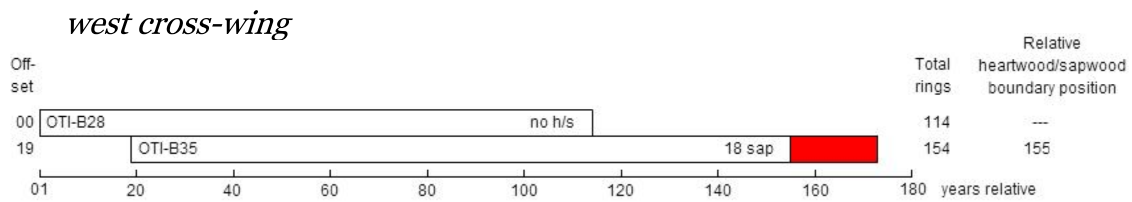


Figure 11: Bar diagram of the samples in site chronology OTIBSQ04

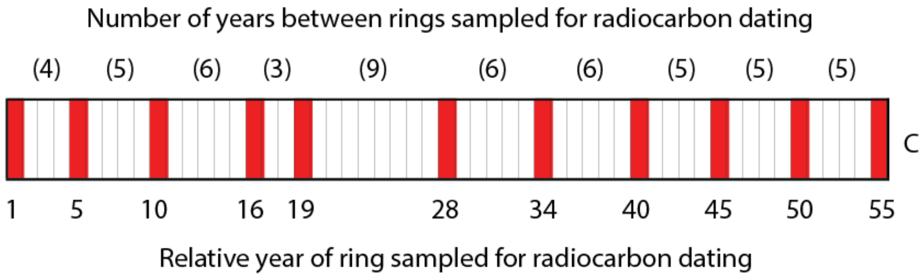


Figure 12: Schematic illustration of sample OTI-B10 to locate the single-ring sub-samples submitted for radiocarbon dating (C = complete sapwood)

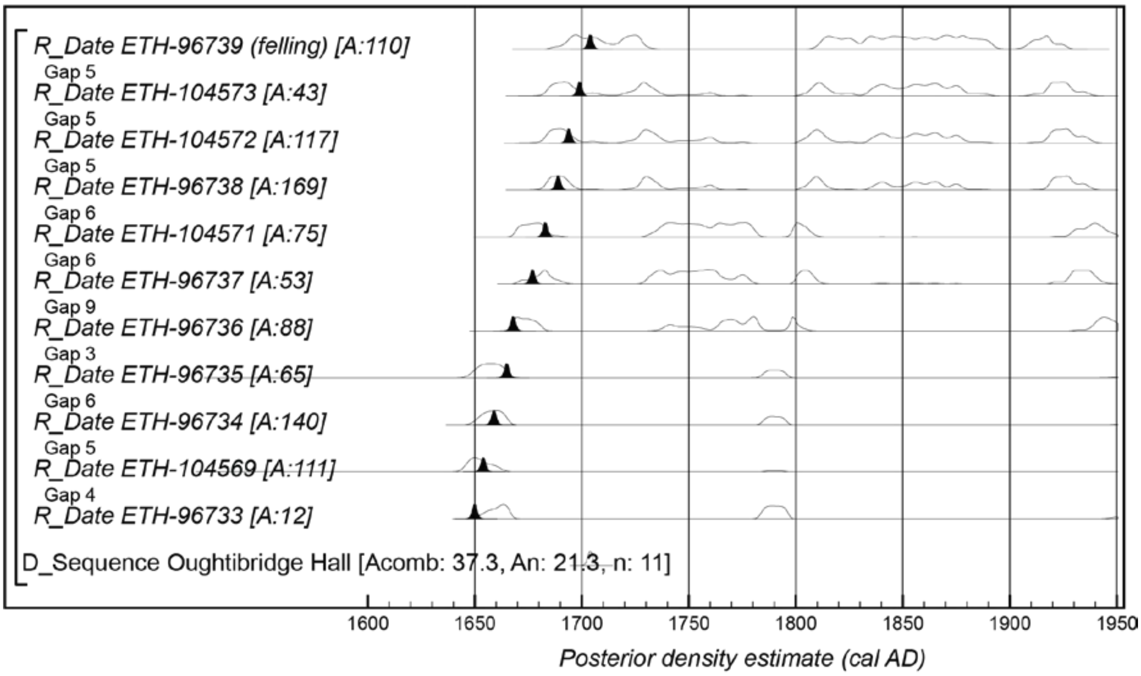


Figure 13: Probability distributions of dates from OTI-B10. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. 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

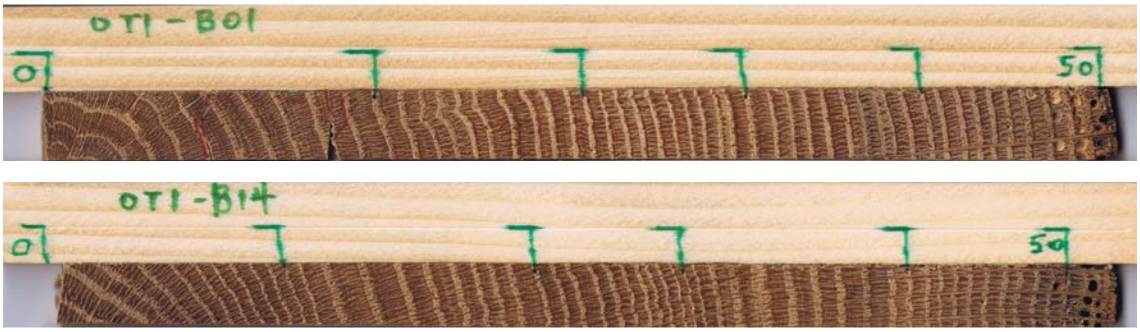


Figure 14: Samples OTI-B01i (top) and OTI-B14i (bottom). Note the presence of glued cracks and ink in OTI-B01i (rings 0-9). Core diameter c 10mm

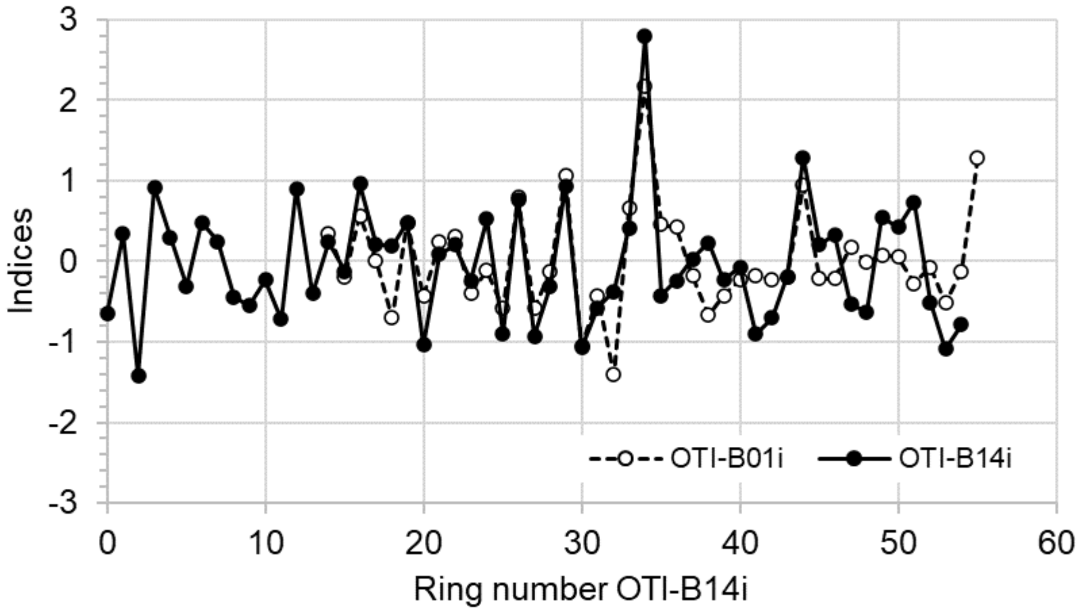


Figure 15: Time series of the filtered and indexed δ^{18}O values from the two samples (all values) plotted at the position of strongest match with a Student's t-value of 6.50

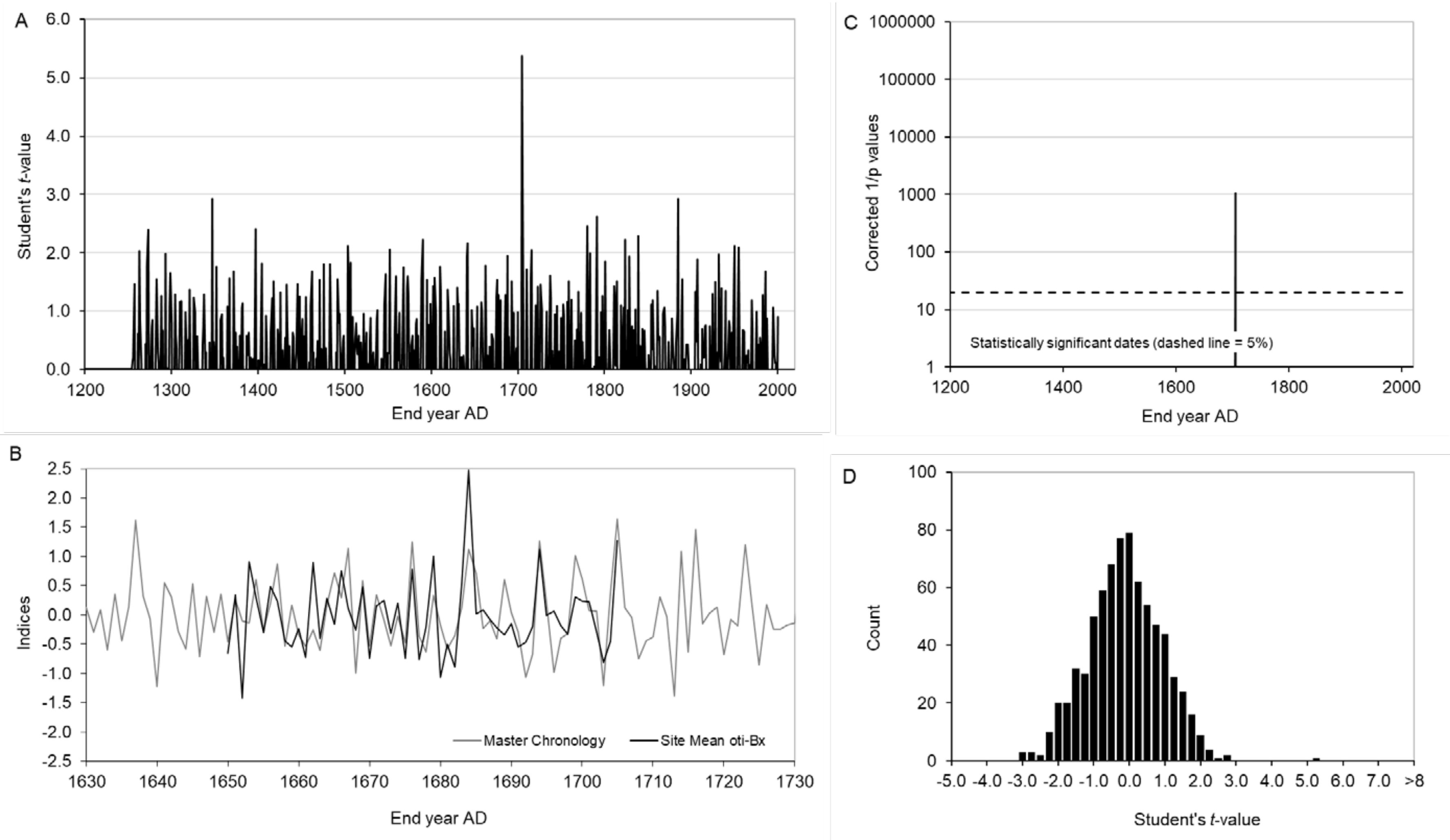


Figure 16: Dating results for the 56-year mean isotope chronology (OTI-Bx A: Student's t-values for all possible end dates with full overlap against the master chronology. B: Time series of the site isotopic mean plotted against the master chronology. C: End dates with corrected probabilities (1/p) of more than one. Those below the dashed line (1/p = 20) are not statistically significant. D: Distribution of Student's t-values for all possible matches

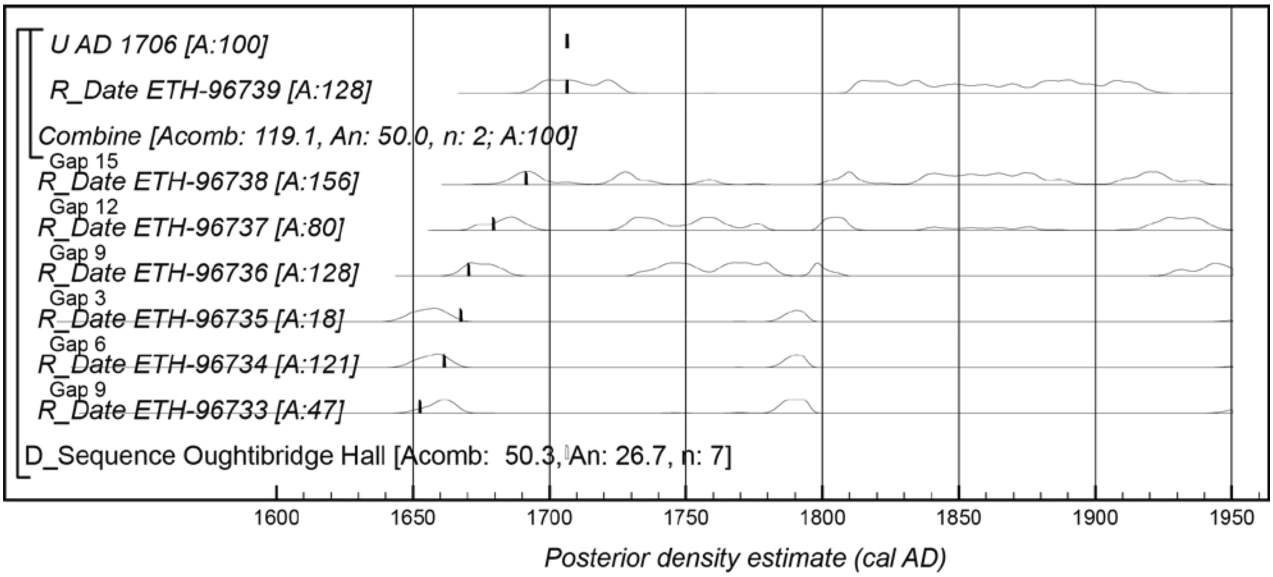
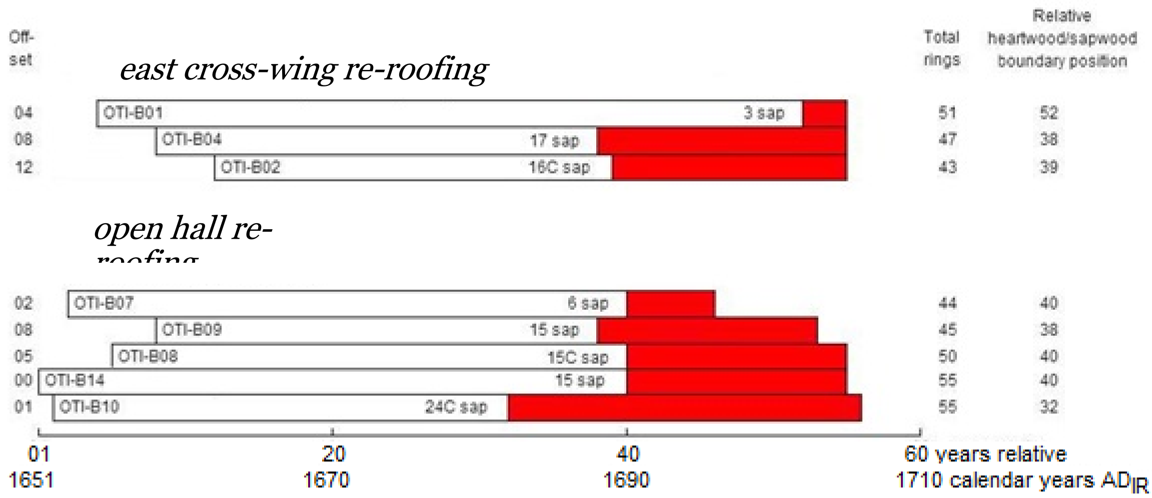


Figure 17: Probability distributions of dates from OTI-B10, when the last ring is constrained to have formed in AD 1706. The format is as for Figure 13. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly



White bars = heartwood rings; shaded bars = sapwood rings; C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the timber represented

Figure 18: Bar diagram of the samples in site chronology OTIBSQ03, as dated by radiocarbon-support oxygen isotope dendrochronology as spanning AD 1651–1706$_{IR}$

DATA OF MEASURED SAMPLES

Ring-width data
Measurements in 0.01mm units

OTI-B01A 51
265 287 353 413 372 407 450 382 437 467 440 366 326 260 285 237 359 350 245 332
261 284 237 225 246 270 238 207 253 167 284 373 274 237 275 317 248 260 168 250
299 228 281 253 238 250 248 330 316 283 300

OTI-B01B 51
270 280 349 423 364 410 443 410 432 461 441 356 334 252 285 271 364 360 239 331
262 275 267 225 257 258 237 204 242 172 312 370 268 235 268 314 251 246 157 248
303 242 283 253 231 254 261 317 321 279 298

OTI-B02A 43
480 405 458 452 515 391 288 464 528 414 482 585 389 419 336 267 353 573 415 465
346 159 187 212 139 101 162 300 168 276 112 134 159 200 232 153 190 148 156 210
284 216 325

OTI-B02B 43
479 419 473 455 516 387 275 476 506 427 471 580 394 413 340 265 360 584 414 462
351 163 183 212 140 105 163 297 174 264 105 125 173 207 251 145 181 146 162 216
292 218 330

OTI-B03A 55
214 307 361 230 189 186 353 395 289 369 400 352 357 357 274 269 298 268 278 273
297 334 331 470 354 385 343 438 289 285 200 304 232 307 349 310 325 206 243 214
290 187 263 185 275 428 283 315 243 178 187 197 185 175 201

OTI-B03B 55
220 289 363 234 182 196 380 390 300 374 396 352 355 364 270 272 300 273 278 279
306 331 325 472 354 378 346 426 272 293 189 305 235 301 362 305 328 203 243 214
271 203 262 189 268 396 286 337 253 181 188 206 169 209 196

OTI-B04A 47
200 188 153 214 404 468 520 376 417 286 298 286 396 355 251 351 268 353 271 268
243 340 401 271 320 181 204 262 175 208 171 243 132 137 85 147 137 159 226 179
159 132 155 171 200 152 204

OTI-B04B 47
195 183 181 199 408 503 512 386 422 282 286 307 395 357 255 346 268 351 272 270
238 364 401 278 306 196 196 262 185 212 170 250 134 139 93 140 145 154 226 176
180 126 154 176 190 148 197

OTI-B07A 38
211 332 308 218 233 191 175 203 191 300 384 273 175 242 253 226 384 553 356 400
339 315 306 296 320 373 373 395 409 405 247 189 228 250 250 215 302 375

OTI-B07B 44
174 260 291 277 226 241 200 191 209 185 298 363 251 185 253 272 236 415 564 366
329 337 323 276 243 269 299 345 347 392 418 235 206 250 212 175 156 272 292 369
236 295 312 296

OTI-B08A 50
423 328 346 359 269 300 318 371 520 475 380 393 302 284 303 387 333 293 263 267
262 189 178 209 256 215 178 195 140 289 445 410 473 418 542 401 425 240 314 388
365 443 395 331 315 343 420 377 356 440

OTI-B08B 50
424 326 350 335 268 285 301 368 526 490 351 396 304 283 306 390 344 272 294 257

281 179 167 207 254 229 173 200 139 301 444 424 459 420 540 396 457 254 314 382
392 447 399 340 309 355 414 382 354 450

OTI-B09A 45
206 293 342 355 389 534 489 401 393 296 261 264 466 460 312 387 372 344 156 176
223 256 214 195 251 132 351 317 296 337 443 573 376 448 262 292 406 414 400 364
321 293 312 350 254

OTI-B09B 45
206 296 330 357 393 523 478 396 394 296 255 278 450 459 285 419 370 350 157 184
232 257 200 203 247 141 309 354 309 350 428 561 367 460 268 287 407 408 412 370
318 272 315 356 258

OTI-B10A 55
266 195 355 345 359 303 253 264 226 251 228 246 459 348 217 149 130 114 192 444
345 185 271 187 212 93 142 186 192 282 199 359 123 217 265 310 298 414 562 345
350 187 187 293 314 362 282 270 271 225 231 143 143 137 190

OTI-B10B 55
264 197 363 374 359 298 259 268 228 244 230 256 450 346 218 153 127 117 199 431
363 180 271 189 210 98 141 190 190 278 196 358 113 233 255 326 295 416 559 332
364 171 184 281 305 318 300 278 253 212 268 146 138 140 189

OTI-B11A 85
395 313 377 346 260 256 193 180 180 127 117 178 212 214 279 403 222 185 264 250
312 198 196 204 191 221 224 273 235 218 237 212 212 190 214 154 128 109 154 125
118 115 93 100 101 134 186 148 160 115 104 128 125 120 148 151 122 113 154 104
90 94 87 68 66 75 95 141 115 96 100 93 57 57 71 65 69 65 63 85
81 96 103 87 119

OTI-B11B 85
382 296 372 368 261 241 179 189 160 146 128 178 195 202 282 384 250 184 260 266
300 189 189 203 197 221 225 265 236 215 240 209 210 189 214 151 126 103 161 112
129 110 92 110 100 129 189 151 145 110 104 121 120 129 142 150 120 120 144 110
98 93 80 68 67 73 95 138 114 90 107 95 56 51 76 63 68 58 58 92
82 98 93 78 121

OTI-B12A 107
95 66 76 67 80 106 171 137 108 100 208 268 212 210 101 225 305 196 259 191
276 285 306 274 200 240 212 164 236 180 136 200 143 150 130 106 159 113 131 142
157 182 159 170 189 123 71 59 76 74 59 76 73 90 90 137 145 67 109 75
89 92 103 67 137 92 121 53 63 78 95 84 85 70 96 75 107 141 151 190
179 184 154 110 104 73 62 54 60 75 43 56 70 70 71 93 87 79 81 106
118 148 117 76 90 56 82

OTI-B12B 107
96 62 73 92 72 96 171 129 108 106 198 284 203 209 110 230 276 184 255 203
281 271 304 260 200 247 207 163 232 183 134 207 142 147 130 114 151 112 132 137
166 170 159 175 189 117 65 67 95 71 70 67 64 85 92 134 146 66 106 77
80 87 93 77 129 85 117 46 58 73 89 93 76 71 94 71 111 129 145 176
176 185 140 106 89 79 51 46 54 81 40 58 75 73 76 93 79 65 89 109
131 137 115 71 98 51 80

OTI-B13A 68
138 117 73 106 112 124 100 93 75 83 100 72 117 89 128 105 101 105 137 162
135 124 139 110 122 108 39 42 39 44 48 47 62 59 72 103 103 173 107 167
143 167 136 133 154 159 164 139 157 154 192 178 193 173 155 140 147 120 99 83
121 117 131 97 110 156 142 154

OTI-B13B 68
132 117 77 102 112 115 108 90 80 98 122 52 117 89 131 111 95 102 154 145
144 121 140 109 116 101 35 42 33 51 50 53 58 68 78 100 111 146 130 169

139 163 132 129 163 150 160 132 167 156 192 180 196 156 132 137 157 124 83 71
132 122 119 107 108 156 143 152

OTI-B14A 55
413 419 316 271 333 264 242 237 230 183 219 217 335 548 555 423 422 295 266 274
423 292 242 339 234 259 215 159 179 201 139 170 213 289 328 526 421 376 398 406
281 290 215 215 205 256 284 230 284 234 228 296 196 181 229

OTI-B14B 55
415 409 331 321 359 235 219 210 264 207 219 216 345 534 560 439 415 330 265 274
407 297 254 340 242 250 217 164 168 201 140 157 231 268 335 539 403 367 407 403
287 290 212 212 194 234 283 225 294 253 246 290 205 167 221

OTI-B17A 138
335 324 331 312 439 498 285 509 471 360 364 453 203 85 78 130 169 200 177 252
268 246 195 181 213 221 240 301 278 250 192 156 188 164 164 205 229 231 225 275
248 167 178 109 137 143 187 204 162 189 240 322 277 278 265 250 180 191 191 151
168 140 144 208 125 184 178 187 156 131 195 257 225 190 187 192 220 99 135 109
129 95 150 140 180 133 141 228 176 161 215 196 146 181 194 178 184 218 165 137
225 165 159 193 75 65 39 57 67 88 113 79 151 188 203 181 112 65 27 48
92 84 138 165 159 228 118 124 118 110 76 54 53 128 103 170 124 150

OTI-B17B 138
326 331 318 309 483 512 281 505 476 351 362 451 193 87 78 128 167 200 181 256
277 242 198 178 218 225 237 302 274 245 209 160 190 159 168 190 234 245 229 264
249 153 179 110 132 146 190 201 170 193 222 326 273 289 253 250 172 187 203 159
160 148 150 190 127 177 175 181 159 131 202 259 218 187 193 188 221 104 147 108
117 98 150 134 167 131 146 231 183 161 215 193 141 190 182 189 175 223 162 149
218 160 158 176 78 68 34 52 63 91 130 59 138 200 215 189 100 65 36 59
87 90 123 152 159 221 100 135 140 102 75 51 81 105 102 178 125 151

OTI-B18A 50
89 122 175 126 174 220 186 82 128 225 196 214 173 215 168 139 103 139 191 139
64 59 60 123 121 124 340 302 270 271 253 182 134 153 217 250 349 342 321 275
253 229 231 298 289 183 170 207 194 180

OTI-B18B 50
89 125 169 118 182 224 194 80 125 224 199 214 182 210 167 139 95 147 178 132
63 56 62 128 121 115 336 298 268 274 240 165 146 122 254 269 358 326 310 290
254 236 217 343 317 187 134 190 228 189

OTI-B19A 53
279 338 450 493 374 259 136 212 217 116 100 69 60 99 296 246 225 167 151 150
185 198 253 261 189 100 96 54 89 125 155 158 125 131 83 152 221 204 206 261
223 184 149 214 207 210 137 73 120 155 131 140 131

OTI-B19B 53
275 328 453 499 375 246 112 201 221 114 94 64 67 98 287 251 218 182 139 146
183 191 258 264 182 105 76 46 71 103 112 134 107 144 67 156 232 200 217 257
229 198 142 210 210 217 139 73 118 170 118 150 128

OTI-B20A 56
265 168 184 94 148 178 139 152 84 60 71 66 123 114 122 116 120 80 100 92
143 192 164 150 196 57 71 78 64 65 53 42 74 100 135 109 126 236 308 179
107 201 232 148 103 148 134 140 117 177 153 131 73 92 81 123

OTI-B20B 56
263 167 169 86 185 177 144 162 96 71 73 81 121 126 108 130 110 74 121 87
131 186 181 171 225 71 65 78 67 71 53 44 89 122 132 99 129 216 271 222
125 204 228 157 101 151 139 114 133 177 153 128 75 87 92 128
OTI-B23A 52
159 151 270 201 244 169 218 218 235 259 250 214 367 220 232 194 210 199 214 172

242 200 192 157 147 109 140 138 116 98 85 116 99 128 131 129 148 190 151 162
143 123 150 150 136 150 118 148 150 159 177 145

OTI-B23B 52
154 156 279 218 255 134 227 216 235 268 237 214 371 214 233 186 220 198 209 178
242 207 186 157 142 113 137 150 113 96 84 123 96 117 133 135 138 196 153 157
176 134 139 174 143 160 109 143 142 154 195 143

OTI-B24A 50
401 510 541 710 522 387 421 416 453 514 389 387 408 385 365 331 350 304 334 275
209 209 185 221 189 230 281 256 203 221 242 284 285 306 243 189 185 229 221 203
202 171 192 143 133 161 157 162 163 181

OTI-B24B 50
399 520 550 719 526 394 421 405 453 524 392 385 391 400 367 331 354 288 305 268
209 209 189 228 181 231 296 253 198 215 246 282 267 319 247 185 186 238 209 203
203 179 176 178 117 146 151 137 171 183

TI-B25A 57
185 108 123 112 118 103 83 83 121 73 104 104 125 150 284 376 259 326 314 291
317 385 404 348 433 357 329 307 333 273 250 214 228 244 264 282 257 271 211 236
210 248 231 189 193 151 201 195 143 200 140 171 192 209 183 173 198

OTI-B25B 57
183 114 121 109 125 104 89 81 120 66 115 93 130 142 303 370 268 321 319 307
323 380 422 357 431 359 326 303 330 276 258 215 242 240 256 282 251 264 210 239
210 246 237 190 198 154 196 207 148 185 145 178 192 196 196 164 187

OTI-B27A 79
202 165 154 186 261 280 257 246 255 242 231 307 251 292 300 232 192 199 202 85
62 62 73 89 125 171 189 250 299 194 207 169 107 112 96 117 173 135 212 190
173 156 246 309 251 148 235 176 136 142 79 63 53 54 67 81 105 131 162 203
184 162 159 86 40 34 40 62 71 115 145 173 134 151 153 140 155 200 221

OTI-B27B 79
199 164 154 187 261 287 261 245 253 237 226 305 250 282 311 226 197 214 202 82
60 67 74 82 129 170 187 252 296 192 207 167 106 115 93 115 170 134 212 197
166 158 243 307 242 153 238 178 132 137 77 63 50 59 64 79 97 132 164 206
190 156 150 84 49 37 45 51 73 119 148 170 131 149 153 125 157 185 221

OTI-B28A 114
244 292 293 319 293 274 353 310 364 323 321 242 318 211 241 358 296 359 375 396
226 238 237 337 217 275 248 208 217 162 150 107 103 162 212 188 153 202 234 212
188 75 45 37 46 51 71 87 89 91 118 120 117 68 56 46 41 42 54 84
93 87 103 85 126 59 20 17 48 65 87 85 75 77 115 115 136 186 187 203
218 163 271 158 184 140 187 151 140 193 256 246 203 160 178 208 159 61 44 50
54 56 53 64 84 64 121 93 112 102 101 107 133 147

OTI-B28B 114
250 288 305 303 271 225 341 323 355 343 351 247 312 210 242 334 296 346 367 401
225 246 231 334 237 244 264 205 211 174 146 108 124 184 216 189 153 191 239 199
181 79 44 37 48 53 65 92 79 98 121 127 111 77 42 37 37 49 52 82
98 90 103 85 128 53 20 14 43 71 92 78 75 79 114 118 137 184 185 200
220 161 270 159 187 137 184 153 143 187 253 243 206 165 178 211 149 61 48 49
60 53 57 65 82 67 114 92 110 106 100 110 128 150

OTI-B30A 111
56 35 67 139 120 64 154 149 86 120 185 191 200 247 200 189 91 53 37 67
130 216 211 219 244 220 169 173 198 218 184 171 146 182 171 141 147 124 236 128
152 142 120 112 154 139 179 129 143 100 131 98 121 115 109 93 70 80 114 125
89 96 121 113 79 67 93 98 76 104 104 103 110 81 104 93 87 85 96 77
72 92 117 79 100 89 77 185 127 167 171 264 187 140 142 181 178 229 236 161

268 273 266 330 274 185 174 166 121 112 137

OTI-B30B 111
56 36 68 142 122 67 143 129 95 127 181 184 198 250 195 172 98 55 39 66
146 223 226 221 235 205 180 167 202 227 179 169 148 185 167 142 153 122 231 132
153 138 121 114 148 143 171 137 140 107 131 96 111 118 106 76 62 78 104 121
95 93 126 112 86 60 93 101 75 97 110 101 112 81 105 95 89 85 90 84
71 96 112 73 89 85 84 188 136 176 167 266 184 145 146 176 163 237 250 168
275 274 271 327 271 179 166 143 116 109 137

OTI-B31A 126
351 438 317 245 320 197 247 168 200 207 210 217 261 341 164 148 146 110 75 111
114 150 128 137 143 121 196 96 73 75 96 111 114 110 140 135 145 146 166 210
253 214 198 196 210 194 220 229 167 199 187 232 187 182 167 185 173 243 256 281
209 243 187 278 213 200 212 288 283 194 195 264 319 217 220 305 468 439 465 421
368 396 253 334 285 257 284 284 228 204 240 226 175 162 212 193 74 50 53 65
80 78 57 60 79 112 145 150 140 215 259 234 275 275 200 275 340 110 164 118
209 152 159 201 168 209

OTI-B31B 126
347 440 313 242 313 201 255 174 192 216 212 214 274 337 165 150 138 113 82 107
117 150 128 136 139 124 194 91 74 74 98 112 114 110 142 148 139 150 160 210
253 222 196 192 218 185 203 246 165 196 177 239 189 185 181 177 170 248 252 290
201 243 191 282 214 193 209 279 287 192 193 262 321 234 219 306 478 431 460 425
347 378 257 340 277 270 279 270 234 206 240 228 178 175 206 187 81 55 47 67
78 75 65 55 73 118 152 144 135 224 253 235 265 284 207 313 338 128 143 131
205 152 150 203 160 211

OTI-B32A 96
248 328 216 305 242 280 268 234 252 319 366 284 263 301 301 212 192 250 408 444
442 351 325 432 268 321 225 217 271 245 220 181 234 250 195 229 242 193 90 54
65 57 57 56 42 57 45 64 79 75 64 106 241 200 343 321 264 331 368 109
118 94 193 195 195 165 134 196 179 259 218 203 131 363 284 354 309 235 140 111
174 178 206 179 237 208 159 160 170 125 148 152 166 170 170 199

OTI-B32B 96
244 335 222 304 235 280 276 231 250 324 351 288 276 309 319 210 178 234 396 426
450 338 323 431 260 318 240 209 251 251 229 189 251 239 195 228 259 181 92 49
66 58 57 50 46 53 50 64 71 80 69 107 250 206 343 315 266 328 379 128
100 101 185 178 165 175 151 193 167 246 237 209 120 365 278 360 308 245 144 98
173 190 201 181 234 215 138 158 199 107 140 152 159 165 167 210

OTI-B33A 140
352 418 365 376 315 281 368 194 368 341 414 332 306 468 389 325 283 286 392 314
184 190 253 232 264 175 183 161 168 190 168 181 184 216 197 187 232 220 243 178
221 243 265 245 253 124 81 51 54 68 70 87 79 79 78 46 50 75 66 67
79 78 87 109 103 139 71 46 42 81 77 75 103 136 124 141 171 122 118 137
109 146 102 137 143 153 127 125 152 126 118 65 59 67 81 66 64 97 130 106
125 69 49 65 81 103 153 162 121 109 179 144 141 221 146 158 103 146 168 107
142 125 138 103 70 84 93 87 89 102 121 75 103 114 116 118 65 56 55 82

OTI-B33B 140
342 415 379 383 310 289 367 207 370 332 429 313 266 457 410 325 271 306 410 298
184 190 245 226 251 178 179 168 172 187 168 180 189 205 203 195 229 229 237 171
229 235 264 253 251 118 84 54 54 62 70 87 73 84 69 40 62 69 65 71
81 84 80 107 112 152 75 44 43 76 74 81 108 132 125 136 178 123 112 131
116 149 101 137 149 153 110 121 152 125 123 66 64 63 78 56 72 100 131 105
124 66 59 55 91 108 160 169 108 115 181 148 143 221 152 144 118 143 168 97
149 125 140 109 56 90 85 89 87 109 103 71 104 110 114 126 73 48 53 81

OTI-B34A 118
294 345 581 373 387 321 411 337 335 375 339 346 430 493 425 382 122 144 153 235

139 252 255 204 170 370 363 434 437 307 139 179 198 253 123 179 145 92 106 88
87 303 376 214 251 280 153 68 84 210 252 284 278 195 248 298 213 179 184 180
316 174 184 147 200 187 143 71 39 38 47 39 21 29 49 78 39 101 123 110
177 140 236 313 258 180 315 268 113 203 296 74 61 44 38 71 48 86 91 111
90 98 93 84 73 236 190 270 469 344 248 221 272 334 333 225 407 655

OTI-B34B 118
340 371 480 362 373 303 384 331 347 392 346 312 427 499 428 398 151 142 144 229
139 234 261 212 175 385 378 403 428 292 132 186 199 246 128 171 170 98 101 89
79 312 393 208 250 283 154 70 92 203 235 293 281 196 242 307 212 196 196 193
312 176 162 140 203 196 134 68 46 34 41 37 29 28 54 78 37 102 118 114
171 146 236 313 259 170 287 277 115 192 304 71 61 37 40 77 59 76 92 113
89 89 96 82 77 234 195 268 468 355 256 234 250 333 277 279 359 651

OTI-B35A 154
397 266 212 182 330 210 213 244 221 192 158 134 128 122 142 156 164 170 196 182
160 130 67 51 36 53 52 82 85 89 89 96 96 82 46 34 30 39 21 48
53 47 60 63 69 97 33 46 61 192 155 157 118 112 137 185 184 198 232 198
181 198 159 198 139 212 151 142 160 123 246 250 226 210 175 232 237 123 65 65
70 82 85 67 73 93 70 114 76 89 94 85 110 132 153 168 129 181 150 124
137 131 195 179 292 84 53 51 71 81 106 68 126 116 185 84 65 52 48 75
87 83 123 133 140 133 125 129 49 37 43 46 40 40 71 109 114 110 125 154
137 115 162 129 162 92 65 84 78 71 88 92 84 121

OTI-B35B 154
392 263 203 184 335 206 213 250 216 200 162 135 123 125 142 157 164 172 187 185
165 129 70 42 39 52 57 76 92 88 78 102 103 82 41 33 26 43 31 42
50 57 57 60 65 88 39 36 64 211 166 171 123 120 146 198 178 212 218 184
187 200 170 209 140 215 160 140 146 117 242 248 217 206 182 254 223 126 67 67
69 81 84 68 75 82 81 110 79 85 96 85 108 139 149 164 133 181 150 117
139 134 193 184 289 86 51 54 71 77 109 62 127 117 194 74 70 56 45 76
85 85 123 132 145 134 119 125 44 41 39 53 29 39 57 104 117 90 133 164
132 124 166 127 168 96 59 80 87 71 91 85 85 123

OTI-B36A 84
326 242 290 257 293 282 232 380 367 409 263 248 355 358 171 155 219 294 299 363
389 368 381 285 256 204 206 260 239 220 184 262 301 251 301 268 306 143 96 109
115 137 118 90 93 95 123 100 126 93 139 157 154 226 209 131 198 224 160 141
138 173 201 181 200 143 221 181 236 190 184 160 196 190 209 273 281 224 218 280
228 249 207 334

OTI-B36B 84
324 245 281 225 297 277 237 396 347 409 314 241 352 337 166 139 226 283 289 371
408 367 381 197 277 211 200 259 226 220 173 303 298 240 295 282 287 139 93 115
125 127 120 85 96 93 121 96 132 91 137 154 150 232 209 139 192 227 173 138
143 159 184 156 218 150 215 187 258 196 175 177 231 191 197 270 271 217 203 281
237 240 218 336

OTI-B37A 90
272 312 309 336 318 337 223 271 258 287 255 242 353 282 323 277 235 307 310 175
160 224 266 268 297 279 246 262 193 304 200 229 268 273 285 240 382 332 260 281
289 239 132 71 68 89 89 66 81 98 87 112 126 149 100 142 143 162 253 206
153 208 232 119 141 112 215 200 209 271 194 234 175 265 202 196 179 266 187 213
249 221 167 203 252 212 284 230 243 271

OTI-B37B 90
280 316 307 335 321 337 225 266 261 275 257 248 296 280 318 289 232 296 312 176
160 217 264 269 300 296 239 275 200 299 214 225 260 273 285 245 370 331 267 281
296 229 132 73 73 78 94 60 84 98 92 107 128 149 97 142 140 167 255 197
155 206 239 118 137 118 244 215 209 271 191 212 168 250 209 219 183 256 253 219
246 241 148 206 244 250 238 222 270 270

OTI-B38A 154
445 529 401 339 319 462 371 446 444 287 268 280 159 207 207 185 203 221 182 264
200 164 138 195 170 267 222 215 287 167 232 176 298 281 243 258 272 273 187 257
198 170 237 281 235 282 140 68 67 70 75 120 179 128 141 175 140 225 244 305
303 266 296 328 218 240 161 154 168 89 38 30 37 31 37 43 38 31 40 78
106 100 101 78 90 105 90 127 128 140 123 125 134 168 187 203 165 101 95 38
82 54 43 32 54 46 60 85 93 75 103 63 117 126 136 96 109 121 74 97
105 60 48 37 36 46 36 41 42 59 58 92 96 64 50 159 87 163 115 155
140 103 103 112 94 149 140 156 140 142 129 80 50 76

OTI-B38B 154
438 538 401 325 316 433 425 446 454 283 260 287 151 196 205 175 207 231 178 253
206 150 142 178 180 267 223 218 290 179 231 162 282 289 240 251 259 275 195 243
195 151 256 285 228 300 140 78 65 60 73 114 194 141 139 170 151 216 243 306
311 277 292 321 229 236 161 162 161 81 28 35 39 35 41 54 45 32 34 81
101 104 96 87 90 105 88 131 125 138 122 134 128 171 183 203 160 106 93 49
71 57 37 39 50 48 62 83 88 86 94 68 111 132 134 96 115 113 68 100
109 62 42 35 37 52 34 40 41 59 59 93 96 62 50 156 87 167 106 159
133 108 104 104 105 137 137 159 148 139 128 81 59 79

OTI-B39A 106
147 145 171 183 86 62 44 35 54 80 152 115 130 165 154 241 264 273 257 191
193 230 137 221 131 142 155 69 35 50 42 43 33 56 50 29 38 80 113 126
124 94 103 109 92 126 137 143 103 143 103 170 195 220 164 93 78 48 76 64
52 42 67 75 88 102 96 92 117 105 130 139 153 110 128 121 85 115 126 78
78 54 50 95 53 57 59 84 84 131 109 84 73 138 111 134 98 120 128 134
104 115 120 112 137 164

OTI-B39B 106
144 147 168 184 83 66 40 38 45 80 159 115 126 167 150 249 245 271 251 187
194 239 146 225 134 152 138 74 40 42 50 31 44 55 62 31 42 82 113 133
113 92 100 110 85 122 139 137 106 123 114 182 219 222 164 79 86 43 81 60
57 35 67 79 89 104 96 87 120 113 131 131 137 113 125 124 83 120 123 85
73 55 64 81 51 50 75 70 90 132 117 78 67 139 106 128 101 123 133 137
103 107 120 117 132 196

OTI-B40A 197
231 318 221 247 312 253 197 244 139 105 58 123 159 187 180 272 335 222 173 136
185 255 344 107 186 154 192 135 148 116 146 124 142 144 185 270 243 250 325 248
212 214 248 225 181 173 200 315 325 115 46 54 70 76 70 95 98 100 125 132
80 72 75 71 68 64 81 124 139 95 96 73 48 45 37 63 100 89 81 50
54 73 74 116 75 80 86 78 103 57 36 29 31 21 34 40 43 41 46 47
35 56 57 62 59 103 100 93 103 128 161 147 213 203 71 78 62 42 62 53
79 89 59 86 88 100 81 58 93 62 30 71 71 88 58 40 33 33 20 28
31 46 54 40 59 60 59 59 53 31 30 59 47 68 41 65 87 83 100 67
33 42 59 57 52 49 54 62 42 37 33 44 62 46 38 55 78 51 71 68
50 61 28 43 47 62 49 43 53 57 68 58 54 62 56 43 71

OTI-B40B 197
229 279 223 260 299 259 231 217 123 96 53 150 141 169 178 265 349 225 177 146
175 260 339 128 175 178 180 121 145 120 149 139 146 121 206 271 240 234 337 271
211 223 251 230 191 195 226 334 318 116 54 56 58 84 65 92 90 123 112 135
78 68 79 69 71 60 89 117 144 91 101 68 46 44 43 73 90 84 85 42
62 72 80 115 67 75 88 89 109 64 41 40 27 31 28 31 39 46 34 43
40 56 51 59 62 103 99 103 103 132 171 146 203 212 65 71 65 37 60 53
85 87 57 91 87 98 81 58 88 65 34 70 68 84 59 37 31 37 20 31
34 46 51 36 62 59 68 59 41 30 34 59 46 62 46 69 87 90 88 73
46 43 47 52 59 47 54 65 37 43 39 35 64 50 46 41 68 56 71 60
62 56 36 40 46 58 50 54 50 47 66 67 52 54 46 62 68

OTI-B41A 62
340 438 351 363 340 405 353 400 405 369 371 429 361 197 150 196 232 217 121 85

39 43 65 93 130 121 181 214 168 186 199 206 193 193 185 221 240 81 40 58
70 60 89 107 78 80 81 112 106 128 65 43 43 50 48 50 69 88 50 85
103 162

OTI-B41B 62
344 401 306 366 349 410 353 391 405 378 379 385 375 194 126 188 218 221 132 74
42 42 64 89 128 124 173 217 170 185 210 198 201 196 182 220 239 85 46 46
67 70 98 109 65 78 89 96 112 145 56 44 40 37 51 62 63 89 53 81
109 168

OTI-B44A 44
235 206 171 261 276 272 192 191 192 214 191 142 412 295 152 186 228 432 330 297
257 285 309 320 343 238 223 275 163 187 314 298 356 195 145 174 195 310 365 456
379 418 176 166

OTI-B44B 44
230 205 163 266 275 268 190 203 193 209 184 148 409 295 143 168 221 431 317 303
239 305 305 334 346 245 245 270 176 198 262 276 343 191 151 184 220 300 364 431
354 428 195 167

OTI-B45A 55
171 156 181 149 121 264 250 166 167 176 337 360 409 347 351 405 375 421 390 318
292 192 189 199 322 230 117 120 126 144 179 276 267 246 185 143 109 107 150 200
186 251 193 286 207 253 204 231 282 221 192 189 202 189 184

OTI-B45B 55
169 156 176 144 121 249 254 146 192 194 323 344 384 350 338 379 385 439 375 307
301 198 198 197 318 226 117 104 108 139 203 278 256 242 192 143 117 104 148 200
179 258 188 312 209 245 193 225 301 199 195 182 201 195 190

OTI-B46A 106
330 200 230 236 276 195 266 253 412 392 182 66 58 57 83 70 109 140 154 134
191 74 74 60 86 75 71 106 169 227 192 199 132 75 60 53 114 180 146 149
88 100 120 132 165 143 116 148 159 195 93 78 48 29 32 42 46 56 64 63
52 56 65 67 54 78 84 114 83 120 146 150 129 258 225 85 71 68 40 81
78 104 120 95 121 115 118 101 86 90 78 54 84 75 115 98 67 45 40 32
28 48 63 88 93 81

OTI-B46B 106
331 198 236 234 276 207 261 263 411 393 181 66 66 57 75 78 109 138 157 136
201 76 78 78 68 78 75 89 175 225 189 195 124 71 57 53 135 196 146 147
82 106 120 132 173 134 132 138 165 189 85 73 51 26 35 37 47 60 73 54
56 48 67 68 56 76 84 114 92 115 139 154 128 271 221 84 70 71 47 74
73 107 111 106 128 118 112 103 89 102 82 53 92 71 125 83 73 46 43 31
29 51 60 87 94 83

OTI-B47A 51
206 309 229 123 144 177 155 92 67 74 97 101 293 150 372 300 259 159 120 92
85 56 126 105 158 99 107 89 64 103 184 340 253 323 432 164 142 206 203 371
392 456 295 209 104 160 203 303 381 409 248

OTI-B47B 51
200 305 236 121 138 182 156 83 62 91 100 98 287 162 360 305 260 162 115 96
89 60 117 110 157 100 103 93 57 107 184 351 238 316 431 167 149 215 191 351
412 459 295 206 126 176 220 274 400 400 246

OTI-B48A 166
127 104 148 136 184 150 204 200 246 279 254 259 284 217 146 117 126 167 192 78
61 45 49 54 68 74 79 90 75 96 42 60 60 78 78 89 90 109 139 107
111 71 43 31 30 44 65 51 45 28 46 71 67 85 92 98 110 146 143 79
42 43 33 41 45 46 62 56 51 54 48 53 60 53 45 78 82 64 82 117
106 123 180 179 73 75 60 48 56 52 61 63 51 79 59 90 85 72 96 95

49 89 84 101 54 56 43 32 25 42 49 65 68 57 71 87 62 76 51 34
46 75 73 60 51 81 95 87 98 106 34 54 46 65 59 57 50 76 54 41
48 56 81 76 53 48 89 65 70 66 66 57 49 44 50 49 44 43 47 49
71 70 75 70 92 93

OTI-B48B 166
131 106 153 133 185 150 196 209 234 301 244 264 278 214 150 115 129 164 199 83
67 50 43 51 53 80 71 94 72 93 46 53 71 87 89 81 99 110 140 110
113 78 39 32 29 53 60 47 42 32 43 67 71 84 87 95 113 139 134 71
45 39 37 40 45 49 56 59 50 56 48 54 60 51 45 79 78 70 82 117
110 120 160 209 68 73 59 43 67 51 62 65 48 79 61 84 79 70 90 80
48 95 73 112 53 51 48 32 26 35 52 59 76 62 62 88 71 62 48 45
43 66 70 65 54 71 100 90 92 87 45 55 44 62 60 60 54 73 54 42
45 56 78 76 43 53 90 65 73 62 71 48 47 43 52 46 40 47 46 56
83 63 71 78 84 96

OTI-B49A 57
130 166 173 247 201 174 134 187 157 143 166 119 185 142 93 96 115 214 153 178
150 142 120 196 244 264 214 224 96 228 135 184 189 232 149 86 100 146 182 176
164 105 75 82 78 135 145 150 117 117 121 101 160 158 182 248 260

OTI-B49B 57
125 166 179 250 184 186 170 182 167 143 157 128 175 155 80 94 110 208 153 185
165 154 136 171 248 264 211 228 97 225 141 188 207 200 125 83 110 134 210 196
178 89 78 90 68 126 156 146 109 128 117 114 178 153 185 239 273

OTI-B50A 120
244 282 323 284 251 191 243 387 312 101 83 41 50 64 68 73 66 80 72 100
71 62 60 65 64 58 69 98 103 101 81 46 31 20 31 29 57 47 48 29
72 74 53 103 76 82 85 75 115 48 31 34 35 35 36 39 50 49 54 59
43 67 82 67 71 87 101 79 100 120 112 123 215 107 35 46 51 35 62 92
112 140 123 156 148 220 129 168 132 101 57 98 95 91 60 49 35 42 21 27
39 48 59 74 70 78 102 79 48 49 56 86 77 96 64 93 114 104 97 80

OTI-B50B 120
239 280 309 277 259 189 239 364 317 101 69 53 44 62 66 67 67 78 69 96
78 67 60 64 60 58 77 96 96 98 83 42 28 25 31 29 54 51 46 29
57 80 55 107 71 80 76 82 110 44 35 33 38 37 38 38 50 47 56 60
42 65 80 60 60 89 103 83 92 114 112 129 215 115 43 40 52 61 65 82
112 139 125 160 148 215 130 170 131 101 65 93 90 96 62 46 40 38 23 23
41 49 62 68 56 72 107 76 43 51 48 72 76 76 65 89 118 84 107 70

OTI-B51A 63
212 245 201 103 71 160 256 217 190 242 169 186 72 101 135 171 180 134 222 141
84 121 120 217 225 188 185 171 112 203 196 271 220 296 145 268 220 234 231 248
111 51 98 143 123 159 131 63 47 37 40 45 117 131 126 101 101 95 114 132
114 78 105

OTI-B51B 63
199 244 203 121 74 177 175 225 189 244 162 176 92 101 155 144 159 142 253 150
90 148 155 221 204 202 200 176 113 209 189 280 232 309 178 239 203 229 239 256
109 52 95 131 162 136 118 65 46 32 28 48 104 136 157 112 123 95 98 134
125 84 99

Oxygen Isotope data

Oxygen isotope ratios ($\delta^{18}O$) for the measured tree ring series. Data are reported as per mille (‰) deviations relative to the VSMOW standard (Coplen 1995).

Sample OTI-B01i (NB: Rings 0-9 omitted from analyses due to potential contamination)

Ring	$\delta^{18}O$	Ring	$\delta^{18}O$
0	-		
1	-	31	28.92
2	-	32	28.88
3	-	33	28.35
4	-	34	27.69
5	-	35	27.61
6	-	36	27.81
7	-	37	27.73
8	-	38	27.63
9	-	39	27.71
10	28.92	40	28.91
11	28.42	41	27.77
12	29.12	42	27.82
13	28.45	43	28.23
14	27.69	44	28.09
15	28.72	45	28.04
16	27.72	46	28.05
17	28.20	47	27.90
18	28.29	48	28.10
19	27.53	49	27.65
20	27.69	50	28.06
21	27.36	51	29.48
22	28.62		
23	27.20		
24	27.61		
25	28.97		
26	27.21		
27	27.87		
28	27.07		
29	29.22		
30	30.59		

Sample OTI-B14i

Ring	$\delta^{18}O$	Ring	$\delta^{18}O$
0	28.05		
1	28.96	31	28.72
2	27.20	32	29.10
3	29.52	33	30.02
4	28.82	34	32.37
5	28.22	35	29.20
6	28.95	36	29.41
7	28.81	37	29.57
8	28.16	38	29.58
9	28.04	39	28.70
10	28.51	40	28.95
11	28.06	41	28.08
12	29.86	42	28.25
13	28.72	43	28.63
14	29.54	44	30.08
15	29.33	45	29.02
16	30.44	46	29.24
17	29.61	47	28.49
18	29.64	48	28.33
19	29.83	49	29.23
20	28.29	50	28.96
21	29.14	51	29.24
22	29.25	52	28.04
23	28.60	53	27.53
24	29.20	54	27.80
25	27.95		
26	29.51		
27	27.76		
28	28.44		
29	29.77		
30	28.25		

APPENDIX: TREE-RING DATING

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 Building* (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	

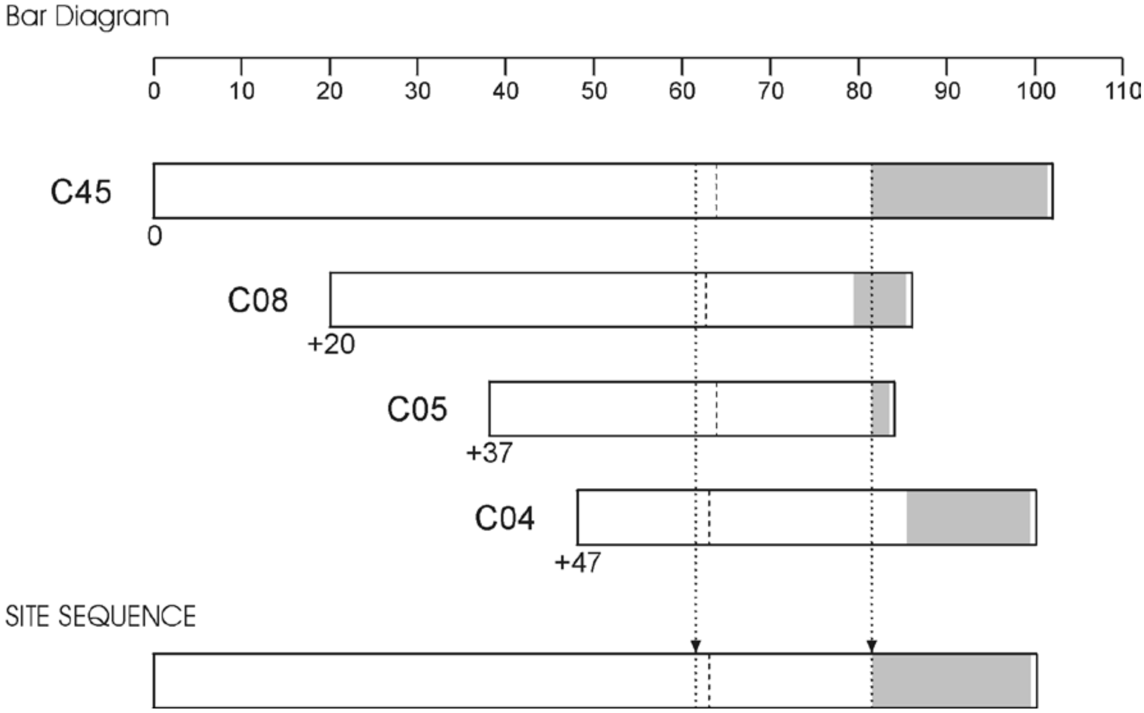


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

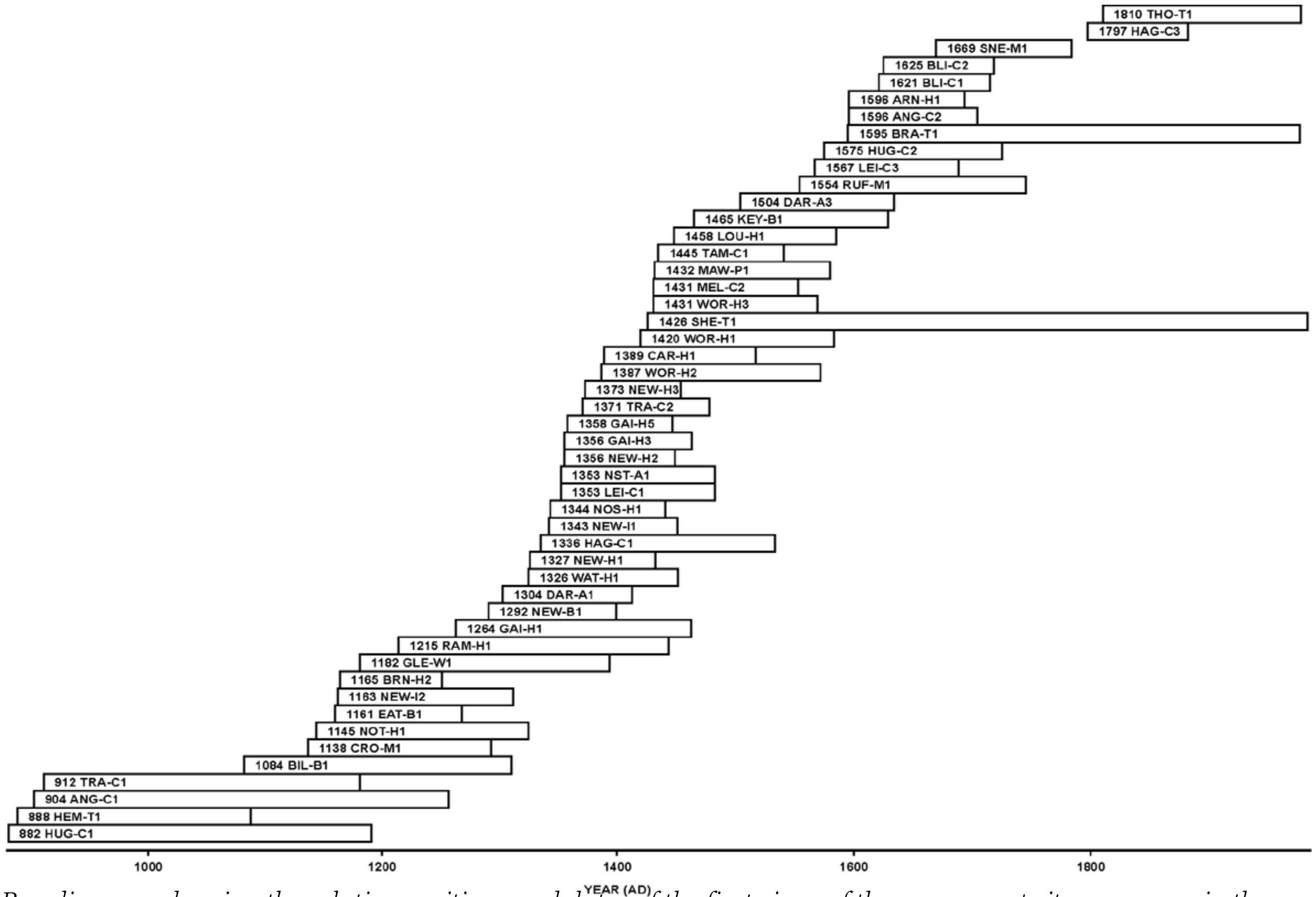
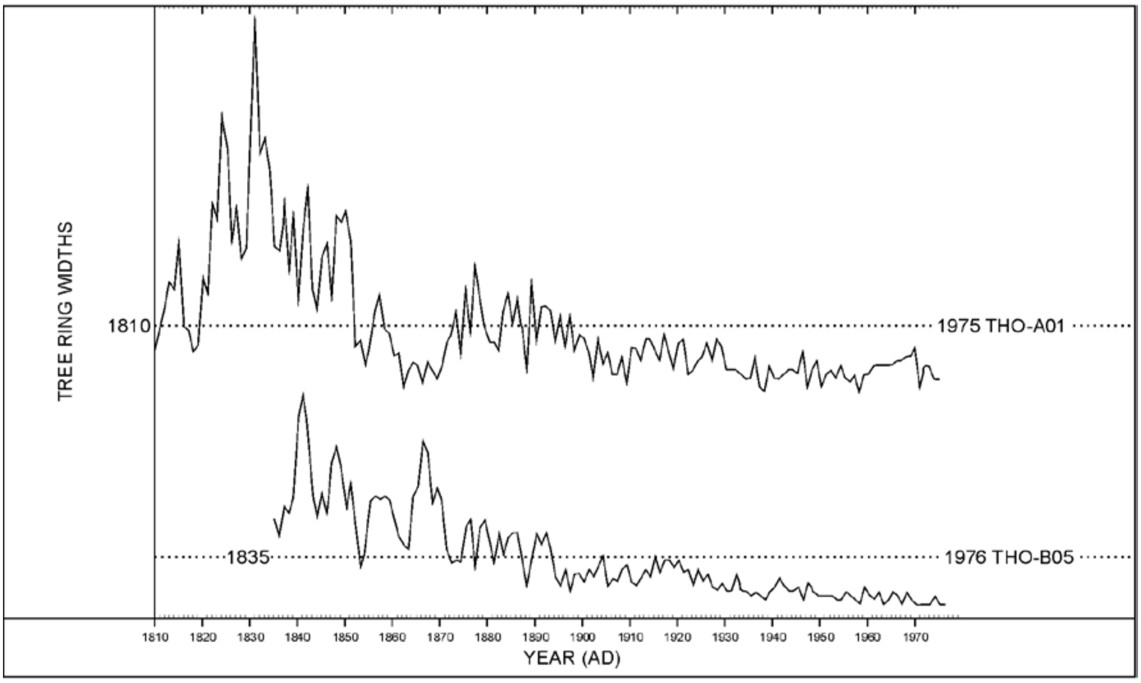


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

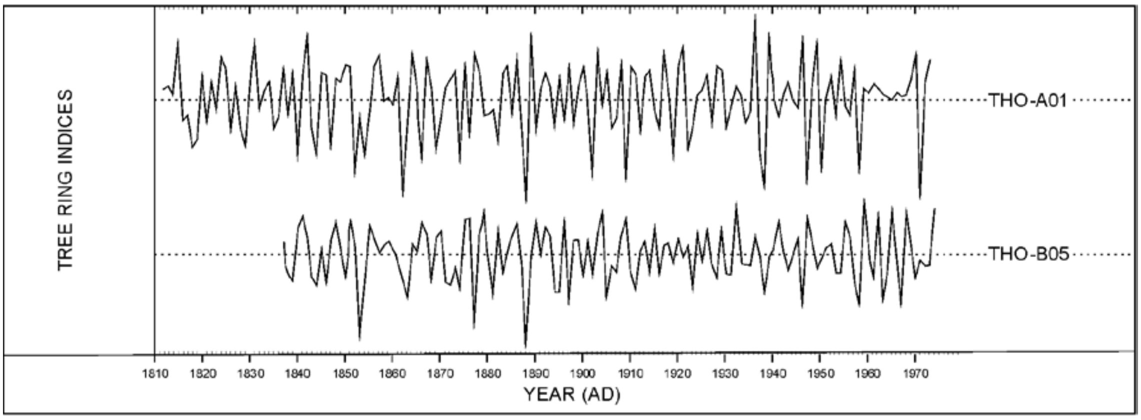


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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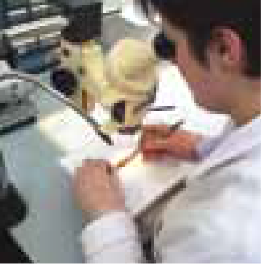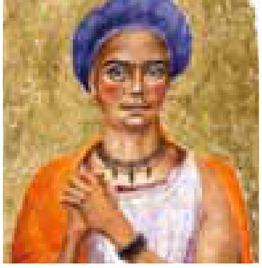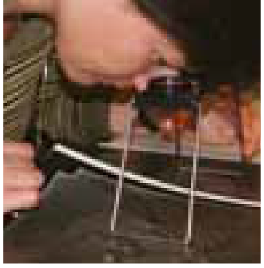

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