Historic England

Scientific Dating

Church of St Michael, Knighton-on-Teme, Worcestershire

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 18-2016

Cover: Church of St Michael, Knighton-on-Teme.

Research Report Series 18-2016

CHURCH OF ST MICHAEL, KNIGHTON-ON-TEME, WORCESTERSHIRE

Tree-ring Analysis of Timbers

Alison Arnold and Robert Howard

NGR: SO 63336 69913

ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)

The Research Report Series incorporates reports by the expert teams within Historic England. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.

Many of the Research Reports are of an interim nature and serve to make available the results of specialist investigations in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation. Where no final project report is available, readers must consult the author before citing these reports in any publication. Opinions expressed in Research Reports are those of the author(s) and are not necessarily those of Historic England.

For more information write to Res.reports@HistoricEngland.org.uk or mail: Historic England, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD

SUMMARY
Analysis undertaken on samples taken from the tower, nave partition, and the roof between the two areas resulted in the successful dating of 31 timbers. The tower contains two timbers felled in AD 1216–41, presumably relating to the primary construction, as well as a series of timbers felled in AD 1445–70, some of which have been reused within an even later phase of work, which are dated by a group of timbers felled in AD 1717.

Three of the timbers of the nave partition have been dated, two as being felled in AD 1439–64, making them broadly coeval to the mid-fifteenth century tower timbers, and a third to AD 1509–34, possibly representing alterations to the partition at the same, or similar, time as the dated roof was constructed.

The portion of roof located between the nave partition and tower is constructed using timber felled in AD 1521–46.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS
The Laboratory would like to thank Captain P D Morgan, churchwarden, for facilitating access for assessment and sampling. Thanks are also given to Cathy Tyers and Shahina Farid of the Historic England Scientific Dating Team for their advice and assistance throughout the production of this report.

ARCHIVE LOCATION
Worcestershire Historic Environment Record
Worcestershire Archive and Archaeology Service
The Hive, Sawmill Walk
The Butts, Worcester
Worcestershire WR1 3PD

DATE OF INVESTIGATION
2015

CONTACT DETAILS

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

CONTENTS

INTRODUCTION

The Grade I listed Church of St Michael, located in Knighton-on-Teme in Worcestershire (Figs 1–3), is thought to date from the early twelfth century, consisting at that time of a chancel, nave, and possibly a detached wooden tower situated to the west of the nave. At the end of the twelfth, or beginning of the thirteenth, century the nave was lengthened and the chancel partly rebuilt. Later, possibly in the fifteenth century, the nave was extended westwards again to enclose the timber-framed tower (Fig 4). Restoration programmes were conducted in the nineteenth and twentieth centuries.

Tower

At ground-floor level there are three massive posts (a fourth is hidden or replaced by a brick pillar at this level), and passing braces, which were thought to represent the primary tower framework (Fig 5). At a higher level, it can be seen that later work has been undertaken, some of it utilising reused timbers (Fig 6). The tower is topped by a shingled bell turret, which dates to 1959. The primary tower framework has been compared to that of St John the Baptist Church in nearby Mamble, which has been tree-ring dated to AD 1214–55 (Tyers 1996).

Nave

Partition

When the nave was extended in the fifteenth century to incorporate the tower the stone west wall of the nave was replaced by a timber-framed partition with rendered brick infill (Fig 7). This partition separates the west end of the nave and the tower, with access between the two areas being via an ogee-headed doorway. The top portion of the partition juts backwards towards the tower and it has been suggested that the partition once supported a minstrel's gallery (http://temevalleynorthparish.co.uk/our-churches/knighton/).

Roof

The roof over the nave consists of arch-braced collar and tiebeam trusses with V-struts in the apex; the tiebeams, purlins, and wallplates are all moulded and the tiebeams have central bosses. The roof runs the complete length of the nave as far as the eastern posts of the tower demonstrating that the nave had been extended by the time this roof was constructed (Fig 8). Stylistically, it is thought to be fifteenth century in date.

SAMPLING

A dendrochronological survey was requested by Katriona Byrne, Historic England Inspector of Historic Buildings and Areas, to provide independent dating evidence for the initial construction of the detached tower and the extension of the nave to incorporate the tower into the main body of the church. It was hoped that this would help inform advice relating to the programme of restoration and repair, supported by a Heritage Lottery Fund grant for Places of Worship, that would lead to the church's eventual removal from the Heritage at Risk Register.

A total of 44 timbers from the tower, the nave partition, and the nave roof between the two was sampled by coring. Each sample was given the code KNT-N and numbered 01–44. Attempts were made during the sampling of the tower to identify timbers thought to be from the primary construction, reused timbers used within a secondary phase of work, and those timbers primary to this secondary phase of work. The location of all samples was noted at the time of sampling and has been marked on Figures 4, 6, and 8–15. Further details relating to the samples can be found in Table 1.

ANALYSIS AND RESULTS

Three samples, one from a timber within the tower thought to belong to the primary phase and two from the nave partition, had too few rings for secure dating and so were rejected prior to measurement. The remaining 41 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 samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in 31 samples matching to form three groups.

Firstly, two samples from the tower matched each other and were combined at the relevant offset positions to form KNTNSQ01, a site sequence of 85 rings (Fig 16). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to span the period AD 1119–1203. The evidence for this dating is given by the *t*-values in Table 2.

Twenty-three samples, from the tower, the nave partition, and the roof between the two areas, grouped to form KNTNSQ02, a site sequence of 191 rings (Fig 17). This was dated to spanning the period AD 1326–1516 (Table 3).

Finally, six samples from the tower matched each other and were combined to form KNTNSQ03, a site sequence of 124 rings (Fig 18). Comparison of this site sequence against the reference material resulted in it being matched at a first-ring date of AD 1594 and a last-measured ring date of AD 1717. The evidence for this dating is given in Table 4.

Attempts to date the remaining ungrouped samples by comparing them individually against the reference chronologies were unsuccessful and all remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 31 timbers from all areas. To aid interpretation each area is dealt with separately below and illustrated in Figure 19. Felling date ranges have been calculated using the estimate that mature oak trees in this region have 15–40 sapwood rings (95% confidence range).

Tower

Eighteen of the samples taken from the tower have been successfully dated, 15 of which have the heartwood/sapwood boundary. Interpretation of these heartwood/sapwood boundary ring dates suggests three separate felling phases are represented amongst these dated samples.

Two of the samples (KNT-N02 and KNT-N05) have similar heartwood/sapwood boundary ring dates that are substantially earlier than the rest of the dated timbers. The average of these is AD 1201 giving the two timbers represented an estimated felling date within the range AD 1216–41.

Nine other samples have similar heartwood/sapwood boundary ring dates, suggestive of a single felling. The average of these is AD 1430, giving an estimated felling date for the timbers represented to within the range AD 1445–70.

Four other samples have similar heartwood/sapwood boundary rings dates, again suggestive of a single felling. Two of these (KNT-N19, KNT-N20) have complete sapwood and the last-measured ring date of AD 1717, representing the felling date of the timbers. The average heartwood/sapwood boundary ring date of the other two samples (KNT-N16, KNT-N17) is AD 1689, giving an estimated felling date for the timbers represented to within the range AD 1715–29 (allowing for sample KNT-N17 having a last-measured ring date of AD 1714 with incomplete sapwood), consistent with these two timbers also having been felled in AD 1717.

Three other samples from the tower do not have the heartwood/sapwood boundary and so estimated felling date ranges cannot be calculated for them, except to say that with last-measured ring dates of AD 1434 (KNT-N15), AD 1673 (KNT-N22), and AD 1681 (KNT-N23), these would be estimated to be at the earliest AD 1450, 1689, and 1697, respectively. Based on an earliest possible felling date of AD 1450, combined with the level of crossmatching found between KNT-N15 and the nine other mid fifteenth-century samples, it appears likely that this timber was also felled in the range AD 1445–70. Samples KNT-N22 and KNT-N23 are clearly broadly coeval with the four timbers felled in AD 1717 and, whilst they could represent a different felling phase, it seems likely that they were also felled in, or around, AD 1717.

Nave

Partition

Three of the samples taken from this structure have been dated, all of which have the heartwood/sapwood boundary ring date.

Two of the samples taken from the lower portion of the partition have the heartwood/sapwood boundary ring date of AD 1424, giving an estimated felling date for the two timbers represented to within the range AD 1439–64.

A sample taken from a stud in the upper half of the partition has a later heartwood sapwood boundary ring date of AD 1494, allowing an estimated felling date to be calculated for the timber represented to within the range of AD 1509–34.

Roof

Ten of the samples taken from roof timbers located between the tower and the nave partition have been dated, eight of which have the heartwood/sapwood boundary ring. The date of these heartwood/sapwood boundary rings is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1506, allowing an estimated felling date to be calculated for the timbers represented to within the range AD 1521–46.

The final two dated samples from this area do not have the heartwood/sapwood boundary ring and so estimated felling dates cannot be calculated for them, however, with last-measured heartwood ring dates of AD 1464 (KNT-N29) and AD 1479 (KNT-N37), these would be estimated to be, at the earliest, AD 1480 and AD 1495, respectively. This, combined with the level of crossmatching with the other sixteenth century timbers, suggests that it is likely that these two timbers were also felled in AD 1521–46.

DISCUSSION

Prior to the tree-ring dating being undertaken the primary phase of the tower had been dated to the early-thirteenth century on the basis of its similarity to the tree-ring dated tower at the Church of St John the Baptist, Mamble (Brooks and Pevsner 2007; Tyers 1996). Two of the ground-floor posts, thought to belong to this primary phase, have now been dated to AD 1216–41, confirming this early-thirteenth century date and demonstrating its contemporaneity with the tower at the Church of St John the Baptist. However, three other timbers (a third post, a passing brace, and a base beam), also thought to be primary, have been found to be somewhat later, dating to AD 1445–70. It is thought that the nave was extended westwards in the fifteenth century to incorporate the tower and it would appear that these clearly mid-fifteenth century timbers relate to alterations undertaken to the tower as part of this work. It may be relevant that the two thirteenth century posts are the western posts in the tower and would therefore, possibly, not be affected by the fifteenth century work in the way that the eastern part of the tower might be.

Other tower timbers, identified as reused, have also been dated to AD 1445–70. These reused timbers have been utilised alongside other timbers dated to AD 1717, demonstrating alterations or modifications being undertaken to the tower in the early-eighteenth century but utilising some mid-fifteenth century timber.

Timbers of two separate dates have been identified within the nave partition. Two studs from the lower portion of the partition have been dated to AD 1439–64, making them broadly contemporary with the mid-fifteenth century timbers of the tower and, therefore, also likely to be related to the extension of the nave. A stud from the upper portion of the partition is a little later, dating to AD 1509–34, possibly representing alterations to the structure. This timber is broadly coeval with the nave roof timbers and suggests changes being made to the partition at the same time as the construction of the present roof.

The section of the nave roof analysed is now known to utilise timber felled in AD 1521–46, suggesting construction in the first half of the sixteenth century, slightly later than the fifteenth century date previously assigned to this roof on stylistic evidence. Samples were only taken from that portion of the roof between the nave partition and the tower and so it could be that this part of the roof is slightly later than the rest, although this seems unlikely on constructional evidence.

At the time of sampling attempts were made to identify which timbers might be primary to a phase and *in-situ* and which had been reused. It is clear from these results that identification is not straightforward as timbers believed to belong to the primary phase of construction have been dated to both the early thirteenth and mid-fifteenth centuries. A detailed architectural survey would perhaps be appropriate now that dendrochronological analysis has identified four clear felling phases within the areas under investigation.

BIBLIOGRAPHY

Arnold, A J, and Howard, R E, 2012 unpubl Tree-ring analysis of timbers from Slackwood Farmhouse, New Road, Silverdale, Slackwood, near Carnforth, Lancashire, unpubl computer file *SKWASQ01/02/03,* NTRDL

Arnold, A J, and Howard, R, 2013 *Oakham Castle, Oakham, Rutland, Tree-ring Analysis of Timbers*, EH Res Rep Ser, **23/2013**

Arnold, A J, and Howard, R E, 2014a *Tree-ring Analysis of Timbers from the St John's Walk, Hereford Cathedral, Herefordshire*, NTRDL rep

Arnold, A J, and Howard, R E, 2014b *Church of St Mary, Neen Savage, Shropshire, Tree-ring Analysis of Timbers,* EH Res Rep Ser, **75/2014**

Arnold, A J, Howard, R E, Laxton R R, and Litton, C D, 2003a *Tree-ring Analysis of Timbers from Exeter Cathedral, Exeter, Devon, Part 3 (Western Roofs, Bays 1–4*), Centre for Archaeol Rep, **49/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2003b *Tree-ring Analysis of Timbers from the Roofs of the Lady Chapel North and South Aisle, and the Choir South Aisle, Worcester Cathedral, Worcester*, Centre for Archaeol Rep, **96/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2003c *Tree-ring Analysis of Timbers from the De Grey Mausoleum, St John the Baptist Church, Flitton, Bedfordshire*, Centre for Archaeol Rep, **48/2003**

Arnold, A J, Howard, R E, and Litton, C D, 2004 *Tree-ring Analysis of Timbers from 25 The Cloisters (Denton's Commons), Windsor Castle, Windsor, Berkshire*, Centre for Archaeol Rep, **82/2004**

Bridge, M C, 1996 Tree-ring dates, *Vernacular Architect*, **27**, 91–2

Brooks, A and Pevsner, N, 2007 *The Buildings of England: Worcestershire*. New Haven and London, 419–20

Groves, C, 2005 *Dendrochronological Research in Devon: Phase 1*, Centre for Archaeol Rep, **56/2005**

Howard, R E, Laxton, R R, and Litton, C D, 1999 *Tree-ring Analysis of Timbers from The Manor House, Medbourne, Leicestershire,* Anc Mon Lab Rep, **63/1999**

Howard, R E, Laxton, R R, and Litton, C D, 2000 *Tree-ring Analysis of Timbers from the Buildings and Living Trees at Stoneleigh Abbey, Stoneleigh, Warwickshire*, Anc Mon Lab Rep, **80/2000**

Hurford, M, Bridge, M, and Tyers, C, 2010 *King John's Hunting Lodge, Lacock, Wiltshire, Tree-Ring Analysis of Timbers*, EH Res Dept Rep Ser, **101/2010**

Miles, D, and Bridge, M, 2008 *Tree-ring Dating of the Chests and Fittings, Westminster Abbey, London*, EH Res Dept Rep Ser, **3/2008**

Miles, D H, and Worthington, M J, 1997 Tree-ring dates, *Vernacular Architect*, **28**, 159–81

Miles, D, and Worthington, M, 2004 *Tree-ring Dating of Cradley Village Hall, Cradley, Herefordshire*, Centre for Archaeol Rep, **10/2004**

Miles, D H, Worthington, M J, and Bridge, M C, 2003 Tree-ring dates, *Vernacular Architect*, **34**, 109–13

Tyers, I, 1996 *Tree-ring Analysis of the Tower of St John the Baptist Church, Mamble, Hereford and Worcester*, Anc Mon Lab Rep **22/96**

Tyers, I, 2003 *Tree-ring Analysis of Oak Timbers from the South Transept and Nave roofs of the Church of St John the Baptist, Bradworthy, Devon*, Centre for Archaeol Rep, **2/2003**

Willis-Bund, J, 1913 *The Victoria History of the County of Worcester, volume **3**,* London, 447–9

TABLES

Table 1: Details of samples from the Church of St Michael, Knighton-on-Teme, Worcestershire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Tower						
Primary timbers						
KNT-N01	East post, north wall	64	04	1368	1427	1431
KNT-N02	West post, north wall	65	h/s	1139	1203	1203
KNT-N03	East passing brace, north wall	NM	--	----	----	----
KNT-N04	Base beam, north wall	71	h/s	1358	1428	1428
KNT-N05	West post, south wall	80	h/s	1119	1198	1198
KNT-N06	East passing brace, south wall	56	h/s	----	----	----
KNT-N07	West passing brace, south wall	104	h/s	1326	1429	1429
KNT-N08	Base beam, south wall	64	h/s	----	----	----
Phase 2 – reused						
KNT-N09	North stud post, west wall, mid-level	100	--	----	----	----
KNT-N10	North upper brace, west wall, mid-level	66	h/s	1371	1436	1436
KNT-N11	South stud post, west wall, mid-level	45	--	----	----	----
KNT-N12	South upper brace, west wall, mid-level	88	h/s	1346	1433	1433
KNT-N13	East brace, north wall, mid-level	87	h/s	1350	1436	1436
KNT-N14	East brace, south wall, bellframe level	69	03	1362	1427	1430
KNT-N15	East lower stud, south wall, bellframe level	79	--	1356	----	1434
KNT-N25	Centre stud, east wall, bellframe level	55	h/s	1370	1424	1424
KNT-N26	East stud, north wall, bellframe level	91	h/s	1343	1433	1433
Phase 2						
KNT-N16	Lower mid stud, west wall, mid-level	58	20	1647	1684	1704
KNT-N17	South lower brace, west wall, mid-level	75	20	1640	1694	1714
KNT-N18	Mid plate, west wall, mid-level	76	20C	----	----	----
KNT-N19	East post, north wall, mid-level	80	23C	1638	1694	1717
KNT-N20	West lower brace, south wall, mid-level	84	26C	1634	1691	1717

KNT-N21	West passing brace (top repair), south wall, mid-level	104	h/s	----	----	----
KNT-N22	West post, south wall, bellframe level	80	--	1594	----	1673
KNT-N23	Centre post, south wall, bellframe level	75	--	1607	----	1681
KNT-N24	Base beam, south wall, bellframe level	95	24C	----	----	----
KNT-N27	West post, north wall, bellframe level	85	--	----	----	----
Nave roof						
KNT-N28	North common rafter 1	91	h/s	1421	1511	1511
KNT-N29	North common rafter 2	72	--	1393	----	1464
KNT-N30	North common rafter 3	85	04	1424	1504	1508
KNT-N31	South common rafter 1	99	h/s	1403	1501	1501
KNT-N32	South common rafter 2	98	h/s	1411	1508	1508
KNT-N33	South common rafter 3	60	h/s	----	----	----
KNT-N34	North inner wallplate	120	h/s	1372	1491	1491
KNT-N35	South inner wallplate	86	h/s	1431	1516	1516
KNT-N37	North principal rafter	91	--	1389	----	1479
KNT-N38	North upper purlin	122	06	1390	1505	1511
KNT-N39	Tiebeam	118	h/s	1392	1509	1509
Nave partition						
KNT-N36	South middle stud, mid-level	117	h/s	1378	1494	1494
KNT-N40	Stud 4, ground floor	50	h/s	1375	1424	1424
KNT-N41	Stud 5, ground floor	NM	--	----	-----	----
KNT-N42	Stud 3, ground floor	50	h/s	1375	1424	1424
KNT-N43	South lower rail	NM	--	----	----	----
KNT-N44	Middle rail, 3rd	45	--	----	----	----

NM = not measured h/s = heartwood/sapwood boundary is the last-measured ring C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence KNTNSQ01 and relevant reference chronologies when the first-ring date is AD 1119 and the last-measured ring date is AD 1203

Reference chronology	t-value	Span of chronology	Reference
Westminster Abbey (Lapidarium chest), London	7.3	AD 1124–1228	Miles and Bridge 2008
Guesten Hall, (Avoncroft Museum), Worcestershire	6.6	AD 1146–1236	Brown pers comm
Exeter Cathedral, Devon	6.2	AD 1132–1337	Arnold et al 2003a
Chimsworthy, Bratton Clovelly, Devon	6.1	AD 1154–1255	Groves 2005
Church of St John the Baptist, Bradworthy, Devon	5.9	AD 1125–1367	Tyers 2003
The Cloisters, Windsor Castle, Berkshire	5.8	AD 1146–1212	Arnold et al 2004
King John's Hunting Lodge, Lacock, Wiltshire	5.5	AD 1148–1318	Hurford et al 2010

Table 3: Results of the cross-matching of site sequence KNTNSQ02 and relevant reference chronologies when the first-ring date is AD 1326 and the last measured ring date is AD 1516

Reference chronology	t-value	Span of chronology	Reference
St John's Walk, Hereford Cathedral, Herefordshire	11.5	AD 1356–1504	Arnold and Howard 2014a
Mercer's Hall, Gloucestershire	10.9	AD 1289–1541	Howard et al 1996
Church House, Areley Kings, Worcestershire	10.5	AD 1365–1535	Miles et al 2003
Cradley Village Hall, Herefordshire	10.0	AD 1347–1530	Miles and Worthington 2004
Old School House, Bayton, Worcestershire	9.9	AD 1348–1525	Bridge 1996
Church of St Mary, Neen Savage, Shropshire	9.1	AD 1227–1469	Arnold and Howard 2014b
Church of St John the Baptist, Mamble, Worcestershire	9.1	AD 1348–1582	Tyers 1996

Table 4: Results of the cross-matching of site sequence KNTNSQ03 and relevant reference chronologies when the first-ring date is AD 1594 and the last-measured ring date is AD 1717

Reference chronology	t-value	Span of chronology	Reference
Worcester Cathedral, Worcester, Worcestershire	6.2	AD 1484–1772	Arnold et al 2003b
De Grey Mausoleum, Flitton, Bedfordshire	5.8	AD 1510–1726	Arnold et al 2003c
Stokesay Castle, Shropshire	5.5	AD 1463–1662	Miles and Worthington 1997
Stoneleigh Abbey, Stoneleigh, Warwickshire	5.4	AD 1398–1658	Howard et al 2000
Slackwood Farmhouse, Slackwood, near Carnforth, Lancashire	5.4	AD 1613–1683	Arnold and Howard 2012 unpubl
Oakham Castle, Oakham, Rutland	5.1	AD 1598–1737	Arnold and Howard 2013

FIGURES

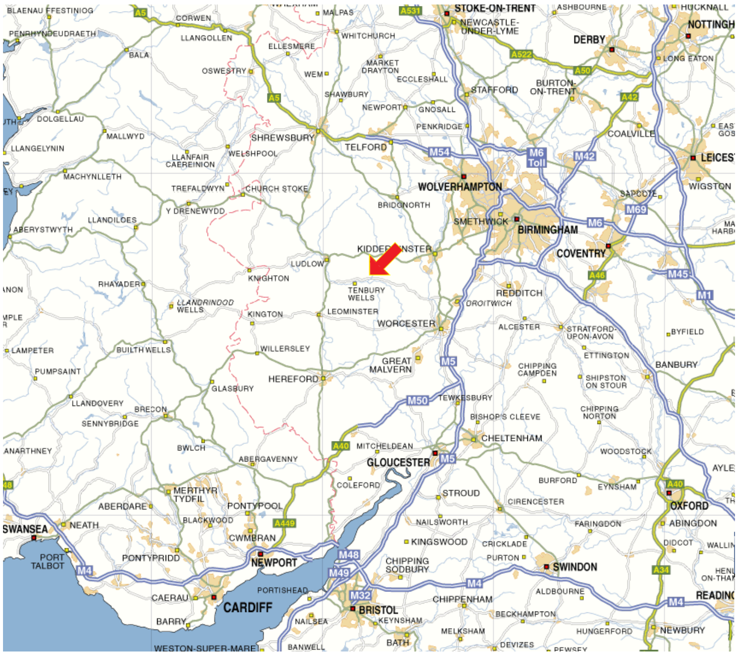


Figure 1: Map to show the general location of Knighton-on-Teme, arrowed. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

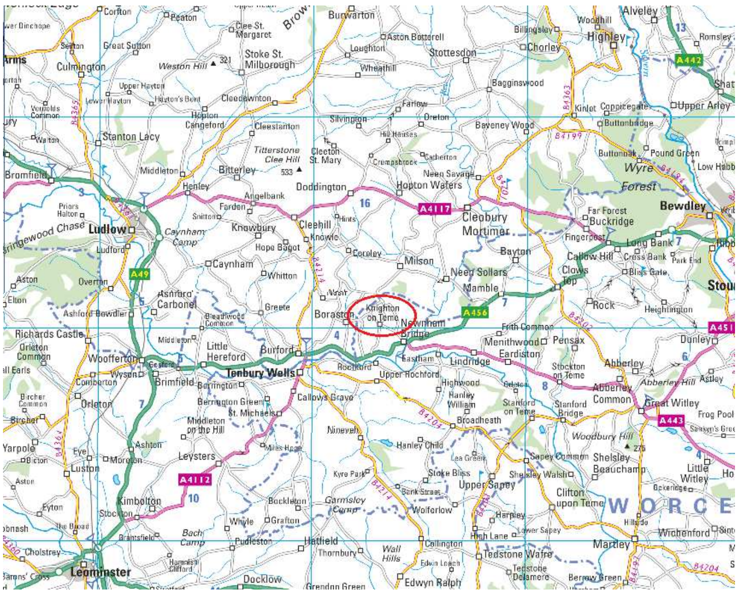


Figure 2: Map to show the location of Knighton-on-Teme, circled. © Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

Figure 3: Map to show the location of the Church of St Michael, hatched.

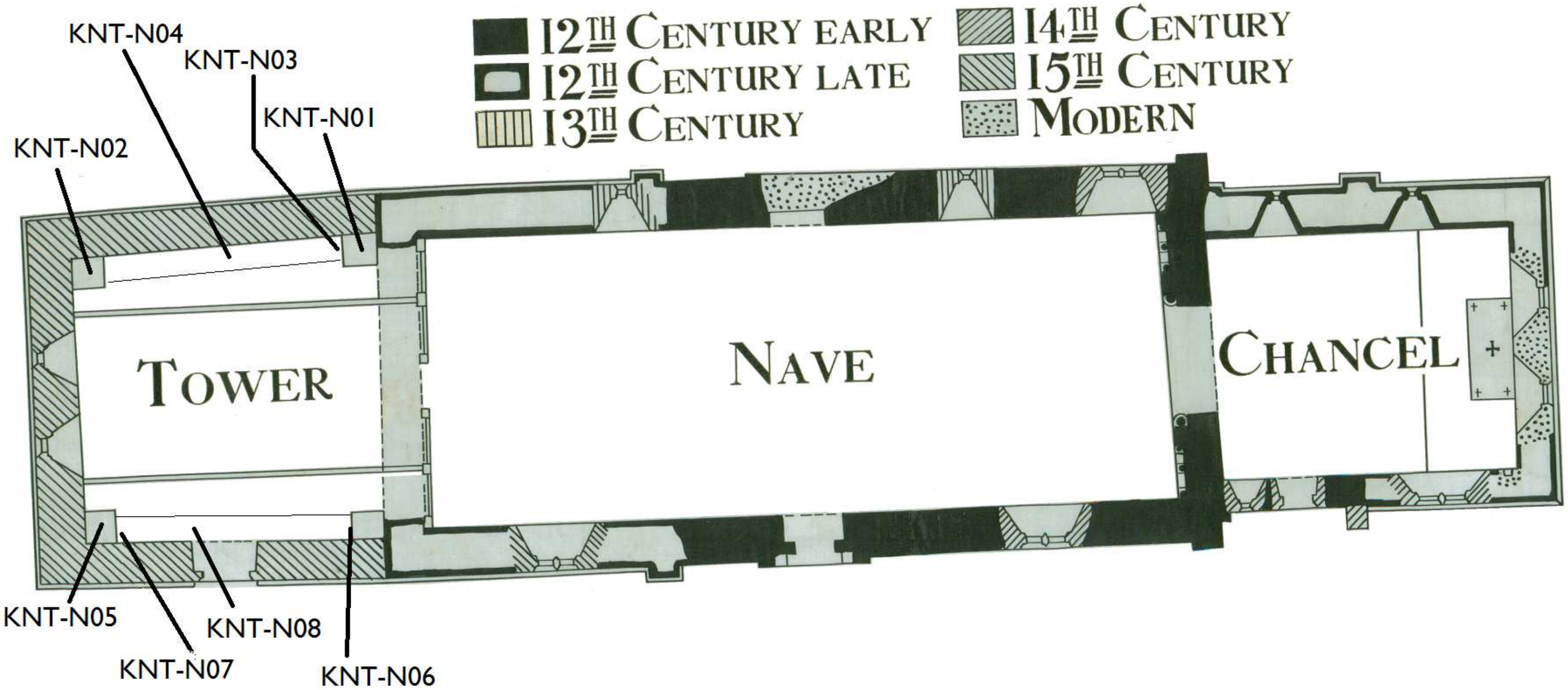


Figure 4: Plan of the Church of St Michael, showing suggested phasing and location of samples KNT-N01–08 (Willis-Bund 1913)

Figure 5: Tower, west post of the north wall, photograph taken from the south-east (Alison Arnold)

Figure 6: North wall at mid level, showing a number of timbers with redundant mortices and the location of samples KNT-N13 and KNT-N19, photograph taken from the south (Alison Arnold)

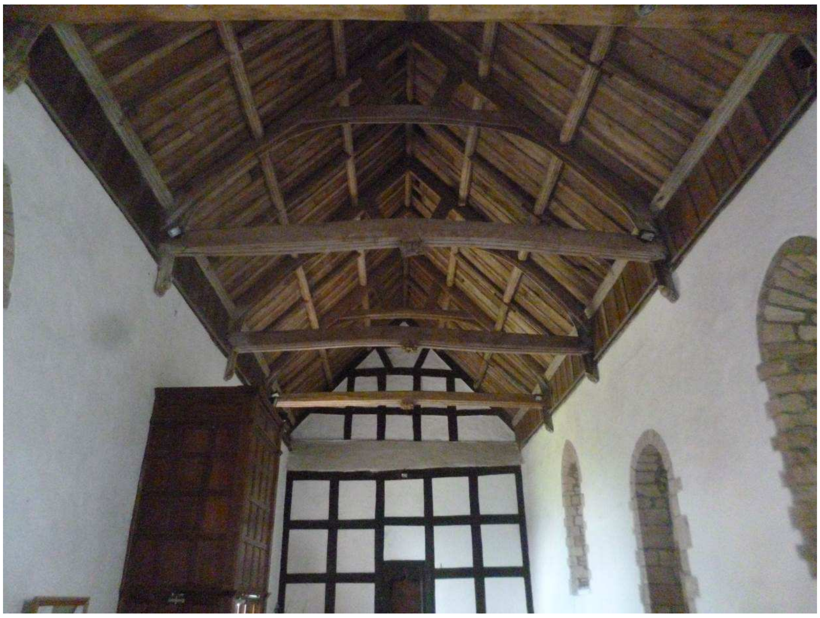


Figure 7: Nave roof with timber-framed partition at the west end, photograph taken from the east (Alison Arnold)

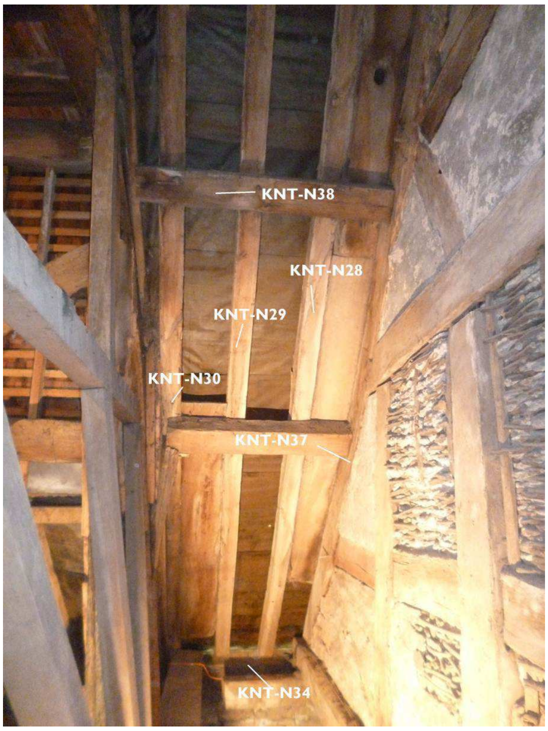


Figure 8: Portion of roof between the tower (to the left) and the nave partition (to the right); location of samples KNT-N28-30, KNT-N34, KNT-N37, and KNT-N38, photograph taken from the south (Alison Arnold)

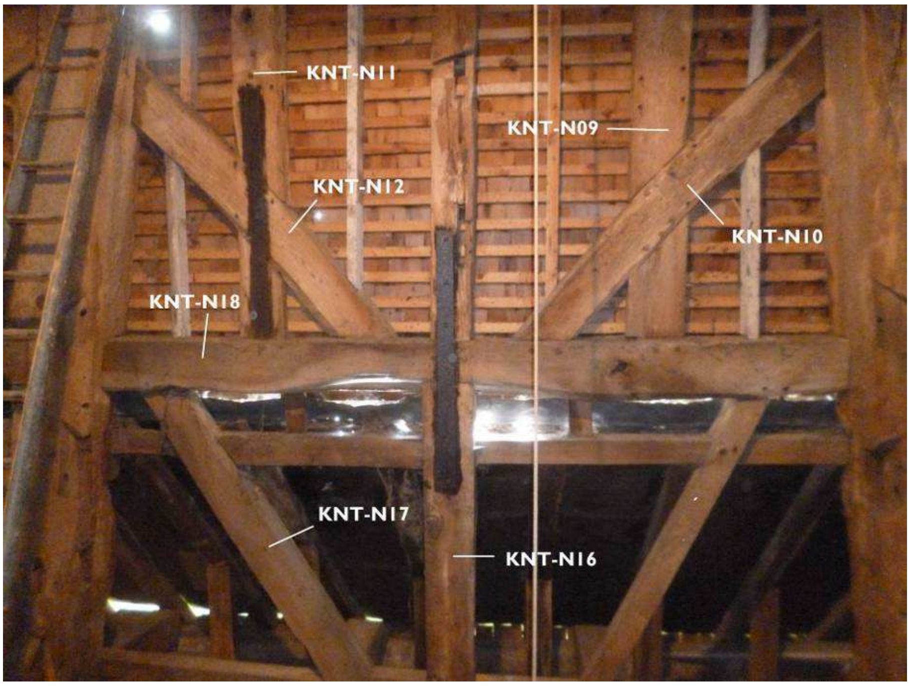


Figure 9: West wall of tower at mid level, showing the location of samples KNT-N09–12 and KNT-N16–18

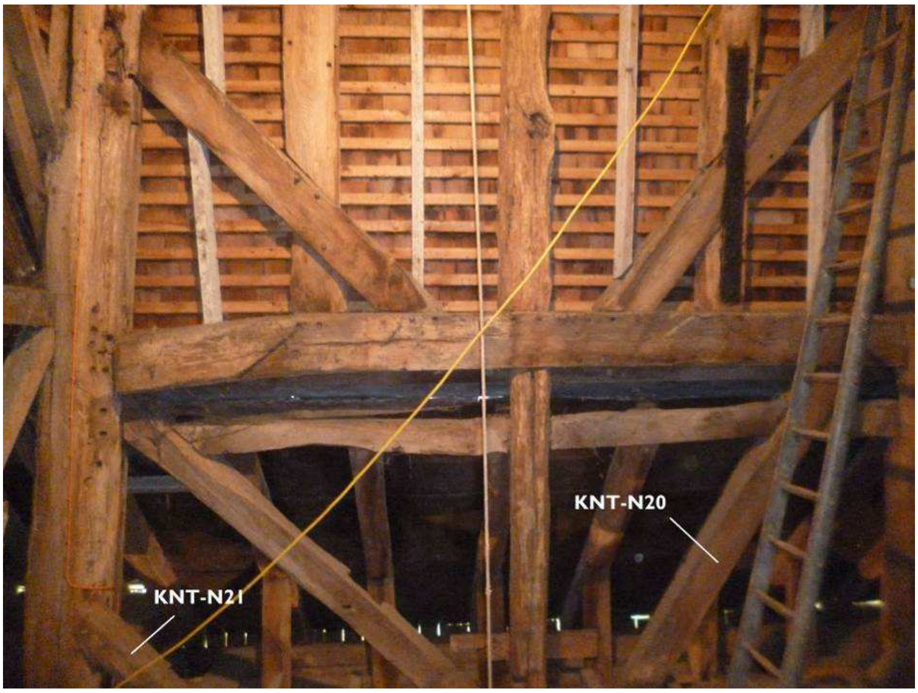


Figure 10: South wall of tower at mid level, showing the location of samples KNT-N20 and KNT-N21

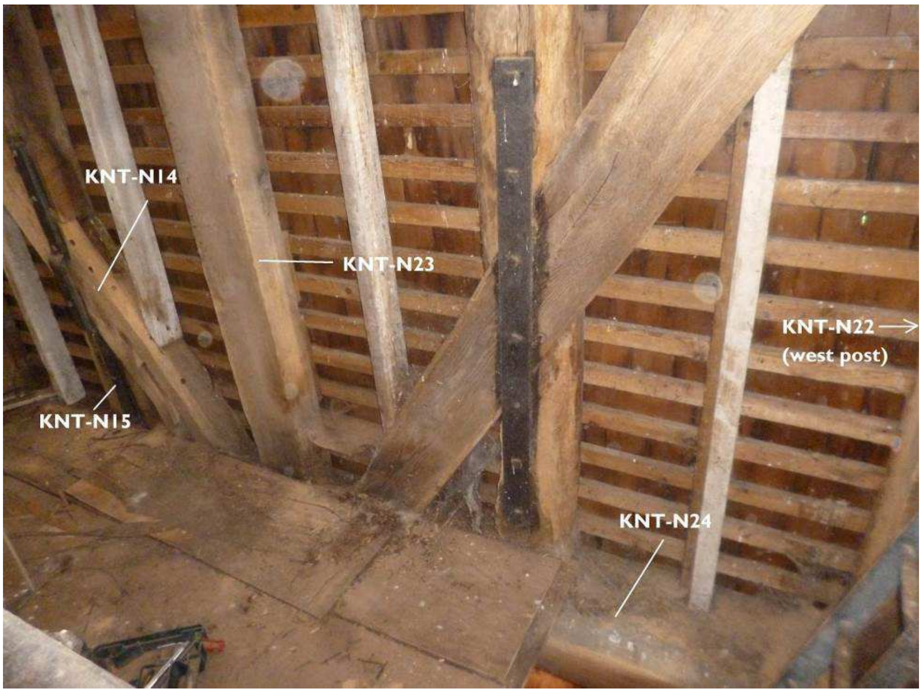


Figure 11: South wall of tower at bellframe level, showing the location of samples KNT-N14, KNT-N15, and KNT-N22–24

Figure 12: East wall of tower at bellframe level, showing the location of sample KNT-N25

Figure 13: North wall of tower at bellframe level, showing the location of samples KNT-N26 and KNT-N27

Figure 14: Portion of roof between nave and tower (south side), showing the location of samples KNT-N31–33, KNT-N35, KNT-N36, and KNT-N39

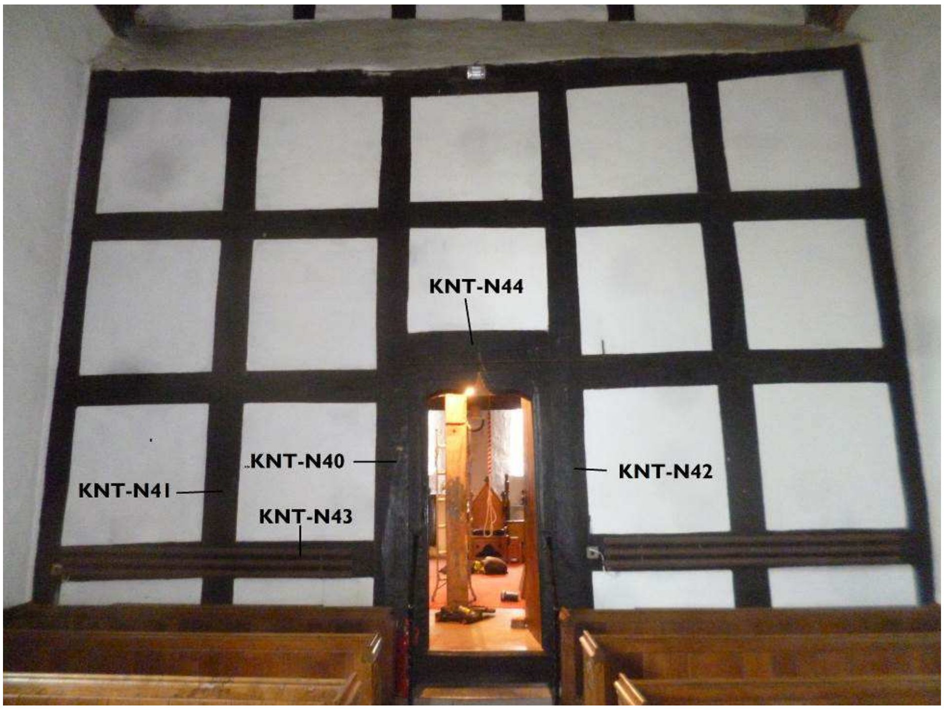


Figure 15: Lower portion of nave partition, showing the location of samples KNT-N40–44, photograph taken from the east (Alison Arnold)

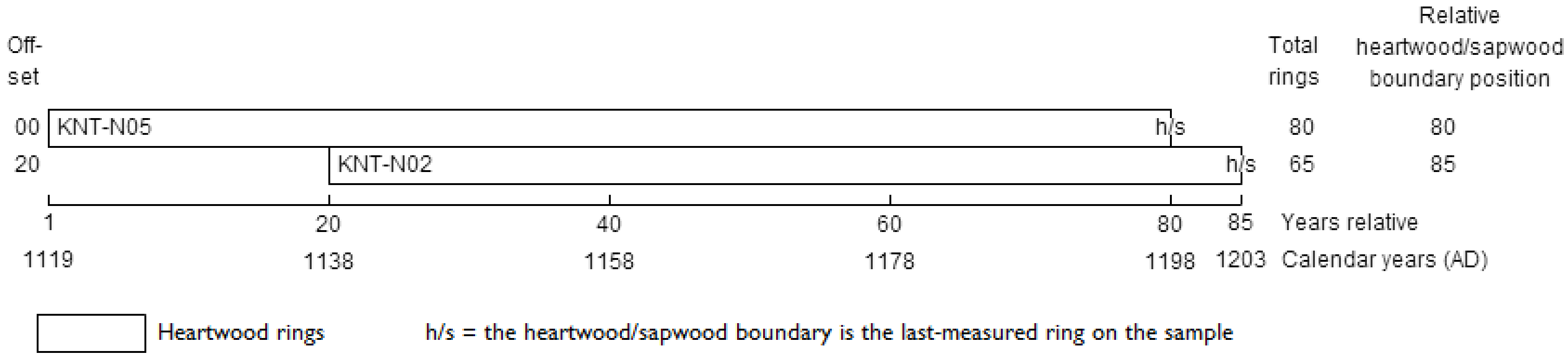


Figure 16: Bar diagram to show the relative position of samples in site sequence KNTNSQ01

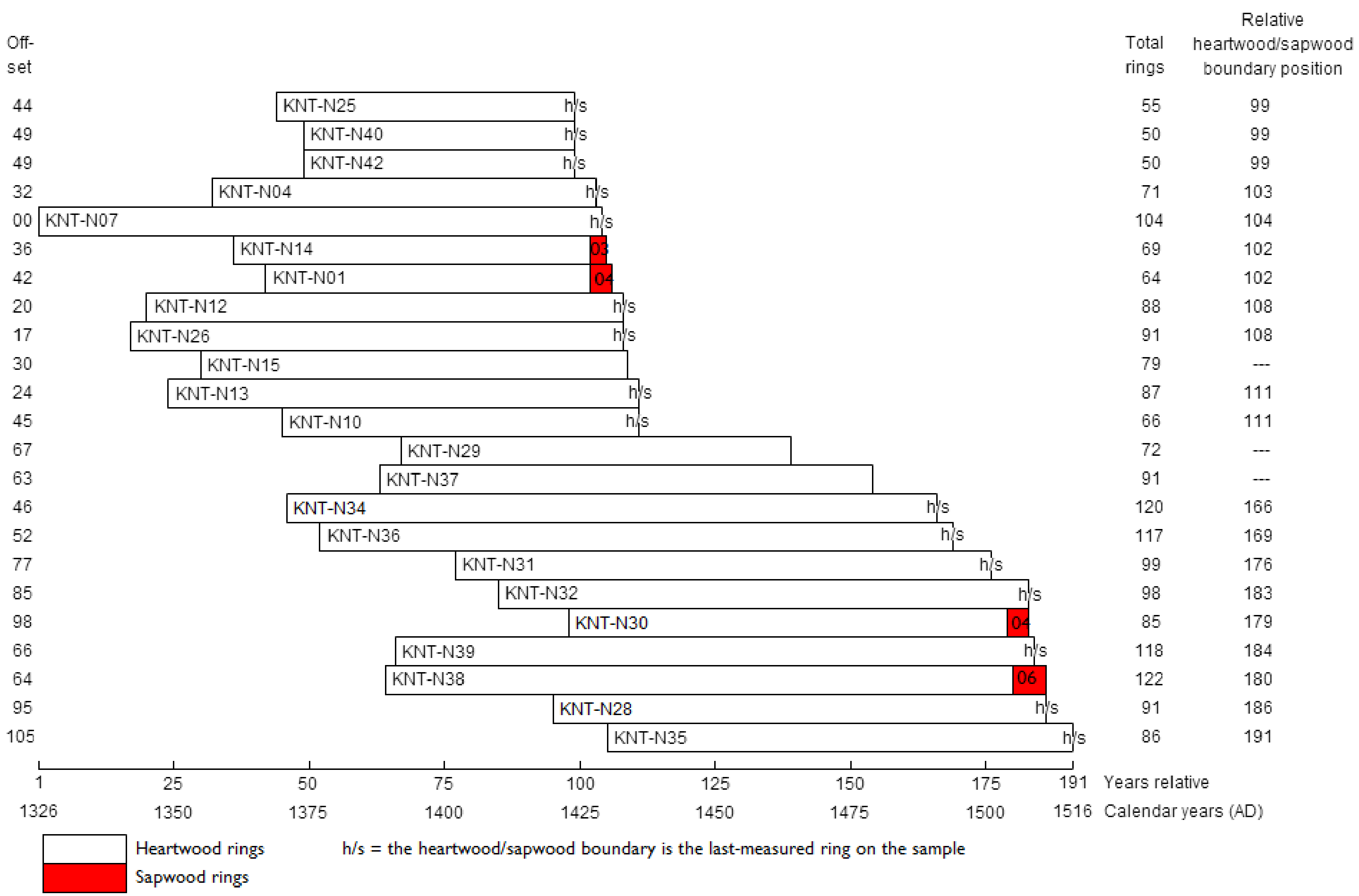


Figure 17: Bar diagram to show the relative positons of samples in site sequence KNTNSQ02

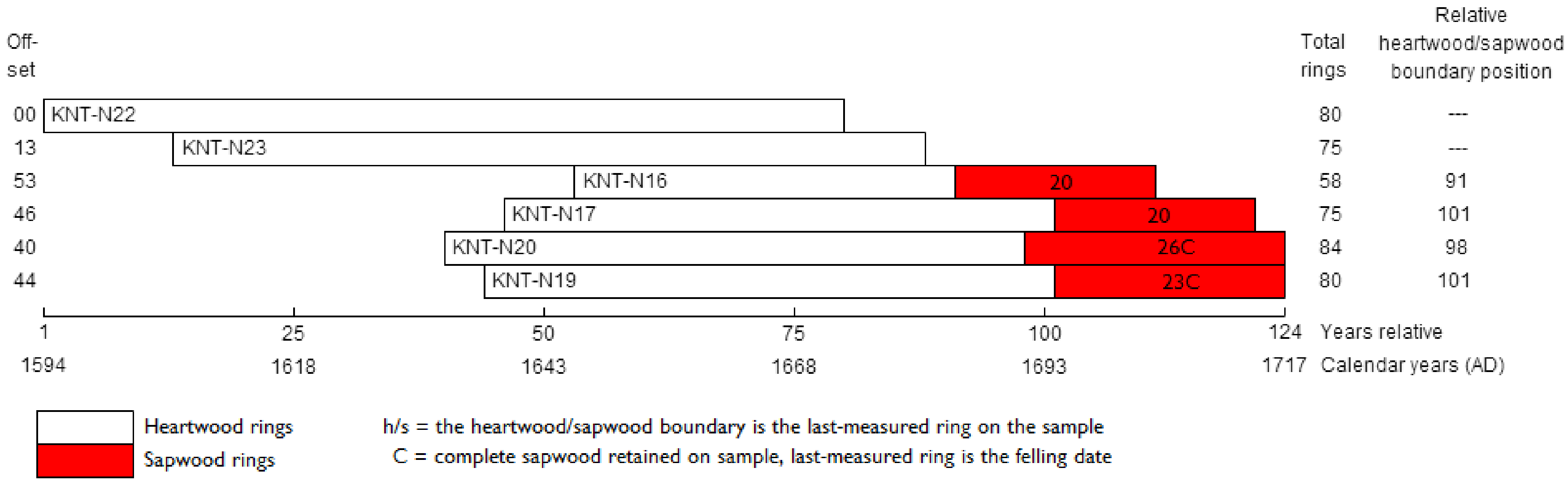


Figure 18: Bar diagram to show the relative position of samples in site sequence KNTNSQ03

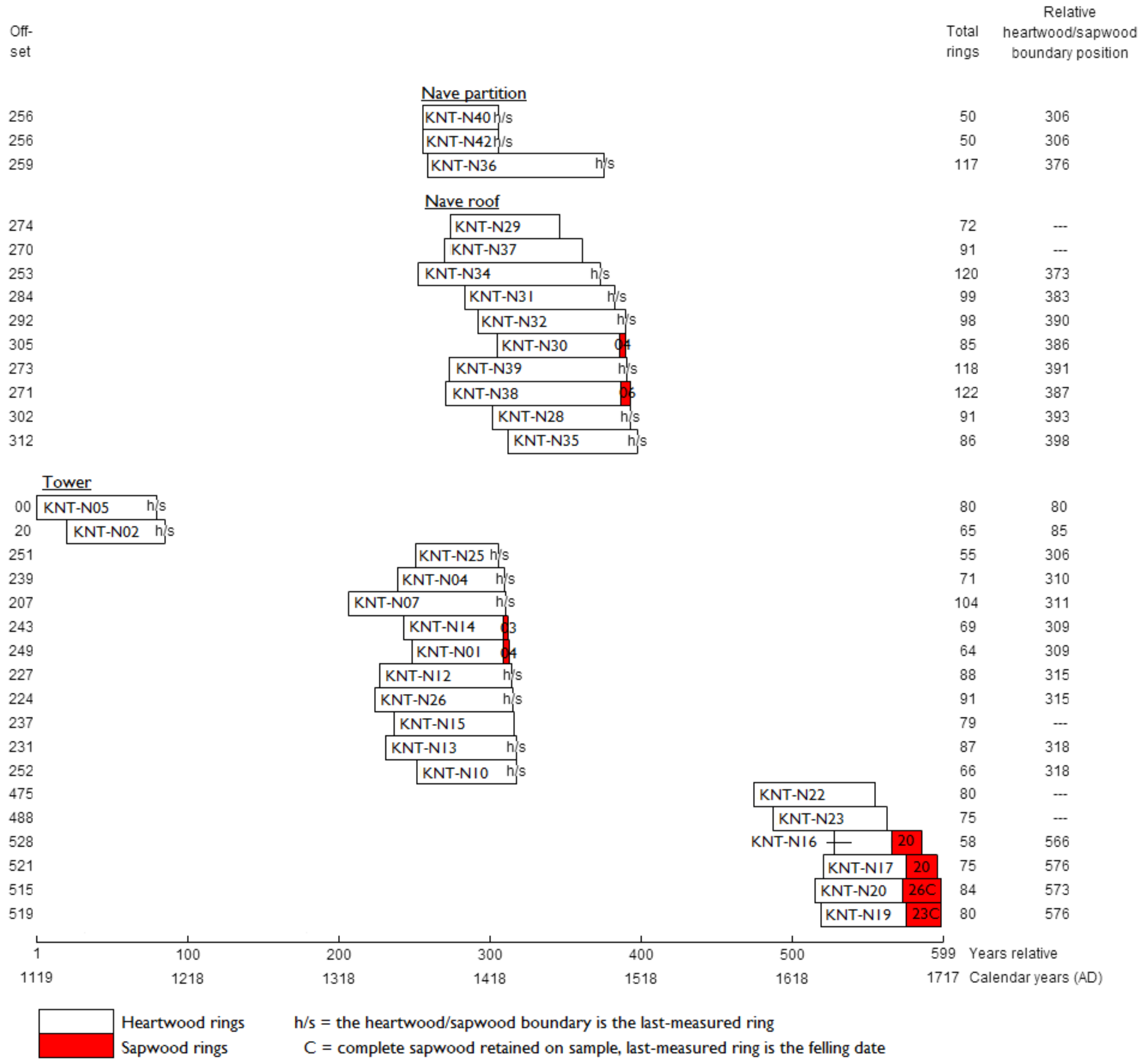


Figure 19: Bar diagram to show the relative position of all dated samples

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

KNT-N01A 64
247 248 217 160 272 168 254 197 164 120 143 236 171 141 215 218 156 231 194 172
184 175 132 245 135 144 131 172 251 241 378 362 354 336 234 233 168 119 145 124
201 324 296 276 259 230 229 268 211 221 306 157 270 257 221 448 357 294 185 195
242 229 230 185
KNT-N01B 64
255 233 238 171 271 165 248 200 153 131 133 233 177 142 223 235 157 228 181 158
182 172 125 242 131 142 137 168 244 244 370 456 345 305 228 217 157 122 149 117
196 290 291 272 254 233 217 263 211 218 307 145 279 263 264 401 354 281 213 173
237 227 213 191
KNT-N02A 65
414 697 420 313 230 312 399 469 263 346 246 206 347 212 388 367 386 274 294 359
412 524 320 430 374 412 469 470 396 619 555 684 653 611 606 485 341 250 178 174
353 355 491 485 336 149 215 182 263 153 215 213 194 141 245 271 207 171 158 172
126 162 224 186 124
KNT-N02B 65
384 713 402 340 239 330 410 475 274 351 244 201 352 214 431 340 379 277 294 376
422 540 330 433 380 430 475 481 408 659 555 700 662 616 619 491 347 255 170 176
364 350 476 491 331 158 217 183 277 153 201 213 191 150 228 272 212 172 157 184
126 161 214 179 158
KNT-N04A 71
404 347 170 271 244 228 196 201 252 279 209 322 187 245 262 210 249 190 230 240
245 352 260 243 273 256 255 255 373 290 288 248 256 244 149 212 154 169 343 361
354 333 384 363 294 408 329 319 220 336 267 369 308 294 315 314 250 271 227 239
324 187 274 264 242 292 233 210 166 206 276
KNT-N04B 71
412 349 161 276 256 227 186 208 263 267 226 329 167 247 250 219 245 183 232 258
253 341 273 230 281 253 263 267 362 290 299 253 258 240 155 211 153 177 349 355
347 342 385 368 314 410 322 335 215 332 261 376 302 298 323 321 245 269 219 250
325 186 279 276 233 288 235 205 169 223 274
KNT-N05A 80
492 517 509 458 128 364 593 418 459 490 377 414 454 557 439 433 446 408 309 444
348 559 644 480 403 427 480 387 379 426 296 317 338 268 393 309 285 381 375 378
313 523 249 377 307 342 372 309 258 341 363 300 332 241 347 353 243 321 202 283
307 378 372 257 278 177 249 265 301 153 208 273 237 191 332 316 270 332 284 192
KNT-N05B 80
504 509 508 480 134 391 560 421 462 482 379 422 454 544 434 432 456 406 310 449
347 557 644 488 398 432 488 389 368 427 296 311 283 312 382 321 269 382 375 375
319 517 255 373 309 347 367 312 256 342 365 297 334 245 344 355 238 321 201 290
303 396 352 260 279 177 244 267 298 152 208 266 241 191 328 322 294 328 285 164
KNT-N06A 56
208 337 361 398 393 397 434 355 281 349 304 237 224 207 177 280 219 176 168 169
284 270 374 322 299 274 273 317 234 259 272 236 242 349 292 260 237 222 228 215
191 190 213 194 211 182 174 219 182 202 226 138 157 170 215 176
KNT-N06B 56
256 326 364 413 390 400 431 354 283 351 298 241 221 206 182 270 205 170 165 182
295 261 366 316 300 279 297 305 232 267 267 239 242 350 289 253 244 213 231 219
184 189 218 192 212 182 174 222 177 201 222 136 163 178 211 181

KNT-N07A 104
222 295 207 220 298 304 286 298 247 314 198 181 206 255 196 208 183 217 211 197
203 215 231 215 129 166 138 137 116 93 85 82 140 133 114 147 153 225 193 135
185 154 134 114 113 100 104 79 141 105 92 105 127 158 145 128 82 85 78 114
99 123 100 117 84 139 83 108 123 114 166 141 160 209 160 269 213 333 220 194
151 190 231 438 412 330 413 349 322 350 172 165 232 159 188 232 167 194 234 203
227 265 358 189
KNT-N07B 104
212 280 196 236 308 293 280 287 251 287 196 191 212 250 196 193 183 204 218 208
206 220 237 214 127 168 146 130 109 96 78 77 140 130 111 155 151 216 214 136
184 163 135 116 111 98 91 84 138 93 103 109 139 183 167 113 99 102 106 98
107 112 92 122 88 128 93 113 122 128 154 136 159 190 155 253 211 288 213 207
159 179 235 434 429 328 425 360 349 347 174 164 234 156 187 236 167 191 238 207
221 265 359 191
KNT-N08A 64
226 207 177 291 205 403 342 355 164 98 67 218 261 435 517 486 490 376 498 432
487 299 267 364 261 196 250 227 194 143 194 149 148 178 181 221 201 200 192 153
189 135 194 162 147 216 123 184 164 188 165 245 302 338 299 230 205 203 208 184
241 231 238 222
KNT-N08B 64
223 214 182 289 212 403 352 357 164 100 88 202 259 444 504 478 486 382 450 434
490 299 291 312 220 157 250 223 185 145 184 163 113 188 183 221 190 202 192 151
204 128 189 198 148 214 124 189 165 186 168 245 280 340 288 237 205 210 200 190
237 236 227 245
KNT-N09A 100
77 156 158 154 215 225 176 117 141 114 116 153 188 222 212 175 138 155 148 211
258 277 213 161 141 212 203 231 187 225 192 170 158 171 157 191 145 166 149 189
180 138 132 144 139 134 116 102 122 95 148 112 91 100 104 118 93 70 102 94
110 85 125 107 114 118 97 91 95 71 68 73 88 111 172 160 155 188 170 144
154 137 140 119 152 231 193 179 163 146 187 227 182 192 150 148 248 247 202 154
KNT-N09B 100
84 195 178 208 230 213 177 134 139 104 120 143 199 218 222 171 138 155 151 208
266 265 216 162 139 204 197 208 188 223 195 167 160 173 159 189 140 165 144 188
186 137 128 134 144 140 98 98 118 104 144 114 100 112 102 116 97 75 94 100
103 82 131 106 120 113 109 89 89 71 76 73 93 109 172 158 156 182 172 141
154 123 139 131 141 237 204 171 161 147 189 231 176 191 148 154 251 240 206 154
KNT-N10A 66
252 401 310 341 292 308 304 272 317 255 177 198 178 195 148 227 182 162 169 167
186 155 125 164 196 176 170 173 185 230 285 183 212 189 167 196 202 182 220 212
171 196 177 198 203 117 156 185 143 152 170 121 167 161 119 122 123 211 149 147
126 125 174 168 202 143
KNT-N10B 66
264 394 309 347 295 309 308 269 324 256 181 192 190 196 153 227 186 158 171 169
188 146 128 165 198 177 174 174 187 226 288 168 214 191 166 189 212 181 203 225
162 203 178 206 201 116 163 185 137 152 178 121 162 165 122 126 133 213 153 148
121 137 164 176 202 142
KNT-N11A 45
141 237 301 190 147 157 275 310 220 279 144 222 309 369 264 267 257 204 197 245
245 280 257 259 223 207 279 181 130 183 157 204 208 203 182 252 180 130 161 109
170 157 140 200 225

KNT-N11B 45
164 215 308 187 142 160 273 315 217 284 133 236 313 354 255 272 256 210 195 248
237 285 254 260 223 195 295 172 130 197 159 179 204 220 193 245 170 112 153 115
167 152 149 195 213
KNT-N12A 88
206 157 178 199 151 183 177 164 156 165 190 204 219 221 169 190 129 189 193 172
167 159 184 182 152 133 184 107 125 177 146 145 177 182 125 105 138 123 126 98
132 105 144 81 98 129 82 89 62 63 102 102 131 113 174 147 169 156 151 153
117 128 123 215 181 143 174 163 213 161 118 128 130 107 141 125 136 173 141 140
113 98 144 158 138 162 196 191
KNT-N12B 88
216 153 174 205 146 187 172 170 163 156 199 206 219 216 174 190 130 188 197 176
170 159 177 179 151 137 186 120 123 183 151 145 166 177 127 105 137 130 117 100
132 102 109 114 92 126 83 83 64 66 98 104 123 115 166 154 166 161 150 146
117 131 130 203 192 151 167 155 203 168 115 121 135 114 132 125 137 170 157 129
113 108 140 153 146 145 204 181
KNT-N13A 87
192 236 134 193 145 137 168 184 191 166 125 161 155 145 124 85 101 105 113 140
75 82 88 75 108 101 109 100 144 126 117 99 115 102 115 108 138 125 117 111
97 104 61 87 88 99 202 204 218 196 236 262 180 215 188 172 186 161 170 248
191 128 175 141 140 154 109 114 122 112 142 153 107 130 121 120 124 134 174 160
175 121 179 150 146 58 75
KNT-N13B 87
158 215 157 186 148 147 155 182 186 163 127 150 150 130 125 87 91 111 105 133
76 76 84 76 113 100 121 94 116 115 110 88 112 94 108 104 134 133 119 106
100 97 66 83 88 94 200 202 220 193 229 252 174 225 182 172 183 158 163 249
188 132 166 146 135 149 112 107 114 106 143 151 106 126 123 119 128 127 171 157
174 123 183 142 125 88 69
KNT-N14A 69
132 135 143 107 111 116 90 119 114 110 94 65 66 98 79 81 79 113 96 118
135 174 172 244 245 189 192 200 185 223 208 210 173 154 173 198 235 219 251 326
281 335 248 231 227 235 252 289 317 302 287 245 239 220 204 215 214 153 320 226
178 258 231 200 187 171 210 210 224
KNT-N14B 69
144 133 137 104 113 122 86 112 105 100 95 74 67 93 81 77 88 115 103 109
135 177 172 245 247 193 196 188 165 206 203 224 150 154 191 197 233 232 245 341
296 317 245 230 228 244 258 273 319 309 302 238 241 218 203 230 212 158 322 223
179 260 235 194 190 172 214 218 233
KNT-N15A 79
305 336 295 250 172 194 202 288 235 190 168 195 156 203 182 162 184 139 130 146
139 147 155 145 129 135 116 123 130 96 139 122 98 119 88 117 82 78 71 64
101 130 153 142 165 166 158 178 151 136 137 156 134 170 166 145 170 190 200 154
141 132 159 129 148 167 158 172 191 157 145 175 181 167 176 120 170 159 164
KNT-N15B 79
299 344 334 234 177 198 201 231 241 194 169 208 182 196 177 159 184 141 141 140
134 145 164 139 131 130 124 127 121 117 126 118 101 119 85 118 81 87 69 70
94 138 147 131 176 165 159 191 152 137 140 156 133 178 166 147 168 190 203 135
152 143 163 124 149 176 166 163 187 161 142 179 178 169 178 123 167 161 169
KNT-N16A 51
318 314 329 231 349 164 123 118 237 382 164 202 166 213 166 167 223 230 259 240
284 322 410 465 513 230 223 199 476 290 472 552 410 359 266 164 152 121 130 129
130 113 121 143 169 210 198 143 103 89 95

KNT-N16B 58
296 326 332 254 322 225 116 126 212 343 160 193 168 204 168 169 212 227 250 224
279 318 410 459 463 231 211 194 478 288 445 572 410 374 260 155 146 141 129 133
129 108 130 138 174 157 188 108 127 83 97 72 47 36 30 51 57 62
KNT-N17A 75
404 521 364 414 398 400 556 435 395 330 372 345 186 180 175 276 280 378 403 424
420 307 397 419 380 391 391 375 403 351 267 326 292 350 420 519 342 403 302 231
280 332 367 316 254 195 342 230 281 237 172 205 184 235 89 74 93 135 95 79
64 90 106 124 137 56 43 39 62 62 58 39 25 45 56
KNT-N17B 75
420 472 368 399 449 391 569 436 382 327 383 343 178 197 177 262 287 385 411 437
422 306 396 409 403 392 385 373 414 353 263 320 273 344 398 503 340 399 313 234
282 326 374 318 255 193 329 188 276 246 189 209 182 241 94 76 89 141 87 70
76 89 124 136 149 52 40 34 65 59 55 41 29 48 49
KNT-N18A 41
305 295 337 249 177 157 226 197 221 312 322 344 286 311 287 283 164 146 166 167
161 207 184 253 240 148 184 232 295 274 206 267 270 248 239 245 292 306 259 188
187
KNT-N18B 66
496 631 625 685 486 597 439 179 336 165 353 231 324 287 261 237 184 243 316 360
383 230 228 179 208 318 309 249 311 299 342 266 289 330 294 368 258 418 290 214
177 335 218 316 344 372 370 332 422 273 317 153 118 145 149 190 213 217 259 302
175 244 245 318 290 264
KNT-N19A 80
243 123 164 214 148 171 203 165 116 107 134 114 159 230 126 147 121 241 265 231
225 247 319 320 295 275 269 218 136 132 168 150 148 110 163 188 186 209 115 132
147 133 181 118 162 113 146 79 197 139 147 131 124 129 134 169 122 99 123 186
220 185 189 179 174 174 152 91 71 130 119 142 130 114 119 127 108 76 87 83
KNT-N19B 80
243 128 168 217 157 164 206 170 111 106 141 111 156 227 127 144 119 245 264 232
206 249 319 312 293 268 257 218 123 143 172 154 141 122 161 188 183 202 114 134
148 130 181 116 163 117 145 79 187 145 148 121 127 129 131 181 117 105 126 178
230 190 196 171 170 173 141 88 80 117 125 149 103 104 113 152 102 89 86 92
KNT-N20A 84
345 352 237 312 469 275 337 358 287 274 201 217 287 238 208 224 208 231 173 202
168 299 368 311 307 275 305 249 287 266 295 324 267 240 302 283 236 366 207 291
264 301 249 355 356 272 349 327 291 285 250 247 368 270 196 230 191 193 215 203
150 85 99 132 98 51 62 74 90 114 138 35 27 45 54 71 85 48 28 56
50 72 89 113
KNT-N20B 84
406 371 223 340 458 283 334 363 294 272 197 224 291 240 217 217 204 236 167 216
171 301 361 287 327 275 312 244 273 273 299 329 265 247 297 290 239 352 221 283
266 289 256 344 353 259 335 346 296 282 267 254 379 271 205 240 182 211 189 215
146 95 95 129 96 60 56 66 100 116 128 41 34 41 42 79 88 47 28 39
69 70 89 113
KNT-N21A 104
122 174 107 205 292 254 190 125 186 199 149 151 158 165 142 172 138 190 180 191
142 161 132 132 103 75 79 85 68 70 69 45 52 52 35 36 20 21 27 29
26 35 43 80 64 62 95 66 55 52 64 66 48 41 44 49 55 70 64 65
57 72 30 58 39 38 53 47 61 67 122 221 265 311 314 323 237 264 296 161
223 243 209 245 252 219 198 246 195 249 283 296 285 291 278 335 321 301 302 269
307 279 231 168

KNT-N21B 104
110 187 99 204 287 264 193 120 186 201 147 144 160 162 150 176 142 190 177 189
147 163 134 123 111 71 85 80 63 71 70 50 50 53 29 38 18 22 23 24
30 43 40 74 73 56 101 65 49 63 59 68 57 38 37 43 66 62 76 69
54 67 35 52 47 43 51 50 55 77 114 218 292 350 325 326 237 262 286 163
272 247 189 241 270 221 211 238 201 246 289 294 284 286 277 335 325 303 311 255
306 274 230 171
KNT-N22A 80
321 289 395 275 289 290 302 340 380 509 478 259 463 326 348 243 218 212 172 226
169 197 278 227 231 199 276 339 466 479 520 467 521 522 578 635 445 393 218 133
87 130 92 149 202 145 125 150 121 105 89 113 182 176 142 131 127 105 91 118
121 276 292 160 183 178 271 207 258 215 246 211 187 175 201 274 287 337 170 355
KNT-N22B 80
347 279 409 268 285 302 308 342 399 498 466 268 470 327 350 247 212 212 178 233
162 206 277 234 225 199 284 340 465 485 515 468 524 518 583 636 446 398 219 122
95 130 89 151 205 146 131 145 124 102 92 122 182 170 141 133 116 115 87 125
116 282 287 159 187 185 274 199 267 210 247 217 194 174 206 262 292 339 192 312
KNT-N23A 75
223 319 436 380 432 336 452 224 268 235 342 357 270 408 598 478 464 473 416 495
490 581 663 478 276 210 217 235 314 248 214 254 209 234 233 239 220 291 279 328
391 255 206 173 203 137 166 181 348 330 217 274 259 322 314 350 321 347 278 236
266 318 344 324 329 253 273 246 211 147 210 169 215 119 157
KNT-N23B 75
235 330 450 365 424 336 420 230 272 230 334 349 276 405 594 475 467 478 408 500
491 575 675 484 271 215 221 224 306 251 215 260 201 236 229 240 228 274 253 344
384 260 213 189 197 123 160 167 325 340 214 293 246 321 317 347 322 347 284 250
264 313 342 322 325 253 276 231 194 151 208 157 222 128 153
KNT-N24A 46
131 133 267 181 220 342 233 287 332 439 244 378 335 300 439 340 364 381 418 254
396 293 368 380 284 118 55 48 67 87 106 86 58 54 174 129 143 126 122 100
86 54 54 46 49 41
KNT-N24B 82
187 266 282 323 227 183 168 180 226 193 156 291 395 459 390 460 392 320 342 332
413 187 191 150 190 206 187 276 209 464 476 561 482 539 386 314 278 496 435 530
396 368 427 453 660 704 494 480 341 245 139 296 183 232 307 230 268 293 414 223
380 290 287 451 332 355 395 422 239 394 308 408 408 296 112 65 54 71 97 118
98 70
KNT-N25A 55
175 191 243 151 173 166 134 131 205 205 184 144 185 208 110 138 155 128 152 150
116 143 93 92 75 59 77 96 97 119 131 159 117 162 112 123 116 100 117 148
114 110 122 108 108 103 88 81 108 79 94 101 64 69 102
KNT-N25B 55
226 196 256 150 176 168 133 127 209 196 177 147 191 207 145 147 148 126 152 155
114 148 103 95 68 64 77 96 107 128 131 159 110 145 113 118 119 94 123 149
120 90 124 113 103 115 84 91 99 80 98 97 69 76 97
KNT-N26A 91
133 102 98 104 173 191 107 141 116 81 104 93 101 81 123 114 96 59 86 80
96 87 50 71 86 64 113 73 85 87 66 72 52 59 58 70 72 56 58 56
41 65 68 71 77 58 85 70 98 65 63 65 53 89 110 116 119 91 131 65
106 95 90 80 69 64 74 67 57 52 77 121 188 193 166 204 103 146 168 115
122 134 109 137 170 168 117 120 91 172 129

KNT-N26B 91
143 107 116 143 198 127 116 154 96 91 103 84 95 82 104 107 93 49 88 76
99 86 57 64 84 75 111 90 83 86 62 67 57 56 59 69 76 57 50 57
52 58 74 75 71 67 76 75 95 61 70 55 62 88 115 108 129 91 120 71
96 99 92 77 65 72 77 63 62 53 78 128 194 190 160 207 108 131 160 106
126 138 117 139 178 182 130 113 83 164 126
KNT-N27A 85
309 290 233 223 463 482 430 307 254 120 231 104 158 208 165 288 323 258 175 225
184 167 200 156 151 236 194 178 332 246 216 230 199 189 146 132 104 90 88 168
186 172 137 124 116 147 161 185 167 155 91 89 89 107 114 97 115 138 162 155
152 150 107 148 120 168 158 103 105 88 86 60 102 118 117 96 78 101 77 80
84 104 162 104 143
KNT-N27B 85
291 293 238 229 466 490 444 322 259 121 231 99 152 209 168 288 329 249 183 220
180 163 200 158 152 235 188 180 323 247 220 205 187 188 151 132 100 90 88 168
193 175 126 118 113 144 156 184 159 145 90 94 97 106 111 107 119 132 159 157
146 162 116 151 122 175 162 104 103 86 93 55 101 116 114 95 74 111 74 75
84 104 161 96 138
KNT-N28A 91
162 132 195 211 146 125 164 165 177 222 155 232 170 161 138 153 189 185 155 141
130 86 122 161 115 106 121 108 88 97 123 120 149 132 128 127 129 115 93 114
112 91 118 77 93 90 121 131 194 192 159 186 223 214 241 228 210 207 234 187
231 198 197 224 194 182 240 171 164 201 157 128 163 138 102 146 132 108 107 96
88 102 86 88 71 114 111 109 97 104 119
KNT-N28B 91
148 134 195 216 153 119 166 162 173 213 153 233 167 162 150 150 186 187 163 139
135 91 126 168 114 103 125 107 103 82 119 124 156 125 130 127 139 109 91 114
123 89 119 75 93 93 124 130 192 195 149 192 217 209 241 227 216 210 223 195
232 203 195 228 199 184 229 180 168 210 151 136 165 142 92 151 135 99 116 96
99 92 79 96 77 108 99 109 99 117 119
KNT-N29A 72
262 229 183 208 209 253 259 255 300 217 289 260 197 207 221 225 279 274 177 174
166 132 146 111 116 126 99 110 144 140 142 155 138 172 151 220 186 168 139 195
170 167 191 160 131 151 146 125 123 114 133 172 137 125 148 144 146 122 143 124
151 124 157 140 158 139 103 128 110 112 103 98
KNT-N29B 72
261 229 185 210 208 254 255 251 301 202 286 254 194 202 221 234 275 274 183 185
169 133 147 109 111 126 94 112 146 138 147 148 134 163 143 203 195 163 140 192
172 166 194 156 137 146 149 122 128 111 131 174 139 128 144 146 145 123 145 120
151 122 163 139 154 144 97 130 109 118 98 98
KNT-N30A 85
145 203 205 210 245 170 147 195 172 158 153 152 126 152 123 112 157 150 117 161
169 123 149 127 184 190 147 161 157 189 183 227 260 256 267 183 216 179 185 185
123 146 109 140 151 169 188 147 235 212 188 195 130 109 99 120 111 126 87 108
110 97 94 95 73 85 74 78 79 76 77 78 82 75 67 89 101 80 82 83
85 76 68 52 65
KNT-N30B 85
132 198 198 196 227 163 143 184 162 157 161 139 126 148 123 116 158 140 120 156
161 120 152 122 183 185 141 159 149 187 189 221 273 260 265 179 219 173 188 186
117 139 122 130 154 174 179 151 237 205 187 194 136 112 98 129 102 124 84 104
107 100 97 99 73 84 77 71 85 80 79 75 87 63 67 81 96 79 71 80
85 80 56 52 61

KNT-N31A 99
220 191 204 148 179 201 226 177 134 165 161 166 166 164 144 142 109 107 159 119
123 169 130 125 155 167 157 166 160 155 206 186 155 150 160 157 167 161 151 102
125 143 114 92 123 108 112 102 146 130 120 118 116 117 154 120 110 137 119 97
114 93 103 110 114 99 112 101 65 74 90 119 126 133 130 118 138 122 145 122
126 126 134 131 128 104 100 93 98 80 105 93 94 100 83 80 93 70 78
KNT-N31B 99
218 194 204 158 171 202 229 163 128 158 145 176 183 161 150 149 107 107 149 119
129 167 126 130 152 167 161 168 142 158 196 192 154 140 158 168 167 165 151 111
111 148 119 100 118 113 117 94 146 127 113 120 117 120 146 126 113 135 115 98
111 84 108 111 113 100 109 99 65 78 87 120 128 143 123 119 135 124 139 126
124 128 134 122 132 93 93 91 104 74 116 93 89 107 82 80 93 66 79
KNT-N32A 98
97 116 141 169 195 161 171 190 130 156 173 103 155 141 132 126 153 173 158 191
181 218 158 171 197 187 200 181 195 167 193 142 169 176 137 119 165 152 159 152
204 138 173 153 136 129 135 130 92 118 131 115 103 79 82 81 99 121 153 117
105 137 185 158 197 228 216 203 216 159 174 117 111 151 129 142 189 124 118 158
108 101 117 129 96 99 93 76 94 90 79 65 65 84 64 73 88 52
KNT-N32B 98
97 106 129 159 192 151 166 194 126 154 171 114 151 136 124 130 158 171 157 187
194 205 156 167 187 174 195 188 194 167 198 136 168 165 138 141 163 142 157 152
207 139 168 160 142 133 132 130 97 111 133 118 102 78 79 87 93 111 156 119
106 140 182 154 212 241 212 212 209 163 178 114 112 148 132 148 182 121 116 153
113 95 120 129 89 109 84 71 92 91 81 64 53 79 70 65 70 47
KNT-N33A 60
133 153 143 122 113 74 95 105 101 145 214 168 245 227 202 255 251 402 431 288
206 180 137 116 151 139 135 127 152 176 216 179 204 159 123 107 153 159 161 129
133 131 161 195 216 152 219 259 219 168 122 120 166 175 168 186 227 234 283 354
KNT-N33B 60
129 153 141 127 103 87 93 102 107 137 215 168 231 223 209 246 229 368 462 249
206 201 127 106 149 134 135 125 152 165 197 181 194 161 130 103 152 156 158 129
133 129 156 197 214 154 225 255 223 161 119 132 160 174 169 186 217 238 288 352
KNT-N34A 120
419 193 267 256 394 372 259 270 219 196 204 106 196 135 200 195 250 193 172 243
183 173 162 188 160 192 244 201 234 272 181 252 150 164 148 153 128 157 180 144
129 151 160 170 146 167 153 150 183 172 154 202 205 220 174 218 212 169 190 181
196 177 166 183 154 164 152 116 98 98 99 93 107 102 80 89 85 105 73 100
89 94 83 89 106 102 78 82 93 81 81 80 59 74 74 96 99 92 97 94
88 98 85 109 97 98 84 88 92 117 66 64 72 69 83 73 71 71 83 79
KNT-N34B 120
427 194 267 256 393 359 316 273 220 195 198 115 195 133 201 193 238 203 180 238
179 171 163 185 170 182 238 199 233 285 195 258 141 170 146 144 116 156 180 148
126 151 155 175 149 172 150 142 184 181 151 199 200 216 175 228 204 172 193 183
191 177 163 186 152 165 149 119 97 98 101 97 114 101 78 91 75 109 69 102
90 94 90 91 109 92 85 77 95 72 75 84 62 74 66 104 92 97 99 90
84 101 84 110 95 96 90 89 91 115 74 62 73 68 81 76 73 67 80 80
KNT-N35A 86
287 311 269 352 318 301 279 273 273 356 323 263 363 317 264 276 299 309 325 263
308 327 345 371 277 294 355 270 230 285 260 258 337 201 196 193 232 279 233 264
200 249 242 321 316 274 188 185 258 234 203 180 236 252 252 243 249 241 180 201
143 164 230 186 202 229 214 149 177 176 172 245 152 153 192 144 226 196 194 215
256 173 220 205 196 177

KNT-N35B 86
289 289 283 355 317 299 278 273 264 370 340 287 358 314 249 272 294 290 341 270
325 350 329 374 264 303 368 253 251 284 270 266 343 199 198 193 230 281 235 262
200 252 246 316 309 280 191 184 263 226 213 173 237 248 252 238 254 239 174 203
143 167 232 177 211 228 204 145 174 175 170 242 152 158 195 147 222 199 191 216
256 172 218 206 197 176
KNT-N36A 117
220 192 156 146 155 105 127 98 134 125 130 144 138 160 129 143 162 169 201 185
265 300 252 296 253 310 223 226 224 228 251 261 287 173 177 154 150 184 135 168
186 150 200 176 135 182 164 174 152 147 208 213 191 153 215 189 167 172 145 156
145 128 117 116 98 66 102 95 74 93 103 81 66 106 94 104 86 81 77 113
73 63 97 101 73 99 60 53 48 57 65 80 78 90 72 88 77 126 107 81
80 100 88 105 118 73 108 87 99 94 80 68 109 96 78 71 82
KNT-N36B 117
211 195 156 146 162 108 116 108 138 113 121 145 156 164 124 146 169 178 199 215
294 296 240 302 257 309 227 245 203 231 258 271 280 166 177 157 147 182 136 172
186 148 204 184 142 168 159 171 149 136 209 208 197 145 214 185 166 167 143 158
145 124 118 116 97 75 114 87 73 103 93 82 72 103 98 108 77 76 80 106
73 57 94 114 74 100 56 58 47 58 64 79 83 86 71 87 80 126 107 84
80 97 84 109 84 102 106 86 102 93 79 68 109 92 86 72 80
KNT-N37A 91
219 239 280 185 224 187 191 150 242 205 184 167 320 210 242 235 261 183 196 210
263 303 271 251 196 198 228 246 243 274 170 311 285 207 325 344 317 302 291 312
312 283 200 259 208 217 239 219 148 204 156 134 141 139 116 121 86 78 139 143
154 111 164 124 137 128 126 156 129 120 114 116 95 103 124 76 120 144 157 179
192 168 162 147 138 145 125 140 146 138 151
KNT-N37B 91
189 233 283 187 223 190 187 151 240 206 201 164 337 229 256 199 218 178 179 185
257 297 253 252 201 212 232 244 231 269 144 301 290 216 314 342 330 268 299 297
306 285 204 251 192 212 257 210 150 209 152 141 124 138 114 125 93 76 136 145
149 119 156 139 127 123 127 154 141 107 117 114 89 104 123 77 120 143 163 173
193 157 171 149 138 145 134 130 151 129 169
KNT-N38A 122
201 260 229 243 191 171 191 199 197 159 153 165 108 155 113 113 87 115 109 133
130 86 107 78 87 107 98 110 124 88 132 110 105 105 122 104 86 116 124 127
139 94 151 129 116 163 143 126 204 123 145 140 109 81 127 101 85 97 94 103
117 146 130 113 112 114 127 138 138 92 142 141 140 133 88 100 86 99 114 129
143 115 87 135 124 162 161 125 124 157 122 172 122 159 148 96 133 126 99 102
120 104 103 121 105 94 130 107 95 136 95 84 89 87 87 71 85 70 67 79
76 112
KNT-N38B 122
203 263 232 236 189 168 194 202 203 155 161 164 114 156 113 112 99 107 122 150
135 87 111 104 62 103 101 111 114 88 127 121 100 113 122 102 91 119 127 123
139 93 137 135 117 162 143 140 206 119 118 148 108 83 128 97 84 101 95 103
115 148 140 112 118 117 135 145 135 95 139 142 130 137 91 97 82 103 115 128
145 114 94 130 114 166 167 118 136 154 123 185 127 158 149 108 138 125 101 117
124 111 104 128 112 90 144 112 82 134 99 81 85 84 86 73 83 72 68 91
89 111

KNT-N39A 118
281 300 299 252 309 251 237 274 292 248 194 283 206 217 172 215 158 202 158 117
122 131 107 128 124 126 113 73 89 73 69 97 135 169 163 232 249 201 223 223
254 204 219 276 201 173 163 126 158 148 114 171 210 167 121 196 199 249 163 183
191 161 198 157 180 185 151 126 150 155 153 139 119 128 152 164 144 158 198 187
171 147 186 225 199 163 179 239 162 172 196 216 182 183 178 172 135 128 165 148
134 173 151 104 148 116 96 152 168 123 149 148 159 166 203 154 150 128
KNT-N39B 118
274 307 300 249 314 243 241 268 293 238 197 272 209 216 171 208 154 214 142 121
117 116 117 131 123 133 110 76 88 84 55 96 140 165 159 226 250 205 218 222
254 199 228 275 198 159 157 116 162 147 113 172 212 172 118 198 204 239 158 194
195 165 193 155 170 174 170 135 145 165 155 141 120 126 152 161 151 161 199 186
166 154 181 223 202 158 179 244 159 185 183 221 180 187 184 166 135 133 160 145
134 173 147 108 149 114 93 155 165 129 143 148 157 167 202 157 162 120
KNT-N40A 50
501 438 412 480 387 414 211 207 132 324 206 274 235 189 189 186 311 221 179 187
154 247 241 224 252 251 307 274 273 208 167 174 223 244 281 293 233 264 236 197
298 205 175 179 109 126 206 151 197 226
KNT-N40B 50
502 443 411 480 386 426 211 204 132 307 198 268 244 194 202 207 299 222 185 191
155 232 243 228 242 262 329 273 274 211 177 167 221 254 286 311 230 263 239 196
291 209 175 180 107 128 208 151 200 215
KNT-N42A 50
525 339 279 320 272 314 186 119 123 210 229 283 280 234 237 250 404 264 245 228
195 264 275 221 237 241 328 214 307 250 217 220 192 230 292 215 171 198 223 189
179 131 129 155 113 175 153 164 199 176
KNT-N42B 50
520 347 302 303 271 327 192 136 146 195 232 303 282 217 235 215 402 254 241 227
203 264 276 221 235 259 325 208 303 254 210 201 208 238 288 212 171 197 222 183
190 127 139 160 104 184 157 161 205 159
KNT-N44A 45
428 584 587 722 708 630 599 302 208 275 333 441 428 690 600 430 378 404 467 489
786 538 821 626 395 341 640 426 618 681 658 898 621 760 424 737 815 970 864 735
580 972 607 779 384
KNT-N44B 45
449 598 602 719 708 623 601 297 218 266 338 442 426 683 592 436 373 410 466 478
810 548 805 634 389 348 638 420 577 687 626 877 604 768 429 745 790 970 848 717
582 937 616 790 378

APPENDIX: 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.

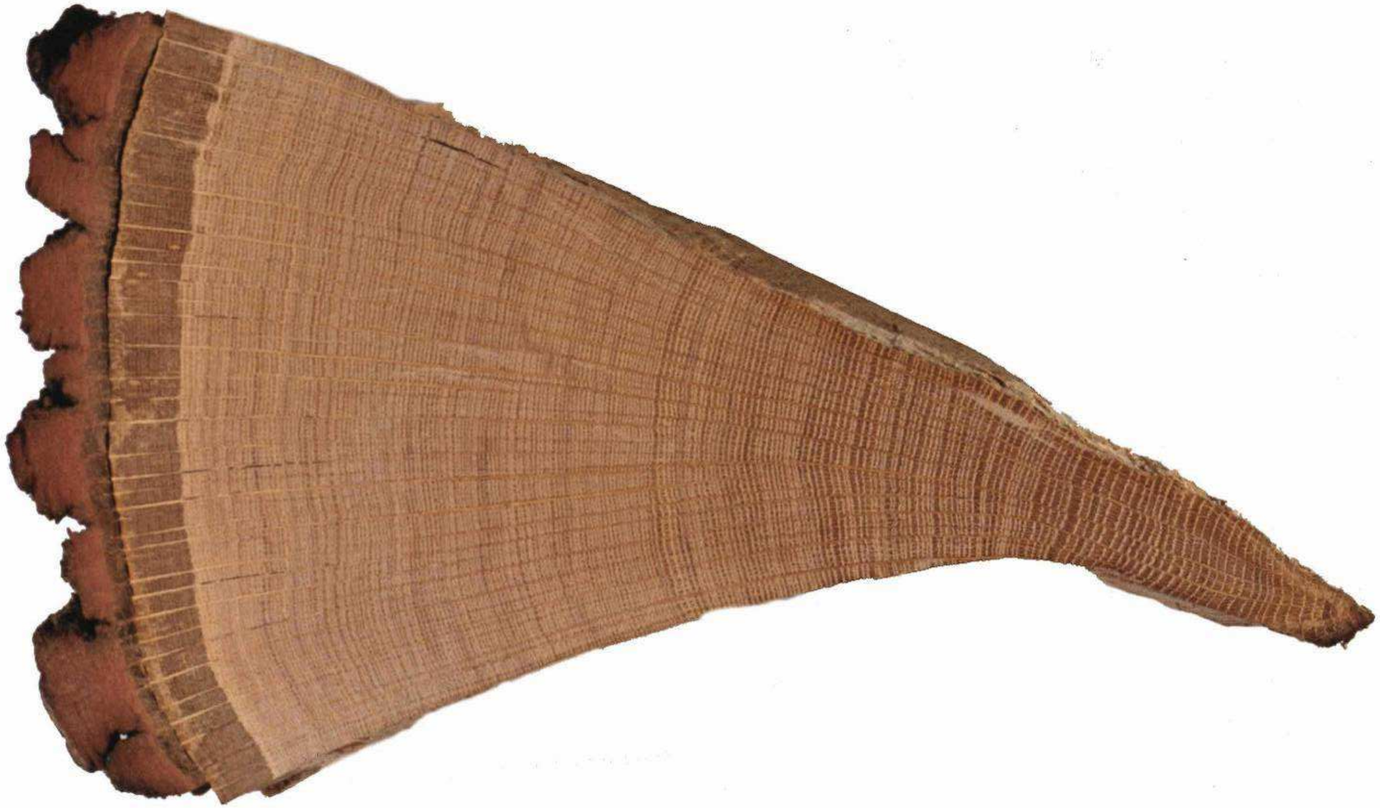


Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

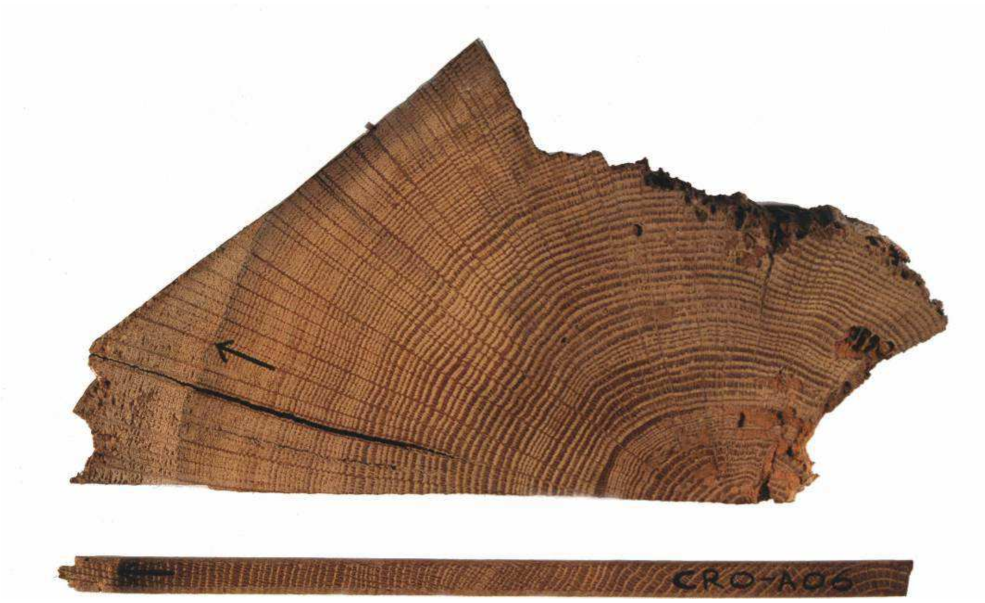


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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 *et al* –1995).

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

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

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

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

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

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

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

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

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

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

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form

they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

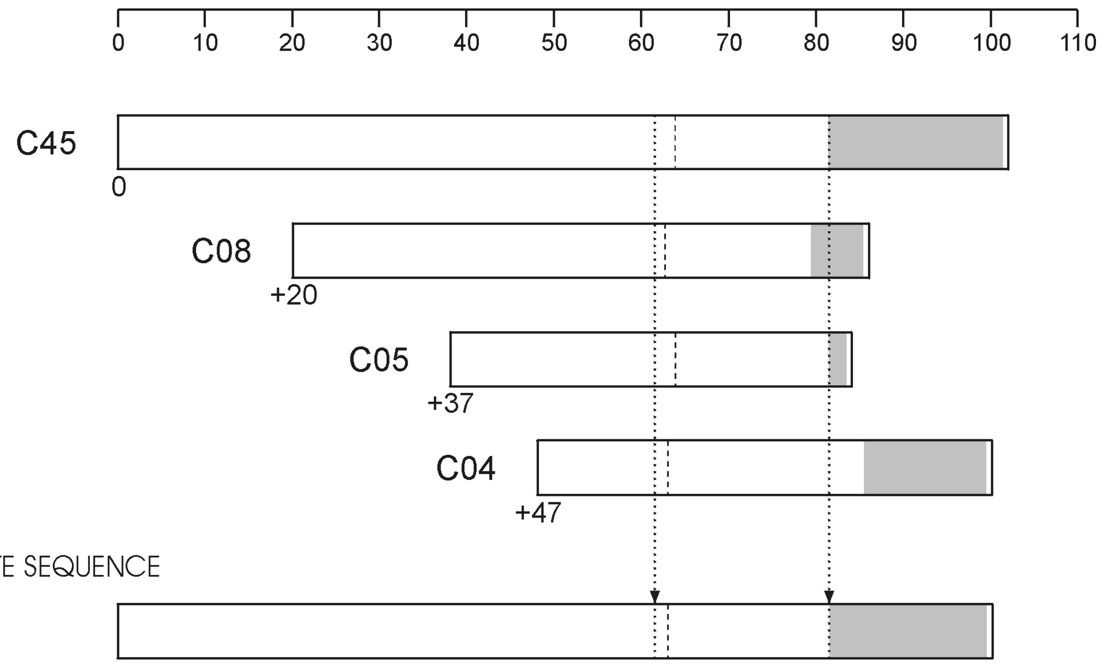


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

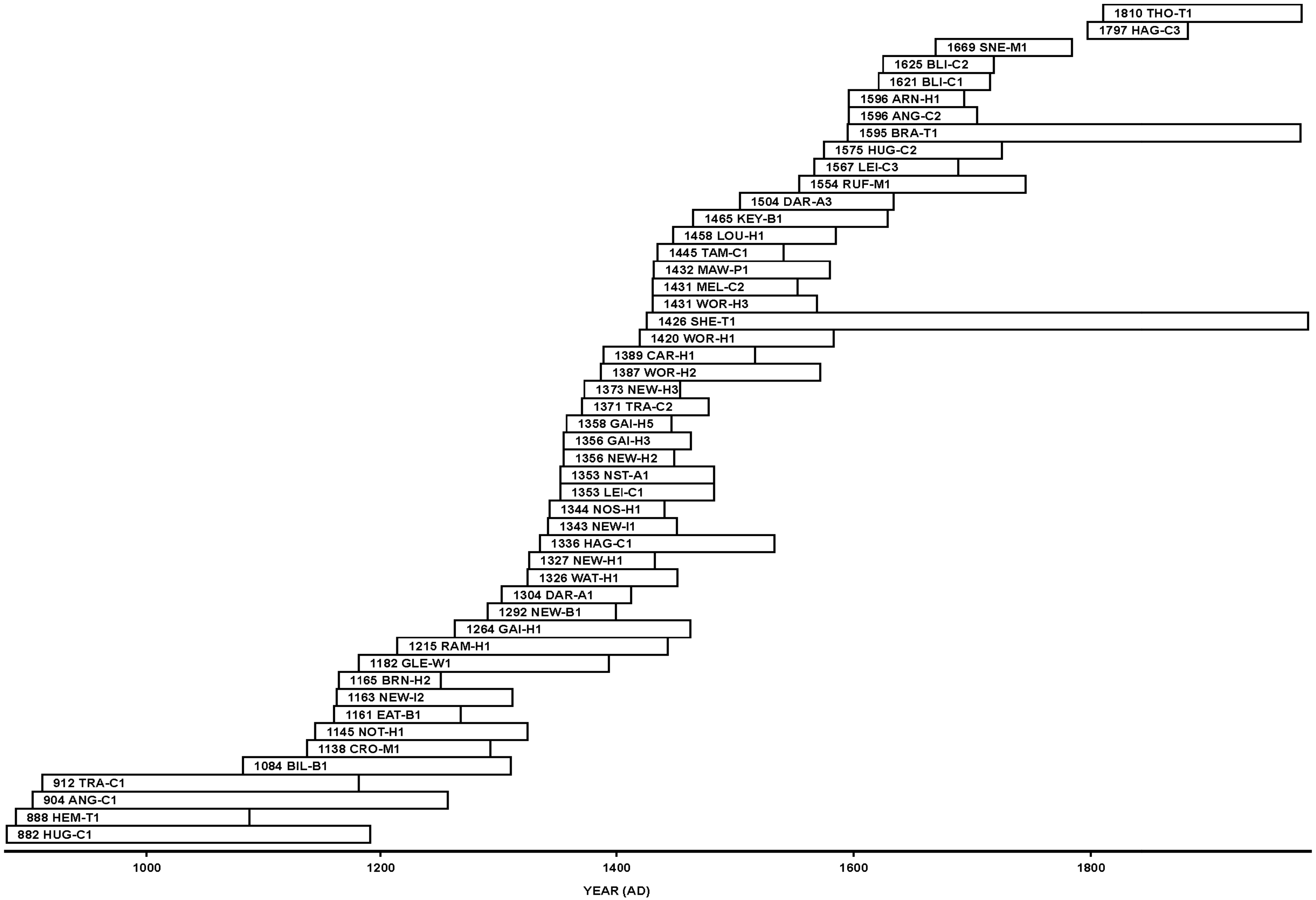
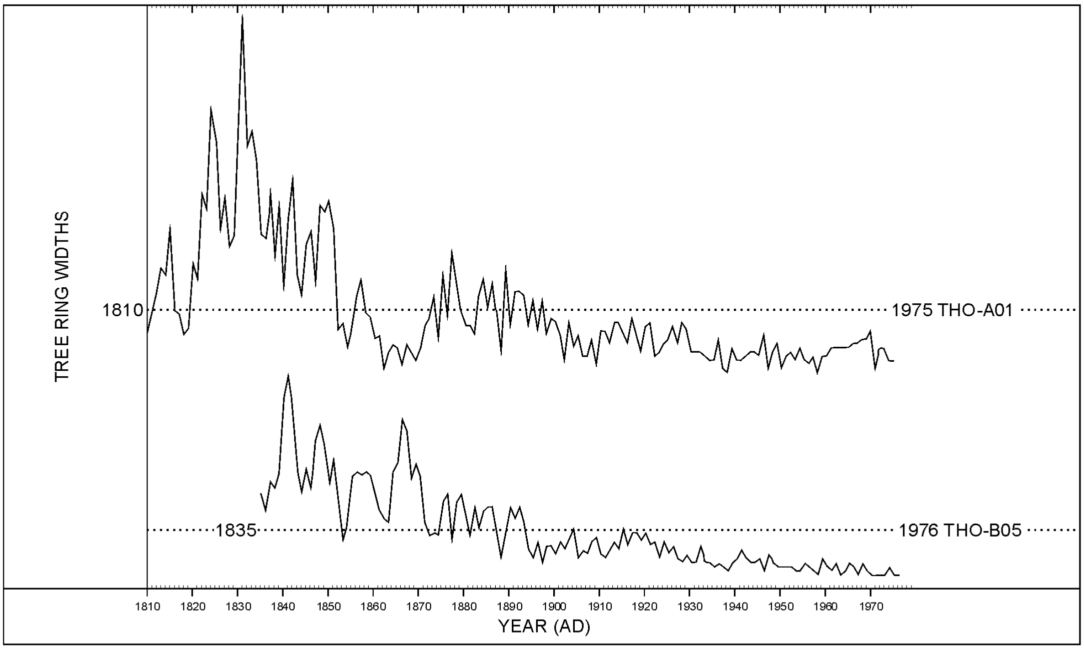


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

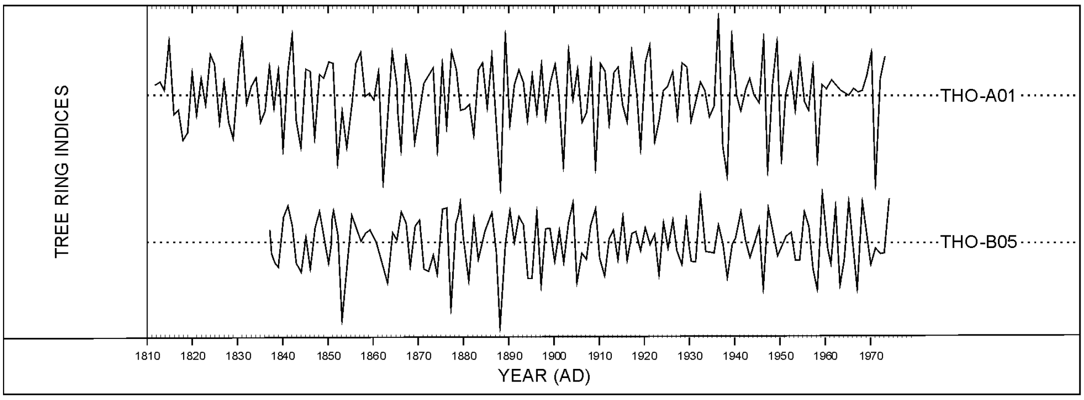


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

References

Baillie, M G L, and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-Ring Bull*, **33**, 7–14

English Heritage, 1998 *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*, London

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984–95 Nottingham University Tree-Ring Dating Laboratory results, *Vernacular Architect*, **15–26**

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1992 List 44 no 17 - Nottingham University Tree-Ring Dating Laboratory: tree-ring dates for buildings in the East Midlands, *Vernacular Architect*, **23**, 51–6.

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25–35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series **III**

Laxton, R R, and Litton, C D, 1989 Construction of a Kent master dendrochronological sequence for oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90–8

Laxton, R R, Litton, C D, and Howard, R E, 2001 *Timber: Dendrochronology of Roof Timbers at Lincoln Cathedral*, Engl Heritage Res Trans, **7**

Litton, C D, and Zainodin, H J, 1991 Statistical models of dendrochronology, *J Archaeol Sci*¸ **18**, 29–40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architect*, **28**, 40–56

Pearson, S, 1995 *The Medieval Houses of Kent, an Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London






Historic England Research and the Historic Environment

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

A good understanding of the historic environment is fundamental to ensuring people appreciate and enjoy their heritage and provides the essential first step towards its effective protection.

Historic England works to improve care, understanding and public enjoyment of the historic environment. We undertake and sponsor authoritative research. We develop new approaches to interpreting and protecting heritage and provide high quality expert advice and training.

We make the results of our work available through the Historic England Research Report Series, and through journal publications and monographs. Our online magazine Historic England Research which appears twice a year, aims to keep our partners within and outside Historic England up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.HistoricEngland.org.uk/researchreports

Some of these reports are interim reports, making the results of specialist investigations available in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation.

Where no final project report is available, you should consult the author before citing these reports in any publication. Opinions expressed in these reports are those of the author(s) and are not necessarily those of Historic England.

The Research Report Series incorporates reports by the expert teams within the Research Group of Historic England, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series

ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)