Historic England

Scientific Dating

Church Tower
100m North of the Church of St John
Shenstone
Lichfield
Staffordshire

Tree-ring Dating of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 65/2022

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NGR: SK 10944 04382

ISSN 2059-4453 (Online)

SUMMARY
Dendrochronological analysis was undertaken on samples taken during renovations resulting in the dating of 21 timbers. Two main floor beams/tiebeams are dated as felled in the range of AD 1707–32, with three joists having *terminus post quem* dates for felling of AD 1467, AD 1490, and AD 1535. A timber identified as a possible joist was retrieved from a skip and has a *terminus post quem* date for felling of AD 1471.

Three *ex situ* timbers accompanying the bellframe were felled in the winter of AD 1625/6, and three bellframe braces, as well as a number of other associated timbers were also likely to have been felled at the same time. Four of the bellframe posts and a cill are slightly later, dating to the AD 1630s.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would like to thank John Tiernan, Historic England Heritage at Risk Architect for the Midlands Region, for facilitating access and all contractors on site for their assistance and patience during the sampling process. Shahina Farid (Historic England Scientific Dating Team) commissioned and facilitated this study.

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

HISTORIC ENVIRONMENT RECORD
Staffordshire Historic Environment Record
Lichfield
Staffordshire WS14 0JB

DATE OF INVESTIGATION
2022

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CONTENTS

INTRODUCTION

It is believed that a church has stood at this location (Fig 1), since the Saxon period, however, the derelict Grade II*-listed tower (List Entry Number: 1038830 https://historicengland.org.uk/listing/the-list/list-entry/1038830?section=official-list-entry), is the only survival of an early thirteenth century church. Records indicate that later in the thirteenth century extensions to the church, including to the nave, were undertaken. In the mid-fifteenth century (AD 1427–61) the church was renewed, at which point the tower was no longer in the centre of the church but at the west end of the nave. Work is also known to have been undertaken in AD 1723 on the chancel, south porch and elsewhere within the church. In 1852 the church was condemned, except for the tower which was still needed to house the bells, and work then began on the new, adjacent church, to replace it.

The tower has recently been awarded an Historic England Heritage at Risk Repairs Grant following an agreed programme of repair and repurpose for community use by the 'Friends of Shenstone Tower' group. The work involves the removal of roof/floor frame timbers (Figs 2 and 3) and some lower stage beams, including what appears to be the remains of the side of a timber bell frame (Fig 4). All elements are believed to be reused and none will be retained in the current renovation scheme.

SAMPLING

Dendrochronological investigation was requested by John Tiernan, Heritage at Risk Architect for the Midlands in order to provide independent dating evidence to inform the significance of the tower in its historic setting for its repair and repurpose for community use.

Thirty-two oak timbers (*Quercus* spp) from this tower have been sampled with each being given the code SHN-S and numbered 01–32. Two main floor beams, which may also have acted as tiebeams for the roof, were sampled by coring; sliced samples were taken from a joist still morticed into one of the beams and tenons lodged in two mortices. Seven sliced samples were taken from timbers retrieved from a skip and 20 sliced samples from a pile of timbers adjacent to the tower; some of these were obviously parts of a bellframe as they were still partially articulated whilst others were individual timbers. Further details relating to all samples can be found in Table 1. Photographs were taken of timbers sampled (Figs 2–4) with the exception of the two cut off tenons.

ANALYSIS AND RESULTS

All 32 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. All measurements were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 22 samples matching to form four groups.

Firstly, three samples grouped at a minimum *t* – value of 5.8 to form SHNSSQ01, a site sequence of 80 rings (Fig 5). Comparison of this site sequence against the reference chronologies resulted in a secure match at a first-ring date of AD 1396 and a last-measured ring date of AD 1475. The evidence for this dating is given in Table 2.

Nine samples matched each other at a minimum value of $t = 13.3$ and were combined at the relevant offset position to form SHNSSQ02, a site sequence of 131 rings (Fig 6). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1495 and a last-measured ring date of AD 1625. The evidence for this dating is given in Table 3.

Eight samples also matched each other at a minimum value of $t = 4.0$ and were again combined at the relevant offset position to form SHNSSQ03, a site sequence of 178 rings (Fig 7). This site sequence was found to match the reference chronologies when spanning the period AD 1530–1707. The evidence for this dating is given in Table 4.

Finally, two samples matched each other at $t = 6.3$ and were combined at the relevant offset position to form site sequence SHNSSQ04, of 67 rings (Fig 8). However, comparison of this site sequence with the reference chronologies did not produce a secure match and it remains undated.

Attempts were then made to date the remaining nine ungrouped samples by comparing them individually against the reference chronologies. This resulted in the successful dating of sample SHN-S03 at a first-ring date of AD 1468 and a last-measured ring date of AD 1520 (Table 5). The remaining samples could not be matched and remain undated.

INTERPRETATION

Tree-ring dating has resulted in the successful dating of 21 samples from the tower, from those associated with the roof/floor frame, the bellframe and a series of timbers retrieved from a skip which may relate to the floor frame or elsewhere within the tower (Fig 9). To aid interpretation these have been dealt with by area, below.

Roof/floor frame

All five of the samples taken from *in situ* timbers of this roof/floor frame have been successfully dated, only two of which have the heartwood/sapwood boundary. The two samples taken from the main beams have similar heartwood/sapwood boundary ring dates, suggestive of a single felling. The combined average heartwood/sapwood boundary ring of these two samples is AD 1692, allowing an estimated felling date to be calculated for the two timbers represented to within the range AD 1708–32. This felling date range allows for sample SHN-S01 having a last-measured ring date of AD 1707, with incomplete sapwood.

The other three floor samples, all taken from joists, do not have the heartwood/sapwood boundary ring and therefore estimated felling date ranges cannot be calculated for them, except to say that, with last-measured ring dates of AD 1452 (SHN-S04), AD 1475 (SHN-S05), and AD 1520 (SHN-S03), these would have been felled after AD 1467, AD 1490, and AD 1535, respectively.

Skip timbers

Sample SHN-S11, from one of the timbers retrieved from the skip, has also been dated. This sample has a last-measured ring date of AD 1456 but without the heartwood/sapwood boundary ring the timber represented has a *terminus post quem* date for felling of AD 1471.

Bellframe

Fifteen of the samples taken from the bellframe or loose timbers that appear associated with it, have been dated, seven of which retain complete sapwood.

Three samples, SHN-S24, SHN-S28, and SHN-S30 all have the last-measured ring date of AD 1625. When looked at under the microscope it is possible to see that the last ring has both spring and summer growth cells demonstrating that the timbers represented were felled in the winter of AD 1625/6. Six of the other dated samples group with these three samples at the high value of t = 13.3, which one would usually expect to signify the timbers represented were either cut from the same tree or from trees growing in relatively close proximity to one another. Hence all nine timbers represented are likely to have been derived from a tree, or trees, felled in the winter of AD 1625/6.

Three other samples with complete sapwood, SHN-S16, SHN-S20, and SHN-S22, have the slightly later last-ring date of AD 1633. Again, when looked at under the microscope both the spring and summer cells of this final ring are present, determining that that the three timbers (all posts) were felled in the winter of AD 1633/4. These three samples, and that taken from the fourth post (SHN-S13), group at a minimum value of t = 11.6, again suggesting that these four timbers were either cut from the same tree or from trees growing in relatively close proximity to each other. Hence, all four posts have the same felling date of winter AD 1633/34.

The seventh sample with complete sapwood, SHN-S18, has the last ring date of AD 1634 and, as the final ring present appears to be complete, can be said to have been felled in the winter of AD 1634/5.

The final dated sample, SHN-S31, has the heartwood/sapwood boundary ring date of AD 1608, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1623–48, making it possible that the timber represented was felled with those dated to AD 1625/6 or to the AD 1630s.

DISCUSSION

The potentially earliest timbers identified during this research are the two joists and one of the timbers retrieved from the skip, which is also possibly a joist (Fig 3). These all have *terminus post quem* dates for felling in the second half of the fifteenth century. However, it is not possible to know how heavily these were trimmed during conversion from tree to timber element and hence, whether they may represent the inner portions of much longer-lived trees. It may be that they were felled at the same time as the third joist but as that sample also only has a *terminus post quem* for felling date (of AD 1535) this could also be any time from the mid-sixteenth century. However, it is unlikely that they were felled at the same time as the main beams they were jointed into, which have a felling date in the range AD1708–32, as this would mean the joists were derived from trees in excess of 300 years old. Whilst this is possible it is unlikely. The felling date range obtained for the main beams raises the possibility that they could belong to the works known to have been undertaken on the chancel and 'elsewhere' in the church in, or about, AD 1723.

The bellframe is now known to have utilised timbers felled in the winter of AD 1625/6 (braces and timbers of unknown purpose), the winter of AD 1633/4 (posts), and the winter of AD 1634/5 (cill). The level of cross-matching between these 15 dated samples suggests the possibility that the timbers may either have been derived from only three or four different trees or alternatively a larger number of trees growing in relatively close proximity to each. These results could suggest construction of the bellframe occurred in the AD 1630s and incorporated stockpiled timber for some of its elements.

The three dated site chronologies and the individually dated sample were compared to an extensive range of reference chronologies but in general the highest levels of similarity are found with reference chronologies from the surrounding regions suggesting that the woodland sources from which the timbers were derived is likely to be relatively local.

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TABLES

Table 1: Details of tree-ring series from The Tower, 100m north of the Church of St John, Shenstone, Lichfield, Staffordshire

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
In-situ roof/floor beams						
SHN-S01	Main beam 1	123	14	1585	1693	1707
SHN-S02	Main beam 2	107	02	1587	1691	1693
SHN-S03	Joist	53	--	1468	----	1520
SHN-S04	Joist – cut off tenon	57	--	1396	----	1452
SHN-S05	Joist – cut off tenon	75	--	1401	----	1475
Timbers retrieved from the skip						
SHN-S06	Unknown timber	42	--	----	----	----
SHN-S07	Unknown timber	51	--	----	----	----
SHN-S08	Unknown timber	44	h/s	----	----	----
SHN-S09	Unknown timber	72	h/s	----	----	----
SHN-S10	Unknown timber	61	--	----	----	----
SHN-S11	Unknown timber	43	--	1414	----	1456
SHN-S12	Unknown timber	37	h/s	----	----	----
Ex-situ bellframe and associated timbers						
SHN-S13	Post, truss 1	83	14	1541	1609	1623
SHN-S14	Brace, truss 1	98	h/s	1507	1604	1604
SHN-S15	Cill, truss 1	86	16	----	----	----
SHN-S16	Post, truss 1	97	26C	1537	1607	1633
SHN-S17	Brace, truss 1	100	h/s	----	----	----
SHN-S18	Cill, truss 2	86	13C	1549	1621	1634
SHN-S19	Brace, truss 2	82	16	1543	1608	1624
SHN-S20	Post, truss 2	104	27C	1530	1606	1633
SHN-S21	Brace, truss 2	105	04	1508	1608	1612
SHN-S22	Post, truss 2	101	29C	1533	1604	1633
SHN-S23	Floor (?) beam nailed to cill, truss 2	58	--	----	----	----
SHN-S24	Loose timber	123	18C	1503	1607	1625
SHN-S25	Loose timber	105	h/s	1495	1599	1599
SHN-S26	Loose timber	96	22C	----	----	----
SHN-S27	Loose timber	55	09	----	----	----

SHN-S28	Loose timber	116	16C	1510	1609	1625
SHN-S29	Loose timber	91	04	1518	1604	1608
SHN-S30	Loose timber	105	17C	1521	1608	1625
SHN-S31	Loose timber	71	h/s	1538	1608	1608
SHN-S32	Loose timber	104	h/s	1499	1602	1602

*h/s = the heartwood/sapwood boundary is the last ring on the sample; C = complete sapwood retained on sample; last-measured ring is the felling date.

Table 2: Results of the cross-matching of site sequence SHNSSQ01 and example reference chronologies when the first ring date is AD 1396 and the last-measured ring date is AD 1475

Site reference	*t* – value	Span of chronology AD	Reference
Nether Hall Barn, Dalton, Huddersfield, West Yorkshire	7.3	1376–1453	Arnold *et al* 2008
Headlands Hall, Liversedge, West Yorkshire	7.2	1388–1487	Tyers 2001
Black Ladies, Brewood, Staffordshire	6.7	1372–1671	Tyers 1999
Castle Dairy, Kendal, Cumbria	6.5	1336–1485	Tyers 2015
Tithe Barn, Bolton Abbey, West Yorkshire	6.3	1350–1518	Arnold *et al* 2015a
Hanson Hall barn, Normanton, West Yorkshire	6.2	1359–1455	Tyers 2008a
Ightfield Hall barn, Shropshire	6.2	1341–1566	Groves 1997
Houndhill barn, Barnsley, South Yorkshire	6.0	1369–1470	Groves and Hillam 1990
Red Gables Cottage, Criggleston,West Yorkshire	5.9	1384–1590	Arnold *et al* 2013
Governors House, 23–24 Stodman Street, Newark, Nottinghamshire	5.7	1319–1471	Arnold *et al* 2002

Table 3: Results of the cross-matching of site sequence SHNSSQ02 and example reference chronologies when the first ring date is AD 1495 and the last-measured ring date is AD 1625

Site reference	*t* – value	Span of chronology AD	Reference
Aston Hall, Aston, Birmingham, West Midlands	7.4	1457–1624	Howard 2005 unpubl
17/21 Boar Lane, Newark, Nottinghamshire	7.3	1507–1657	Arnold *et al* 2002
Raynor House, Bradfield, South Yorkshire	7.3	1468–1593	Howard *et al* 1994a
The Old Coach House, Eastcote Manor, Hillingdon, London	7.2	1569–1697	Arnold and Howard 2012
Ledston Hall, Ledston, Leeds, West Yorkshire	7.2	1424–1668	Arnold *et al* 2015b
Colston Bassett Church, Nottinghamshire	7.1	1465–1609	Howard *et al* 1995
Hathershaw Hall, Oldham, Lancashire	7.1	1497–1693	Arnold *et al* forthcoming a
Sutton Scarsdale Manor (house), Derbyshire	7.4	1521–1658	Howard *et al* 1996a
Bolsover Little Castle, Derbyshire	6.9	1532–1749	Arnold *et al* 2003
Rose Cottage, Lount, Leicestershire	6.9	1498–1612	Arnold *et al* 2010

Table 4: Results of the cross-matching of site sequence SHNSSQ03 and example reference chronologies when the first ring date is AD 1530 and the last-measured ring date is AD 1707

Site reference	*t* – value	Span of chronology AD	Reference
Kirby Hall, Northamptonshire	8.8	1509-1795	Arnold *et al* forthcoming b
Sinai Park, Burton-on-Trent, Staffordshire	8.8	1227–1750	Tyers 1997
Bingham, Nottinghamshire	7.9	1445–1752	Arnold and Howard 2014 unpubl
Sneath’s Mill, Lutton Gowts, Lincolnshire	7.9	1593–1728	Arnold and Howard 2016
Pontefract Castle, West Yorkshire	7.8	1507–1656	Arnold and Howard 2005
Church of St Nicholas, Bringhurst, Leicestershire	7.3	1502–1687	Arnold *et al* 2005
Southwell Minster, Nottinghamshire	7.5	1573–1716	Howard *et al* 1996b
Bolsover Castle (Riding House), Derbyshire	7.3	1494–1744	Howard *et al* 2005
Ledston Hall, Ledston, Leeds, West Yorkshire	7.2	1424–1668	Arnold *et al* 2015b
Bretby Hall, Derbyshire	7.2	1494–1719	Howard *et al* 1999

Table 5: Results of the cross-matching of sample SHN-S03 and example reference chronologies when the first ring date is AD 1468 and the last-measured ring date is AD 1520

Site reference	*t* – value	Span of chronology AD	Reference
Wolverton Manor, Shropshire	7.5	1325–1580	Miles *et al* 1993
Church of St Mary, Neen Savage, Shropshire	6.7	1227–1469	Arnold and Howard 2014b
Church of St Catherine, Cossal, Nottinghamshire	6.6	1388–1492	Arnold *et al* 2016
Jordanthorpe barn, Sheffield, South Yorkshire	6.5	1425–1531	Hillam 1983
St John the Baptist, Muston, Leicestershire	6.4	1437–1611	Arnold *et al* 2005
Bleathwood Manor Farm, Tenbury Wells, Herefordshire	6.3	1461–1581	Tyers 2008b
Sinai Park, Burton-on-Trent, Staffordshire	6.1	1227–1750	Tyers 1997
Unthank Hall, Holmesfield, Derbyshire	6.1	1401–1540	Howard *et al* 1994b
Court House, Shelsley Walsh, Worcestershire	6.1	1328–1419	Arnold *et al* 2008
7–12 Church Street, Dronfield, Derbyshire	6.0	1313–1526	Arnold and Howard 2014a

FIGURES

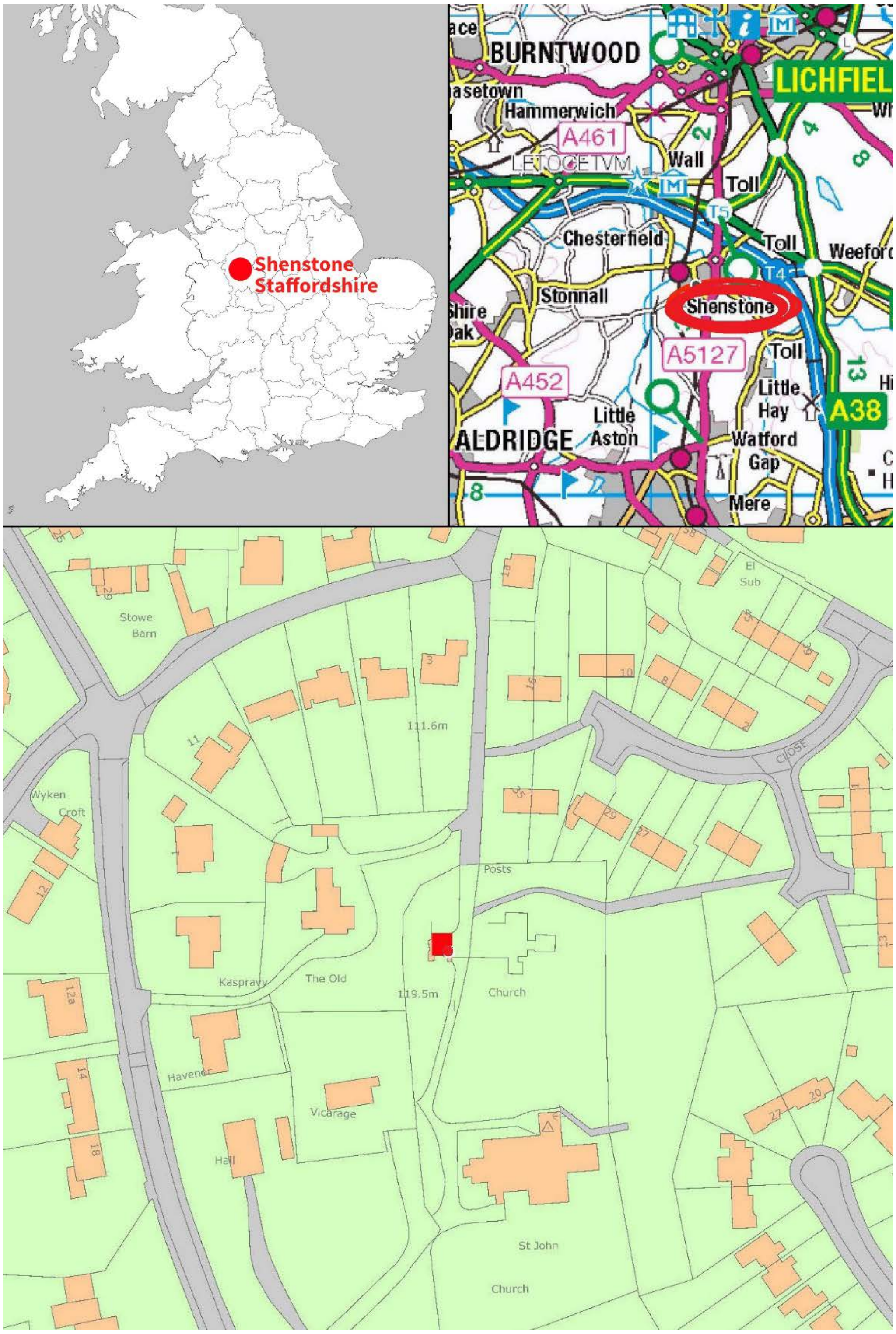

Figure 1: Maps to show the location of the Church Tower in Shenstone, Saffordshire; marked in red. Scale: top right 1:105,000; bottom: 1:1,500. © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900.

Figure 2: Floor/roof beams, north beam with in-situ joist (standing upright) in foreground; samples SHN-S01–SHN-S03 (samples SHN-S04 and SHN-S05 cut off tenons not shown), photograph taken from the north-west (Photograph: Alison Arnold)

Figure 3: Photographs of samples taken from timbers retrieved from a skip, SHN-S06–12 (Photograph:Alison Arnold)


SHN-S13
SHN-S14
SHN-S15
SHN-S17
SHN-S16


SHN-S18


SHN-S19


SHN-S20


SHN-S21


SHN-S22


SHN-S23


SHN-S24
SHN-S27
SHN-S25
SHN-S26


SHN-S28

Figure 4: Photographs of sampled bellframe and associated timbers, samples SHN-S13–32 (Photograph:Alison Arnold)

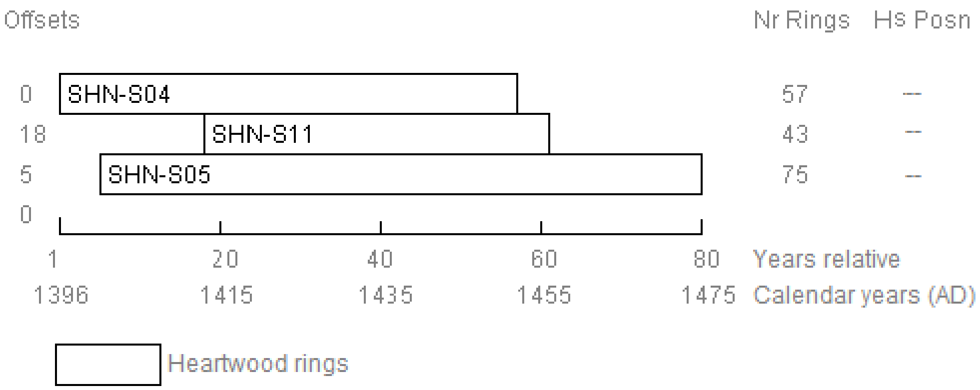

Figure 5: Bar diagram of samples in site sequence SHNSSQ01

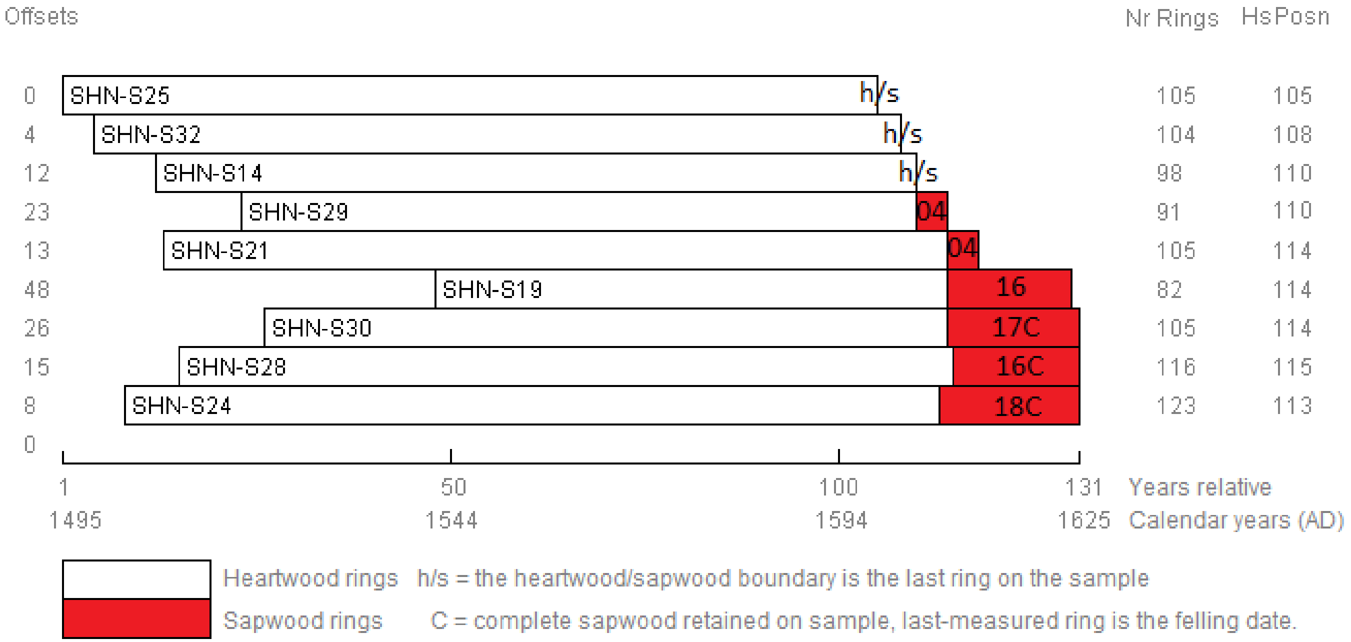

Figure 6: Bar diagram of samples in site sequence SHNSSQ02

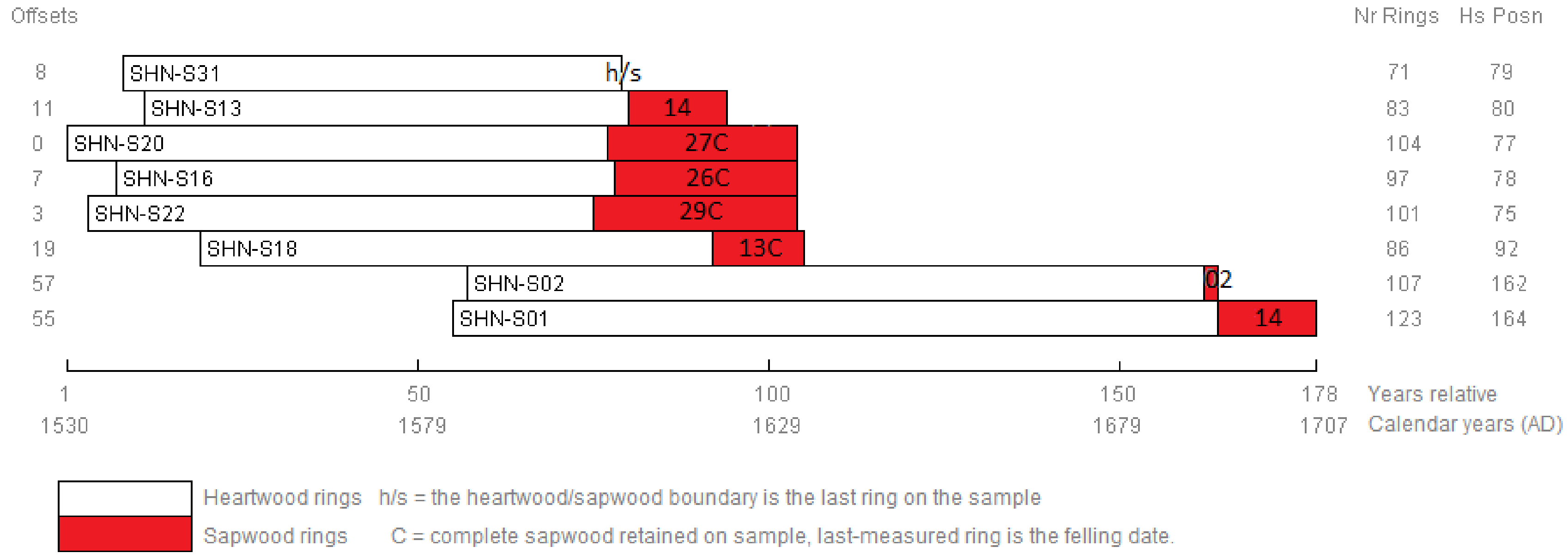

Figure 7: Bar diagram of samples in site sequence SHNSSQ03

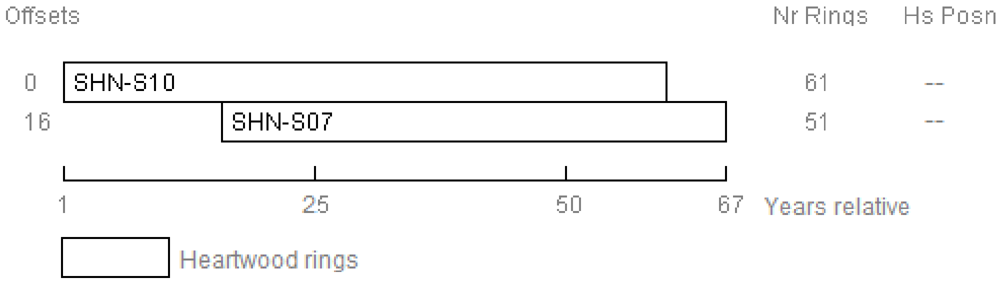

Figure 8: Bar diagram of samples in undated site sequence SHNSSQ04

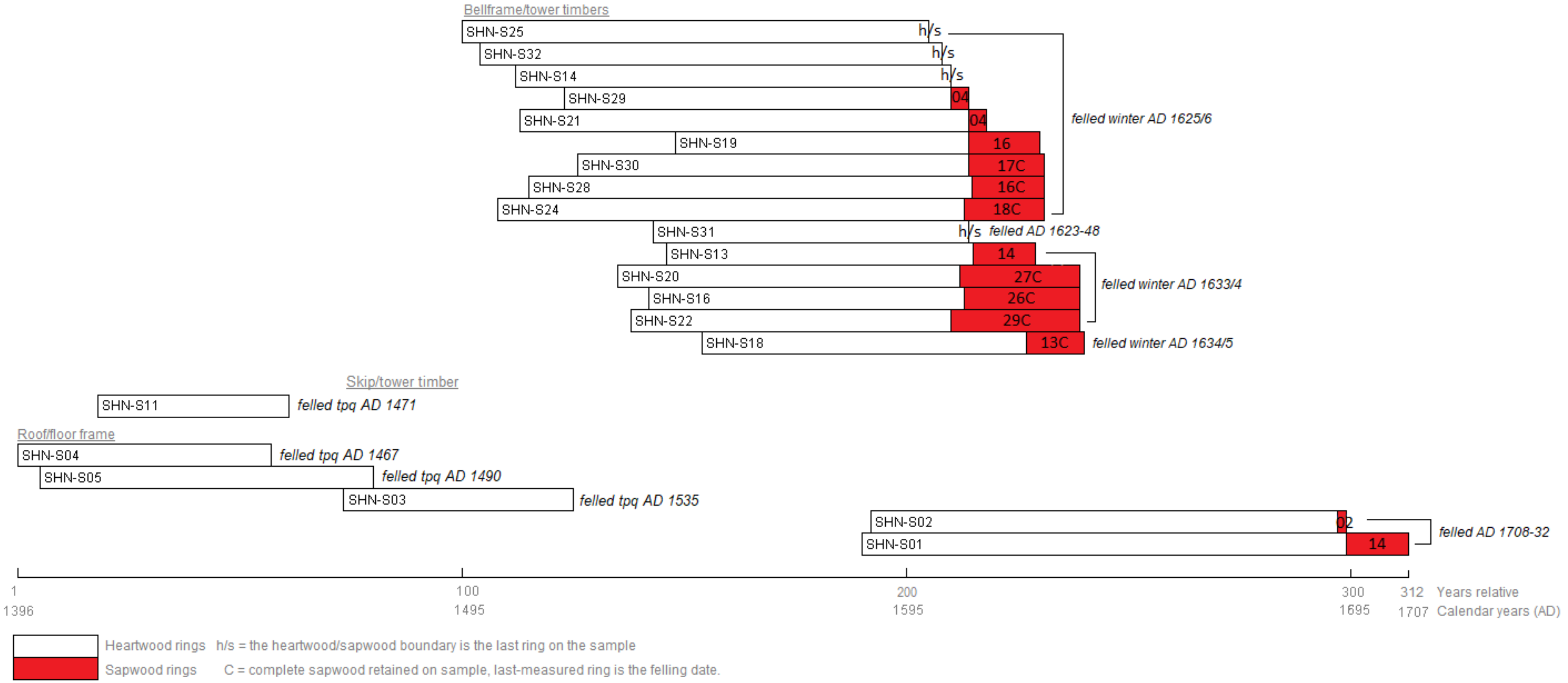

Figure 9: Bar diagram of all dated samples, sorted by area

DATA OF MEASURED SAMPLES

SHN-S01A 123
267 143 143 241 204 189 155 206 234 329 256 326 294 376 372 313 219 192 227 273
215 360 304 233 254 257 112 156 177 130 136 160 182 170 180 175 139 152 160 83
107 87 142 175 166 155 98 166 127 95 87 93 149 116 87 143 129 128 125 123
117 183 184 201 131 76 67 82 96 150 189 164 122 119 89 74 79 119 138 111
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111 180 191 190 134 81 65 74 104 152 194 157 120 111 92 78 72 118 148 103
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170 155 172
SHN-S11B 43
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225 226 241 186 206 141 148 161 130 217 255 201 123 137 215 241 191 206 195 139
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SHN-S12B 37
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127 158 105
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87 80
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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 outside ring, which grew in 1976

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

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

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

2. *Measuring Ring Widths.*

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

3. *Cross-Matching and Dating the Samples.*

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

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

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

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

4. Estimating the Felling Date.

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

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

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

Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

5. Estimating the Date of Construction.

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

6. Master Chronological Sequences.

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

Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices.

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

t value/offset Matrix

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

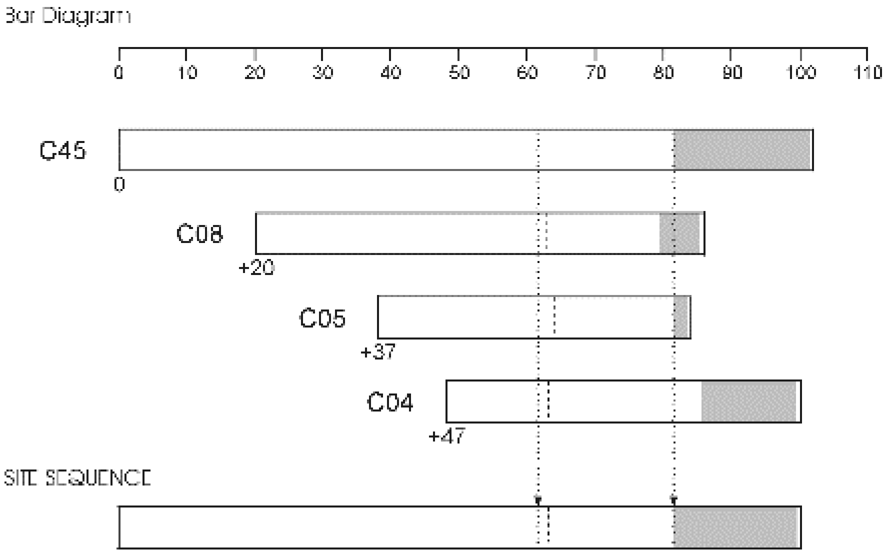


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

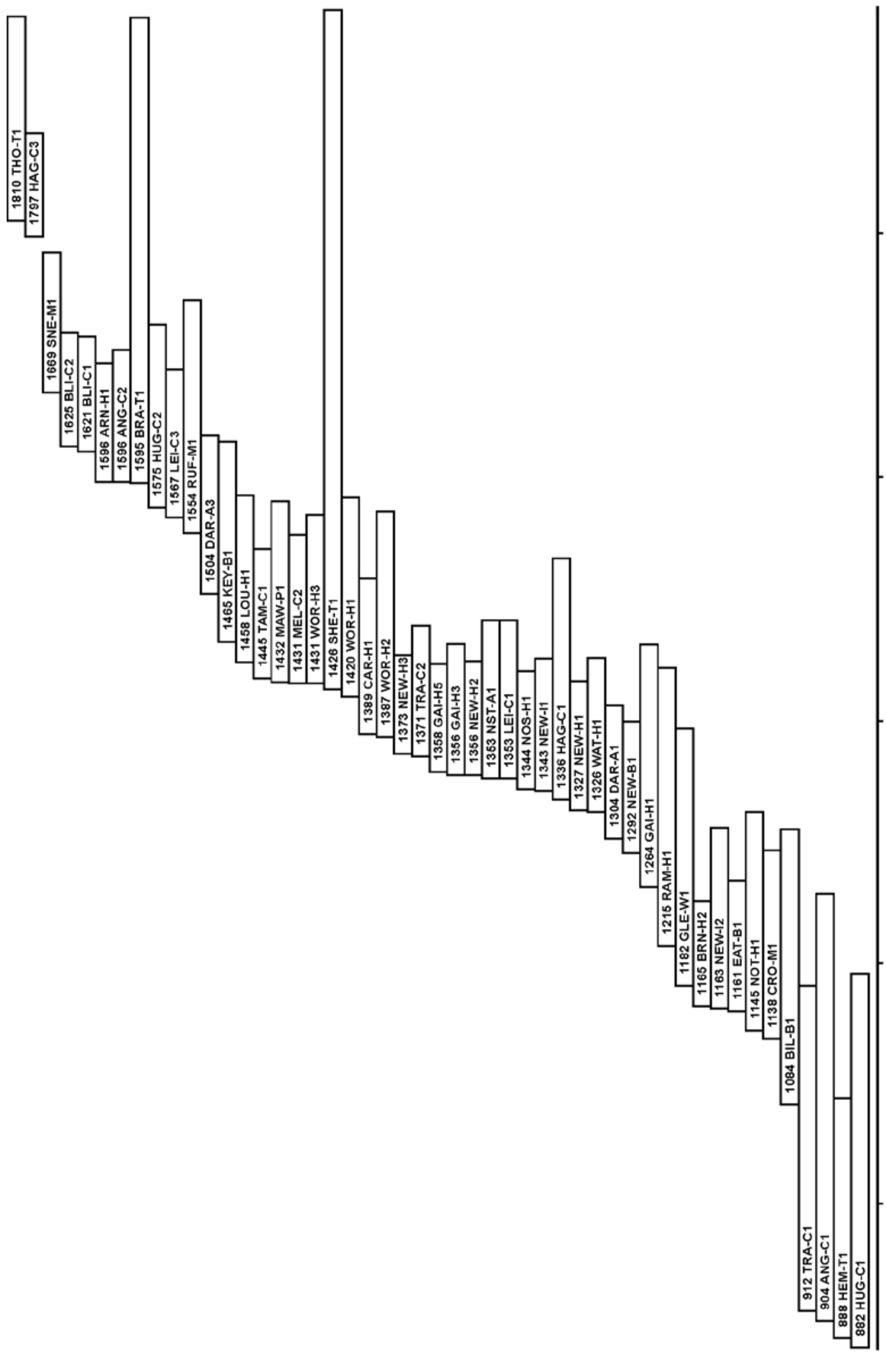
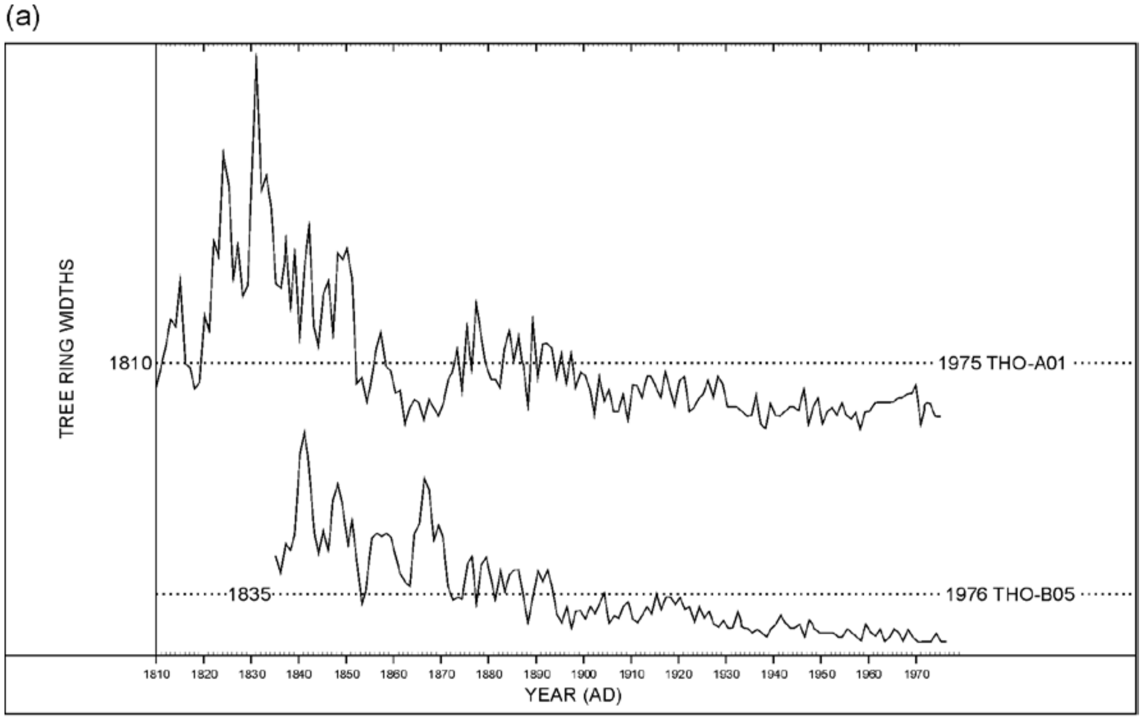


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87



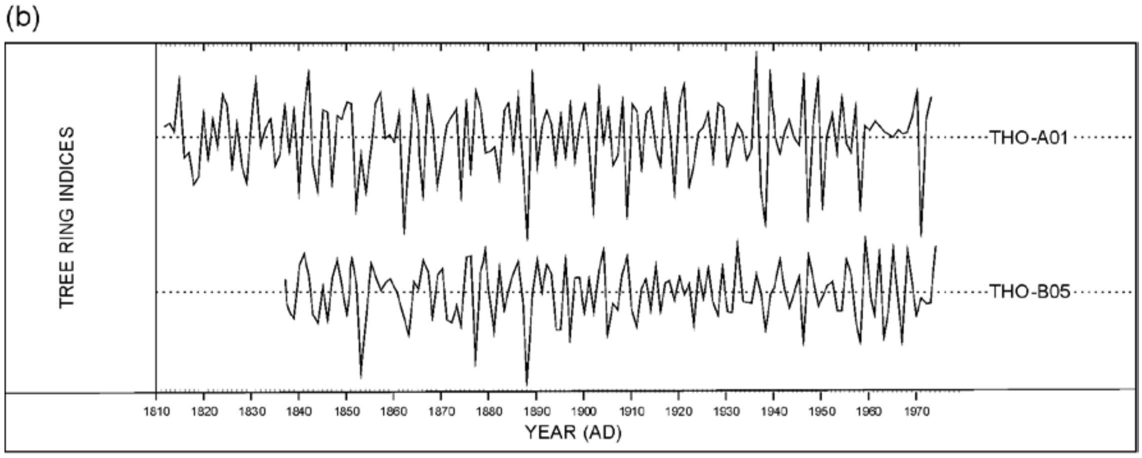


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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ISSN 2059-4453 (Online)