Research Report Series 78/2023

The Cedars, 1A & 3 New Road, North Walsham, Norfolk

Tree-ring analysis and radiocarbon wiggle-matching of oak timbers

Alison Arnold, Robert Howard, Cathy Tyers, Michael Dee, Bisserka Gaydarska and Peter Marshall

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Summary

Dendrochronological analysis was undertaken on two samples taken from principal rafters at this building. The two principal rafters are shown to be coeval but the two-timber site sequence, NHWCSQ01, could not be securely matched with the reference chronologies. Radiocarbon dating was undertaken on five single-ring samples from a timber in the site master chronology. Wiggle-matching of these results suggests that the final ring of this site master chronology formed in *cal AD 1648–1668* (*95% probability*) or *cal AD 1652–1662* (*68% probability*). This is compatible with the tentative dating produced for the site master chronology by ring-width dendrochronology, which suggests that it spans AD 1589–1656. The tentative tree-ring date can only be accepted because it is supported independently by the radiocarbon wiggle-matching, but together they suggest that the timber represented in site master chronology was felled in AD 1657–80$_{\mathrm{DR}}$.

Contributors

Alison Arnold, Robert Howard, Cathy Tyers, Michael Dee, Bisserka Gaydarska and Peter Marshall.

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Front cover image

[DP278235], taken by Patricia Payne on the 7th October 2020, shows North Walsham High Street Heritage Action Zone, The Cedars, New Road, North Walsham, Norfolk. View from south south-east © Historic England Archive

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Introduction

North Walsham High Street Heritage Action Zone

North Walsham, located some 24km north of Norwich (Fig 1) has just over 100 listed buildings which is the highest number of any town in North Norfolk, with most of these thought to date from the 18th and early 19th centuries. The town was badly damaged by a fire on 25 June AD 1600, but fabric pre-dating this event is believed to survive, possibly in cellars and around the Market Place. The town (HSEE014) is one of over 60 successful High Street Heritage Action Zones (HSHAZ) bids selected in AD 2019, which are being delivered by Historic England, in partnership with local bodies, to unlock potential of high streets across England, fuelling economic, social and cultural recovery. Dendrochronology is one of the supporting elements to the HSHAZ programme, as part of improving the understanding of the town centre area to inform and support future planning and improvement decisions. The centre of North Walsham was designated as a conservation area in AD 1972, with the area being extended in AD 2009.

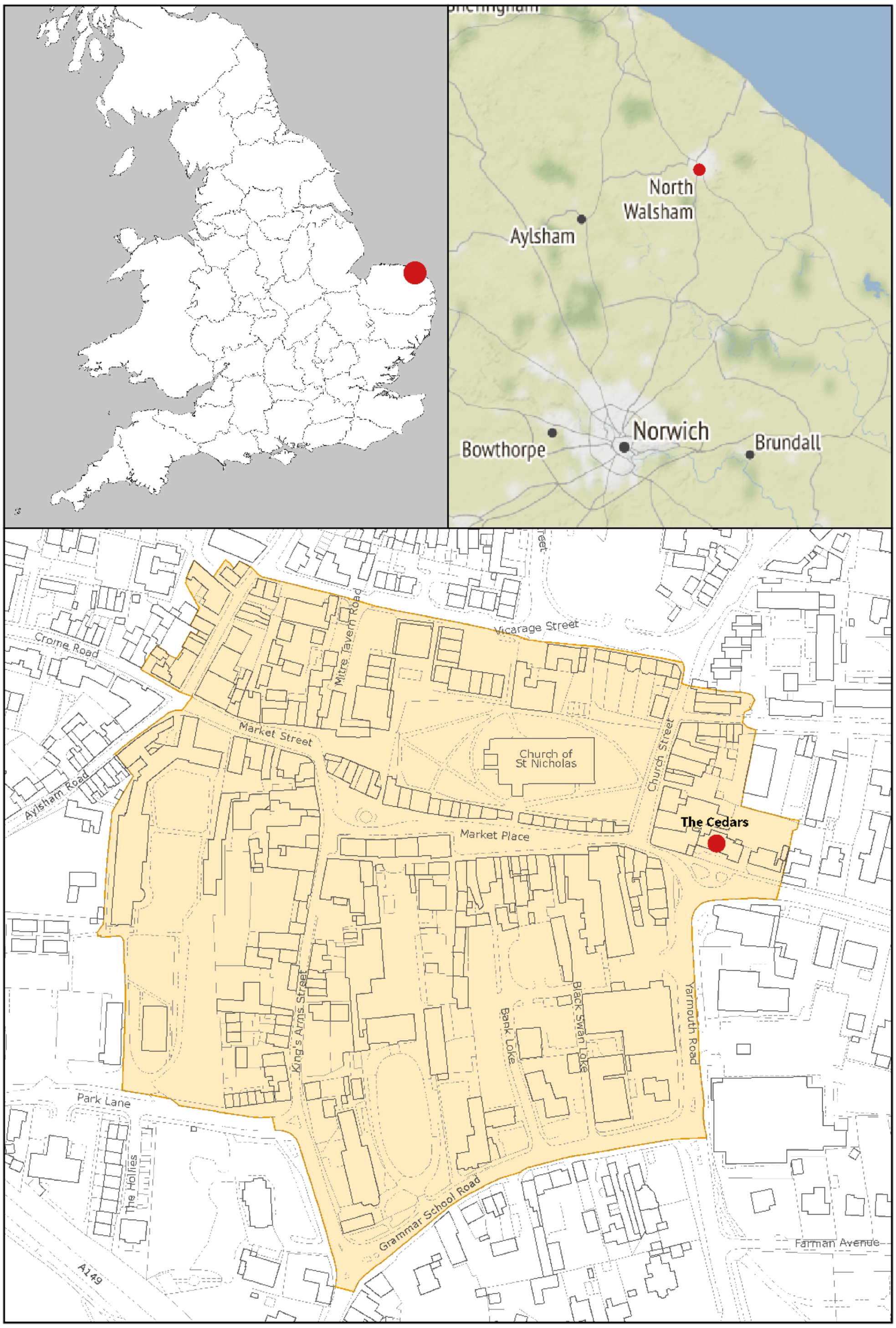

Figure 1: Maps to show the location of North Walsham (red dot), and The Cedars within the North Walsham conservation Area. Scale: top right 1:25000; bottom 1:2000. © Crown Copyright and database right 2023. All rights reserved. Ordnance Survey Licence number 100024900

The Cedars

This Grade II listed building, currently listed as Urban District Council Offices (https://historicengland.org.uk/listing/the-list/list-entry/1039484) and formerly known as The Cedane, is located on the north side of New Road to the east of the Market Place (Fig 1). Originally, it was built to a simple rectangular plan, only one room deep and with service rooms at the west end. At a later date, the taller, projecting block to the east was added as were various additions to the rear (Fig 2). Associated with a substantial house and estate to its immediate south (The Oaks), it is thought to have been built as a private residence in the late-18th century, with alterations being undertaken in the AD 1860s/70s and to a lesser degree in the 20th century. It was used as local council offices after the Second World War but has been empty for some time. It is currently being refurbished as a high-profile part of the HSHAZ programme.

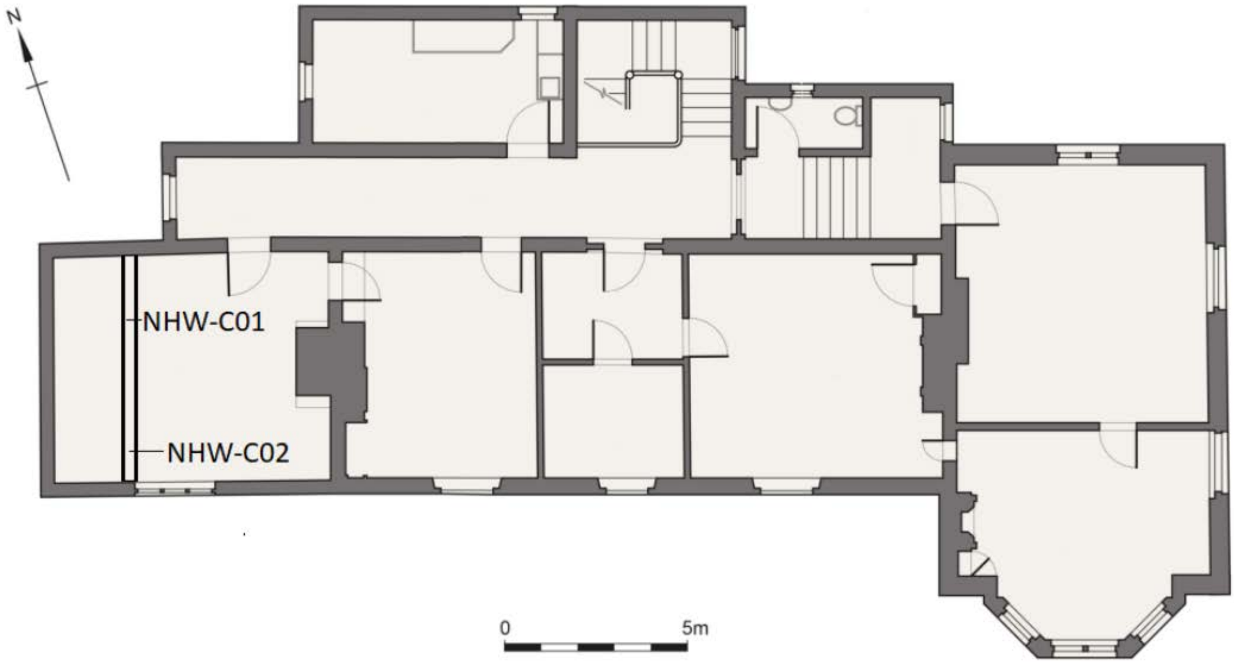

Figure 2: Plan at first-floor level, showing the approximate position of sampled timbers (after Kings and Dunne Architects)

The roof over the primary phase of the building appears to be mainly a series of softwood common rafter couples with a single tier of purlins to each side. However, there is a single oak truss of principal rafters, potentially survivals from an earlier roof incorporated in later work (Fig 3).

Figure 3: The roof over the primary part of the building with the oak principal rafters in the foreground, photograph taken from the south-west (Alison Arnold)

Tree-ring analysis

Sampling

The majority of the timbers of the roof are thought to be relatively recent (possibly late-19th or 20th century) and softwood. The exception are the two oak (*Quercus* spp) principal rafters (Fig 3). These were both sampled by coring, with each sample being given the code NHW-C and numbered 01–02. Further details relating to these samples can be found in Table 1. The location of these two sampled timbers has been indicated on Figure 2.

Table 1: Details of tree-ring series from The Cedars, 1a & 3 New Road, North Walsham, Norfolk

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
NHW-C01	North principal rafter	62	13	1593$_{DR}$	1641$_{DR}$	1654$_{DR}$
NHW-C02	South principal rafter	68	17	1589$_{DR}$	1639$_{DR}$	1656$_{DR}$

Key: DR = dates spanning derive from tentative ringwidth cross-dating, supported independently by radiocarbon wiggle-matching.

Analysis and Results

Both samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. They were then compared with each other by the Litton/Zainodin grouping programme (see Appendix) and were found to match at a value of t = 9.4.

The two samples were combined at the relevant offset positions to form NHWCSQ01, a site sequence of 68 rings (Fig 4). The site chronology was then compared with an extensive range of oak reference chronologies but no conclusive cross-match position was identified and thus these two cross-matched timbers remain undated by ring-width dendrochronology. However, some low but consistent cross-dating was noted against a number of reference chronologies when the site master chronology spans AD 1589–1656 (Table 2).

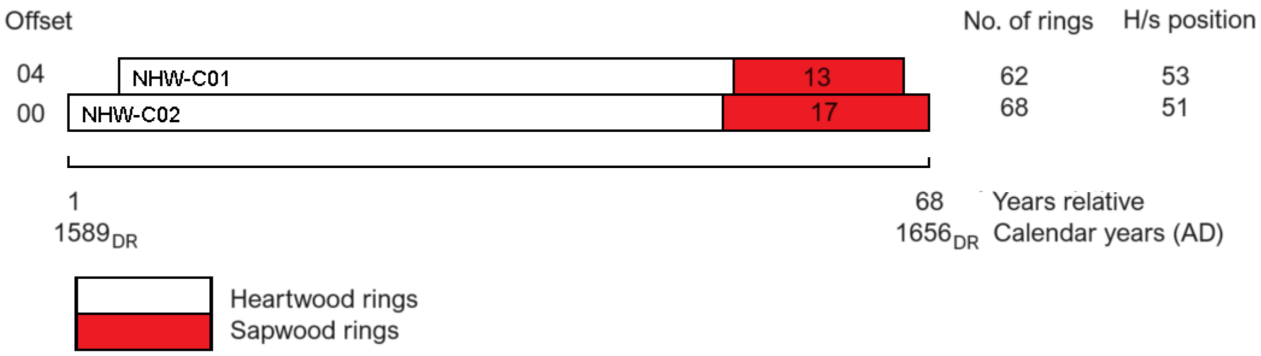

Figure 4: Bar diagram showing the relative position of samples in site sequence NHWCSQ01

Table 2: Results of the cross-matching of site sequence NHWCSQ01 and the reference chronologies when the first-ring date is AD 1589 and the last-measured ring date is AD 1656

Site reference	***t* – value**	**Span of chronology**	**Reference**
Felbrigg Hall (Samwell Wing), Norfolk	4.5	1536–1684	Tyers 1998
Church of St Nicholas, Dereham, Norfolk	4.4	1578–1681	Arnold and Howard 2008
Kirklington Church (bellframe), Notts	4.4	1567–1757	Arnold *et al* 2016
Shaw House Farm, Yorks	4.3	1577–1695	Arnold *et al* 2017
De Grey Mausoleum, Flitton, Beds	4.2	1510–1726	Arnold *et al* 2003
St Leonard’s Church, Apethorpe, Northants	4.2	1579–1665	Arnold and Howard 2009a
Stoneville Farm, Lyddington, Rutland	4.2	1556–1658	Arnold and Howard 2021
Thetford Abbey Farm, Norfolk	4.1	1556–1628	Howard *et al* 2000a
Stoneleigh Abbey, Warwicks	4.1	1398–1658	Howard *et al* 2000b
Bentley Hall, Hungry Bentley, Derbys	4.1	1444–1675	Arnold and Howard 2009b

Radiocarbon dating

In order to provide independent validation of the tentative calendar dating for NHWCSQ01 suggested by the tree-ring analysis, the longest tree-ring sequence, NHW-C02, from site sequence NHWCSQ01 (Fig 4) was selected for radiocarbon dating and wiggle-matching. NHW-C02 has 68 rings including 17 sapwood rings and comprises relative years 1–68 of NHWCSQ01 that potentially spans AD 1589–1656.

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

Table 3: Radiocarbon measurements and associated δ^{13}C values from oak sample NHW-C02 (NHWCSQ01)

Laboratory Number	**Sample**	**Radiocarbon Age (BP)**	**$\delta^{13}C_{IRMS}$ (‰)**
GrM-32417	NHW-C02, ring 2 (*Quercus* spp., heartwood)	302±23	−22.84±0.15
GrM-32418	NHW-C02, ring 18 (*Quercus* spp., heartwood)	328±20	−24.55±0.15
GrM-32419	NHW-C02, ring 40 (*Quercus* spp., heartwood)	314±22	−23.34±0.15
GrM-32849	NHW-C02, ring 52 (*Quercus* spp., sapwood)	288±16	−23.52±0.15
GrM-32848	NHW-C02, ring 62 (*Quercus* spp., sapwood)	232±18	−23.86±0.15

Radiocarbon measurements have been obtained from five single annual tree-rings from timber NHW-C02 (Table 3, Fig 5). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

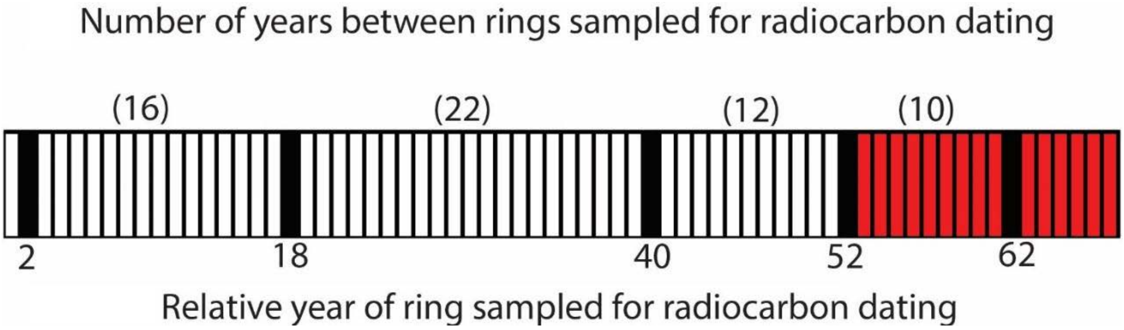

Figure 5: Schematic illustration of NHW-C02 to locate the single-ring sub-samples submitted for radiocarbon dating

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen, the Netherlands in 2023. Each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee et al. 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma et al. 1996; Aerts-Bijma et al. 1997). The graphite was then pressed into aluminium cathodes and dated by AMS (Synal et al. 2007; Salehpour et al. 2016). Data reduction was undertaken as described by Wacker et al. (2010).

The Centre for Isotope Research maintains a continual programme of quality assurance procedures (Aerts-Bijma et al. 2021), in addition to participation in international inter-comparison exercises (Scott et al. 2017; Wacker et al. 2020). 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 3). The quoted $\delta^{13}C$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Wiggle-matching

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer et al. 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from timber NHW-C02, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 6.

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

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey et al. 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 6–7 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 6 illustrates the chronological model for NHW-C02. This model incorporates the gaps between each dated annual ring known from tree-ring counting (e.g. that the carbon in ring 2 of the measured tree-ring series (GrM-32417) was laid down 16 years before the carbon in ring 18 of the series (GrM-32418), with the radiocarbon measurements (Table 3, Fig 6) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer et al. 2020).

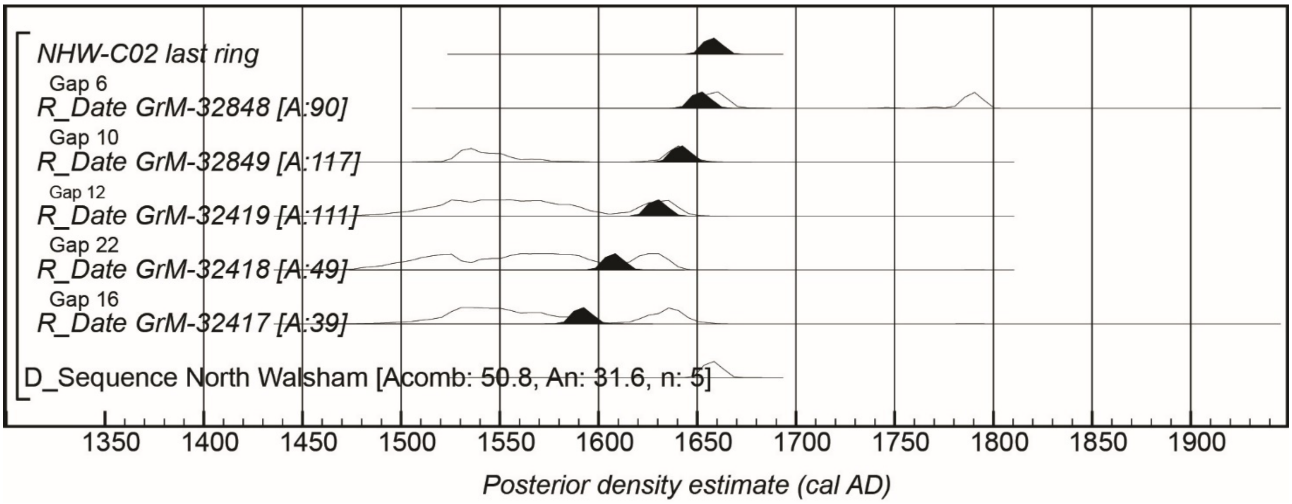

Figure 6: Probability distributions of dates from timber NHW-C02. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

The model has good overall agreement (Acomb: 50.8, An: 31.6, n: 5; Fig 6), with two radiocarbon dates having poor individual agreement (A < 60): *GrM-32417* (A:39), *GrM-32418* (A:49). It suggests that the final ring of NHW-C02, and thus the final ring of site sequence NHWCSQ01, formed in *cal AD 1648– 1668* (*95% probability*; *NHW-C02 last ring;* Fig 6), probably in *cal AD 1652– 1662* (*68% probability*).

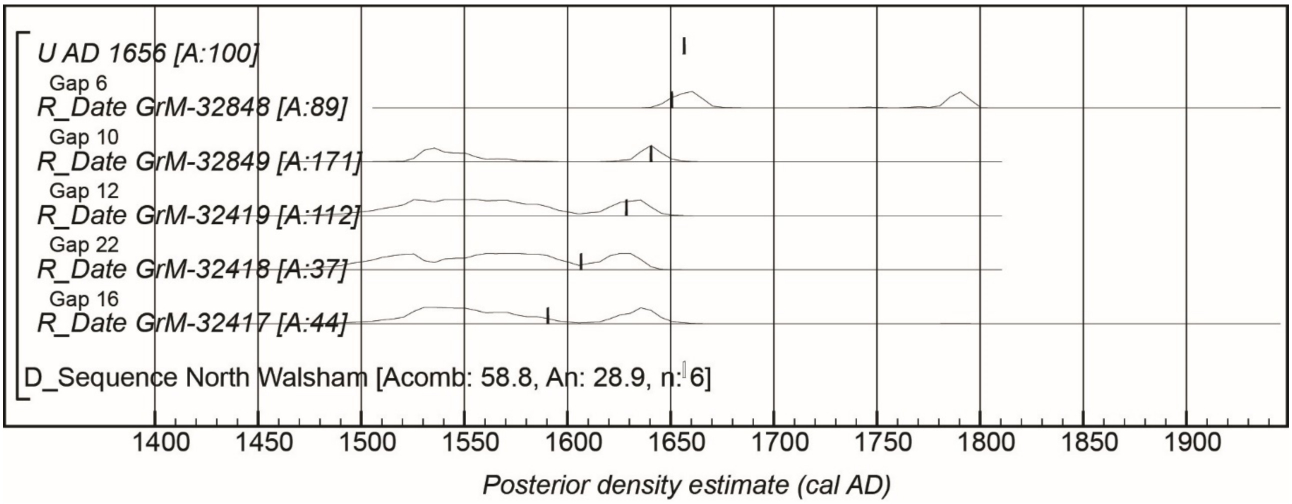

Figure 7: Probability distributions of dates from the undated site sequence NHWCSQ01, including the tree-ring date of AD 1656 for ring 68. The format is identical to Figure 6

When the last surviving ring of this timber is constrained to have formed in AD 1656, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 58.8, An: 28.9, n: 6; Fig 7), with two of the radiocarbon dates again having poor individual agreement (A < 60): *GrM-32417* (A:44), *GrM-32418* (A:37).

Discussion and Conclusion

It is unfortunate that site sequence NHWCSQ01 could not be dated securely by ring-width dendrochronology. This is despite both samples contained within it having sufficient growth rings for secure dating, and neither of them showing any features such as distortion or compression which might cause problems with cross-matching against reference material. The site sequence is, however, both poorly replicated (containing only two samples) and not particularly long (68 rings). With the two samples grouping at the high level of $t = 9.4$ it may also be that the timbers represented were actually cut from the same tree in which case one is in effect trying to date a ‘singleton’, and while such single samples can sometimes be dated, it is often more difficult than with groups of samples which cross-match and hence produce well replicated data.

The radiocarbon wiggle-matching, however, confirms the end date for the site master chronology tentatively identified by ring-width dendrochronology (Fig 6). When the last ring of the wiggle-match sequence is constrained to be AD 1656, the model has good overall agreement (Acomb: 58.8, An: 28.9, n: 6; Fig 7), and most of the individual dates have good individual agreement (A > 60). This allows the tentative dating provided by the ring-width dendrochronology to be considered as a radiocarbon supported dendrochronological date. The subscript $_{\mathrm{DR}}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, NHWCSQ01, should not be utilised as a ring-width master sequence for dating other sites.

The heartwood/sapwood boundary ring positions for the two component samples of NHWCSQ01 can be seen to be broadly coeval (Fig 4), suggesting a single felling. The average heartwood/sapwood boundary ring date for these two samples is AD 1640$_{\mathrm{DR}}$ which, using the estimate that 95% of mature oak trees in this area have 15–40 sapwood rings, allows an estimated felling date range of AD 1657–80$_{\mathrm{DR}}$ to be calculated. This range allows for sample NHW-C02 having a last-measured ring date of AD 1656$_{\mathrm{DR}}$ with incomplete sapwood.

The Cedars was thought to have been built in the late 18th century but is now known to contain at least two timbers of the late 17th century, which would make the building somewhat earlier than previously thought. Alternatively, it may be that, rather than being survivals from the primary roof, and despite no obvious signs of reuse were noted at the time of sampling, that these two principal rafters have been reused in their present location from an earlier building. Further investigation by an architectural specialist may be able to determine which of the scenarios is accurate.

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Data of Measured Samples

Measurements in 0.01mm units

NHW-C01A 62
420 439 650 412 435 295 361 433 234 226 382 328 247 327 254 276 193 232 179 237
171 146 178 180 232 172 130 169 173 162 127 94 121 133 200 188 271 211 153 243
125 187 149 214 210 253 255 245 242 217 248 196 189 147 131 145 127 89 125 105
103 138
NHW-C01B 62
448 443 643 431 444 301 354 428 235 232 383 352 239 344 254 282 199 230 185 230
172 146 180 179 229 168 136 168 176 158 131 94 125 131 200 193 238 224 149 235
126 188 156 223 204 251 238 245 249 195 240 203 185 152 130 136 130 81 132 97
102 130
NHW-C02A 68
351 250 194 135 226 246 464 368 312 230 349 385 273 240 301 256 171 283 201 165
158 203 182 246 200 163 180 173 197 162 104 144 170 206 198 175 188 216 247 236
344 309 188 336 106 178 140 150 188 259 163 153 136 145 203 236 201 157 90 153
150 74 145 163 142 187 186 158
NHW-C02B 68
350 243 210 131 222 227 470 368 311 229 355 383 284 235 302 257 167 280 198 171
146 206 187 249 201 144 164 161 194 156 117 149 180 211 195 168 173 209 240 227
336 289 179 353 109 174 141 153 187 253 164 156 165 109 208 226 199 159 93 149
143 74 151 163 147 183 186 150

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

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

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

1. Inspecting the Building and Sampling the Timbers.

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly, the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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 (i.e. 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).

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; e.g. 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.

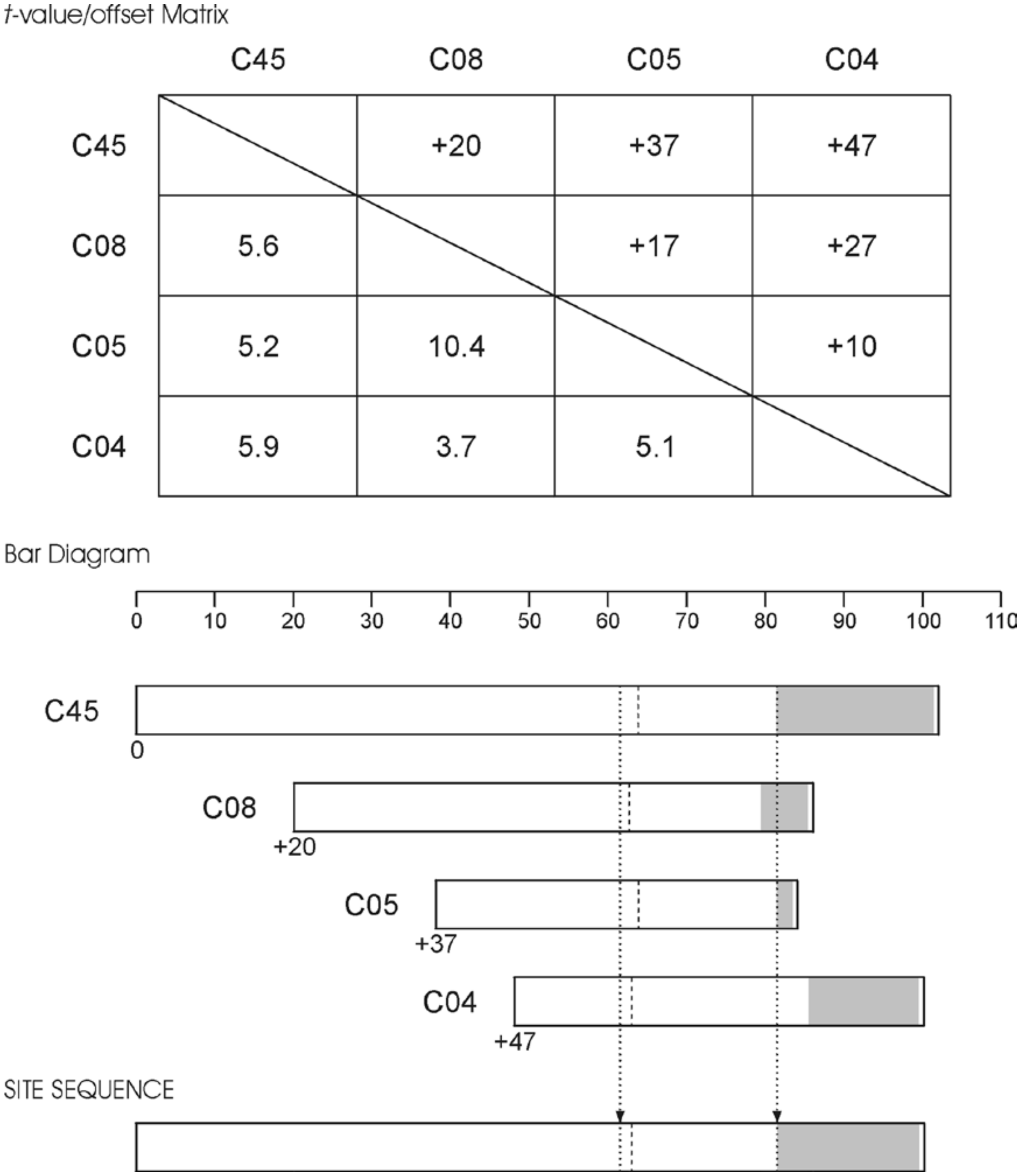
There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges 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 (e.g. 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 AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 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.

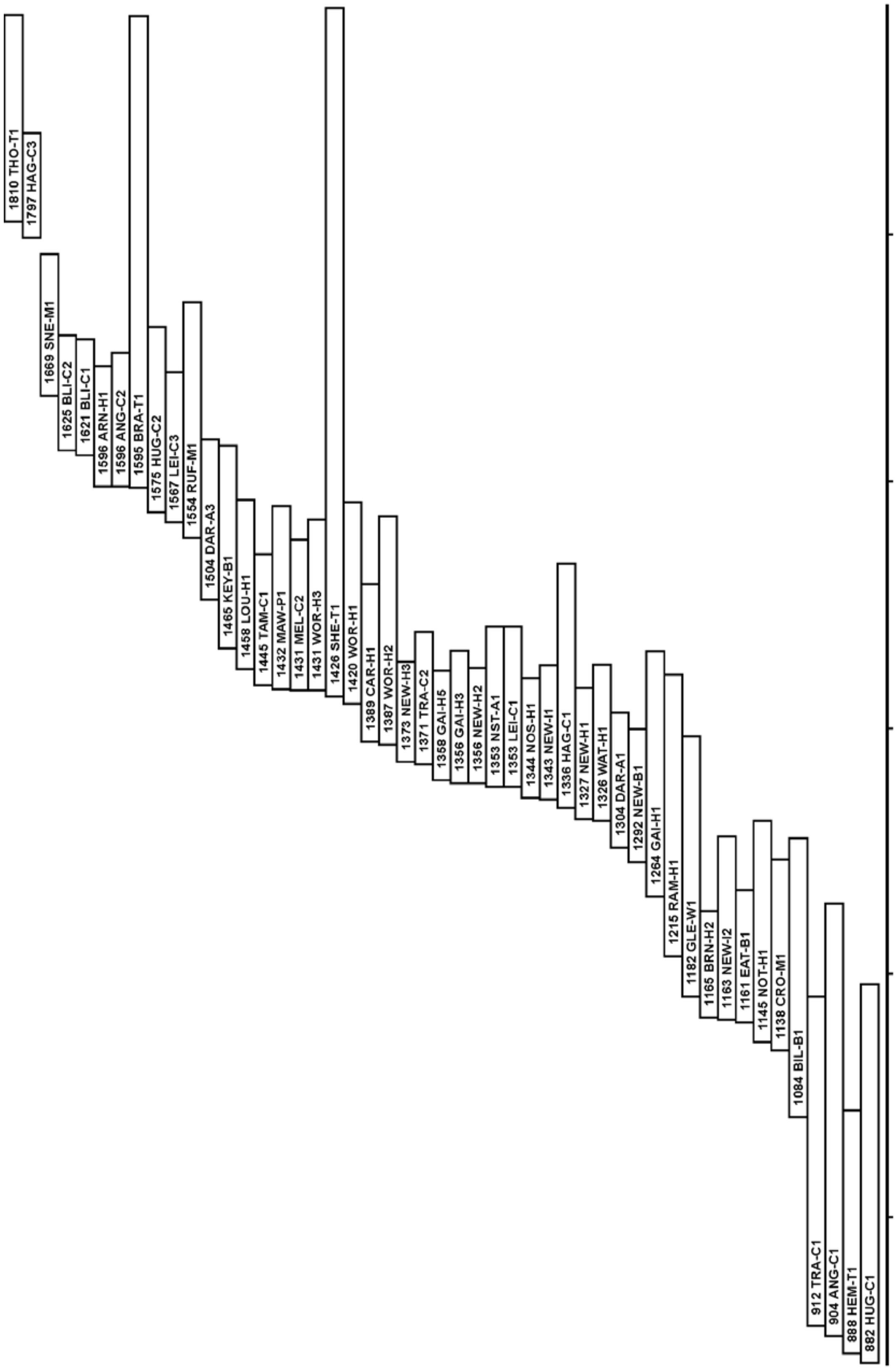
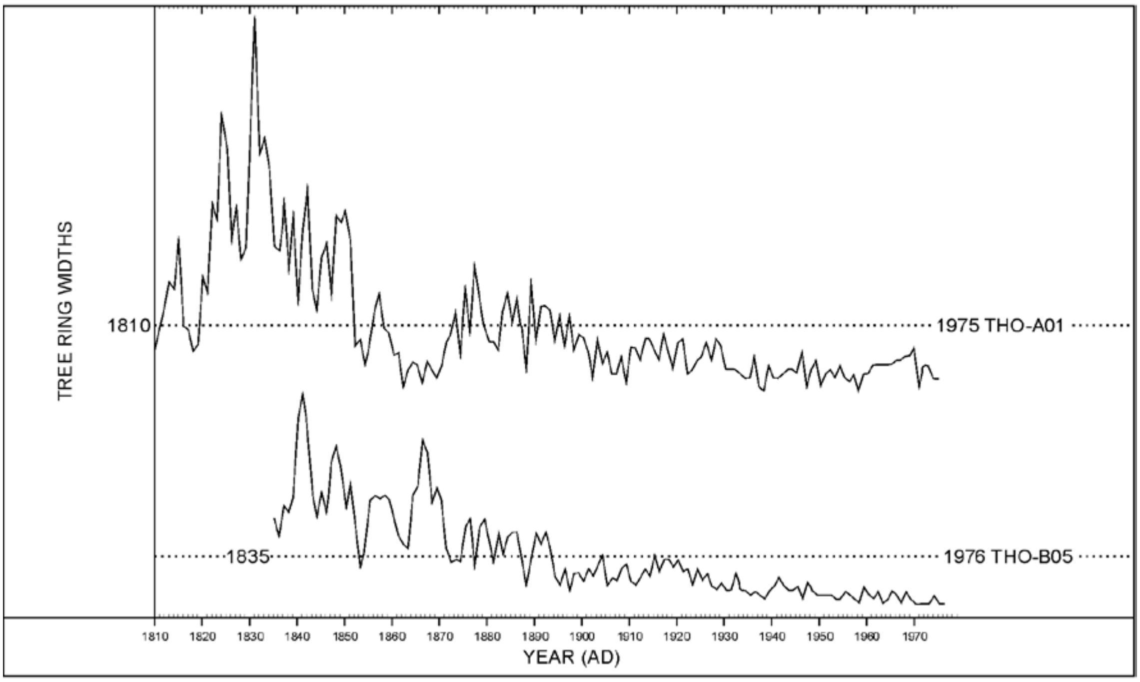


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

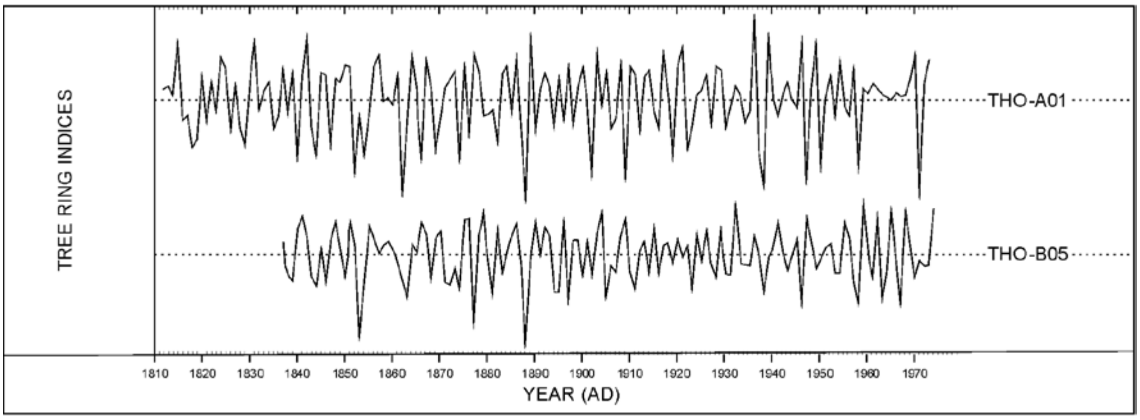


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young 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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