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1 and 3 Market Place, Snaith, Snaith and Cowick, East Riding of Yorkshire

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

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

Scientific Dating

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Summary

Dendrochronological analysis was undertaken on core samples from six timbers from 1 and 3 Market Place, Snaith. This analysis produced a single site chronology, SNTBSQ01, comprising five samples from roof timbers and being 64 rings long. The site master chronology, however, could not be conclusively dated by ring-width dendrochronology when compared to an extensive range of relevant reference chronologies. Radiocarbon dating was undertaken on seven 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 1729–1746 (95% probability)* or *cal AD 1732–1739 (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 1669–1732. The tentative tree-ring date can only be accepted because it is supported independently by the radiocarbon wiggle-matching. Interpretation of the sapwood on these samples indicates the timbers represented were all felled in AD 1732$_{DR}$. The sixth sample, from a possibly re-used cruck blade, remains undated.

Contributors

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

Acknowledgements

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Front cover image

1 and 3 Market Place, Snaith from west (photograph Robert Howard)

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Introduction

The Grade II listed (List Entry Number 1162168) 1 and 3 Market Place, Snaith, Snaith and Cowick, East Riding of Yorkshire (Fig 1), is described as a late seventeenth- or early eighteenth-century house with later additions, and as having late nineteenth-century or twentieth-century shop fronts. It is a brick rendered building with a pantile roof, originally L-shaped, with a two-room central lobby area and single room wing to the rear right. A later single-room addition was added at an angle on the street corner to the left, an extension made to the inner (rear) angle, and further wings added to the rear (Fig 2). The interior contains spine beams on the ground floor supported on cast iron columns, the spine beams perhaps supporting common joists.

Most of the roofs comprise common rafters which have been made to look like trusses, many of these made of conifer (possibly of eighteenth- or nineteenth-century date), and it is believed that the structure has evolved rather than been designed (Fig 3). The roof of the rear range has been more recently replaced in conifer (Fig 4). The hip truss at the west end is the feature with most historical significance, this possibly being an original or early feature. There is also a curved beam on the west side of the chimney which was initially thought to be a reused cruck blade. This beam is not part of the current roof structure and supports only a few courses of, possibly seventeenth-century, brickwork.

Dendrochronological analysis was requested by Emma Sharpe, Historic England Inspector of Historic Buildings and Areas. It was hoped that tree-ring analysis would provide independent dating evidence for the timbers, thus enhancing understanding of the historic development of the building and informing advice in relation to the Listed Building Consent application for the replacement of the unsafe roof.

Tree-ring sampling

An initial assessment of the dendrochronological potential of the timbers suggested that almost all those which were accessible in the roof, ground, and first floors (some areas initially being unsafe and/or inaccessible), both oak and conifer timbers, were derived from fast-grown trees with too few rings for reliable dating purposes. Subsequently, following stabilisation works, further areas became accessible, particularly in the roof of the main front range. It was seen at this time that the timbers in the hip truss at the west end of the building appeared to have sufficient rings for dating purposes.

Thus, from the suitable timbers available a total of six samples was obtained by coring. Each sample was given the code SNT-B (for Snaith, site ‘B’) and numbered 01–06 (Table 1). Of this number, five were obtained from the hip truss and roof, with one being taken from the reused cruck blade. The sampled timbers are located on annotated photographs (Figs 5 and 6).

Tree-ring analysis and results

Each of the six samples thus obtained from the roof of 1 and 3 Market Place was prepared by sanding and polishing and their annual growth ring widths were measured, the data of these ring-width measurements being given at the end of this report. The six measured series were then compared with each other by the Litton/Zainodin grouping procedure (Litton and Zainodin 1991; see Appendix). This comparative process resulted in the production of a single group of five samples, all of them from the hip and common rafters of the roof, these cross-matching with each other as shown in the bar diagram, Figure 7, at a minimum *t*-value of 8.7.

The five cross-matching samples were combined at their indicated offset positions to form SNTBSQ01, a site chronology with an overall length of 64 rings. Site chronology SNTBSQ01 was then compared to an extensive corpus of reference chronologies for oak, this indicating a consistent and repeated cross-match with a number of these when the date of its first ring is AD 1669 and the date of its last measured ring is AD 1732 (Table 2). Although the *t*-values listed in Table 2 are not especially high, the date AD 1732 produces the maximum figures, as well as many other slightly lower unlisted *t*-values. This is likely to be a reflection of the relative paucity of reference chronologies for the post-medieval period in this region, combined with this area, in the vicinity of the Humber Estuary and the Humberhead Levels and southern reaches of the Vale of York, having previously proven challenging with respect to successful dendrochronological analysis.

As a further check on the validity of this potential dating evidence, the ring-width series of the individual samples were compared to the individual component ring-width series for the three reference chronologies with which SNTBSQ01 shows the highest levels of similarity (Table 2), along with the reference chronology. These chronologies, BEVKSQ01 from Beverley Minster (Table 3), THUBSQ01 from the Church of St Firmin, Thurlby (Table 4), and SOMCSQ03 from Somerton Castle (Table 5), all have good sample depth ($n \geq 9$). In each case the individual series from 1 and 3 Market Place produced *t*-values of a level and consistency that would have meant they would have been incorporated as dated within these chronologies (if they had been found on these sites).

The site chronology from Snaith, SNTBSQ01, was compared with the single remaining ungrouped sample (SNT-B06), from the reused cruck blade, but there was no further satisfactory cross-matching. This single ungrouped sample was, therefore, compared individually with the full corpus of reference data, but again there was no satisfactory cross-matching at any position and this sample must remain undated.

Radiocarbon dating

In order to provide independent validation of the tentative calendar dating for SNTBSQ01 suggested by the tree-ring analysis, the longest tree-ring sequence, SNT-B02, from site sequence SNTBSQ01 (Fig 7) was selected for radiocarbon dating and wiggle-matching. SNT-B02 has 64 rings including complete sapwood and comprises relative years 1–64 of SNTBSQ01 that potentially spans AD 1669–1732.

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 6, 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).

Radiocarbon measurements have been obtained from seven single annual tree-rings from timber SNT-B02 (Table 6). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen, 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 6). 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 SNT-B02, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 8 and 9.

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 a Bayesian approach 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 8–9 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 8 illustrates the chronological model for SNTBSQ01. 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-32850) was laid down 10 years before the carbon in ring 12 of the series (GrM-32851), with the radiocarbon measurements (Table 6) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer et al. 2020).

The model has good overall agreement (Acomb: 33.3, An: 26.7, n: 7; Fig 8), with two radiocarbon dates having poor individual agreement (A < 60): GrM-32853 (A:37) and GrM-

32855 (A:33). It suggests that the final ring of SNTBSQ01 formed in *cal AD 1729–1747* (*95% probability*; *SNTBSQ01_felling*; Fig 8), probably in *cal AD 1732–1739* (*68% probability*).

When the last surviving ring of this timber is constrained to have formed in AD 1732, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 27.4, An: 25.0, n: 8; Fig 9), however, four of the radiocarbon dates have poor individual agreement (A > 60): GrM-32850 (A:47), GrM-32855 (A:40), GrM-32857 (A:42) and GrM-32858 (A:42). This may reflect the difficulties of accounting for all sources of error in constructing the radiocarbon calibration curve (Heaton et al. 2020).

Discussion

The radiocarbon wiggle-matching of SNT-B02 (Fig 8) includes the end date for the site master chronology tentatively identified by ring-width dendrochronology (Tables 2–5). When the last ring of the wiggle-match sequence is constrained to be AD 1732, the model has good overall agreement (Acomb: 27.4; An: 25.0; n: 8; Fig 9), although four dates have poor individual agreement. This allows the tentative dating provided by the ring-width dendrochronology to be considered as a radiocarbon supported dendrochronological date, with site sequence SNTBSQ01 spanning AD 1669–1732$_{\mathrm{DR}}$. The subscript $_{\mathrm{DR}}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, SNTBSQ01, should not be utilised as a ring-width master sequence for dating other sites.

The scientific dating at 1 and 3 Market Place has thus dated five of the six samples which were sampled. Of these dated samples, two (SNT-B02, SNT-B05) retain sapwood complete to the bark, this meaning that they have the last growth ring produced by the trees represented before they were felled. In both cases this last growth ring, and thus the felling of the trees represented, is the same, both having last rings dated AD 1732$_{\mathrm{DR}}$ (Table 1; Fig 7). Two other samples, SNT-B01 and SNT-B03, are from timbers which have complete sapwood on them, but from which (due to its soft and fragile nature) small amounts of sapwood were lost from the samples in coring. In both cases, taking into account the date of the last measured sapwood ring on each sample, the amount of sapwood lost would suggest that SNT-B01 and SNT-B03 also represent trees felled in AD 1732$_{\mathrm{DR}}$. The relative position and date of the heartwood/sapwood boundary on the fifth dated sample, SNT-B04, is compatible with that that on the other four samples. Such consistency is indicative of a group of timbers felled at the same time as each other. It is thus very likely that the tree represented by sample SNT-B04 was felled in AD 1732$_{\mathrm{DR}}$ as well. It therefore appears likely that all timbers used in this part of the roof at 1 and 3 Market Place were felled at the same time in AD 1732$_{\mathrm{DR}}$.

Although site chronology SNTBSQ01 has been compared with reference material from all parts of England, there is a distinct tendancy for it to cross-match best with chronologies from sites in the north-east Midlands and East Yorkshire, with a particular emphasis on north Nottinghamshire (Table 2). Thus, although the exact woodland source of the timbers used for this particular part of the roof at 1 and 3 Market Place cannot be determined with reliable precision, this cross-matching would strongly suggest that they were of relatively local origin.

Wherever the source woodland was, it is likely, judging by the level of cross-matching between samples, that the trees used were growing very close to each other in the same copse or patch of woodland. Indeed, having a cross-match at a value of *t*=10.8, it is possible that the north-east and south east hip rafters (samples SNT-B01 and SNT-B02) may have both been derived from the same tree, with common rafters 4t and 19t (samples SNT-B04 and SNT-B05) which cross-match with a value of *t*=10.3, both potentially being derived from another tree.

The sample from the reused cruck blade, SNT-B06, remains undated. As may be seen from Table 1, this sample has a low number of rings, being towards the minimum required for secure dating purposes using ring-width dendrochronology. This difficulty is compounded by the sampled timber possibly being of a different date to the others which were cored, and thus being a ‘singleton’. While on occasion single samples can be reliably dated, this is often much more difficult than with groups of replicated samples and usually requires samples with higher ring numbers than that found in SNT-B06. It is, however, very common in most programmes of tree-ring analysis to find that some sample remain ungrouped/undated often for no apparent reason.

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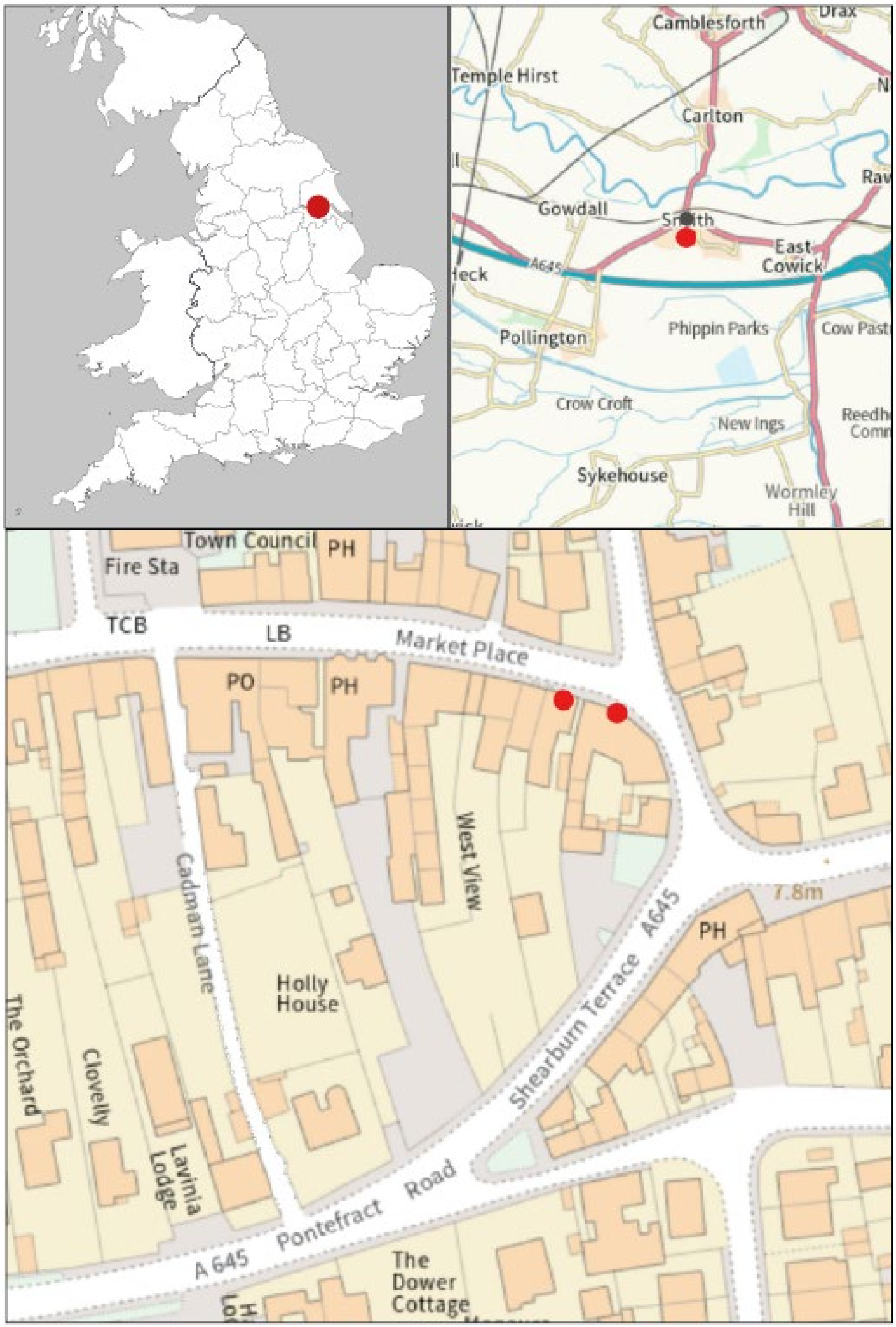


Figure 1 : Maps to show the location of 1–3 Market Place, Snaith, in red. Scale: top right 1:150,000; bottom 1:1,600. © Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900.

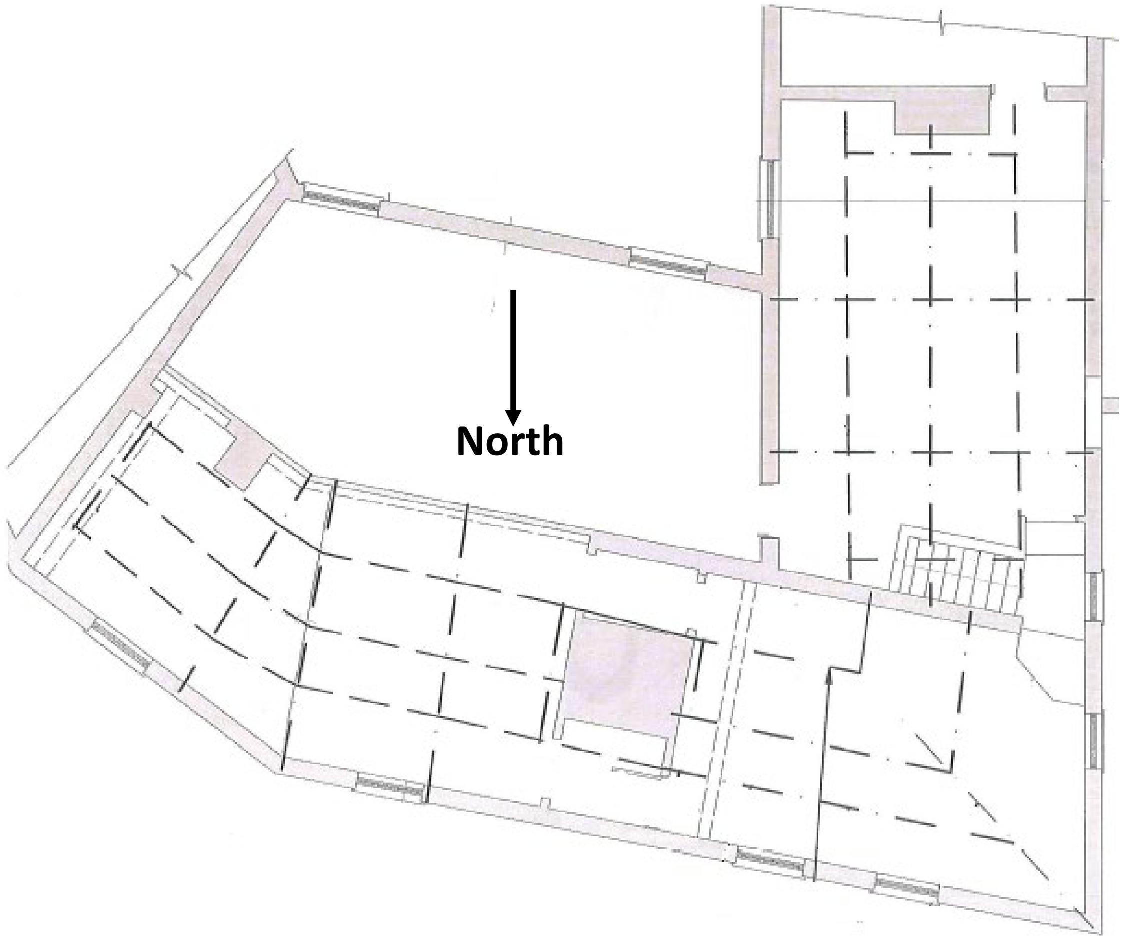


Figure 2: Plan of 1–3 Market Place, Snaith (after Structural and Civil Consultants Ltd)

Figure 3: General view, facing west, of the main, front range (photograph Robert Howard)

Figure 4: General view, facing south, of the largely replaced roof of the rear range (photograph Robert Howard)

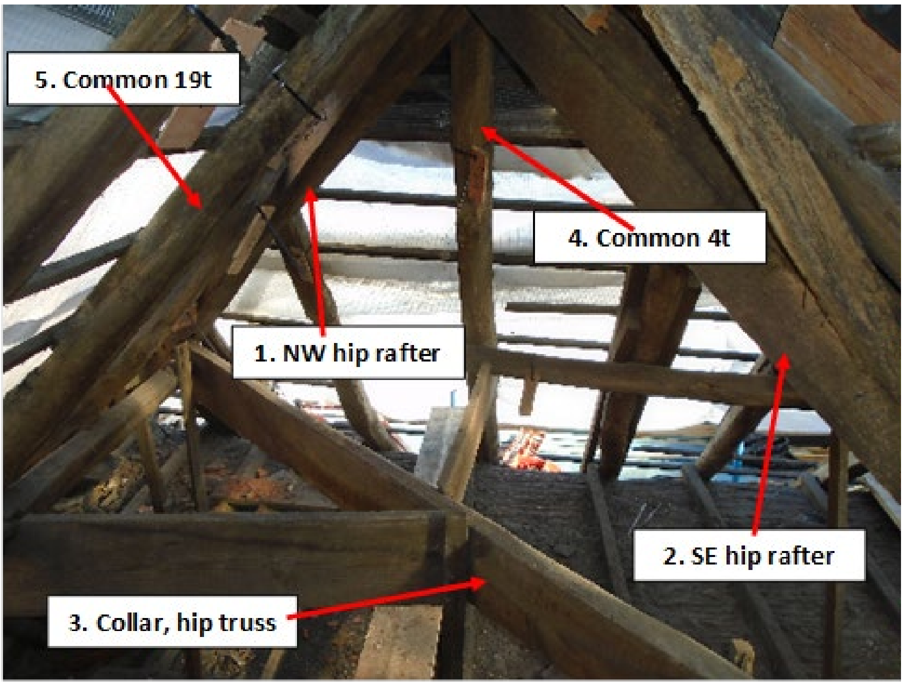


Figure 5: Annotated photograph, facing north, to help locate sampled timbers 1–5 (see Table 1) (photograph Robert Howard)

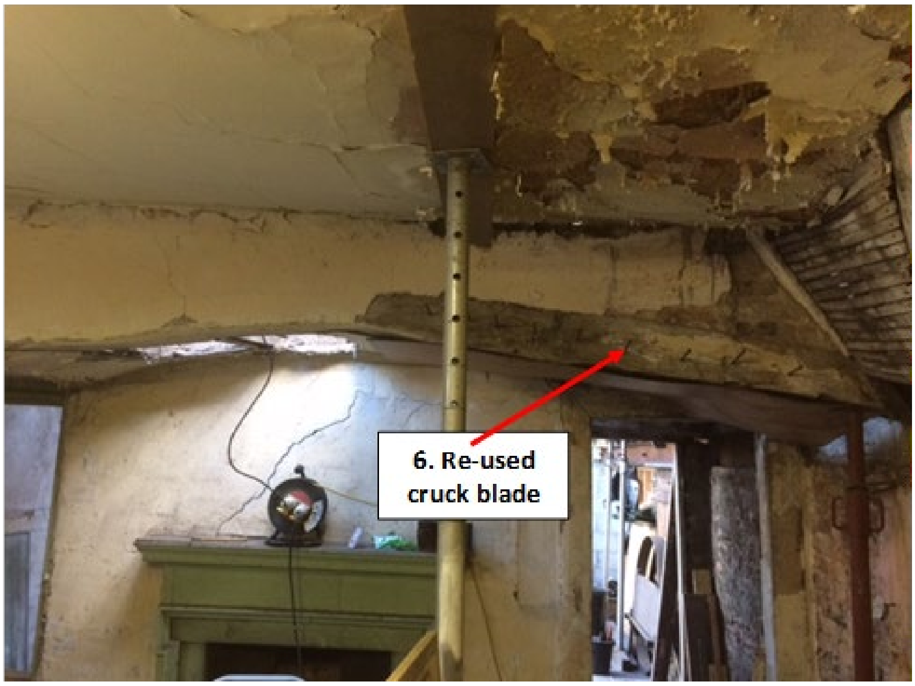


Figure 6: Annotated photograph, facing east, to help locate sampled timber 6 (see Table 1) (photograph Robert Howard)

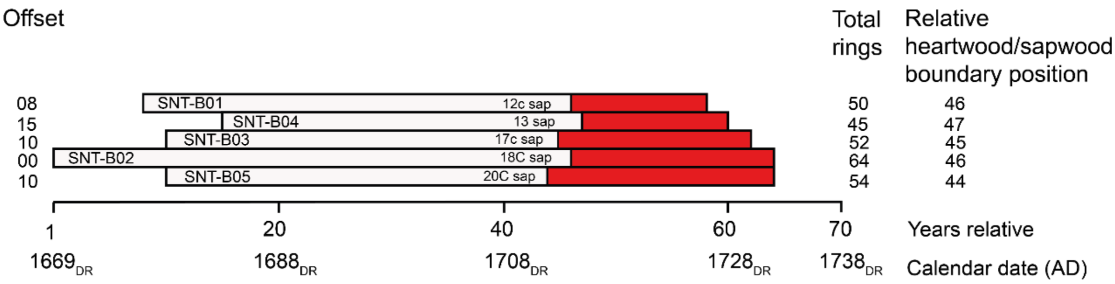


Figure 7: Bar diagram of cross-matching samples in site chronology SNTBSQ01
White bars = heartwood rings; Shaded bars = sapwood rings
h/s = heartwood/sapwood boundary
c = complete sapwood is found on the timber, but a portion has been lost from the sample in coring
C= complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

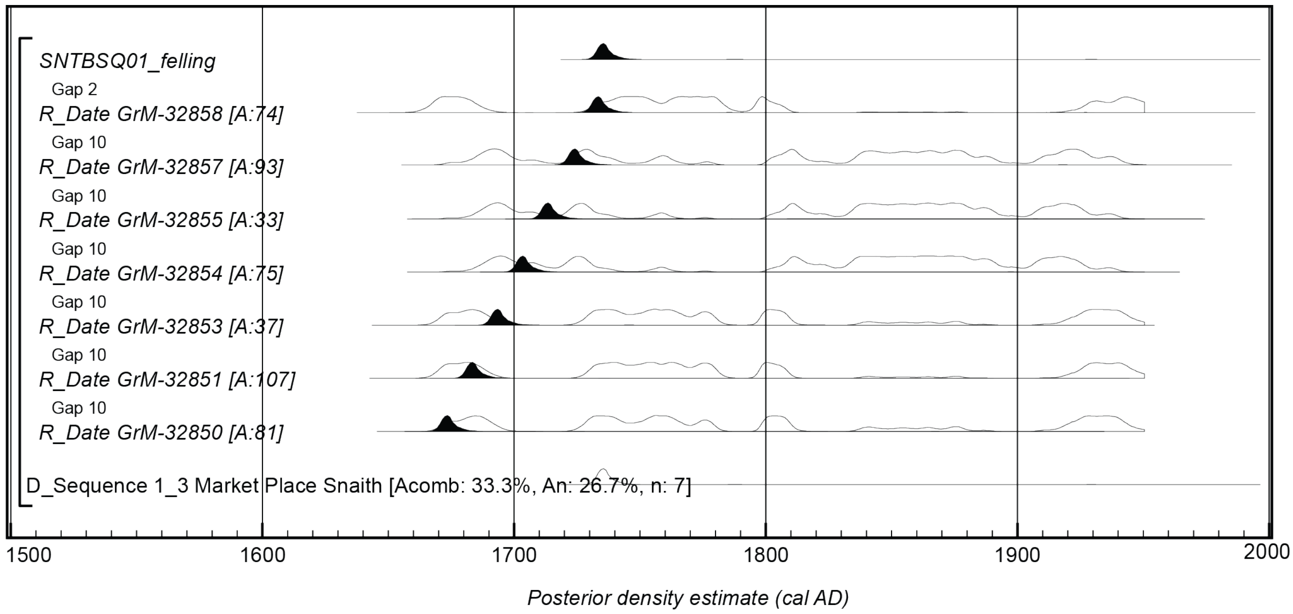


Figure 8: Probability distributions of dates from the undated site sequence SNTBSQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, 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.

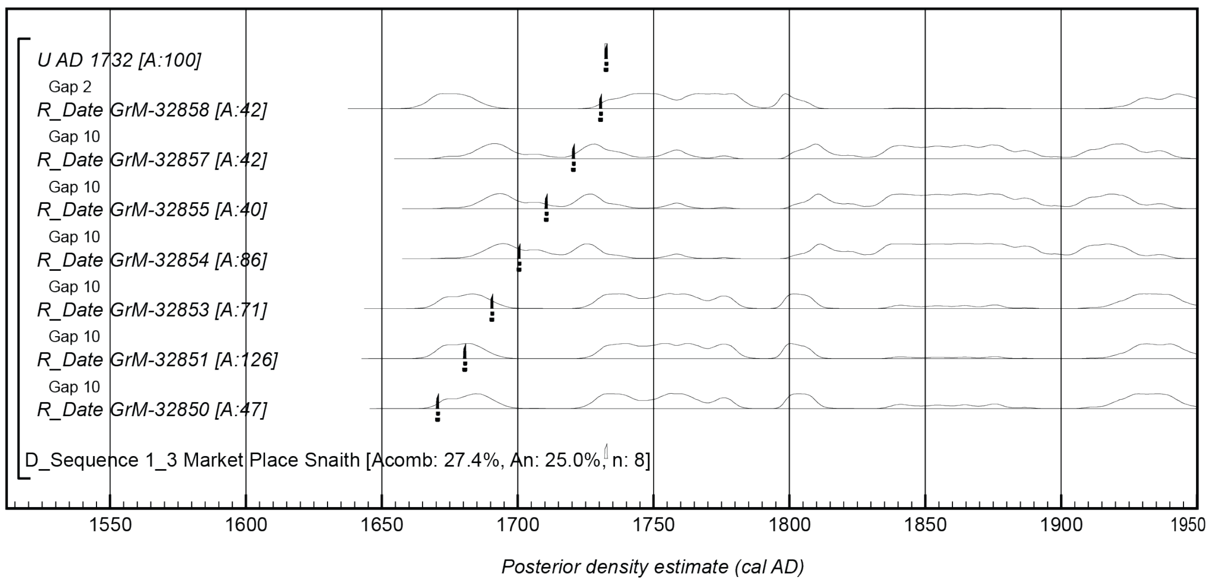


Figure 9: Probability distributions of dates from SNTBSQ01, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1732. The format is identical to Figure 8. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly.

Table 1: Details of tree-ring samples from 1 and 3 Market Place, Snaith, East Riding of Yorkshire.
h/s = the heartwood/sapwood ring is the last ring on the sample
c = complete sapwood is found on the timber, but a portion has been lost from the sample in coring
C= complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
SNT-B01	North-west hip rafter	50	12c	1677_{DR}	1714_{DR}	1726_{DR}
SNT-B02	South-east hip rafter	64	18C	1669_{DR}	1714_{DR}	1732_{DR}
SNT-B03	Collar, hip rafter	52	17c	1679_{DR}	1713_{DR}	1730_{DR}
SNT-B04	Common rafter 4t	45	13	1684_{DR}	1715_{DR}	1728_{DR}
SNT-B05	Common rafter 19t	54	20C	1679_{DR}	1712_{DR}	1732_{DR}

Table 2: Results of the cross-matching of site sequence SNTBSQ01 and relevant reference chronologies when the first-ring date is AD 1669 and the last-ring date is AD 1732.

Reference chronology	Span of chronology	*t*-value	Reference
Church of St Firmin, Thurlby, Lincolnshire	AD 1599–1792	5.8	Arnold and Howard 2010a
The Minster, Beverley, East Riding of Yorkshire	AD 1573–1736	5.6	Arnold and Howard 2020
Manor Farm, Askham, Nottinghamshire	AD 1629–1724	5.2	Howard et al. 2003
Ragnall barn, Ragnall, Nottinghamshire	AD 1607–1717	5.1	Howard et al. 1997
Southview Cottage, Norwell, Nottinghamshire	AD 1650–1773	5.0	Hurford et al. 2010
Potterdike House, Newark, Nottinghamshire	AD 1603–1740	4.7	Arnold et al. 2002
New Inn, Stowe, Buckinghamshire	AD 1628–1782	4.5	Arnold and Howard 2010b
St John The Baptist, Grimstone, Leicestershire	AD 1574–1754	4.5	Arnold et al. 2005
Middleton Hall, Middleton, Warwickshire	AD 1593–1718	4.5	Arnold et al. 2006
Somerton Castle, Lincolnshire	AD 1650–1760	4.3	Arnold and Howard 2016
Halstead Manor, Stixwould, Lincolnshire	AD 1593–1736	4.3	Arnold and Howard 2006

Table 3: Cross-matching between the five individual ring-width series from site chronology SNTBSQ01 from 1 and 3 Market Place, Snaith with the individual ring-width series comprising BEVKSQ01, plus the reference chronology itself, from The Minster, Beverley. \ = overlap less than 30 years; - = *t*-values less than 3.0.

	***t*-values**				
	SNT-B01	SNT-B02	SNT-B03	SNT-B04	SNT-B05
BEV-K01	4.9	3.6	-	-	3.5
BEV-K03	3.7	3.6	-	-	4.2
BEV-K04	5.2	4.4	3.4	3.6	3.6
BEV-K05	4.3	4.5	-	3.2	-
BEV-K06	3.7	3.6	-	-	3.3
BEV-K07	-	3.5	3.6	3.2	3.1
BEV-K08	4.5	3.0	3.1	3.4	3.2
BEV-K09	4.4	3.1	-	3.8	3.4
BEV-K10	4.6	-	\	\	\
BEV-K11	6.6	4.5	-	3.6	4.0
BEV-K12	5.5	-	-	3.4	4.0
BEV-K13	4.3	-	-	3.1	-
BEV-K14	3.7	-	-	3.1	3.1
BEV-K15	6.4	3.5	-	3.2	-
BEV-K16	3.3	-	4.2	3.5	3.5
BEV-K17	-	-	3.7	-	3.8
BEV-K18	-	-	3.5	-	3.5
BEV-K21	-	-	3.6	-	4.1
BEV-K23	-	3.4	4.4	3.3	3.9
BEV-K24	-	4.5	4.5	4.4	4.4
BEVKSQ01	6.0	5.1	4.3	4.3	5.9

Table 4: Cross-matching between the five individual ring-width series from site chronology SNTBSQ01 from 1 and 3 Market Place, Snaith with the individual ring-width series comprising THUBSQ01, plus the reference chronology itself, from the Church of St Firmin, Thurlby. \ = overlap less than 30 years; - = *t*-values less than 3.0.

	***t*-values**				
	SNT-B01	SNT-B02	SNT-B03	SNT-B04	SNT-B05
THU-B01	3.6	3.8	-	3.0	-
THU-B02	3.2	3.8	-	3.4	-
THU-B03	-	4.7	-	\	3.6
THU-B05	-	3.0	-	-	-
THU-B07	3.2	3.4	-	3.3	-
THU-B09	-	4.0	-	-	-
THU-B10	-	3.2	4.0	-	3.9
THU-B11	3.9	5.7	5.3	3.4	5.8
THU-B12	4.1	5.4	5.1	3.9	5.1
THUBSQ01	4.2	5.6	3.1	3.8	4.2

Table 5: Cross-matching between the five individual ring-width series from site chronology SNTBSQ01 from 1 and 3 Market Place, Snaith with the individual ring-width series comprising SOMCSQ03, plus the reference chronology itself, from Somerton Castle. \ = overlap less than 30 years; - = *t*-values less than 3.0

	***t*-values**				
	SNT-B01	SNT-B02	SNT-B03	SNT-B04	SNT-B05
SOM-C01	-	-	-	3.6	3.2
SOM-C03	-	3.5	-	3.3	4.0
SOM-C08	3.4	-	-	3.3	3.8
SOM-C09	3.4	-	4.9	3.5	4.3
SOM-C10	4.0	-	3.8	4.5	4.7
SOM-C11	-	-	3.1	-	3.7
SOM-C12	3.5	-	3.9	3.5	4.9
SOM-C31	3.2	-	-	-	4.1
SOM-C32	-	-	-	-	3.2
SOM-C40	4.0	4.5	4.5	6.5	4.6
SOM-C44	3.2	4.1	3.9	4.1	4.1
SOM-C45	-	-	-	-	4.0
SOM-C46	3.3	-	-	4.4	3.6
SOM-C47	3.7	3.2	4.7	4.3	4.7
SOM-C49	3.1	-	-	-	3.6
SOM-C53	3.8	4.9	4.7	5.0	4.8
SOMCSQ03	4.2	3.5	4.7	5.3	6.1

Table 6: Radiocarbon measurements and associated δ^{13}C values from oak sample SNT-B02 (SNTBSQ01)

Laboratory Number	Sample	Radiocarbon Age (BP)	δ13CIRMS (‰)
GrM-32850	SNT-B02, ring 2 (*Quercus* spp., heartwood)	159±16	−25.30±0.15
GrM-32851	SNT-B02, ring 12 (*Quercus* spp., heartwood)	168±16	−24.29±0.15
GrM-32853	SNT-B02, ring 22 (*Quercus* spp., heartwood)	163±17	−25.60±0.15
GrM-32854	SNT-B02, ring 32 (*Quercus* spp., heartwood)	128±17	−24.37±0.15
GrM-32855	SNT-B02, ring 42 (*Quercus* spp., heartwood)	132±16	−25.54±0.15
GrM-32857	SNT-B02, ring 52 (*Quercus* spp., sapwood)	138±17	−24.53±0.15
GrM-32858	SNT-B02, ring 62 (*Quercus* spp., sapwood)	180±18	−25.66±0.15

Data of Measured Samples

Measurements in 0.01mm units

SNT-B01A 50
275 259 346 286 207 320 169 112 137 238 236 187 162 146 150 151 244 289 267 171
199 263 226 216 236 214 260 336 298 341 290 301 159 105 184 253 292 212 168 128
105 159 265 267 225 135 134 162 139 185

SNT-B01B 50
275 260 346 243 192 308 173 122 150 226 228 187 153 148 147 156 240 291 278 159
198 260 227 228 225 210 250 341 310 331 289 301 170 96 186 245 290 221 170 118
114 156 270 259 229 143 131 167 139 187

SNT-B02A 64
331 332 300 301 245 100 149 253 351 230 337 329 270 294 167 97 161 228 264 191
115 117 123 130 165 153 172 121 110 151 152 166 139 175 187 239 200 223 217 228
112 80 136 189 229 200 159 123 134 135 175 194 192 154 110 154 117 101 132 178
148 205 153 168

SNT-B02B 64
333 320 273 304 231 106 154 242 353 229 341 334 266 285 174 101 164 230 272 175
125 116 125 125 161 149 178 114 110 153 147 163 145 167 187 246 204 217 222 216
118 81 143 194 219 200 151 126 122 143 184 193 195 125 115 179 93 123 137 160
162 189 155 169

SNT-B03A 52
194 398 285 310 250 178 269 312 284 207 157 158 221 207 191 224 221 202 203 254
223 164 193 192 219 248 228 275 303 329 173 146 173 204 234 228 212 168 145 176
203 192 234 174 150 171 114 160 139 162 181 170

SNT-B03B 52
200 363 278 308 258 178 314 301 295 220 151 166 210 207 198 239 217 192 197 236
217 164 197 200 217 253 225 281 290 334 175 146 171 198 237 221 223 154 134 187
204 210 217 182 150 176 117 152 136 165 173 171

SNT-B04A 45
289 287 329 344 238 160 169 244 223 294 305 243 187 234 288 207 176 226 208 282
321 258 308 294 269 157 104 196 212 231 192 147 107 92 134 226 229 173 114 92
157 119 143 145 156

SNT-B04B 45
288 288 332 356 235 159 175 246 205 309 299 248 185 228 278 197 209 225 227 293
350 253 310 296 257 165 113 186 219 234 192 148 132 109 125 207 226 173 112 92
151 117 139 144 158

SNT-B05A 54
211 252 291 280 257 138 187 307 212 162 121 130 171 176 209 238 238 160 186 221
243 166 167 185 200 256 207 256 251 255 146 128 164 227 237 210 181 134 115 150
167 216 217 190 139 166 128 140 128 150 178 152 182 226

SNT-B05B 54
208 254 288 259 248 143 197 292 212 159 130 128 175 167 210 234 245 161 189 225
237 175 164 180 213 255 207 257 246 250 150 129 178 229 220 213 198 121 120 156

151 214 221 195 135 150 132 151 135 126 179 154 185 230

SNT-B06A 47
298 339 264 401 411 423 330 310 207 231 225 147 152 157 139 164 126 85 57 82
89 102 133 174 153 110 134 114 143 145 168 120 143 126 137 159 138 148 165 215
161 144 213 186 148 151 113

SNT-B06B 47
310 335 275 391 410 416 321 301 175 244 217 152 144 146 134 190 141 89 62 86
97 90 133 171 174 101 132 118 142 150 159 132 132 132 121 159 142 145 167 196
139 160 212 182 151 154 108

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 (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 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	

Bar Diagram

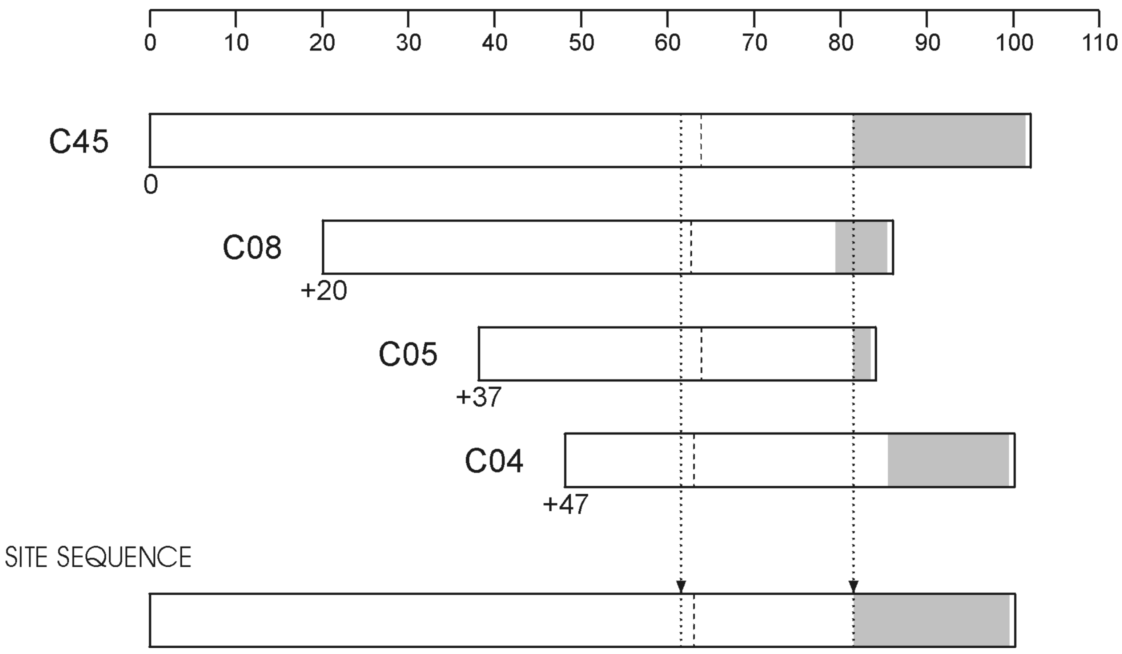


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

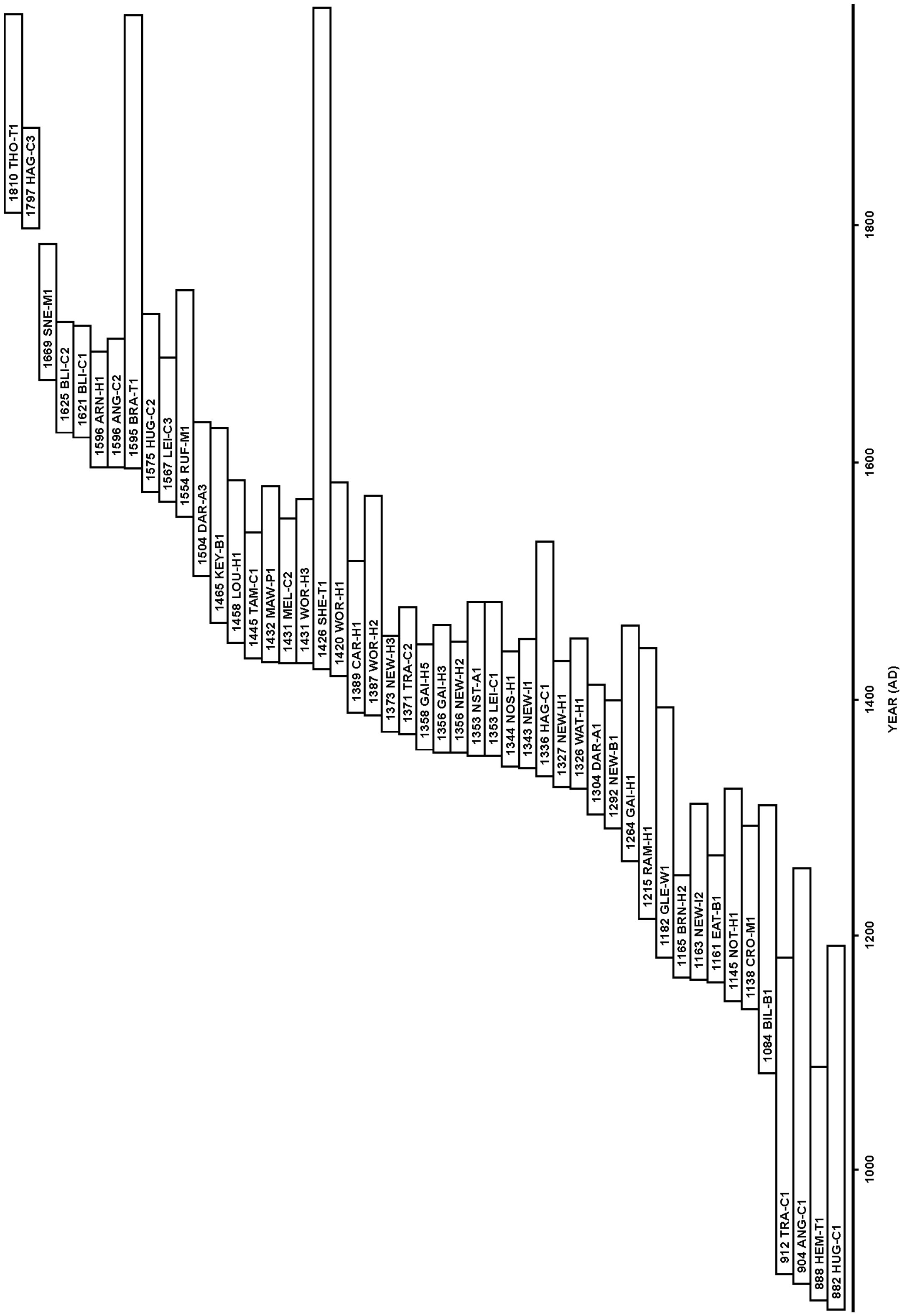
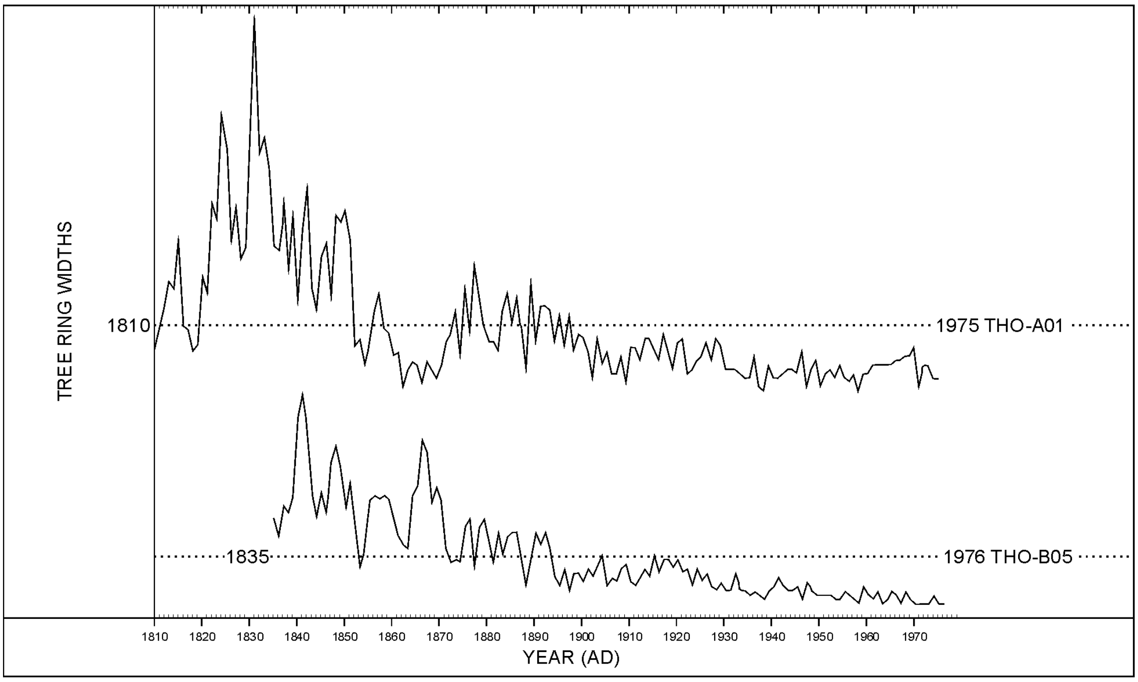


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

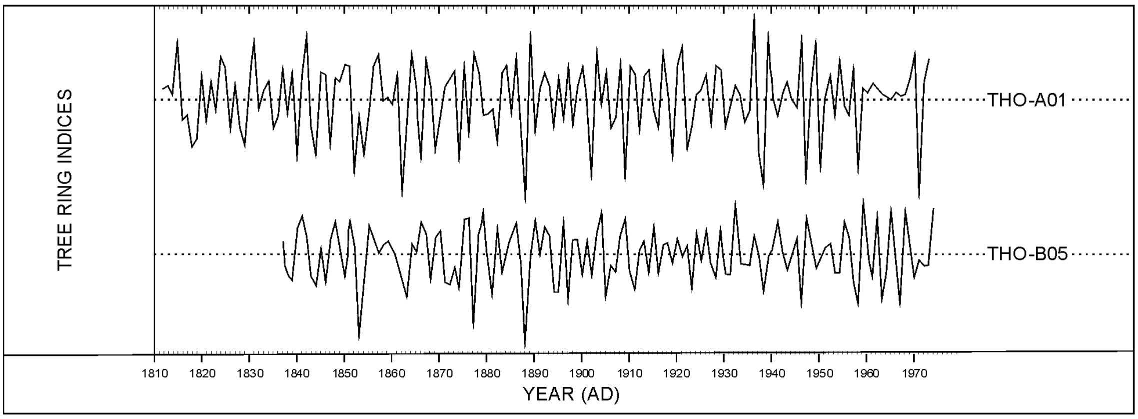


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely

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